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Identification of the Groundwater Potential Recharge Zones Using MCDM Models: Full Consistency Method (FUCOM), Best Worst Method (BWM) and Analytic Hierarchy Process (AHP)

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Abstract

In arid and semi-arid regions, groundwater is considered being the most available natural resources for different water use. However, it is being limited in quantity. As such, its sustainable development and managementent depends on based on various criteria (e.g. climatic conditions, scale, aquifer properties, etc.). This study presents three multi-criteria index approaches (Analytic Hierarchy Process (AHP), Best–Worst Method (BWM), and Full Consistency Method (FUCOM) to classify groundwater potential maps in the Sarakhs Plain in North-east Iran. In this study, 10 parameters (layers) that affect groundwater potential recharge mapping (GPRM) are used using ArcGIS10.2. These layers include-ground surface elevation, surface slope, aspect, relative slope position (RSP), plan curvature, topographic wetness index (TWI), terrain ruggedness index (TRI), drainage density, landuse, and lithology. These layers and their features were assigned properweights based on the conceptual frameworks of AHP, BWM, and FUCOM techniques, and then using a weighted overlay summation process (WOSP), final maps of groundwater potential in Sarakhs plain are obtained. The developed groundwater potential maps are classified into four classes, including low, medium, high, and very-high. The results show that among the 10 driving parameters, land use, and lithology have the highest importance and the surface slope has the lowest importance in the mapping of groundwater potential recharge. The best groundwater potential zones are concentrated in northeast and southeast, central parts, and a few parts in the areas of the western regionof the Sarakhs plain due to its nearly gentle slopes with quaternary alluvial and agriculture land and lower drainage density. The obtained results are of high value for decision-makers in the Sarakhs plain in specific and for entire Iran in general to apply sustainable groundwater utilization plans.

Keywords Groundwater · GIS · Sarakhs plain · FUCOM · AHP · BWM

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1 Introduction

Worldwide, groundwater is considered an essential natural water resource. In arid and semi-arid regions, groundwater is the major available water resource for different uses (Todd and Mays 2005; Mukherjee et al. 2012). It provides water with good quality and enough quantity to sustaineconomic development (Nobre et al. 2007). In many developing countries including Iran, population has rapidly increased,thus, putting pressure on the water demand for different uses (domestic, agricultural and industrial) pose a direct threat to its groundwater resources availability (Krishna et al. 2020). In Iran, groundwater contributes to 50% of the total domestic water requirement, followed by 20% and 40% of total agricultural and industrial water demand, respectively (Arabameri et al. 2020; Naghibi et al. 2018; Barmaki et al. 2020; Panahi et al. 2017). However, groundwater quality in Iran is being deteriorated due to overexploitation and misusemainly in agriculture and urban areas. This situation urged the need to thoroughly monitorgroundwater quality in Iran (Mueller et al. 2018). Further, variations in groundwater potential due to frequent droughts, land use, and climate changes have compelled the dire need to build a national groundwater model for entire Iranto study and simulate different scenarios and to take proper and sustainable decisions accordingly at the national, regional and local scales (Arabameri et al. 2019; El-Naqa and Al-Shayeb 2008; Magesh et al. 2012; Vaux 2011; Abbaspour et al. 2009; Baghvand et al. 2010). Groundwater Recharge Potential Mapping (GPRM) imparts an effective way to identify spatial differences in groundwater recharge potential with fewer sources when compared to traditional groundwater exploration techniques, including drilling, geophysical, geological, and hydro-geological methods, which require significant costs and the use of time and human resources for field studies (Oh et al. 2011; Arabameri et al. 2019). GPRM has been substantially defined as a tool for sustainable management, systematic development, and planning of groundwaterresources (Elbeih 2015). GPRM effectively identifiesthose areasthat might be more positive for groundwater advancement inside a given topographical setting (Díaz-Alcaide 2019). The need to use the Geographic Information System (GIS) and Remote Sensing (RS) techniques for the generation of prospective groundwater recharge maps is undeniable (Lee et al. 2017; Zeinivand and Nejad 2017; Naghibi 2018).

Application of Multi-Criteria Decision Making (MCDM) methodology would substantiate to be a powerful method for prioritizing different analysis combinations and for estimating the most suitable solutions in a multi-dimensional context. An approach to MCDM is characterized as a selection process based on a collection of driving criteria to achieve one or more management objectives (Stojčić et al. 2019; Siksnelyte et al. 2018). There exist many studies in GPRM through the individual or combined application of various MCDM techniques. A broad variety of MCDM methodologies were proposed under various hypotheses during the previous decade. Some instances include the Analytical Hierarchy Process (AHP), Best–Worst Method (BWM) as well as the Full Consistency Method (FUCOM), which have been employed in this study for the assessment of possible groundwater zones (Saaty 1980a, b; Rezaei 2015, Pamučar 2018a, b, c).

