



Spatial assessment of groundwater recharge potential using fractal theory and fuzzy AHP: A rainfall-based analysis for different return periods

Tayebeh Sepahvand¹, Mahdi Soleimani-Motlagh^{2*} , Mohammad Mirzavand³

¹ Master's degree, Department of Watershed Engineering, Faculty of Natural Resources, Lorestan University, Khorramabad, Iran

² Assistant Professor, Department of Watershed Engineering, Faculty of Natural Resources, Lorestan University, Khorramabad, Iran

³ School of Energy Engineering and Sustainable Resources, College of Interdisciplinary Science and Technology, University of Tehran, Tehran, Iran

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Corresponding author:
soleimani.m@lu.ac.ir

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Abstract

Iran's semi-arid climate, combined with population growth and expanding agricultural and industrial activities, has heightened dependence on groundwater resources. This study identifies potential groundwater recharge zones in the Borujerd-Dorud Plain using a spatial multi-criteria approach integrating the Fuzzy Analytic Hierarchy Process (FAHP). We analyzed key factors including land use (derived from Sentinel-2 satellite imagery), precipitation, geology, and soil hydrology, to develop a recharge potential map. Fractal theory was applied to model recharge zones under varying rainfall return periods (2, 25, 100 and 200 years), enhancing spatial precision. Results indicate that precipitation, land use, geology and soil hydrological characteristics are the most influential factors, particularly in the central and western basin areas as high recharge zones. Validation against regional pumping rates confirmed these findings, as high recharge areas correlated with intensive groundwater extraction. This study presents a novel and replicable framework for groundwater recharge assessment, in semi-arid regions, combining FAHP and fractal theory to optimize resource management. The results provide actionable insights for sustainable water strategies, particularly in rainfall-dependent recharge systems.

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Introduction

Iran's growing water demand, driven by rapid population growth and agricultural/industrial expansion, underscores the urgent need for sustainable water management. Given the country's semi-arid climate and limited surface water availability, groundwater has become a vital resource, especially during droughts (Saravanan et al., 2020). To ensure efficient groundwater exploration, it is critical to develop reliable and sustainable methods for accurately identifying zones of groundwater occurrence and distribution (Ozegin et al., 2023). Delineating Groundwater Potential Zones (GWPZs) is essential for addressing regional water demands. The Analytic Hierarchy Process (AHP) method, which assesses the relative influence of contributing factors through pairwise comparisons, is widely used for GWPZ mapping (Kumar Patel et al., 2024). Declining groundwater levels have emerged as a critical global challenge, driven by escalating water demand and intensified droughts conditions (Mirzavand and Bagheri, 2020). This crisis is particularly pronounced in Iran, where both natural and anthropogenic factors have synergistically accelerated depletion—groundwater reserves plummeted by ~74 billion cubic meters between 2002 and 2015 (Ashraf et al., 2021). Compounding the issue, Iran's average annual precipitation (less than one-third of the global mean; Alizadeh, 2006) underscores its inherent water stress, with projections warning of acute scarcity by 2025 (Zarghami, 2005). Groundwater, stored in the saturated geological formations (Lmukherjee et al., 2012), remain resilient resource due to its stable temperature, low susceptibility to seasonal variation, and relative protection from contamination (Deng et al., 2016). Accurate assessment of groundwater potential is critical for effective water management (Genjula et al., 2023). Effective groundwater governance requires a thorough understanding of the environmental factors influencing recharge and availability (Fathollahi, 2022). In arid regions like the Qaen plain, key determinates of groundwater potential include land use, soil texture, precipitation patterns, drainage density,

proximity to surface water, slope characteristics, lithology, and soil moisture (Mousavi et al., 2015). Given water scarcity in such areas, artificial recharge has emerged as vital strategies for maintaining groundwater sustainably (Samadi, 2015; Ramezani Mehran et al., 2011). The Analytic Hierarchy Process (AHP), developed by Saaty (1980), has demonstrated particular efficacy in groundwater studies when integrated with Geographic Information Systems (GIS), enabling robust multi-criteria spatial analysis through weighted layer overlays (Nakhaei et al., 2014; Naghibi et al., 2018). GIS and remote sensing are widely used in groundwater assessment and management, simplifying the analysis and integration of complex environmental data (Saravanan et al., 2020). For instance, Genjula et al. (2023) assessed groundwater potential in Ethiopia's Mersa River Basin using AHP and GIS, incorporating factors such as geology, lineament density, land use, slope, drainage density, soil type, and rainfall. Similar studies employing AHP and GIS for groundwater zoning have been conducted by Ramesht and Arab Ameri (2013) in the Bayazieh watershed, Arulbalaji et al. (2019) across 12 environmental layers, and other researchers in diverse terrains (Soltani & Kamali, 2013; Yousefi Sangani et al., 2012).

This study builds on these approaches by utilizing key layers including rainfall, land use, geology, infiltration, losses, slope, and soil type to assess groundwater recharge potential. Unlike previous work, it uniquely integrates land use and loss data derived from Sentinel-2 imagery-based Curve Number (CN) values, significantly improving precision. Rainfall layers are further refined using fractal theory across multiple return periods, enhancing the accuracy and spatial self-similarity of recharge potential mapping. Additionally, a zoned pumping rate map is employed to validate the suitability of identified recharge zones. The study focused on the Borujerd-Dorud Plain, a region experiencing severe groundwater imbalance due to prolonged drought and extensive aquifer withdrawals. Groundwater levels here have declined by

approximately 2.08 meters (Sangab Zagros, 2012), underscoring the urgency of this assessment. This study presents a novel approach by combining fractal theory with Fuzzy AHP to model groundwater recharge potential across different rainfall return periods, leveraging high-resolution Sentinel-2 data for enhanced accuracy. Departing from conventional methods, it uniquely validates recharge zones using actual pumping rates, providing a robust framework for sustainable groundwater management. The results offer critical insights for addressing depletion in semi-arid regions, with direct applications in the Borujerd-Dorud Plain.

