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Integrating Geographic Information Systems and Multi-Criteria Decision Analysis for Evaluating Artificial Groundwater Recharge

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Abstract
The excessive exploitation of groundwater has led to a significant decline in water levels in recent years, emphasizing the need for sustainable water resource management strategies. Artificial groundwater recharge has emerged as an effective solution to address this challenge. This study integrates Geographic Information System (GIS) and Multi-Criteria Decision Analysis (MCDA) techniques to identify suitable areas for artificial groundwater recharge in the Ardabil plain, located in northwest Iran. Key parameters, including geology, slope, unsaturated zone thickness, soil texture, specific yield, drainage density, and land use, were analyzed. These parameters were weighted using three methodologies: Analytic Network Process (ANP), Analytic Hierarchy Process (AHP), and Fuzzy Analytic Hierarchy Process (FAHP). The final suitability map was developed by overlaying and combining the weighted information layers. The analysis revealed that 53.3%, 6%, and 42% of the plain area were classified as "very good" for artificial recharge according to the AHP, FAHP, and ANP methods, respectively. The southern part of the plain was consistently identified as a suitable area across all methods, characterized by pasture lands with young alluvial sediments, a deep unsaturated zone, gentle slopes, low drainage density, and high specific yield. To evaluate the performance of these methods, the results were cross-validated against natural recharge estimates, considering factors influencing water level fluctuations and recharge rates. Among the methods, ANP demonstrated the highest consistency with natural recharge estimates, making it the preferred approach.

Keywords Groundwater management · Multi-criteria decision making · Decision support system

Extended author information available on the last page of the article

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1 Introduction

Iran, with its unique geographical location, lies within arid and semi-arid regions, experiencing significant climatic variability. The country faces challenges such as low annual rainfall, poor spatial and temporal distribution of precipitation, and episodes of intense rainfall that often result in destructive floods, causing substantial loss of life, property, and natural resources (Pakparvar et al. 2023; Saleh et al. 2023; Hayati et al. 2006). These recurrent droughts and catastrophic floods underscore the urgent need for effective water resource management strategies. Key approaches include surface water collection, groundwater recharge, and regulated water use and conservation. Among these, artificial recharge of aquifers stands out as a crucial solution to mitigate the quantitative and qualitative depletion of groundwater reserves. This process involves the deliberate infiltration of water through the soil, allowing it to percolate downwards through the unsaturated zone to replenish groundwater (Bouwe 2002). To ensure the success of artificial recharge initiatives, thorough preliminary studies and the careful selection of criteria for site identification are essential. Accurately and efficiently identifying suitable areas for artificial groundwater recharge is critical for optimizing water resource management.

The first operational step in managed aquifer recharge is selecting suitable sites, which requires consideration of multiple interacting factors, such as soil texture, slope, unsaturated zone thickness, and drainage density. Multi-Criteria Decision Analysis (MCDA) offers an effective approach for integrating and analyzing these factors while considering technical, economic, and environmental aspects. A variety of MCDA methods have been developed, including the Analytic Network Process (ANP), Analytic Hierarchy Process (AHP), and Fuzzy Analytic Hierarchy Process (FAHP). These methods have been applied across diverse scenarios, from evaluating ecological suppliers (Shen et al. 2013) to ranking optimal sites for artificial aquifer recharge (Kim et al. 2013). Comprehensive reviews of these methods and their applications are available in Kiker et al. (2005) and Sallwey et al. (2019).

The geospatial dimension of site selection highlights the critical role of Geographic Information Systems (GIS) combined with MCDA in spatially analyzing relevant factors and generating site suitability maps. Numerous studies have demonstrated the advantages of integrating GIS and MCDA for site selection and land allocation. For example, Sheikhipour et al. (2018) proposed a hybrid MCDA model for sustainable aquifer management, while Al-Weshah and Yihdego (2018) employed a multi-criteria approach to evaluate, rank, and select remediation options. Al-Abadi et al. (2020) identified groundwater recharge zones in southern Iraq using a GIS framework with AHP and TOPSIS methods. Jahangirzadeh and Ghanbarzadeh Lak (2021) used the ELECTRE I method, integrated with GIS, to determine optimal sites for floodwater spreading and artificial aquifer recharge. Similarly, Mohieldeen et al. (2021) employed a GIS-based framework for artificial aquifer recharge to secure sustainable water reserves in Qatar's arid peninsula. Other examples include Makonyo and Msabi (2021), who identified groundwater recharge zones in the Manyara fractured aquifer using GIS and AHP, and Hussaini et al. (2022), who combined GIS and MCDA techniques to locate optimal areas for managed aquifer recharge in Kabul, Afghanistan. Recent advancements include Papadopoulos et al. (2022), who introduced a hybrid fuzzy MCDA methodology for selecting Managed Aquifer Recharge (MAR) sites using floodwaters, and Al Saud (2023), who mapped groundwater recharge zones in Saudi Arabia using multi-criteria analysis and satellite imagery. Mouhoumed et al. (2023) applied an integrated FAHP and TOPSIS approach to delineate site suitability maps for artificial recharge in Kayseri, Turkey. Finally, Kodihal and Akhtar (2024) utilized Ordered Weighted Averaging (OWA) and AHP to identify sustainable recharge zones, demonstrating that the AHP-OWA combination significantly enhances the robustness of decision-making.

In the Ardabil Plain, located in northwestern Iran, the overexploitation of groundwater resources, coupled with increasing demands for agricultural, domestic, and industrial uses, has led to a significant decline in the water table and a reduction in aquifer capacity (Ghafari et al. 2018, 2021). This issue is further exacerbated by reduced atmospheric recharge due to prolonged water scarcity and recurrent droughts. To protect and sustainably manage the alluvial aquifer of the Ardabil Plain, a long-term and optimal management strategy is crucial. This study aims to identify suitable areas for artificial groundwater recharge in the Ardabil Plain by integrating GIS and MCDA methods. The analysis incorporates key factors such as geology, unsaturated zone thickness, slope, soil texture, specific yield, drainage density, and land use. A novel aspect of this research is the comparative evaluation of different MCDA methods for estimating artificial groundwater recharge. To validate these methods, the study utilizes results from natural recharge estimations in the Ardabil Plain (Ghafar 2015). Since natural factors such as slope, geology, and soil texture influence recharge rates and groundwater level fluctuations, the most accurate method is expected to align closely with natural recharge estimations.

2 Materials and methods

2.1 Study area

The Ardabil Plain, located in northwestern Iran, covers an area of approximately 1,097.27 km² and lies within the geographic coordinates of 48°08'45" to 48°37'30" E longitude and 38°02'15" to 38°31'00" N latitude. Situated in the central part of Ardabil Province, the plain is bordered by the elevated terrain of the Alborz Mountain range (Talesh Heights) on the eastern slopes of Mount Sabalan. Its only natural outlet is to the northwest, where the Qarasu River drains the area.

The plain receives recharge from multiple sources, including groundwater inflow at its boundaries, surface runoff from adjacent sub-basins, and several critical rivers, such as the Balkhloo, Ghori, Hir, Namin, Narges, Sola Chai, and Noran, all of which contribute to the Qarasu River system. Elevation across the plain ranges between 1,300 and 1,500 m above sea level (masl), with slopes varying from 0 to 60%. The flattest areas, with slopes between 0% and 2%, are located in the central portions of the plain, while the slopes increase toward the surrounding mountainous periphery.

The central region is predominantly an alluvial plain, encircled by higher elevations. Figure 1 provides a visual representation of the Ardabil Plain and its geographic setting.

