Identification of Groundwater Potential Zones Using GIS and Fuzzy-AHP in Arid and Semi-Arid Regions: A Case Study of Nayband, Iran

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Abstract

Groundwater represents a primary source of water supply in arid and semi-arid regions where surface water availability is severely limited. Increasing demand driven by rapid population growth, agricultural expansion, and industrial development requires robust and cost-effective assessment strategies for groundwater resource planning. This study delineates groundwater potential zones in the Nayband Plain, Tabas County, eastern Iran. The analysis integrates Geographic Information Systems (GIS) with the fuzzy Analytical Hierarchy Process (Fuzzy-AHP). Seven hydro-environmental factors—slope, geomorphology, soil texture, lineament density, land cover, precipitation, and proximity to drainage networks—were selected and weighted based on expert knowledge within a fuzzy multi-criteria decision-making framework. The resulting groundwater potential map was classified into five categories: very good, good, moderate, poor, and very poor. Findings indicate that approximately 36% of the region exhibits good to very good groundwater potential, predominantly in the northern and northwestern sectors of the plain. Model validation using 10 wells, 3 qanats, and 3 springs demonstrated a strong spatial agreement between high-potential zones and existing groundwater extraction structures. The results confirm that coupling GIS with fuzzy-AHP provides a reliable and transferable methodology for groundwater resource evaluation, especially in data-scarce arid regions. This approach supports informed decision-making for sustainable groundwater exploitation and artificial recharge projects in environments with high water scarcity.

Keywords: Groundwater Potential, Fuzzy Analytical Hierarchy Process, Geographic Information Systems, Nayband Plain, Groundwater Resource Assessment.

Introduction

Groundwater is a fundamental component of the global hydrological cycle and plays a critical role in sustainable water resources management. It supports multiple domains, including food security, human health, ecosystem services, and socio-economic development (Mussa et al., 2020). In many regions, groundwater provides a more reliable supply than surface water due to its relative stability and lower susceptibility to climatic variability. Approximately 30 % of the world's freshwater is stored as groundwater, whereas surface water sources such as rivers and lakes constitute only a very small fraction of freshwater reserves (U.S. Geological Survey, 2025).

Despite its importance, groundwater resources globally face increasing pressures from climate change, pollution, population growth, and unsustainable extraction. These pressures are particularly acute in arid and semi-arid regions, where surface water availability is limited, and reliance on subterranean aquifers is high (Doad et al., 2022; Panneerselvam et al., 2023). Over-extraction in recent decades has led to declining water tables and heightened risk of resource depletion (Al-Addous et al., 2023; Zaryab et al., 2023). Therefore, identifying and quantifying groundwater potential zones is essential for optimizing extraction and recharge planning (Subba Rao, 2006).

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In regions with hard-rock geology, rugged topography, and fractured aquifers, groundwater distribution is complex and controlled by geological, geomorphological, and hydrological factors (Khadr et al., 2020; Pande et al., 2021). Effective management requires a comprehensive understanding of these factors (Das & Pardeshi, 2018; Pathak, 2017). Traditional field-based methods, while valuable, often lack the spatial resolution or efficiency needed for regional planning. In contrast, Geographic Information Systems (GIS) and remote sensing (RS) provide effective tools for integrating diverse datasets (e.g., lithology, lineaments, drainage, slope, land cover) and for spatial analysis of groundwater potential (Abdalla, 2012; Hoffmann & Sander, 2007; Jhariya et al., 2021; Jothibasu & Anbazhagan, 2017; Tayyab et al., 2023). Traditional methods such as expert judgment and weighted sum techniques often cannot robustly handle complex, multi-dimensional datasets (Kumar et al., 2017).