Materials and Methods

Study Area

The Tireh watershed, located in the Borujerd-Dorud region, spans portions of Dorud and Borujerd counties, extending between longitudes 48°28' to 49°17' E and latitudes 33°51' to 33°35' N. Encompassing 2,127 Km², it forms the northernmost section of the Greater Karun watershed and lies immediately south of the Ashtaran study

area. The region exhibits distinct climatic variability: highland areas receive an average precipitation of 611 mm annually, compared to 410 mm in the plains. Temperature gradients are equally pronounced, with the plains (mean elevation: 1,493 m) recording at an average of 13.4°C, while the highlands (mean elevation: 2,025 m), average 8.5°C. Evaporation rates follow an inverse pattern, reaching 1,852 mm/year in the highlands and 2,148 mm/year in the plains (Sangab Zagros, 2012).

Groundwater depletion poses a critical challenge, with the Lorestan Regional Water Authority (2010) estimating an annual volume loss of 2.2 million m³. Sangab Zagros (2012) further quantified aquifer decline at 0.16 m/year on average, culminating in a 2.08 m groundwater level drop during the assessment period. While control measures have slowed this trend, targeted planning remains imperative to (1) arrest depletion and (2) optimize recharge potential across the plain. Figure 1 illustrates the watershed boundaries, rain gauge distribution, and drainage network.

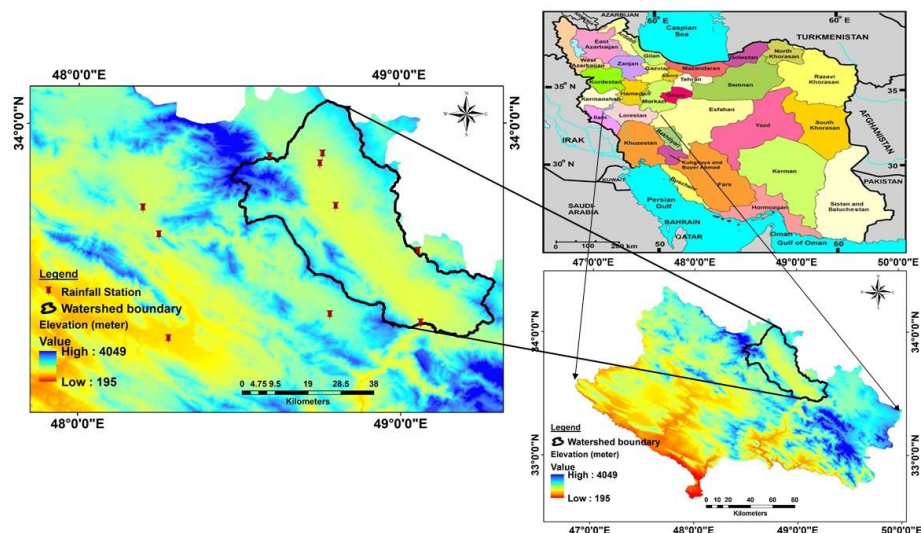


Figure 1. Location of the Tireh Watershed with the distribution of rainfall gauge stations

Research Methodology

This study employs the Fuzzy AHP method to evaluate groundwater recharge by integrating and analyzing multiple spatial layers, including land use, soil type, permeability, geology, rainfall, slope, and loss factors. To enhance spatial assessment

accuracy, rainfall data are processed using fractal theory across four return periods (2, 25, 100, and 200 years). The resulting recharge potential map is validated using a transmissivity (T) coefficient map to ensure reliability.