A combination of AHP and Analytical Network Method (ANP) was proposed by Agarwal et al. (2013) to assess the weights (coefficients of significance) of the various themes and their grades for the estimation of prospective groundwater areas with each criterion. The methods of AHP/ANP were utilized to assess the potential groundwater areas in an Indian region (Agarwal et al. 2013). A similar approach was taken by Mundalik et al. (2018) to categorize various thematic GIS layers for preparing the groundwater potential map through the integrated approach of GIS-APH (Mundalik et al. 2018).

In the sectors of supplier segmentation, freight bundling arrangement, and technical innovation, the adoption of a modified AHP approach-BWM method has showed more accurate and consistent findings than AHP etc. (Rezaei 2015; Rezaei et al. 2015, 2016; Gupta and Barua 2016). Through the integration of the BWM method, optimum weight coefficient values are achieved in criteria pairs with fewer pairwise (only 2n-3) comparisons. During the comparison of standards, a small number of pair comparisons eliminate incoherence (Pamučar et al. 2020). The consequence of this is further affected by the fact that transitive relationships are less compromised and thus a more stable outcome is obtained. The results are more accurate (in comparison to AHP). Unlike the AHP, only reference comparisons in the BWM include determining the best criterion advantages over all other criteria and taking advantage of those other criteria over the worst criterion. It is much easier, much more precise, and removes (secondary) unnecessary comparisons (Pamučar et al. 2020).

The FUCOM method represents a novel method for determining criteria weights. The findings from FUCOM are better than those of BWM and AHP approaches because of the slightly lower number of pair-wise comparisons ($n-1$ only) if we consider the the accuracy and the necessary quantity of comparisons (Pamucar et al. 2018b).

The FUCOM application in the assessment of air traffic lines was demonstrated by Badi and Abdulshahed (2019). For the evaluation of routes of transport by road of hazardous goods, Noureddine and Ristic used the hybrid FUCOM-MABAC (Multi-Attributive Border Approximation Area Comparison) model (Noureddine and Ristic 2019). In evaluating the level crossings in installed security equipment, Pamucar et al. (2018b) presented the feasibility of the FUCOM-MAIRCA Model. Apart from the previous studies, the FUCOM was also used in the logistic field: selection of storage systems equipment, sustainable selection of suppliers, and management of supply chain (Fazlollahtabar et al. 2019; Matic et al. 2019; Prentkovskis et al. 2018; Erceg and Mularifovic 2019).

One of the major challenges in multi-criterion analysis models is the determination of the weights of parameters (Pamučar et al. 2018c). A very critical stage in the decision-making procedure is the choice of an adequately suitable method for deciding requirements for weight in the problems of MCDM. Because parameter weights can affect the outcomes of the decision-making process significantly, the objective essence of assigning weights to requirements must be given careful attention (Pamučar et al. 2018c).

MDCM methodology is growing rapidly, as it is being adapted in several sectors including logistics and in many fields such as energy, urban growth, waste handling, and passenger compliance assessment (Pamučar and Ćirović 2015; Tsafarakis et al. 2018; Milosavljević et al. 2018; Petrović and Kankaraš 2018; Liu et al. 2018; Vesković et al. 2018; Pamučar et al. 2018a; Meshram et al. 2019, 2020a, b, 2021a, b; Forootan Danesh et al. 2020; Dahmardeh Ghaleno et al. 2020; Alvandi et al. 2021). MCDM approaches are usually used to assist decision-making in the problems of many competing goals (Badi and Abdulshahed 2019).

The functional management of groundwater resources would greatly improve the welfare of the local community. In general, designing groundwater recharge prospective maps seems to have a significant impact on improving the integrated development of groundwater resources in the Sarakhs plain specifically and in entire Iran generally. A comprehensive analysis has therefore been carried out to classify possible locations of groundwater reserves for sustainable use. Accordingly, the added value of this studyis to provide decision-makers with a map that identified different groundwater potential zones through implementing RS/GIS-based MCDM approach which inturn will help them towards sustainable use of groundwater resources for different purposes in Sarakhs plain. In this work, ten driving factors namely, elevation, slope, aspect, drainage density, relative slope position (RSP), plan curvature, terrain ruggedness index (TRI), topographic wetness index (TWI), lithology, and land use were used based on the literature survey.