The selection of effective criteria for identifying suitable areas for artificial recharge in the Ardabil Plain was guided by a comprehensive review of the literature, relevant research findings, and expert opinions. The key criteria included geology, unsaturated zone thickness, slope, drainage density, soil texture, specific yield, and land use. Maps corresponding to each criterion were classified, integrated, and weighted within a GIS environment using the ANP, AHP, and FAHP methodologies.

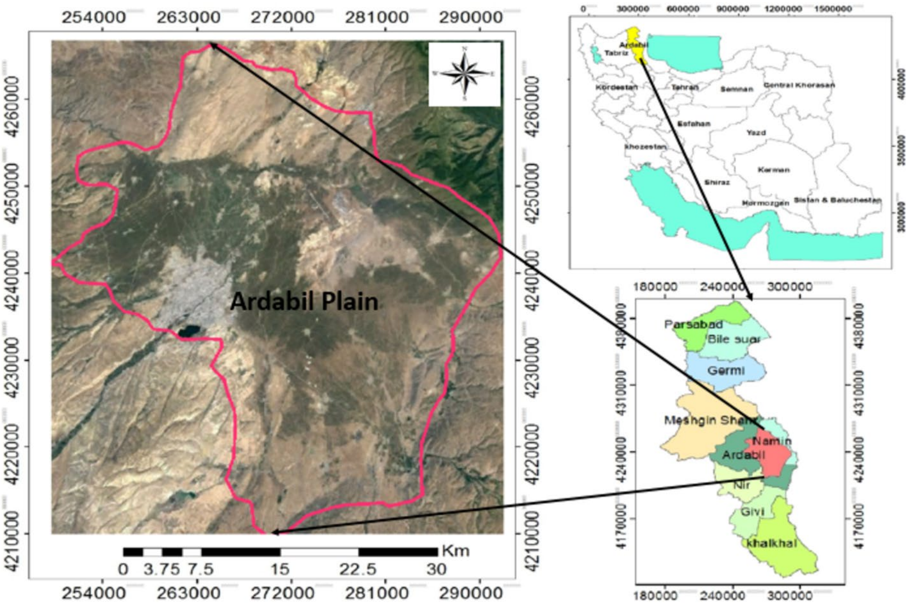

Fig. 1 Location of the Ardabil Plain

2.1.1 Geology

Geological assessments play a critical role in evaluating the suitability of sites for artificial recharge, as geological conditions significantly influence water resource availability and behavior. Coarse-grained and calcareous alluvium are particularly favorable for aquifer formation due to their high permeability, discharge capacity, and substantial storage potential. Granular materials (such as sand) and fractured or karst formations generally exhibit superior hydraulic conductivity and water transfer efficiency (Chowdhury et al. 2010).

To develop the geological map for the study area, we utilized the 1:200,000 scale map provided by the Geological Survey of Iran (GSI). This map was processed using ArcGIS 10.1, producing a raster layer that was subsequently classified into four distinct categories (see Table 1).

2.1.2 Slope

Slope is a critical factor that influences both flooding and permeability. Research indicates that areas with slopes of less than 5% are generally optimal for flood spreading and artificial recharge (Krishnamurty et al. 1996). In contrast, steeper slopes are less suitable due to their propensity to increase runoff, erosion, and soil instability, potentially compromising the security of recharge basins (Kallali et al. 2007).

For the Ardabil Plain, slope suitability was assessed using a Digital Elevation Model (DEM) with a 20-meter resolution. The resulting slope map was processed and classified into five categories using ArcGIS 10.1, as detailed in Table 1.

Table 1 Classification and properness of effective criteria for artificial recharge

Criterion	Sub-criterion	Recharge prospect
Geology	Younger alluvium	Excellent
	Older alluvium	Appropriate
	Conglomerate	Moderate
	Others	Poor
Slope (%)	0–1	Excellent
	1–3	Appropriate
	3–5	Moderate
	5–8	Poor
	8–62	Highly poor
Drainage density (km km^{-2})	0–1	Excellent
	1–2	Appropriate
	2–3	Moderate
	3–6	Poor
	6–10	Highly poor
Unsaturated zone thickness (m)	0–8	Poor
	8–15	Moderate
	15–25	Appropriate
	25–54	Excellent
Soil texture	Gravelly clay loam	Excellent
	Clay loam	Appropriate
	Calcareous clay loam	Moderate
	Salinity clay	Poor
	Shallow sandy loam	Highly poor
Specific yield (-)	0.013–0.04	Poor
	0.04–0.07	Moderate
	0.07–0.1	Appropriate
	0.1–0.21	Excellent
Land use / cover	Grassland	Excellent
	Forest	Appropriate
	Lake	Appropriate
	Wastelands	Moderate
	Road	Poor
	Agriculture	Poor
	Mountain	poor
	Urban areas	Highly poor

2.1.3 Drainage density

The drainage density, denoted as μ [L L^{-2}], is defined as the ratio of the total length of all waterways in a watershed to its area. This metric is directly related to the maximum discharge within the watershed and is calculated as follows:

$$\mu = \frac{\sum L}{A} \tag{1}$$

where L and A represent the length of waterways and area of the basin, respectively.

Drainage density and permeability exhibit an inverse relationship. Low-permeability rocks reduce infiltration, resulting in greater surface runoff concentration and the formation of more well-defined drainage systems. As a result, drainage density serves as an indirect indicator of an area's suitability for artificial recharge.

To create the drainage density map, a 20-meter resolution layer of waterways was utilized. This raster layer was processed and classified into five categories using ArcGIS 10.1 (see Table 1).

2.1.4 Unsaturated zone thickness

The thickness of the unsaturated zone plays a critical role in the effectiveness of artificial recharge. A thin unsaturated zone may lead to rapid drainage, while a thicker zone suggests extended water pathways and increased water retention. However, an excessively thick unsaturated zone may be unsuitable for recharge applications. In areas where the alluvium layer is thin, infiltrated water may reach the bedrock, provided other conditions are favorable. Conversely, in alluvial regions with shallow bedrock, ponded water can cause significant environmental challenges, underscoring the importance of this criterion.

To determine the unsaturated zone thickness, statistical data from 26 piezometric wells within the study area were analyzed. These data points were georeferenced in ArcGIS 10.1 using their coordinates. A continuous thickness map was then generated through kriging interpolation and classified into four categories, as detailed in Table 1.

2.1.5 Soil texture

Soil characteristics play a crucial role in the infiltration of surface water (Selvam et al. 2016). Soils with high clay content generally have low permeability, whereas medium-textured soils are often more suitable for artificial recharge due to their optimal balance between infiltration and water retention (Fernández-Gálvez et al. 2019).

To evaluate soil suitability for recharge in the study area, a soil texture map derived from land resource and capacity assessment studies conducted in 1994 (Ghafari et al. 2021) was utilized. This map was processed into a raster layer using ArcGIS 10.1 software and classified into five distinct categories, as detailed in Table1.

2.1.6 Specific yield

Specific yield represents the volume of water released from an aquifer due to drainage and reductions in water level. Coarse-grained sediments generally exhibit higher specific yield compared to fine-grained sediments, indicating greater storage capacity within the aquifer (Singh et al. 2013).

In this study, specific yield values were obtained from data collected at 26 piezometric wells within the study area (Ghaffari 2015). These values were input as point data into ArcGIS 10.1, interpolated using the kriging method, and subsequently classified into four distinct categories, as detailed in Table1.