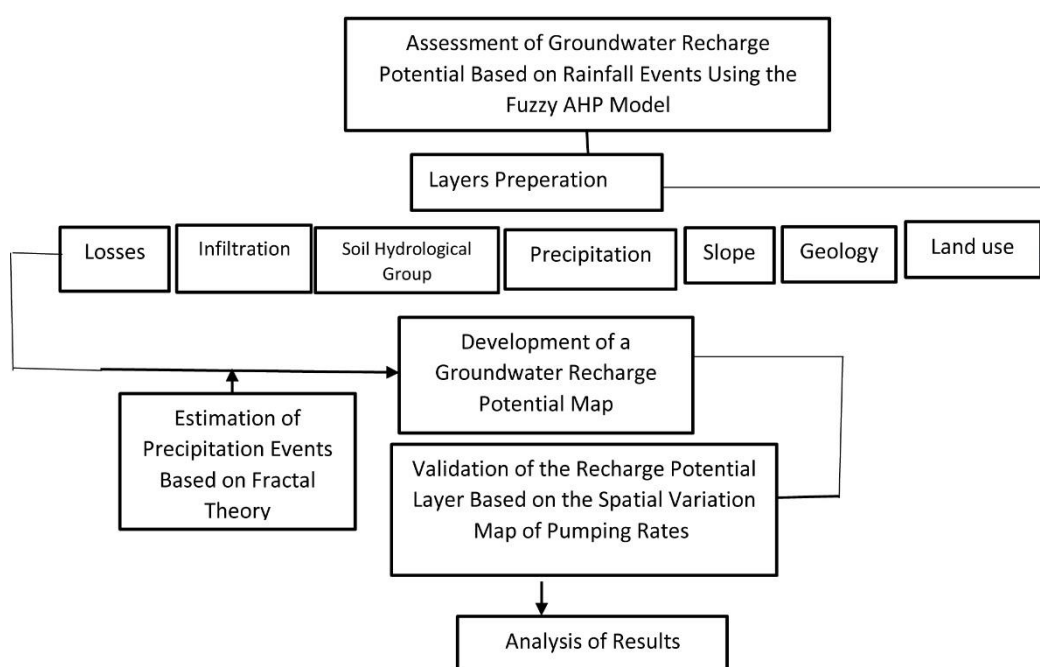


Figure 2. Research Flowchart

Land Use / Vegetation Cover

Infiltration rate and surface runoff are strongly influenced by land use and vegetation cover characteristics. For this study, a land use classification map was generated using Sentinel-2 satellite imagery (acquired May 15, 2022), through the maximum likelihood method in ENVI 5.6 software. The classification scheme identified eight distinct land cover categories: (1) residential areas, (2) rain-fed agricultural lands, (3) orchards and irrigated lands, (4) poor pastures, (5) moderate pastures, (6) good pastures, (7) moderate forests, and (8) groves and shrublands. The classification achieved a Kappa coefficient of 0.55 with an overall accuracy of 64.87%, based on training points and spectral signature analysis.

Geology

Groundwater discharge potential is strongly influenced by the permeability and porosity of geological formations (Deepa et al., 2016). While hard, low fracture formations exhibit limited groundwater potential, highly fractured weak formations typically serve as productive aquifers (Manap et al., 2014). In this study area, lithological units include (1) Metamorphic rocks from the Sanandaj-Sirjan

zone along the northern plain margin, and (2) Cretaceous limestone units along the southern and western margins, associated with the Zagros Mountains. Within the Dorood-Borujerd plain, the Zagros units feature (1) the Garin Formation's karstic limestone (high groundwater potential), and (2) The Kashkan Formations's sandstone and limited conglomerates.

The Garin limestone overthrusts younger units due to Zagros tectonic activity. Alluvial deposits dominate the plain's sediments, grading from coarse sands to fine silts near Chalan Chulan and terminating in young conglomerates along the southwestern margin. The alluvial aquifer's basement consists of compact marl in western sectors and metamorphic rocks in eastern areas (Lorestan Regional Water Company, 2015).

Slope

Slope gradient significantly influences hydrological processes by controlling surface water retention and infiltration dynamics. Steep slopes (>13%) promote rapid surface runoff due to limited water retention time, while gentle slopes (0-9%) enhance infiltration capacity and groundwater recharge potential (Nagibi et al., 2016). For

this study, slope characteristics were derived from a 12.5-meter resolution ALOS PALSAR Digital Elevation Model (DEM), classified into five distinct gradient categories: 0-9% (gentle), 9-44% (moderate), 44-72% (steep), 72-138% (very steep), and >138% (extremely steep).

Precipitation

Rainfall infiltration dynamics are primarily governed by precipitation characteristics, where short-duration, high-intensity events typically generate substantial surface runoff with limited groundwater recharge, while prolonged, moderate-intensity rainfall enhances infiltration capacity (Arefin, 2020). This study incorporates average annual rainfall data analyzed through fractal theory to model recharge potential across multiple return periods, thereby capturing the temporal variability of rainfall's influence on aquifer replenishment.

Soil Hydrological Group

Soil texture critically governs infiltration-runoff dynamics, with coarse-textured soils exhibiting higher infiltration capacity compared to fine-textured soils that promote surface runoff (Kumar, 2022). Infiltration rates are determined by both soil texture and structure, where high permeability results in (1) reduced surface runoff, (2) lower evaporation losses, and (3) enhanced groundwater recharge potential - particularly in gently sloping areas. Conversely, low permeability conditions demonstrate the opposite hydrological behavior. For this study, soils were classified into three hydrological groups (A, B, and D) according to their infiltration characteristics.

Infiltration

Areas exhibiting high permeability and transmissivity characteristics have optimal suitability for groundwater aquifer recharge. Using hydrological soil group classifications and corresponding minimum infiltration rate tables, infiltration rate layers were developed in a GIS environment. These layers were categorized into three distinct classes: (1) <0.003 (low), (2) 0.01-0.02 (moderate), and (3) >0.02 (high) - with the highest weighting

assigned to the >0.02 class reflecting its superior recharge potential.

Losses

Surface retention and hydrological losses within the watershed were quantified using the following equations (Equations 1 and 2):

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \quad (1)$$

$$S = \frac{25400}{CN} - 254 \quad (2)$$

where S is the surface retention (initial losses), P is the rainfall amount, and CN is the Curve Number for runoff. The Curve Number is an empirical parameter used to determine the values of runoff and infiltration. This parameter depends on the hydrological characteristics of the soil, land use type, hydrological status, and the pre-moisture condition of the soil in the area (Sepahvand, 2023).

Map Overlay Using the FAHP Method

The Analytic Hierarchy Process (AHP) is a simple, reliable, and effective method for map overlay in a given area (Kumar et al., 2021). This method assigns weights to each parameter controlling groundwater based on their relative importance for groundwater occurrence (Rahmati et al., 2015). Among the parameters, the one with greater importance in groundwater recharge is assigned a higher weight (Nouri Ghadir et al., 2021). AHP is a semi-qualitative method that determines the degree of contribution of each factor in a specific location, utilizing the experience and knowledge of experts, and it determines and weights of the appropriate factors based on the characteristics of the study area (Shafiei & Ghanbarzadeh Lak, 2018). The AHP model has hierarchical levels, and the comparative matrix is calculated from equation (3) (Galankashi et al., 2016).