2 Study Area

Sarakhs plain with an area of 1953.7 Km^2 is located in the north-east Khorasan Razavi Province and the north-east of Iran and the neighborhood of Turkmenistan boundary (Fig. 1). The geospatial extent of this plain is between 60° 50′ 0″ E to 61° 7′ 0″ E longitude and from 36° 5′ 0″ N to 36° 39′ 0″ N latitude and it has an elevation of 275 m above sea level. According to the data of stations of the Sarakhs synoptic and the Pol-Khatoon evaporation, the climate of the study area is arid and cold based on the Amberje climate classification method and is arid based on the Domarten climate classification method. The average rainfall of Sarakhs plain is 226 mm, with the highest monthly rainfall in March and the

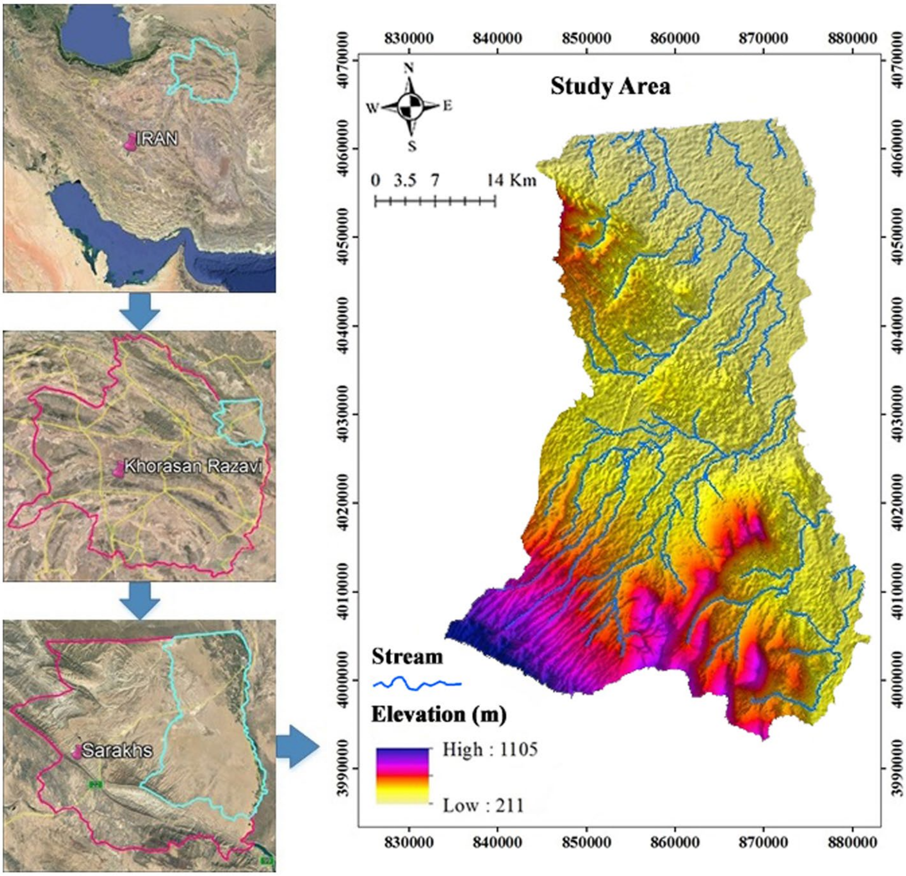

Fig. 1 Location map of the study area

lowest in summer. The maximum observed temperatures in the stations of the Sarakhs synoptic and Pal Khatoon evaporationwere + 46.6 and + 48.5 °C, respectively, related to June and July, and the minimum temperatures were − 31 and − 22.5 °C related to January and February (Azamirad et al. 2018). Regarding the geology of the study area, it can be said that almost all geological units in this area are composed of sedimentary rocks and debris sediments and do not have much variety. Surface water resources of Sarakhs plain include the permanent river of Harirud (border river of Iran and Afghanistan) and seasonal rivers of Kashafrud (river of Mashhad watershed), Shorluq, and Chakodar. One of the main problems of the study area is related to the shortage of drinking water. Based on reports of the last decade (2010–2020) of the general department of natural resources of Mashhad province, the average water level in wells from 16.65 m and the average annual potential evaporation is 1952 mm and Sarakhs plain aquifer is an unconfined type and shape from a layer of alluvial. Therefore, for compensating for the shortage of drinking water, the extraction of groundwater in the plains should be increased. GPRM provides decision-makers with an opportunity to consider vital resources that exist in pore spaces and fractures below the earth's surface in rock and sediment, and it is essential for the sustainable use of groundwater for different potential uses.

3 Material and Methods

For this study, 10 criteria (layers) i.e., slope angle, RSP, plan curvature, elevation, drainage density, slope aspect, TWI, lithology, and land use havebeen used for GPRM (Fig. 2).