2.1.7 Land use

Certain land uses, such as residential areas, agricultural fields, gardens, and salt marshes, can restrict groundwater recharge. In contrast, pasturelands are particularly favorable for water catchment initiatives due to their optimal conditions for infiltration and recharge.

The land use map for the study area was created using Google Earth and converted into a raster layer. This layer was subsequently classified in ArcGIS 10.1, with the classification details provided in Table 1.

2.2 Integrating thematic layers

Various methods can be used to integrate thematic layers in site selection processes. In this study, three approaches—Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), and Fuzzy Analytic Hierarchy Process (FAHP)—were applied to identify suitable areas for artificial recharge. Criteria and sub-criteria were evaluated and weighted for each model based on expert opinions. Consistency coefficients were calculated using Super Decisions and MATLAB software to ensure reliability. The final weights derived from these analyses are presented in the subsequent tables. A summary of each method is provided below.

2.2.1 Analytic Hierarchy Process, AHP

The AHP, introduced by Saaty in the 1970s, is one of the most widely used tools in Multi-Criteria Decision Analysis (MCDA) (Latinopoulos et al. 2012). This method facilitates the hierarchical structuring of complex problems, enabling the integration of both quantitative and qualitative factors into the decision-making process (Saat 1980). A key advantage of AHP lies in its use of pairwise comparisons, which simplifies judgments and calculations while providing a mechanism to assess the consistency of decisions. Notably, AHP quantifies the degree of consistency and inconsistency in decision-making, which is particularly important in MCDA applications.

The AHP process involves three main steps: (1) constructing a hierarchical tree to graphically represent the problem, (2) performing pairwise comparisons to establish the relative weights of the criteria, and (3) calculating the consistency ratio to evaluate the reliability of the pairwise comparison matrices. In this study, all relevant parameters were weighted using the AHP method, and the results are detailed in Table 2.

2.2.2 Analytic Network Process, ANP

The ANP, developed by Saaty (2001) as an extension of the Analytic Hierarchy Process (AHP), replaces the hierarchical structure with a network-based approach. ANP retains all the strengths of AHP, such as simplicity, flexibility, and the ability to incorporate both quantitative and qualitative criteria. However, it surpasses AHP by accounting for complex relationships, including interdependencies and feedback loops among elements, through a network structure (Garcia-Melon et al. 2008).

ANP models problems as networks composed of criteria, sub-criteria, and options, organized into clusters. Unlike AHP, which relies on a strictly hierarchical structure, ANP allows for interactions both within and between clusters, enabling feedback and mutual influences among elements. The ANP framework comprises two main components: (1) the control hierarchy, which defines the relationships among objectives, criteria, and sub-criteria, and (2) the network communication, which addresses dependencies among elements and clusters.

The results of the weighting process using the ANP method are provided in Table 3.

Table 2 Assigned and normal weights for artificial recharge by the AHP method

Criterion	Normalized weight	Sub- criterion	Assigned weight	Normalized weight
Geology	0.245	Younger alluvium	5	0.417
		Older alluvium	4	0.333
		Conglomerate	2	0.167
		Others	1	0.084
Slope (%)	0.194	0–1	6	0.333
		1–3	5	0.278
		3–5	4	0.222
		5–8	2	0.111
		8–62	1	0.056
Drainage density (km km-^{2})	0.095	0–1	5.5	0.324
		1–2	4.5	0.265
		2–3	4	0.235
		3–6	2	0.117
		6–10	1	0.059
Unsaturated zone thickness (m)	0.194	0–8	1	0.080
		8–15	2	0.160
		15–25	4	0.320
		25–54	5.5	0.440
Soil texture	0.126	Gravelly clay loam	7	0.350
		Clay loam	6	0.300
		Calcareous clay	4	0.200
		loam	2	0.100
		Salinity clay	1	0.050
		Shallow sandy loam		
Specific yield	0.083	0.013–0.04	1	0.077
		0.04–0.07	2	0.154
		0.07–0.1	4	0.308
		0.1–0.21	6	0.462
Land use / cover	0.064	Grassland	Excellent	0.258
		Forest	Appropriate	0.226
		Lake	Appropriate	0.226
		Wastelands	Moderate	0.161
		Road	Poor	0.065
		Agriculture	Poor	0.065
		Mountain	Poor	0.065
		Urban areas	Highly poor	0.032

2.2.3 Fuzzy Analytic Hierarchy Process, FAHP

The theory of fuzzy sets is a generalization and natural extension of classical set theory, aligning closely with human language and intuition. In fuzzy sets, membership is expressed on a continuum from full membership (1) to non-membership (0). Unlike traditional methods that assign weights using precise, crisp values, the Fuzzy Analytic Hierarchy Process (FAHP) assigns weights within a range of 0 to 1, effectively incorporating uncertainty and ambiguity. Basic maps are then combined using fuzzy operators such as AND, fuzzy multiplication, fuzzy addition, and fuzzy gamma.

While traditional logic evaluates statements as either true or false, many scientific and real-world problems involve degrees of uncertainty that binary logic cannot adequately capture. FAHP addresses this limitation by leveraging the principles of fuzzy logic. Developed by Chang (1996), FAHP is among the most straightforward and widely used fuzzy multi-

Table 3 Normal weights calculated for artificial recharge by the ANP method

	Aim	H&G	T&M	PH	TUZ	SY	DD	S	G	ST	LU
Aim	0	0	0	0	0	0	0	0	0	0	0
H&G	0	0	0	0	0	0	0	0	0	0	0
T&M	0	0	0	0	0	0	0	0	0	0	0
PH	0	0	0	0	0	0	0	0	0	0	0
TUZ	0.0989	0.0989	0.0989	0.0989	0.0989	0.0989	0.0989	0.0989	0.0989	0.0989	0.0989
SY	0.1008	0.1008	0.1008	0.1008	0.1008	0.1008	0.1008	0.1008	0.1008	0.1008	0.1008
DD	0.1095	0.1095	0.1095	0.1095	0.1095	0.1095	0.1095	0.1095	0.1095	0.1095	0.1095
S	0.1365	0.1365	0.1365	0.1365	0.1365	0.1365	0.1365	0.1365	0.1365	0.1365	0.1365
G	0.2087	0.2087	0.2087	0.2087	0.2087	0.2087	0.2087	0.2087	0.2087	0.2087	0.2087
ST	0.2246	0.2246	0.2246	0.2246	0.2246	0.2246	0.2246	0.2246	0.2246	0.2246	0.2246
LU	0.121	0.121	0.121	0.121	0.121	0.121	0.121	0.121	0.121	0.121	0.121

TUZ thickness of Unsaturated Zone, *SY* specific yield, *DD* Drainage Density, *S* slope, *G* geology, *ST* Soil texture, *LU* Land Use, *H&G* Hydrology, and geohydrology, *T&M* Topography, and morphology, *PH* Physics

criteria analysis methods. It employs triangular fuzzy numbers and pairwise comparisons to derive weights (Nepal et al. 2010).

The results derived using FAHP in this study are summarized in Table 4.

3 Results and Discussion

All parameters used in this study were mapped and zoned within a GIS environment. These parameters were weighted and integrated using the AHP, ANP, and FAHP methods, and the outcomes of the analyses are presented below.