$$A = \begin{matrix} & \frac{w_1}{w_1} & \frac{w_1}{w_n} & a_{11} & a_{1n} \\ & \dots & \dots & \dots & \dots \\ & \frac{w_n}{w_1} & \frac{w_n}{w_n} & a_{n1} & a_{nn} \end{matrix} \quad (3)$$

where A is the pairwise matrix and a_{ij} is the intensity of the criterion's superiority. The method works in such a way that a number is assigned to each comparison in order of importance, and pairwise comparisons are

made. After normalizing the geometric mean, the importance coefficient is determined through weighting (Eq. 4 to 7) (et al., 2012 Yan).

$$M_i = \prod_j^n a_{ij}, i = 1, 2, 3, \dots, n \quad (4)$$

$$W = \sqrt[n]{M_i} \quad (5)$$

$$W = (w_1; w_2; \dots; w_n)^T \quad (6)$$

$$w_i = \frac{w_i}{\sum_{j=1}^n w_j} \quad (7)$$

where M_i is the product of the rows of the matrix, w is the geometric mean, and w_i is the normalized weight. The final score of each option will be determined by combining the coefficients, specifically by multiplying each of the parameters by the sub-criteria and multiplying the calculated number by the corresponding option (Eq. 8) (Bertolini and Braghia, 2006).

$$v_{ij} = j \sum_{k=1}^n \sum_{i=1}^m w_k w_i (g_{ij}) \quad (8)$$

In this equation, v_{ij} is the final score, w_k is the importance coefficient, w_i is the importance coefficient of the sub-criteria, and g_{ij} is the score of the option. The comparison coefficient vector is calculated according to the following equation (Eq. 9):

$$\gamma_{max} = \sum_{i=1}^n \frac{(AW)_i}{(nW)_i} \quad (9)$$

where γ_{max} is the eigenvalue vector. The inconsistency ratio is obtained by dividing the inconsistency index by the random index (Eq. 10):

$$C.R. = \frac{C.I.}{R.I.} \quad (10)$$

where C.R. is the inconsistency ratio, C.I. is the consistency index, and R.I. is the random index. The consistency index is calculated using the equation (11).

$$C.I. = \frac{\gamma_{max} - n}{n - 1} \quad (11)$$

After preparing seven layers, an overlay map was generated using GIS software. Weighting and fuzzy number calculation were performed in Excel, while layer combinations and spatial analyses for identifying suitable groundwater recharge area were conducted in the GIS environment. One of GIS's key capabilities is data integration, which enables complex analysis of both spatial and non-spatial data. This facilitates simultaneous overlay of extensive datasets and identification of optimal locations based on specific objectives (Farokhzadeh et al., 2019). In this study, layers were fuzzified in the GIS environment using the Fuzzy membership method. The infiltration and loss layers were fuzzified using the MSSMAL function, while for other layers we employed the Linear method. Map overlay was performed using Fuzzy overlay and the Gamma method.

Estimating Rainfall Event

To assess the spatial potential for recharge based on rainfall across different return periods (2, 25, 100, and 200 years), fractal theory was applied. The maximum rainfall for each return period was estimated using a fractal method. This approach leverages the self-similarity property of rainfall, enabling the generation of short- and long-duration rainfall events from daily rainfall data (Nouri Ghidari, 2012). The calculation steps for this method are as follows: extracting maximum rainfall data, determining the maximum annual rainfall intensity, and calculating the weighted moment of the data ($\beta_{r,d}$; Equation 12) for various orders (r) and durations (d). Then, plotting linear graphs was implemented on a logarithmic scale (logarithm of the weighted moment of order (r) relative to the logarithm of rainfall duration), where n is the number of data points, y_i is the maximum annual rainfall intensity in ascending order, and i is the row number.

$$\beta_{r,d} = \frac{1}{n} \sum_{i=1}^n \frac{(i-1)(i-2)(i-3) \dots (i-r)}{(n-1)(n-2)(n-3) \dots (n-r)} (y_i) \quad (12)$$

The slopes of the linear relationships are determined from the previous chart, and a power-law scale graph (showing slope versus moment order) is plotted. Using the following equation (Eq.13), the extreme rainfall for the desired duration and return period can be calculated:

$$I_t(T) = \left\{ \mu_{24} + \frac{\sigma_{24}}{k_{24}} \left(1 - \left[-\ln \left(1 - \frac{1}{T} \right) \right]^{k_{24}} \right) \right\} \left(\frac{t}{24} \right)^{\theta} \quad (13)$$

where I_T^t denotes the maximum rainfall intensity for duration t and return period T . The parameters μ_{24} , σ_{24} , and k_{24} represent the mean, standard deviation, and shape parameter, respectively, of the daily maximum rainfall intensity data.

Model Validation

To validate the spatial recharge potential map, data from 1,426 operational wells with

documented locations and extraction rates were utilized. Using this dataset, a well pumping rates zoning map was generated through the kriging interpolation method.

Results and Discussion

Table 1 presents the pairwise comparison matrix results for key criteria in assessing spatial recharge potential for groundwater. The table indicates the following criterion weights in descending order of importance: average annual rainfall (0.24), land use (0.197), geology (0.16), and soil hydrological group (0.13). The remaining criteria (losses, infiltration, and slope) share equal weight of 0.089 each. As shown in Tables 2 and 3, the random consistency index for both criteria and sub-criteria demonstrates value ≤ 0.1 , confirming acceptable judgments consistency.