- Slope angle is one of the fundamental indices to groundwater potentiality because, in low slope areas, the phenomena of water ponding are dominant on runoff generation (Chakrabortty et al. 2018; Ferozur et al. 2019). The slope map was extractedfrom a digital elevation model (DEM) of 30 m'resolution in ArcGIS 10.1 software. Low slope areas arelocated in the northern parts of the study area in the vicinity of streams (Fig. 2).
- Ground surface elevation in the study area ranges between 211 to 1105 m. Like the slope map, downstream areas play a significant role in groundwater replenishment where ponding time is high (Arabameri et al. 2019; Gaber et al. 2020) (Fig. 2).
- Relative Slope Position is an index for recognizing topography characteristics such as hill slopes, valleys, and flat areas. The range values of this parametervary between 0 for flat areas and valleys and 1 for hill slopes and rigid tops (Moghaddam et al. 2020; Razandi et al. 2015) (Fig. 2).
- Regarding plan curvature which affects flow convergence and divergence, the positive values represent convex areas whereas zero and negative values represent flat and concave areas. The concave down areas are the most susceptible areas for groundwater recharge (Chakrabortty et al. 2018; Ferozur et al. 2019; Arnous 2016) (Fig. 2).
- Drainage density is the ratio of the sum of drainage length per unit area which shows the potential of streamflow. Since drainage density is accompanyingwith groundwater aquifer properties, therefore, there is an indirect relationship between the rate of drainage density and groundwater potential recharge (Moghaddam et al. 2020; Razandi et al. 2015; Tolche 2020) (Fig. 2).
- Topographic Wetness Index has themain role in spatial zoning soil moisture. This parameteris extracted from the topographicmap and represents the ratio of upslope

area and unit contour length, as, divided by the local gradient. The higher value of this parameter ensures good groundwater potential recharge (Chakrabortty et al. 2018; Ferozur et al. 2019; Arnous 2016) (Fig. 2).

- The slope aspect is another driving parameter extracted from the topographic map. This parameter is influenced by the main precipitation direction and the physiographic trends and effect on precipitation amount and vegetation type (Moghaddam et al. 2020; Razandi et al. 2015; Tolche 2020). In the study area, the slope aspect was classified into flat and 8 other directions (Fig. 2).
- Lithology has an impact on the future recharge of groundwater because lithological changes in rock formations and subsequent soils are correlated with different values of aquiferrporosity and hydraulic conductivity. The lithologicalmap was obtained from the Iran Geology Survey (1997) (scale 1:100,000) and classified into 10 categories (Fig. 2) (Moghaddam et al. 2020; Razandi et al. 2015; Tolche 2020).
- Land use is known as the greatest determinant of groundwater production which affects permeability, runoff, and evapotranspiration (Naghibi et al. 2017; Pham et al. 2019). The land use map which is classified into 11 categories was prepared on a scale of 1:50,000 from the Natural Resources Organization of Khorasan Province (Table 1; Fig. 2).

4 Developing Groundwater Potentiality Models

In this research, integration of the 10 driving GPRM parameters is accomplished by utilizing the AHP, BWM, and FUCOM methods. The flowchart of the MCDM process has been shown in Fig. 3.

4.1 AHP Method

The AHP is one of the most commonly usedmethods in the MCDM process (Zietsman and Vanderschuren 2014; Badi and Abdulshahedb 2019). A simple decision-making strategy to deal with contradictory problems is the AHP technique (Saaty 1980a, b). The complex issues are first stratified and ordered in a hierarchical order and then graded to achieve precise weight values based on their importance (Jenifer and Jha 2017). Weights associated with the key factors were assignedtoevaluatetheinfluence of drivingfactors to groundwater recharge potential capacity. The multi-criteria AHP weighting is assigned given the linguistic scale of Saaty's 9-level (Table 2).

To ensure a representative pair-wise comparison matrix, the consistency index (CI) was determined and tested with an appropriate limit. This index is determined using Eq. 1:

$$\mathrm{CI} = \frac{\left(\lambda_{max} - \mathrm{n}\right)}{(\mathrm{n} - 1)} \tag{1}$$

where λ_{max} and n are the eigenvalue and rank of the comparison matrix and the consistency ratio (CR) was then estimatedas follows:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

Table 1 Literature review of identification of the groundwater potential zones

Groundwater potential related variables	Weight (AHP)	Weight (BWM)	Weight (FOCUM)	Reference
Slope angle (%)	0.019654	0.016044	0.022282	Chen et al. (2018); Nampak et al. (2014)
Relative Slope Position (RSP)	0.031852	0.083883	0.089185	Moghaddam et al. (2020)
Plan curvature	0.038349	0.102383	0.110105	Chen et al. (2018)
Elevation (m)	0.052977	0.099149	0.106406	Chen et al. (2018); Nampak et al. (2014)
Drainage Density	0.060312	0.098626	0.10581	Chen et al. (2018); Nampak et al. (2014)
Slope aspect	0.081776	0.098638	0.105823	Khosravi et al. (2018); Chen et al. (2018)
Topographic Wetness Index (TWI)	0.129242	0.093908	0.10045	Chen et al. (2018); Nampak et al. (2014)
Topographic Roughness Index (TRI)	0.158538	0.094639	0.101278	-
Lithology	0.209452	0.114109	0.123672	Chen et al. (2018); Nampak et al. (2014)
Land Use	0.217848	0.19862	0.13499	Chen et al. (2018); Nampak et al. (2014)