As shown in Fig. 2a, the central region of the Ardabil Plain is dominated by young alluvial sediments, extending toward its borders. The northern part of the plain primarily consists of older alluvial deposits, while the peripheral areas feature various formations, including volcanic andesite, basalt, sedimentary rocks, pyroclastics, and igneous rocks. Geologically, the most suitable areas for artificial recharge are located within the young alluvial sediment class (Selvam et al. 2016). Figure2b illustrates that most of the central and western regions of the plain exhibit slopes between 0 and 1%. The northern and eastern regions have slopes ranging from 0 to 5%, forming an axial hill, while the southern region has slopes of 0–8%, with a maximum slope of 62% observed along the southern border. The optimal slope for artificial recharge falls within the 0–1% range (Ghyoumian et al. 2007).

Figure 2c shows that drainage density across the plain is generally favorable for recharge, with the most suitable areas classified within the 0–1 drainage density range (Chenini et al. 2010). Figure2d highlights that the southern regions have the highest unsaturated zone thickness, while the northern regions have the lowest. The ideal unsaturated zone thickness for artificial recharge is between 25 and 54 m, which represents the most favorable classification (Shekhar and Pande et al. 2015).

Figure 3a indicates that the plain is predominantly covered by medium to heavy soil textures, identified as the most suitable for artificial recharge (Mahmoud et al. 2014). Figure3b reveals that the highest specific yield values (0.07–0.21) are concentrated in the northern and southern regions, whereas the central, western, and eastern areas show lower values

Table 4 Allocated and normal weights for artificial recharge by the FAHP method

Criterion	TUZ	SY	DD	S	G	ST	LU	$\sum_{j=1}^{m} M_{kj}$	Normalizedweight
TUZ	1,1,1	1.5,2,2.5	1.5,2,2.5	1,1.5,2	0.5,0.7,1	1,1.5,2	2.5, 3, 3.5	9,11.7,14.5	0.236
SY	0.4,0.5,0.7	1,1,1	0.5,1,1.5	0.5,0.7,1	0.3,0.4,0.5	0.5,0.7,1	1,1.5,2	4.7,5.7,7.2	0.074
DD	0.4,0.5,0.7	0.7,1,2	1,1,1	0.5,0.7,1	0.3,0.4,0.5	0.5,0.7,1	1,1.5,2	4.7,5.7,7.2	0.074
S	0.5,0.7,1	1,1.5,2	1,1.5,2	1,1,1	0.5,0.7,1	1,1.5,2	2,2.5,3	7,9.3,12	0.167
G	1,1.5,2	2,2.5,3	2,2.5,3	1,1.5,2	1,1,1	1.5,2,2.5	3,3.5,4	11.5,14.5,17.5	0.309
ST	0.5,0.7,1	1,1.5,2	1,1.5,2	0.5,0.7,1	0.4,0.5,0.7	1,1,1	1.5,2,2.5	5.9,7.8,10.2	0.110
LU	0.3,0.3,0.4	0.5,0.7,1	0.5,0.7,1	0.3,0.4,0.5	0.2,0.3,0.3	0.4,0.5,0.7	1,1,1	3.3,3.9,4.9	0.032

TUZ thickness of Unsaturated Zone, *SY* specific yield, *DD* Drainage Density, *S* slope, *G* geology, *ST* Soil texture, *LU* Land Use

(0.013–0.07). The optimal specific yield for recharge is within the 0.1–0.21 range (Singh et al. 2013).

Figure 3c demonstrates that water cultivation predominates in the southeast and northwest regions, covering the largest areas, while population and industrial centers are primarily located in the central and western parts of the plain. Pastures and rainfed cultivation dominate the southern, northern, and northeastern areas. The most suitable land use for artificial recharge is found in areas designated for pastures and rainfed cultivation.

Weights derived from the AHP, FAHP, and ANP methods were applied to the respective maps in the ArcGIS 10.1 software environment. These maps were then integrated using Spatial Analyst Tools and categorized into four classes: very good, good, moderate, and poor. Figure 4a and b, and 4c present the classified maps generated using the AHP, ANP, and FAHP methods, respectively. While the AHP and ANP methods produced similar results (Fig. 4a and b), the FAHP method yielded significantly different outcomes. The AHP and ANP methods classified most areas of the plain as having very good potential for artificial recharge, whereas the FAHP method classified most of the plain as having poor potential.

The quantitative results of the AHP, ANP, and FAHP methods are summarized in Table 5, divided into the four classes: very good, good, moderate, and poor. According to the AHP method, apart from the central, northern, and marginal areas of the plain, most regions were classified as very good for artificial recharge. Table 5indicates that 584.8 km² (53.3%) of the plain falls into the very good class, followed by 194.7 km² (17.7%) in the good class, 237.8 km² (21.7%) in the moderate class, and 80.0 km² (7.3%) in the poor class. Areas classified as poor are characterized by heavy and saline soil textures, as well as low specific yield, drainage density, and unsuitable land use. Among the regions classified as suitable, the southern and eastern areas predominantly feature rainfed cultivation, young alluvial sediments, and slopes below 3%, aligning with the findings of Nasiri et al. (2013) and Singh et al. (2013).

Results from the ANP method suggest that the southern, western, northern, and eastern regions are suitable for artificial recharge, while the central areas are less favorable. Table 5shows that 460.4 km² (42.0%) of the plain falls into the very good class, 240.5 km² (21.9%) into the good class, 316.5 km² (28.8%) into the moderate class, and 79.9 km² (7.3%) into the poor class. The most appropriate areas for recharge are located in young alluvial sediments with significant depth, slopes below 3%, and low drainage density, consistent with the results of Singh et al. (2013) and Nasiri et al. (2013).

Finally, the FAHP method indicated that only the southern areas are suitable for artificial recharge. According to this method, 65.3 km² (6.0%) of the plain is classified as very good, 121.1 km² (11.0%) as good, 205.7 km² (18.7%) as moderate, and 705.2 km² (64.3%) as poor (Table 5). The southern areas, deemed most appropriate, are located in young alluvial sediments and predominantly feature rainfed cultivation and pastures.

These methods estimate the potential for artificial recharge by weighting factors such as land slope, soil texture, geology, unsaturated layer thickness, land use, and other relevant characteristics. However, since the weighting schemes vary between methods and none of them has been directly compared to measured recharge values, determining their relative superiority remains challenging.

As noted, the three methods produced differing results, with AHP and ANP showing a degree of similarity. However, it remains unclear which method provides results that are more consistent with actual recharge patterns. To address this, natural recharge from pre-