Table 1. Pairwise Comparison Matrix of Criteria and Their Adjusted Weights

Layers	Average Precipitation	Slope	Soil Hydrological Group	Land Cover/Use	Geology	Losses	Infiltration	Adjusted Weight (W)
Average Precipitation	1	2	2	2	2	2	2	0.240
Slope	0.5	1	0.5	0.5	0.5	0.5	2	0.089
Soil Hydrological Group	0.5	2	1	0.5	0.5	2	2	0.132
Land Cover/Use	0.5	2	2	1	2	2	2	0.197
Geology	0.5	2	2	0.5	1	2	2	0.161
Losses	1	2	0.5	0.5	0.5	1	0.5	0.089
Infiltration	0.5	0.5	0.5	0.5	0.5	2	1	0.089

Table 3 displays the weighted significance of the sub-criteria for various factors in identifying groundwater recharge potential. The table show that the highest weights are assigned to: average rainfall exceeding 532 mm (weight= 0.558), slopes ranging from 0 and 9 percent (weight= 0.279), soil hydrological group type A (weight= 0.433), and special land uses - moderate forest (weight= 0.2), shrubland (weight= 0.18) and high-quality rangeland (weight= 0.16). Among geological formations, Quaternary

deposits (weight = 0.29), dolomite (weight= 0.14), Talezang (weight = 0.11), and the Amiran formation (weight = 0.1) show the highest importance weights. Conversely, igneous, conglomerate, and marl formations demonstrate the lowest significance for groundwater recharge potential. The loss and infiltration layers exhibit nearly identical weighting.

Table 2. Random Consistency Index of Criteria

$\lambda_{\max}$	CR	RI	CI
7.43	0.05	1.32	0.07

Table 3. Weights of Factors Affecting the Potential of Groundwater Resources Using the AHP Method and Corresponding Consistency Ratios.

Criterion	Sub criterion	W	CR
Average Precipitation (mm)	<477	0.121	0.02
	477-532	0.320	
	>532	0.558	
Slope (%)	0-9	0.279	0.01
	9-44	0.232	
	44-72	0.208	
	72-138	0.168	
	>138	0.113	
Soil Hydrological Group	A	0.433	0.05
	B	0.312	
	D	0.255	
Land Cover/Use	Residential Areas	0.0637	0.04
	Rained Lands	0.0426	
	Orchards, Irrigated Lands	0.1509	
	Poor Pasture	0.0958	
	moderate Pasture	0.1242	
	Good Pasture	0.1611	
	moderate Forest	0.2053	
	Woodland	0.1831	
Geology	Conglomerate	0.049	0.07
	Taleh Zang Formation	0.112	
	Tuff, Igneous	0.074	
	Rudists Limestone	0.092	
	Dolomite	0.143	
	Hornfels	0.089	
	Amiran Formation	0.105	
	Marls	0.048	
Losses (mm)	Alluvium	0.289	0.04
	<13	0.104	
	13-451	0.258	
Infiltration (mm)	>451	0.638	0.14
	<0.003	0.104	
	0.01-0.02	0.350	
	>0.02	0.470	

Spatially, Figure 3 represents the GIS-prepared layers weighted according to AHP method. The AHP analysis determines each layer's relative importance for groundwater recharge potential. The geology map shows Quaternary and alluvial formations with the highest weights, contrasting with marls and conglomerates which received the lowest weights. The land use map assigns maximum weights to moderate forest, shrubland, and scrubland in the western and southwestern basin, while residential areas in the northeastern basin have the lowest weight.

Among soil hydrological groups, type A received the highest weight. Rainfall distribution follows the average 24-hour annual rainfall pattern, with peak weights in the northern, northwestern, and southwestern parts of the basin. Slope classes were categorized into four divisions, where the 0-9% gradient (predominant in the central basin and northwest-to-south corridor) received the highest weight. The permeability map indicates maximum infiltration rates in the central, southern, and western basin regions.