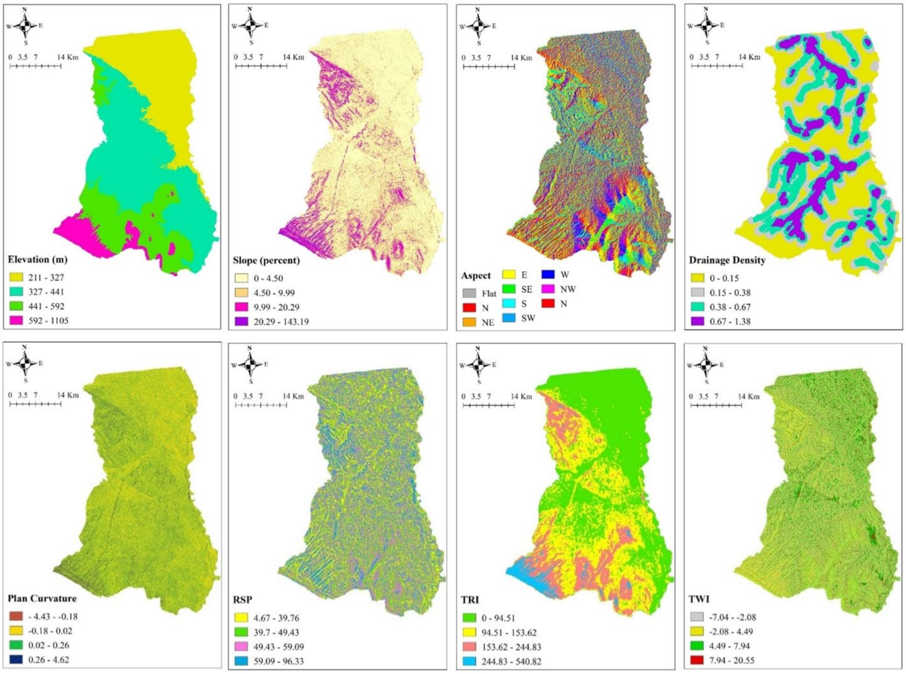

Fig. 2 Parameters used for the mapping of groundwater potential in the Sarakhs plain

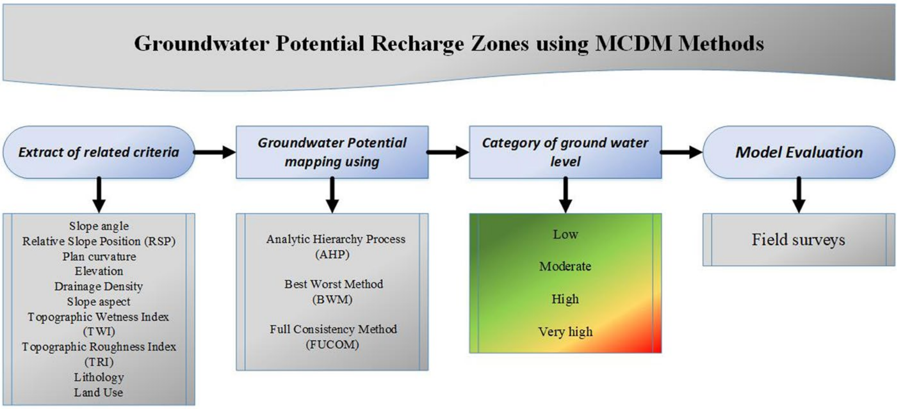

Fig. 3 Flowchart of the used methods

where CI is the consistency index, and RI is the random index which depends on the number of criteriaused in the pair-wise matrix (Saaty 1980a, b).

Table 2 The comparison scale between two criteria (Saaty 1980a, b)

Preference factor	Degree of preference	Explanation
1	Equally	Two factors contribute equally to the objective
3	Moderately	Experience and judgment slightly to moderately favor one factor over another
5	Strongly	Experience and judgment strongly or essentially favor one factor over another
7	Very strongly	A factor is strongly favored over another and its dominance is shownin practice
9	Extremely	The evidence of favoring one factor over another is of the highest degree possible of an affirmation
2,4,6,8	Intermediate	Used to represent compromises between the preferences in weights1, 3, 5,7and 9
Reciprocals	Opposites	Used for inverse comparison

4.2 Best Worst Method (BWM)

BWM can effectively tackle the inconsistency derived from pair-wise comparisons as one of the new MCDM methods. Compared to other subjective approaches, such as the AHP, ANP, and Basic Multi-Attribute Rating Technique (SMART), this approach is more reliable (Rezaei 2015). BWM has been used in numerous research areas, including the selection and creation of suppliers; water management; complex bundling configurations; the application of urban sewage sludge; social sustainability of supply chains; assessment of logistics performance; identification of success factors; selection of cloud services; evaluation of doctoral projects from the university–industry (Yucesan and Gul 2019).