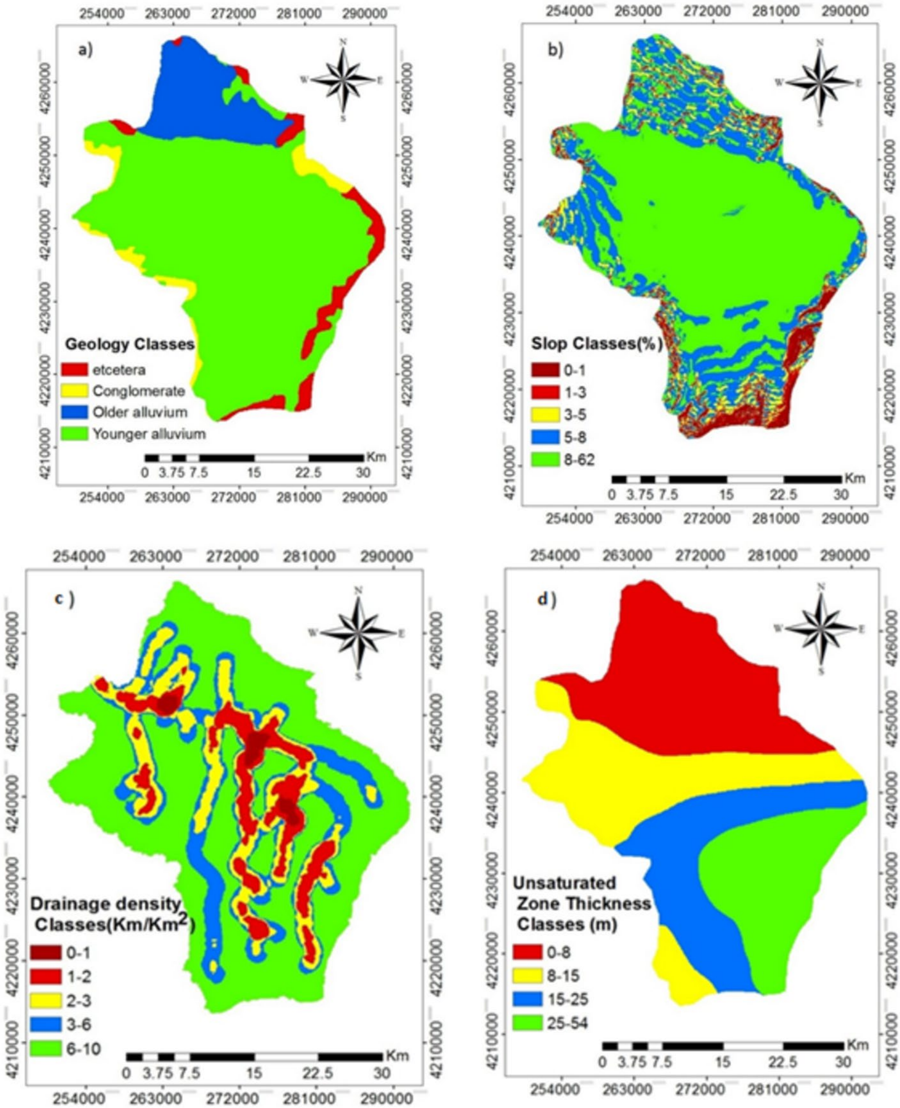

Fig. 2 (**a**) Geology classes, (**b**) Slope classes, (**c**) Drainage density classes, and (**d**) Unsaturated zone thickness classes

cipitation was used in this study as a benchmark to evaluate the performance of the methods. Natural recharge incorporates the influence of all relevant factors and thus serves as a reliable reference for assessing the accuracy of artificial recharge potential estimations. A method that closely aligns with natural recharge is presumed to offer more accurate predictions for artificial recharge potential.

The natural recharge data used in this study were derived from Ghafari (2015) and Ghafari et al. (2018), who calculated natural recharge for the Ardabil Plain using the Water Table Fluctuation (WTF) method. The results for natural recharge from precipitation are presented

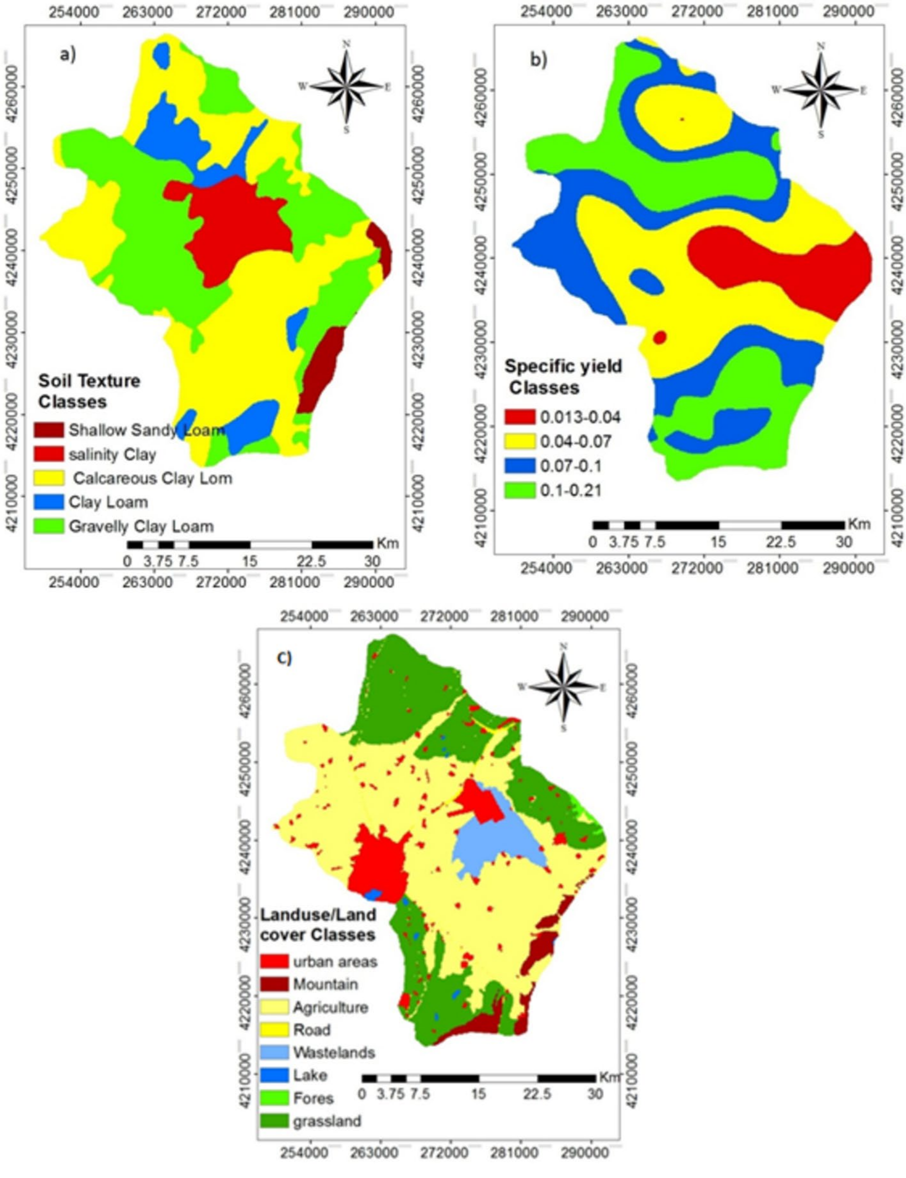

Fig. 3 (**a**) Soil texture classes, (**b**) Specific yield classes, and (**c**) Land use/ cover classes

in Fig.5. Recharge values ranged from a minimum of 1% to a maximum of 54.5%. To enable comparison, these values were classified into four categories: very good, good, moderate, and poor. In arid and semi-arid regions like Iran, groundwater recharge from precipitation is typically less than 20% (Pourseyadi and Kashkul 2012; Nasiri et al. 2021; Heydari and Jabbar 2022). Accordingly, recharge values above 20% were classified as very good, values between 10 and 20% as good, values between 5 and 10% as moderate, and values below 5% as poor.