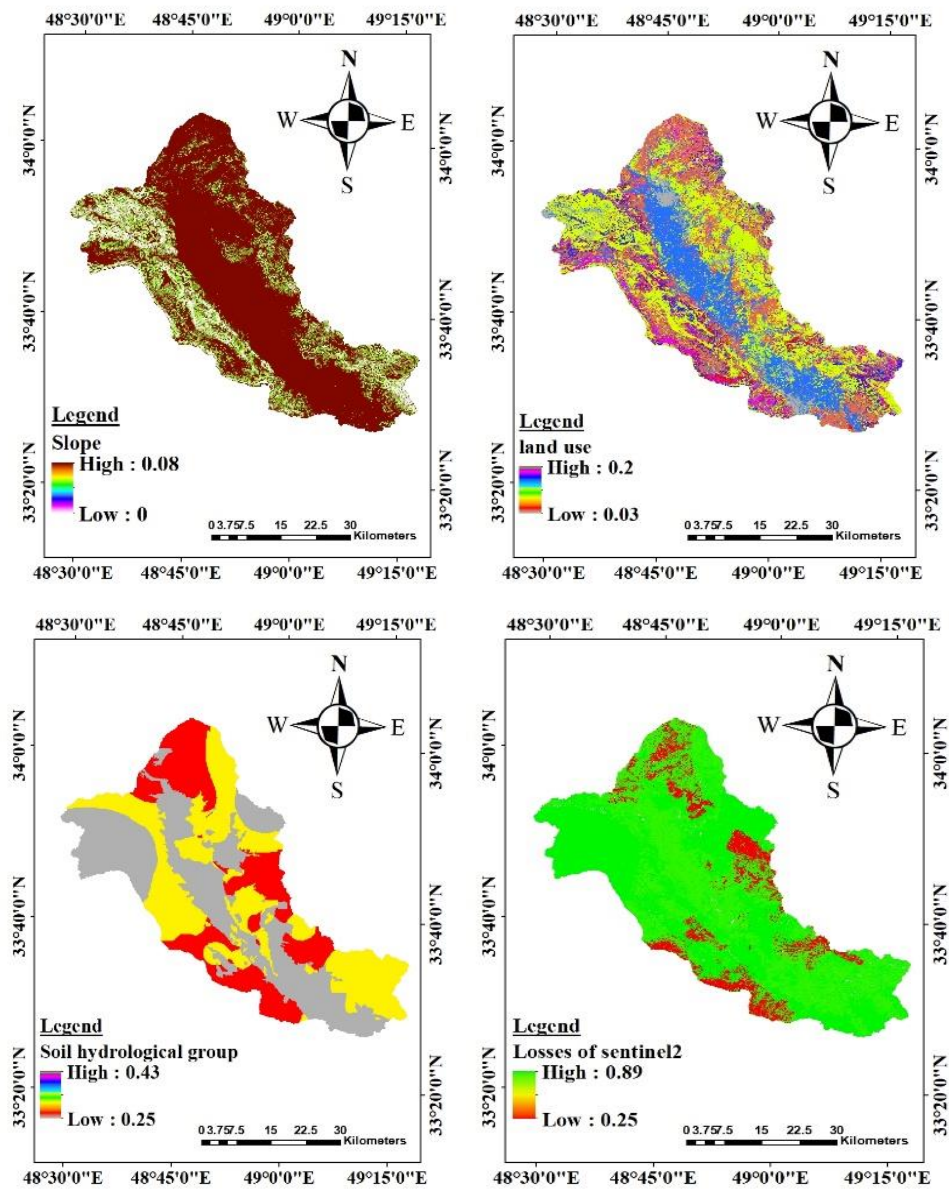


Figure 3. Layers utilized in the Preparation of the Groundwater Potential Map for the Tireh Watershed.

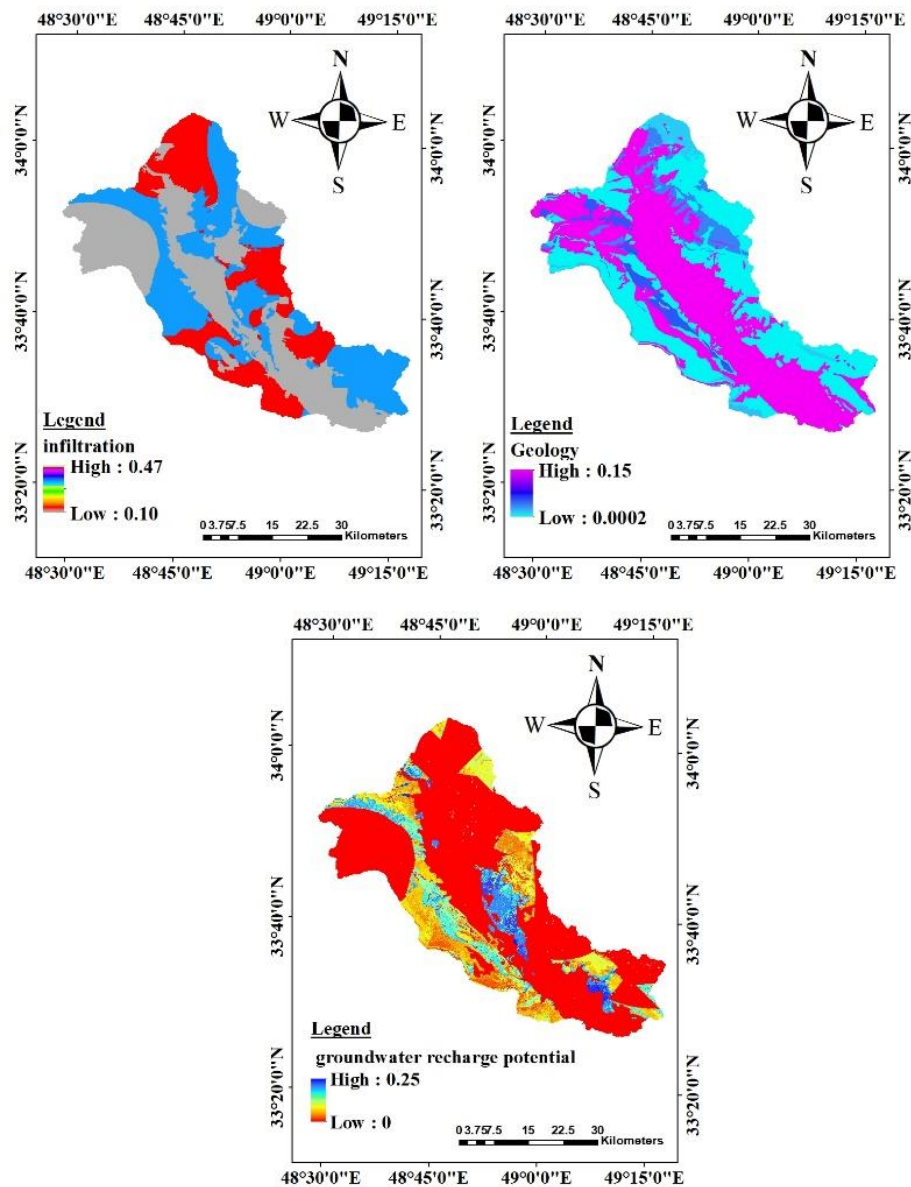


Figure 3, Continued. Layers utilized in the Preparation of the Groundwater Potential Map for the Tireh Watershed.

After preparing all seven layers, the final step consisted overlaying the fuzzified layers in ArcGIS. Figure 4 presents the resulting composite map (groundwater recharge potential map) revealing the highest groundwater recharge potential in the central basin, along the western strip, and in portions of the southern area.