The BWM process structure and basic steps are as follows (Rezaei 2015):

Step 1. Common collection and identification of criteria; analysis of literature, expert ideas, and other possible forms.
Step 2. Determining and choosing the best and worst parameters based on the ideas and views of experts.
Step 3. Design the preference matrix by adding numbers ranging from 1 to 9 based on the contrast of the best criterion over all others.

$$\mathrm{A_b} = \left(\mathrm{a_{1B}}, \mathrm{a_{2B}}, \mathrm{a_{3B}}, \ldots, \mathrm{a_{nB}}\right) \tag{3}$$

Step 4. Designing the preference matrix by adding numbers between 1 and 9 based on comparing the worst criterion to all others.

$$\mathrm{A_b} = \left(\mathrm{a_{1W}}, \mathrm{a_{2W}}, \mathrm{a_{3W}}, \ldots, \mathrm{a_{nW}}\right) \tag{4}$$

Step 5. Via the estimation of final and optimum weights $\left(\mathrm{w}_1^*, \mathrm{w}_2^*, \mathrm{w}_3^*, \ldots, \mathrm{w}_n^*\right)$ by solving the following optimization model, finding the relative value of parameters.

$$Minmax_{\mathrm{j}} = \left\{ \left|\left(\mathrm{w_B}/\mathrm{w_j}\right) - \mathrm{a_{Bj}}\right|, \left|\left(\mathrm{w_j}/\mathrm{w_w}\right) - \mathrm{a}_{j\mathrm{w}}\right| \right\} \tag{5}$$

Subject to $\sum_{\mathrm{j}} \mathrm{w_j} = 1$

It is easy to convert Model (3) to Model (4) to find out the optimal weights $\left(\mathrm{w}_1^*, \mathrm{w}_2^*, \mathrm{w}_3^*, \ldots, \mathrm{w}_n^*\right)$ and the optimal reliability level value (ξ^*)

$$\begin{gathered} Min\xi \\ \left| \begin{array}{l} \frac{W_B}{W_j} - a_{Bj} \,| \leq \xi \; for\; all\; j \\ \frac{W_j}{W_w} - a_{jw} \,| \leq \xi \; for\; all\; j \end{array} \right. \\ \sum_j w_j = 1 \\ w_j \leq \; 0 \, for\; all\; j \end{gathered}$$

where,w_B and w_w represent the weights, respectively, of the best and worst parameters. $\mathrm{a_{Bj}}$ is the preference over criterion j for the most relevant (best) criterion and $\mathrm{a_{jw}}$ is the preference over the worst(least important) criterion for criterion j.

Step 6:Consistency ratio ($\mathrm{K_{si}}$) estimation to check the degree of reliability of the pair-wise comparisons using Eq. (4). A consistency index (CI), as shown in Table 3,

Table 3 CI values for BWM method

a_{BW}	1	2	3	4	5	6	7	8	9
CI($max\xi^*$)	0	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

helps to evaluate the K_{si} value, just like the AHP process. The K_{si} values vary between 0 (higher consistency) to 1 (lower consistency).

$$K_{si} = \frac{\xi^*}{CI} \tag{6}$$

In Table 2, $\dashv_{BW}$ shows that the best criterion is chosen over the worst criterion. It is important to note that CR is basically utilizedto validate the comparisons in the AHP process, but its primary role in BWM to find the levelof reliability of pair-wise comparisons, thereby providing more reliable outcomes. In addition, by forming comparison-vectors, the BWM employs far fewer comparisons ($2n$-3). Compared to the weights derived from the AHP process, this phenomenon guarantees greater reliability of the weights obtained by BWM (Rezaei 2015). These advantages of the BWM approach have provided the basis for choosing it to solve complex problems (Rezaei 2015). In addition to this, no fractional numbers are used in BWM, which makes DMs easier to calculate. Rezaei (2015) statistically verified that, in terms of CR, absolute divergence and consensus, BWM measures parameters weights substantially better than AHP.

4.3 Full Consistency Method (FUCOM)

The FUCOM is based on the concepts of contrast in pairs of parameters and results from validation as the AHP and BWM methods by deviating from the full consistency (Pamučar et al. 2018a). The benefits of applying the methods of FUCOM are: (1) a limited number of contrasts in pairs of parameters (only n-1 comparison), (2) the possibility of validating the outputsby specifying the variance from the maximum accuracy of the comparison; (3) the possibility of taking transitivity into account in the comparison of pairs of criteria; and (4) the removal of the question of the redundancy of comparisons in pairs of criteria existingin such subjective methods for the calculation of criteria weights. The procedure for obtaining the weights of different criteria is as follows:

Step 1. The parameters are graded according to their importance.

$$C_{j(1)} > C_{j(2)} > \cdots > C_{j(k)} \tag{7}$$

where,k represents the rank of the criterion observed. If there is a decision that two or more criteria of the same meaning exist, the sign of equality is put in the expression instead of " > " between these criteria (Eq. 1).