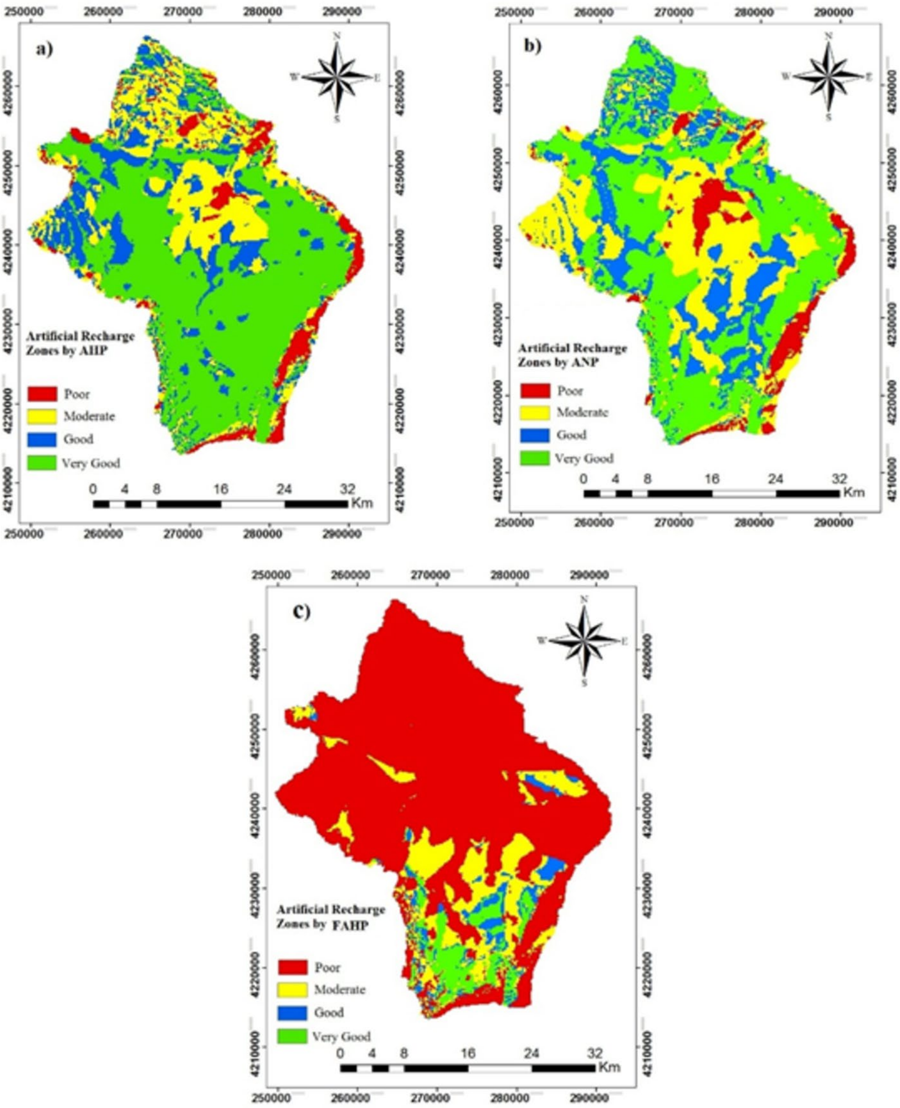

Fig. 4 Zoning of appropriate places for artificial recharge, (**a**) AHP method, (**b**) ANP method, and (**c**) FAHP method

Table 5 Results of the final maps

Appropriateness	AHP		ANP		FAHP	
	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Very good	584.8	53.3	460.4	42.0	65.3	6.0
Good	194.7	17.7	240.5	21.9	121.1	11.0
Moderate	237.8	21.7	316.5	28.8	205.7	18.7
Poor	80.0	7.3	79.9	7.3	705.2	64.3

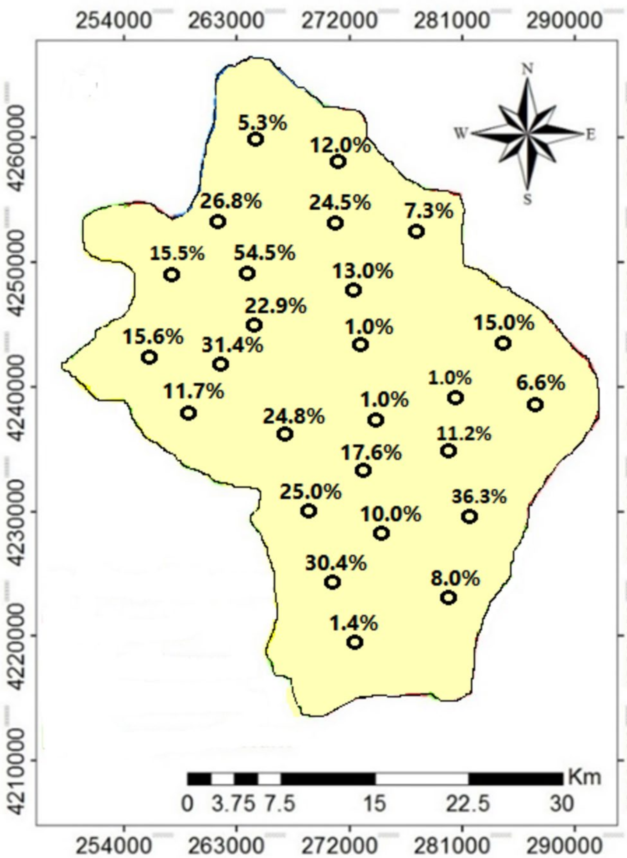

Fig. 5 Natural recharge from precipitation estimated using the WTF method

The results of the natural recharge classifications were then compared with the artificial recharge potentials estimated using the ANP, AHP, and FAHP methods. This comparison is illustrated in Fig. 6 using a Taylor diagram. As shown, the ANP method demonstrated the highest correlation with natural recharge values, achieving a correlation coefficient above 0.75, indicating superior compatibility with natural recharge data. In contrast, the FAHP method exhibited the least consistency with natural recharge estimates.

4 Conclusions

The accelerated depletion of groundwater resources in recent decades highlights the urgent need for effective artificial recharge strategies. This study employed the AHP, ANP, and FAHP methods, integrated with GIS and key parameters—such as geology, slope, unsaturated zone thickness, soil texture, specific yield, drainage density, and land use—to identify suitable areas for flood spreading and artificial groundwater recharge in the Ardabil Plain.

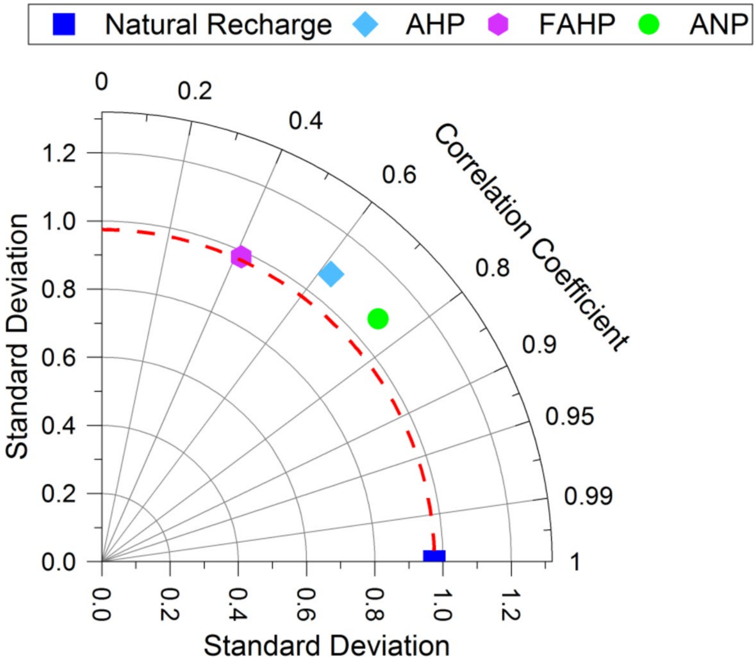

Fig. 6 Comparing AHP, ANP, and FAHP methods using a Taylor diagram

The area was classified into four categories (very good, good, moderate, and poor) based on recharge potential.