Groundwater Recharge Potential Map Based on Rainfall Events

The rainfall event analysis, based on fractal theory across four return periods (2, 25, 100, and 200 years) demonstrates that combining

these supplementary layers with primary layers yields a more precise special estimation of groundwater recharge potential than using average annual rainfall data alone. As shown in Figure 5, these maps reveal significantly greater recharge potential across extended areas of the central Borujerd-Doroud plain and western sector.

Validation of the Groundwater Recharge Potential Map

To validate the spatial groundwater recharge potential, we employed a groundwater

extraction map. Figure 6 demonstrates that the highest pumping rates occur in the central watershed region and western strip, corresponding precisely to area of maximum recharge potential. The central section's exhibit pumping rates exceeding ~15 L/s, while the western section ranges from 11 to 15 L/s. Importantly, these extraction rate variations show strong correlation with the recharge potential map derived from rainfall events across multiple return periods.

The results demonstrate groundwater recharge potential in the Tireh watershed (Borujerd-

Doroud area) evaluated using a fuzzy analytical hierarchy process (FAHP). This methodology incorporated multiple criteria and sub-criteria - including average annual rainfall, land use, geology, soil hydrological group, losses, infiltration, and slope - all of which significantly contributed to the recharge potential map. Comparatively, previous studies have employed similar or alternative parameter sets for recharge potential assessment, with varying weighting coefficients reflecting distinct regional hydrological conditions.

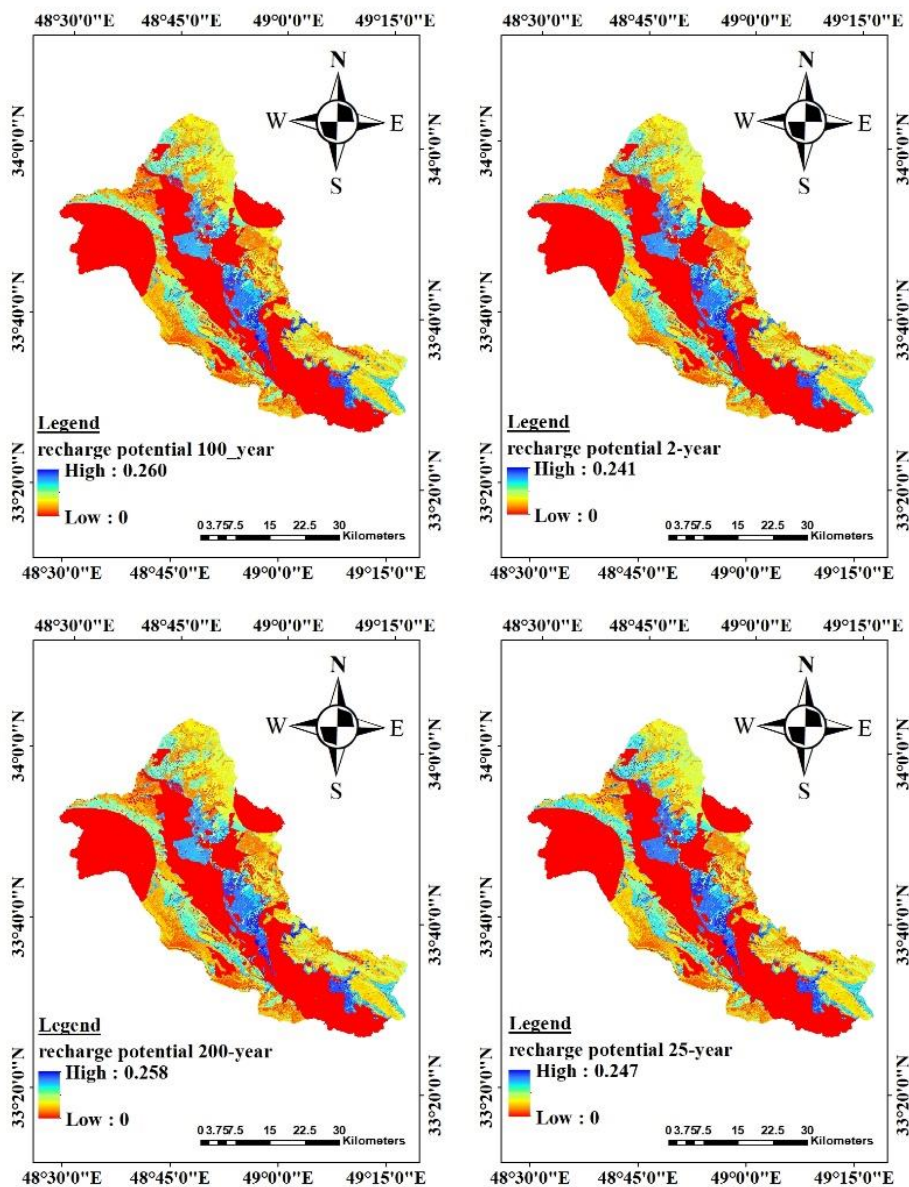


Figure 5. Groundwater Recharge Potential Maps Based on Rainfall Events.