Step 2. Determining, as in the expression (7), the vectors of the comparative importance of assessment criteria:

$$\phi = \varphi_{1/2}, \varphi_{2/3}, \dots, \varphi_{k/(k+1)} \tag{8}$$

where $\varphi_{k/(k+1)}$ reflects the value (priority) that the $C_{j(k)}$ rank criterion has relative to the $C_{j(k+1)}$ rank criterion.

Step 3. The final weight values of the assessment criteria are determined $\left(w_1, w_2, \dots, w_n\right)^T$ which must meet two limitations:

Restriction 1: The ratio of the criterion's weight equals the comparative importance of the criterion observed, i.e.

$$\frac{W_k}{W_{k+1}} = \varphi_{k/(k+1)} \tag{9}$$

Restriction 2: The calculated weights should satisfy the mathematical transitivity condition, i.e.

$$\varphi_{k/(k+1)} \otimes \varphi_{(k+1)/(k+2)} = \varphi_{k/(k+2)} \tag{10}$$

Step 4. Defining a model for the determination of the final criterion weights.

$$\begin{gathered}
\min \ \chi \\
s.t \\
\left|\frac{W_j(k)}{W_j(k+1)} - \varphi_{\frac{k}{(k+1)}}\right| \le \ \chi, \ \forall j \\
\left|\frac{W_j(k)}{W_j(k+1)} - \varphi_{\frac{k}{(k+1)}} \otimes \ \varphi_{\frac{k+1}{k+2}}\right| \le \chi, \forall j \\
\textstyle\sum_{j=1} \ W_j = 1, \forall j \\
W_j \ge \ 0, \forall j
\end{gathered}$$

Step 5. Calculation of the final values of the criteria/sub-criteria assessment $\left(\mathrm{W}_1, \mathrm{W}_2, \ldots, \mathrm{W}_\mathrm{n}\right)^\mathrm{T}$.

5 Result and Discussions

Based on weights of the criteria which were calculated using the aforementioned methodological approach of the AHP, BWM, and FOCUM methods, it can be found that among all used criteria, land use and lithology are the most important criteria for spatially predicting groundwater recharge, whereas slope angle has the lowest weight which these resultsareconsistent with the resultsobtained by Rahmati et al. (2018); Chen et al. (2018); Moghaddam et al. (2020) and Mukherjee and Singh (2020), thus, corroborating that the land use and lithology are known as most effective criteria to identify groundwater potential recharge sites. After assigning weights to used criteria, groundwater potential maps were developed for the Sarakhs plain area as presented in Fig. 4. Based on the natural breaks approach (under the ArcGIS 10.7 software), the study area was divided into four classesof groundwater potential recharge zones. These are low, moderate, high, and very-high.

Based on Fig. 4, For the AHP, BWM, and FOCUM methods, the areas (%) of the four groundwater potential recharge zones together with the number of wells located in each class in the study area are tabulated in Table 4. From Table 4, it is found that the general spatial extend of groundwater potential recharge in the study area is almost the same asthe three methods. Low to moderate potential recharge areas are mostly located in the northwest and southwest parts of the study area. However, most of the study area is under high to very-high groundwater potential recharge areas which are concentrated in eastern and central parts and few portions in the western parts of the study area, cover 70%, 66%, and 69% of the study area respectively, where all groundwater wells located (20 wells).

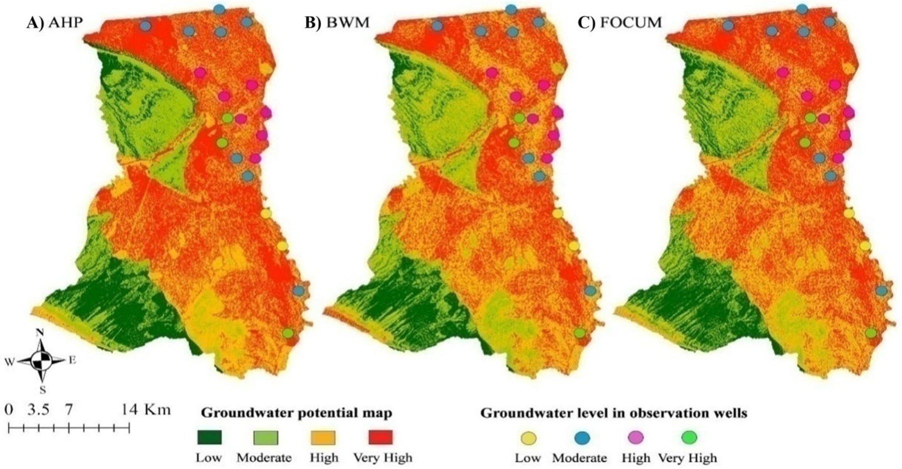

Fig. 4 Groundwater potential recharge maps using AHP, BWM, and FOCUM Methods

Conformity and overlap of groundwater potential maps (Fig. 4) with driving parameters for the mapping of groundwater potential (Fig. 2) shows that zones with high and very-high groundwater potential are mostly located in quaternary units and limestone, urban areas, agricultural lands, and rangelands, concave slopes, flat or low-slope areas, north directions, the highest value of topographic wetness index and the lowest values of terrain ruggedness index, relative slope position and drainage density.