The results from the AHP method indicated that 71% of the plain falls within the very good and good categories, demonstrating high potential for artificial recharge. Similarly, the ANP method classified 63% of the area as having high recharge potential. However, the FAHP method produced contrasting results, with 64% of the area categorized as poor, indicating limited recharge potential.

While the AHP and ANP methods produced relatively similar results, significant differences were observed in specific regions. For example, the AHP method classified most northern areas of the plain as moderate, whereas the ANP method categorized these same areas as very good or good. These discrepancies underscore the challenges in selecting the most reliable method for evaluating artificial recharge potential.

A key contribution of this study lies in comparing the results of these methods against natural recharge by precipitation to determine their accuracy. The comparison revealed that the ANP method exhibited the highest consistency with natural recharge data, followed by the AHP method, while the FAHP method showed the least agreement. This finding supports the ANP method as the most reliable approach for assessing artificial recharge potential in this study.

Previous research by Panahi et al. (2017) and Vafadar et al. (2023) identified geology, lineament density, and slope as the most sensitive parameters for groundwater potential, and their sensitivity analysis aligned with the weights assigned to these factors. Similarly, in this study, the ANP method highlighted soil texture, geology, and slope as the most weighted and sensitive parameters. In contrast, the AHP and FAHP methods identified geology, unsaturated zone thickness, and slope as having the highest weights and sensitivities. Notably, geology and slope were common influential parameters across all three methods (AHP, ANP, and FAHP), underscoring their significance in groundwater recharge processes due to precipitation (Pahlevani Majdabady et al. 2020; Banerjee et al. 2024). Consequently, the ANP method is better suited for evaluating groundwater recharge influenced by precipitation, given its emphasis on these critical factors.

This study provides valuable insights into the application of multi-criteria decision-making methods for artificial recharge site selection, emphasizing the importance of validating these approaches with observed data to enhance their reliability and accuracy. Future research could explore additional parameters, methodologies, and advanced models to further refine the assessment of artificial recharge potential and improve decision-making for sustainable groundwater management.

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Data Availability The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request. Any additional materials, including specific methodologies or software used in the study, can also be provided to ensure reproducibility of the results.

Declarations

Ethical Approval The authors confirm that this article is original research and did not involve Human Participants and/or Animal.

Consent to Participate and Publish All authors confirmed their participation, approved submitting the final manuscript, and consent the publication of this manuscript by Water Resources Management journal.

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Al-Abadi AM, Ghalib HB, Al-Mohammdawi JA (2020) Delineation of Groundwater recharge zones in Ali Al-Gharbi District, Southern Iraq using multi-criteria decision-making model and GIS. J Geovis spat anal 4(9):1–12. https://doi.org/10.1007/s41651-020-00054-7

Al-Saud MM (2023) Multi-criteria analysis using satellite images and GIS for mapping groundwater recharge zones in Saudi Arabia: a case study of the Riyadh Region. Hydrol Res 54(9):1017. https://doi.org/10.2166/nh.2023.028

Al-Weshah RA, Yihdego Y (2018) Multi-criteria decision approach for evaluation, ranking, and selection of remediation options: case of polluted groundwater. Kuwait Environ Sci Pollut Res 25:36039–36045. https://doi.org/10.1007/s11356-018-3723-2

Banerjee D, Ganguly S, Kushwaha S (2024) Forecasting Future Groundwater recharge from Rainfall under different climate change scenarios using comparative analysis of Deep Learning and Ensemble Learning techniques. Water Resour Manage 38:4019–4037. https://doi.org/10.1007/s11269-024-03850-8

Bouwer H (2002) Artificial recharge of groundwater. Hydrogeology and engineering. Hydrogeol J 10:121–142. https://doi.org/10.1007/s10040-001-0182-4

Chang DY (1996) Applications of the extent analysis method on fuzzy AHP. Eur J Oper Res 95:649–655. https://doi.org/10.1016/0377-2217(95)00300-2

Chenini I, Mammou AB, May EL (2010) Groundwater recharge zone mapping using GIS-based multi-criteria analysis: a case study in central Tunisia (Maknassy Basin). Water Resour Manage 24:921–939. https://doi.org/10.1007/s11269-009-9479-1

Chowdhury A, Jha KM, Chowdary VM (2010) Delineation of groundwater recharge zones and identification of artificial recharge sites in west Medinipur district, West Bengal, using RS & GIS and MCDM techniques. Environ Earth Sci 59:1209–1222. https://doi.org/10.1007/s12665-009-0110-9

Fernández-Gálvez J, Pollacco JAP, Lassabatere L, Angulo-Jaramillo R, Carrick S (2019) A general Beerkan Estimation of Soil transfer parameters method predicting hydraulic parameters of any unimodal water retention and hydraulic conductivity curves: application to the Kosugi soil hydraulic model without using particle size distribution data. Adv Water Res 129:118–130. https://doi.org/10.1016/j.advwatres.2019.05.005

Garcia-Melon M, Ferris-Onate J, Aznar-Bellver J, Aragonés-Beltran P, Poveda Bautista R (2008) Farmland appraisal based on the analytic network process. J Glob Optim 42:143–155. https://doi.org/10.1007/s10898-007-9235-0

Ghafari H (2015) Estimation of groundwater recharge using CRD and WTF models in Ardabil Plain Estimation of groundwater recharge using CRD and WTF models in Ardabil Plain, Master's Thesis, University of Mohaghegh Ardabili, Ardabil. (In Persian)

Ghafari H, Rasoulzadeh A, Raoof M, Esmeali Ouri A (2018) Estimation of natural groundwater recharge using WTF method (case study: Ardabil plain aquifer). J Civil Environ Eng 48(1):43–52 (In Persian). https://doi.org/10.22034/CEEJ.2018.7576

Ghafari H, Rasoulzadeh A, Raoof M, Esmeali Ouri A (2021) Estimation of natural recharge of Ardabil aquifer using CRD method. J Civil Environ Eng 53(1):115–124 (In Persian). https://doi.org/10.22034/JCEE.2021.37698.1893

Ghyoumian J, Mohseni Saravi M, Feiznia S, Nouri B, Malekian A (2007) Application of GIS techniques to determine areas most suitable for artificial groundwater recharge in a coastal aquifer in southern Iran. J Asian Earth Sci 30:364–374. https://doi.org/10.1016/j.jseaes.2006.11.002

Hayati D, Karami E, Slee B (2006) Combining qualitative and quantitative methods in the measurement of rural poverty: the case of Iran. Soc Indic Res 75:361–394. https://doi.org/10.1007/s11205-004-6299-9

Heydari A, Jabbari I (2022) Simulation of Marvdasht groundwater level and investigation of forecast scenarios using MODFLOW mathematical code. Hydrogeomorphology 8(29):149–179 (In Persian). https://doi.org/10.22034/hyd.2022.49139.1612

Hussaini MS, Farahmand A, Shrestha S, Neupane S, Abrunhosa M (2022) Site selection for managed aquifer recharge in the city of Kabul, Afghanistan, using a multi-criteria decision analysis and geographic information system. Hydrogeol J 30:59–78. https://doi.org/10.1007/s10040-021-02408-x

Jahangirzadeh H, Ghanbarzadeh Lak M (2021) Developing a decision–making model to enhance artificial aquifer recharge site selection through floodwater spreading based on GIS and ELECTRE I. Water Resour Manage 35:5169–5186. https://doi.org/10.1007/s11269-021-02993-2