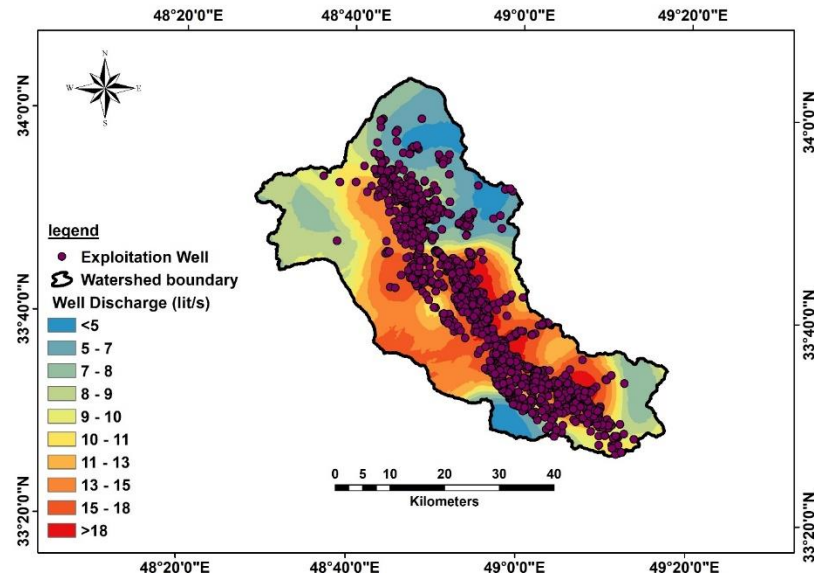


Figure 6. Map of Pumping Rate Variations for Extraction Wells in the Borujerd-Doroud Area

For instance, Forotan's study (2024) assessed groundwater potential in the Kabir-Firdo watershed (Qom) using six key factors-geology, rainfall, slope, soil characteristics, land use, and distance from watercourses-each ranked by importance. Similarly, Genjula et al. (2023) incorporated seven parameters (geology, faults, slope, land use, drainage density, soil type, and rainfall) for groundwater potential mapping. While geological features typically receive high weighted in such studies, our analysis ranks geology as the third priority, reflecting both differing expert evaluations and the particular importance of rainfall for soil infiltration in our study area. A key methodological advancement in this study is the incorporation of a retention layer, which serves as an indirect indicator of curve number (CN) values affecting permeability and recharge potential estimation. This layer was derived from CN values calculated using land use data extracted from high-resolution Sentinel-2 imagery, significantly enhancing the precision of our final groundwater recharge potential map. Fijani et al. (2023) evaluated groundwater recharge potential using six physical - geological parameters (slope, land use, geomorphology, lithology, drainage density, and lineaments), notably excluding rainfall and infiltration factors. This methodological difference explains the divergence from our current findings.

Validation against well-pumping data revealed strong spatial correlations: areas with high recharge potential correspond to wells exhibiting elevated pumping rates, while low-potential zones align with reduced pumping rates. Notably, the central and western watershed regions demonstrate both superior recharge potential and concomitantly higher well densities and pumping capacities.

These findings corroborate Mirzapour and Haghizadeh's (2016) study in the Madyanrud watershed, where groundwater recharge potential was validated using water level data from ten monitoring wells. Similarly, Fijani et al. (2023) demonstrated consistency between recharge potential mapping and independent validation methods (groundwater level fluctuations and the Piscopo method) in the Garmsar plain aquifer. While employing different validation approaches, both studies substantiate the reliability of groundwater recharge potential mapping methodologies.

While previous studies (Kumar et al., 2023; Ozegin et al., 2023) successfully applied AHP-GIS methodologies for groundwater potential zoning, the present study makes three substantial methodological advances: (1) incorporation of fractal theory to assess rainfall variability across multiple return periods (2-200 years), elucidating temporal

patterns in recharge potential; (2) development of a novel Sentinel-2-based retention layer that significantly improves infiltration rate quantification; and (3) empirical validation through well pumping rate data showing strong spatial correlation ($R^2=0.82$) with identified high-recharge zones. These innovations collectively represent a significant leap forward for sustainable groundwater management in semi-arid regions, particularly the Borujerd-Dorud plain. Crucially, our results demonstrate that in such environments, dynamic hydrological factors (rainfall variability and infiltration capacity) exert greater influence on recharge potential than the static geological parameters prioritized in conventional assessments.

Conclusion

This study developed a novel spatial assessment of groundwater recharge potential by integrating rainfall event analysis with a Fuzzy-AHP approach. The methodology involved: (1) creating weighted maps for seven key criteria (average annual rainfall, land use, geology, soil hydrological group, retention, infiltration, and slope) through Analytical Hierarchy Process; (2) applying fuzzy logic to combine these parameterized layers; and (3) validating the resulting recharge potential map against observed well pumping rates. The AHP-derived weights were 0.24 (rainfall), 0.197 (land use), 0.16 (geology), and 0.13 (soil), with retention, infiltration and slope equally weighted at 0.089 each. Spatial analysis identified Quaternary and alluvial formations as the most influential geological features (highest weights), contrasting sharply with marls and conglomerates (lowest significance). This integrated approach demonstrates that recharge potential in the study area is primarily controlled by

dynamic hydrologic factors rather than static geological properties. For land use, moderate forests, shrublands, and grasslands in the basin's western and southwestern areas received the highest weights, while residential areas in the northeastern region were given the lowest weights. Soil hydrological groups A and B exhibited the greatest influence, with rainfall having the most significant impact in the northern, northwestern, and parts of the southwestern basin. Regarding slope, the highest weights were allocated to areas with gentle slopes (0-9%), particularly in the central basin extending from northwest to south, where permeability is greatest. The recharge potential map shows that the central basin, western strip, and southern section possess the highest recharge potential. Additional spatial analysis of rainfall events - applying fractal theory across return periods of 2, 25, 100, and 200 years - further confirmed that the central Borujerd-Doroud plain and western plain have the greatest recharge potential. Validation procedures verified the map's accuracy, and its reliability was strengthened by analyzing the spatial distribution of extraction well pumping rates. The results demonstrate that areas with high recharge potential correspond to higher pumping rates, whereas areas with low recharge potential correspond to lower pumping rates. Overall, this study indicates that integrating a rainfall-event-based approach through fractal theory, combined with other critical layers, can enable optimized groundwater management and offer valuable insights for researchers and water resource managers.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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