The high groundwater potential in quaternary alluvial because of their high infiltration rate has been approved by Mukherjee and Singh (2020). Also, most of the urban areas, agricultural lands, and rangelands of Sarakhs plain are located on these sediments and are composed of sand, rubble, etc. Dense forest lands and agriculturallands in the study of Dar et al. (2020) are having the excellent capability to recharge and hold the groundwater. Grassland, agricultural lands and recent alluvium in high groundwater potential (Biswas et al. 2020). Further carbonate rocks have a great ability to penetrate and transfer groundwater resources. The lithology of carbonate rocks affects their porosity and permeability.

According to geophysical researches, most groundwater recharge of Sarakhs plain is done along the old bed of HarirroodRiver which is currently covered by alluvium. Furthermore, the main streams have a significant impact on groundwater recharge and potential.

Table 4 Comparison of area (%) and number of wells of different groundwater potential recharge zones through AHP, BWM, and FOCUM methods in the Sarakhs plain

Class	AHP		BWM		FOCUM	
	Area (%)^1	Number of wells	Area (%)^1	Number of wells	Area (%)^a	Number of wells
Low	13	–	12	–	13	–
Moderate	17	–	22	–	18	–
High	30	6	33	9	33	6
Very high	40	14	33	11	36	14

[a] Area of each groundwater potential class to the total study area.

Also, these quaternary units are located at low altitudes and on low slopes (less than 5%) which are the result of sedimentary load deposition of streams in sedimentation areas in flood conditions and have a high penetration rate. The previous studies have confirmed the high potential of groundwater recharge in flat or low-slope areas (Mukherjee and Singh 2020; Falah and Zeinivand 2019; Abd Manap et al. 2014; Patra et al. 2018). The northern directions are also less exposed to sunlight, so there is less evaporation and more time for infiltration and transfer of precipitation to groundwater sources.

Eventually, to estimate the accuracy of the three methods, the location map of the wells in the plain has been used. By comparing the wells map with the estimated potential maps, it was found that the existence of wells corresponds to zones with high and very high potential, which indicates the high accuracy of these three methods in producing groundwater potential maps.

The main point must be considered is related to similar results of used subjectively methods. However, these results show the superiority of the FUCOM and BWM methods rather than AHP method. In FUCOM for calculating the criteria weights of a problem with n criteria (in here criteria for groundwater potential recharge) only requires the (9) pairwise comparison of criteria whereas for BWM and AHP methods, this pairwise comparison will be reached to (17) and (45), respectively. Generally, in the AHP and BWM methods, the number of the required pair-wise comparisons are increasingsignificantlywith the number of parameters to be compared and in this state, the uncertainty of the considers will be increased (Ildoromi et al. 2019; Sepehri et al. 2020).

6 Conclusion

The present study presents three multi-criteria index approaches including AHP, BWM, and FUCOM methods to develop groundwater potential recharge maps in the Sarakhs Plain in the northeast of Iran. In this study, the 10 driving parameters (criteria) were identified and used. In three AHP, BWM and FUCOM methods, among the 10 mentioned parameters, land use and lithology parameters have the highest weight and slope parameter has the lowest weight. The best groundwater potential recharge zones are concentrated in northeast and southeast, central parts, and few parts in the west sidesof the study area. This can be attributedtotheflat terrain nature with quaternary alluvial and agriculturalland and lower drainage density. About 70% of the total area of Sarakhs plain has high and very-high groundwater potential recharge, and about 30% has a moderate and low potential for groundwater existence.

The results obtained during this work, in turn, will positively impact the sustainability of the existing groundwater wells to potential fulfill the water demand of local communities for different uses. Moreover, digging new groundwater wells hasto be avoided in the low groundwater potential recharge areas which are mostly located in the southeastern parts of Sarakhs plain. This argues the necessity to apply more sustainable water supply options (e.g., surface water) in the low groundwater potential recharge areas to fulfill water needs therein.

Generally, preparing groundwater potential mapsdoes not mean that in zones with high potential, there are more wells and more water resources, or vice versa. These results show only the percentage of probabilities and approximate positions of water resources. To obtain more accurate information about groundwater resources, more detailed studies such as exploratory experiments should be performed, which naturally requires a lot of time and cost.

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Data Availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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