Kallali H, Anane M, Jellali S, Tarhouni J (2007) GIS-based multi-criteria analysis for potential wastewater aquifer recharge sites. Desalination 215:111–119. https://doi.org/10.1016/j.desal.2006.11.016

Kiker GA, Bridges TS, Varghese A, Seager TP, Linkov I (2005) Applications of multi criteria decision analysis in environmental decision making. Integ Environ Assess Manag 1(2):95–108. https://doi.org/10.1897/IEAM_2004a-015.1

Kim Y, Chung ES, Jun SM, Kim SU (2013) Prioritizing the best sites for treated wastewater in stream use in an urban watershed using fuzzy TOPSIS. Resour Conserv Recycl 73:23–32. https://doi.org/10.1016/j.resconrec.2012.12.009

Kodihal S, Akhtar MP (2024) Sustainable Groundwater Recharge Potential Zone Identification: An AHP-OWA Approach Integrating Future Rainfall and Land-Use Projections. Water Resour Manage 38:1079–1098. https://doi.org/10.1007/s11269-023-03710-x

Krishnamurty J, Venkatesa Kumar N, Jayaraman V, Manivel M (1996) An approach to demarcate groundwater potential zones through remote sensing and geographical information system. Int J Remote sens 17:1867–1884. https://doi.org/10.1080/01431169608948744

Latinopoulos D, Konstantinou Z, Krestenitis Y (2012) Simulation and multicriteria analysis in sustainable coastal planning: the case of aquaculture in Thermaikos Gulf, Greece. Environ Dev Sustain 14:1027–1045. https://doi.org/10.1007/s10668-012-9370-8

Mahmoud SH, Alazba A, Amin T (2014) Identification of potential sites for groundwater recharge using a GIS-Based decision support system in Jazan Region-Saudi Arabia. Water Resour Manag 28:3319–3340. https://doi.org/10.1007/s11269-014-0681-4

Makonyo M, Msabi MM (2021) Identification of groundwater potential recharge zones using GIS-based multi-criteria decision analysis: a case study of semi-arid midlands Manyara fractured aquifer, North-Eastern Tanzania. Remote Sens Appl: Soc Environ 23:100544. https://doi.org/10.1016/j.rsase.2021.100544

Mohieldeen YE, Elobaid EA, Abdalla R (2021) GIS–based framework for artificial aquifer recharge to secure sustainable strategic water reserves in Qatar arid environment peninsula. Sci Rep 11:18184. https://doi.org/10.1038/s41598-021-97593-w

Mouhoumed RM, Ekmekcioğlu Ö, Özger M (2023) A hybrid MCDA approach for delineating sites suitable for artificial groundwater recharge using drywells. J Hydrol 620:129387. https://doi.org/10.1016/j.jhydrol.2023.129387

Nasiri H, Darvishi Boloorani A, Faraji Sabokbar HA, Jafari HR, Hamzeh M, Rafii Y (2013) Determining the most suitable areas for artificial groundwater recharge via an integrated PROMETHEE II-AHP method in GIS environment (case study: Garabaygan Basin, Iran). Environ Monit Assess 185:707–718. https://doi.org/10.1007/s10661-012-2586-0

Nasiri Sh, Ansari H, Ziaei AN (2021) Analysis of groundwater balance of samalqan plain aquifer using SWAT and MODFLOW models. J Water Soil Sci 25(3):45–57. (In Persian) https://doi.org/10.47176/jwss.25.3.41772

Nepal B, Yadav OP, Murat A (2010) A fuzzy AHP approach to prioritization of CS attributes in target planning for automotive product development. Expert Syst Appl 37:6775–6786. https://doi.org/10.1016/j.eswa.2010.03.048

Pahlevani Majdabady M, Rasoulzadeh A, Kanooni A, Ahmadzadeh G (2020) Estimation of groundwater recharge originating from agricultural irrigation and rainfall in Shyramyn Plain, Iran. Irrig Drain 69(1):107–120. https://doi.org/10.1002/ird.2398

Pakparvar M, Nekooeian G, Gh G, Cheraghi SAM, Majidi A (2023) Direct measurement and simulation of flooding amount effect on recharge rate in Gareh Bygone floodwater spreading system. Water Soil Manage Model 3(3):256–276 (In Persian). https://doi.org/10.22098/mmws.2022.11883.1183

Panahi MR, Mousavi SM, Rahimzadegan M (2017) Delineation of groundwater potential zones using remote sensing,GIS, and AHP technique in Tehran–Karaj plain, Iran. Environ Earth Sci 76:792. https://doi.org/10.1007/s12665-017-7126-3

Papadopoulos C, Spiliotis M, Pliakas F, Gkiougkis I, Kazakis N, Papadopoulos B (2022) Hybrid fuzzy Multi-criteria analysis for selecting Discrete. Preferable Groundw Recharge Sites Water 14:107. https://doi.org/10.3390/w14010107

Pourseyadi A, Kashkuli HA (2012) Studying of groundwater conditions in Jiroft Basin with Modflow. J Irrig Sci Eng 35(2):51–63. (In Persian)

Saaty TL (1980) The Analytical Hierarchy process. McGraw Hill, New York

Saaty TL (2001) Decision making with interdependence and feedback, the Analytic Network process. RWS Publications. University of Pittsburgh, USA

Saleh I, Khazaei M, Naeimi M (2023) Desertification intensity affected by groundwater and land subsidence in Maharloo-Bakhtegan watershedarticle should be cited here according to the format of the references at the end of this guidelines. Water Soil Manage Model 3(2):171–184 (In Persian). https://doi.org/10.22098/mmws.2022.11906.1187

Sallwey J, Valverde JPB, López FV, Junghanns R, Stefan C (2019) Suitability maps for managed aquifer recharge: a review of multi-criteria decision analysis studies. Environ Reviews 27(2):138–150. https://doi.org/10.1139/er-2018-0069

Selvam S, Dar FA, Magesh NS, Singaraja C, Venkatramanan S (2016) Application of remote sensing and GIS for delineating groundwater recharge potential zones of Kovilpatti Municipality, Tamil Nadu using IF technique. Earth Sci Inf 9:137–150. https://doi.org/10.1007/s12145-015-0242-2

Sheikhipour B, Javadi S, Banihabib ME (2018) A hybrid multiple criteria decision-making model for the sustainable management of aquifers. Environ Earth Sci 77(712):1–16. https://doi.org/10.1007/s12665-018-7894-4

Shekhar S, Pandey AC (2015) Delineation of groundwater potential zone in hard rock terrain of India using remote sensing, geographical information system (GIS) and analytic hierarchy process (AHP) techniques. Geocarto Int 30:402–421. https://doi.org/10.1080/10106049.2014.894584

Shen L, Olfat L, Govindan K, Khodaverdi R, Diabat A (2013) A fuzzy multi criteria approach for evaluating green supplier's performance in green supply chain with linguistic preferences. Resour Conserv Recy 74:170–179. https://doi.org/10.1016/j.resconrec.2012.09.006

Singh A, Panda SN, Kumar KS, Sharma CS (2013) Artificial groundwater recharge zones mapping using remote sensing and GIS: a case study in Indian Punjab. Environ Manag 52(1):61–71. https://doi.org/10.1007/s00267-013-0101-1

Vafadar S, Rahimzadegan M, Asadi R (2023) Evaluating the performance of machine learning methods and Geographic Information System (GIS) in identifying groundwater potential zones in Tehran-Karaj plain. Iran J Hydrol 624:129952. https://doi.org/10.1016/j.jhydrol.2023.129952

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