Multi-Criteria Decision Making (MCDM) techniques, such as the Analytical Hierarchy Process (AHP), are widely used for groundwater potential mapping (An et al., 2016; Hussain et al., 2023; Kumar Ghadai et al., 2023). However, AHP relies on subjective judgments for weight assignment, which can reduce robustness under expert uncertainty. Hybrid approaches combining fuzzy logic with GIS can mitigate this limitation and improve reliability (Azimi et al., 2018; Li et al., 2009; Mallick et al., 2019; Minh et al., 2019; Nadiri et al., 2017; Nourani et al., 2023; Zavadskas et al., 2016a, 2016b). Several studies have demonstrated the utility of GIS and MCDM in assessing groundwater potential in diverse regions (Allafta et al., 2020; Das, 2017; Ganesan & Subramaniyan, 2024; Ghanim et al., 2023; Makonyo & Msabi, 2021; Multaniya et al., 2024; Murthy & Mamo, 2009; Omosuyi et al., 2021; Roy et al., 2022; Saranya & Saravanan, 2020; Shekar & Mathew, 2023).

While recent studies have explored hybrid approaches combining Fuzzy-AHP with machine learning techniques, Fuzzy-AHP alone remains valuable in data-scarce contexts due to its transparency, simplicity, and minimal data requirements.

Although numerous studies have applied GIS-MCDM or GIS-Fuzzy-AHP methods for groundwater potential mapping, a gap remains in hyper-arid basins of eastern Iran, where data scarcity and over-extracted aquifers limit reliable assessment. Moreover, few studies have explicitly linked groundwater potential mapping to artificial recharge planning in such settings (Pinto et al., 2017; Pocco et al., 2024).

In response to these gaps, this study focuses on the Nayband Plain in Tabas County (South Khorasan Province, Iran), a region with severe water scarcity and limited surface water recharge. The objectives are:

1. To assess the influence of key hydro-environmental factors on groundwater occurrence using expert judgment and Fuzzy-AHP, based on a panel of 20 experts with experience in hydrogeology, geomorphology, and water resources management, with consensus mitigating potential biases;
2. To generate a classified groundwater potential map via GIS;
3. To validate the zonation against existing wells, qanats, and springs;
4. To identify suitable zones for artificial groundwater recharge.

While recent studies have explored hybrid approaches combining Fuzzy-AHP with machine learning, Fuzzy-AHP remains valuable in data-scarce contexts due to its transparency, simplicity, and minimal data requirements.

Study Area

The study area, Nayband village, is situated in Tabas County, South Khorasan Province, eastern Iran, on the western edge of the Lut Desert. Its geographical coordinates range approximately from 29°54'N to 29°55'N latitude and 56°32'E to 56°33'E longitude, with an average elevation of about 1095 meters above sea level (South Khorasan Regional Water Company, 2004). The region experiences an arid climate characterized by extreme temperature fluctuations: summer temperatures frequently exceed 45°C, whereas

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winter temperatures can drop to around -5°C. Annual precipitation is limited and primarily occurs during winter and early spring.

The study area lacks perennial rivers; however, seasonal rainfall occasionally generates temporary river flows. The total annual surface water flow is estimated at approximately 400 million cubic meters, which is predominantly utilized through traditional water management systems such as qanats and surface water diversion (South Khorasan Regional Water Company, 2004). The principal source of water in the province is atmospheric precipitation, amounting to more than 12 billion cubic meters annually, of which approximately 90% is lost through surface evaporation, leaving only 10% to infiltrate aquifers and contribute to groundwater recharge. Of this total precipitation, approximately 2–3% contributes to surface water runoff, consistent with the estimated 400 million cubic meters of annual surface water.

Tables 1 and 2 summarize the characteristics of the qanats and springs included in this study, while Fig. 1 illustrates the location and spatial extent of the study area. This description establishes the hydroclimatic and geographical context necessary for evaluating groundwater potential.

Table 1. Characteristics of Qanats Used for Validation (South Khorasan Regional Water Company, 2022)

Average Discharge (L/S)	Year	Name	City	Qanat
7.76	2019	Nayband	Tabas	Zardgah Nayband
0.09	2019	Nayband	Tabas	Ab Reza
3.51	2019	Nayband	Tabas	Dehnonayband

Table 2. Characteristics of Springs Used for Validation (South Khorasan Regional Water Company, 2022)

Average Discharge (L/S)	Year	Name	City	Spring
2.275	2019	Nayband	Tabas	Dig Rostam2
2.15	2019	Nayband	Tabas	Dig Rostam1
0.045	2019	Nayband	Tabas	Ab Reza

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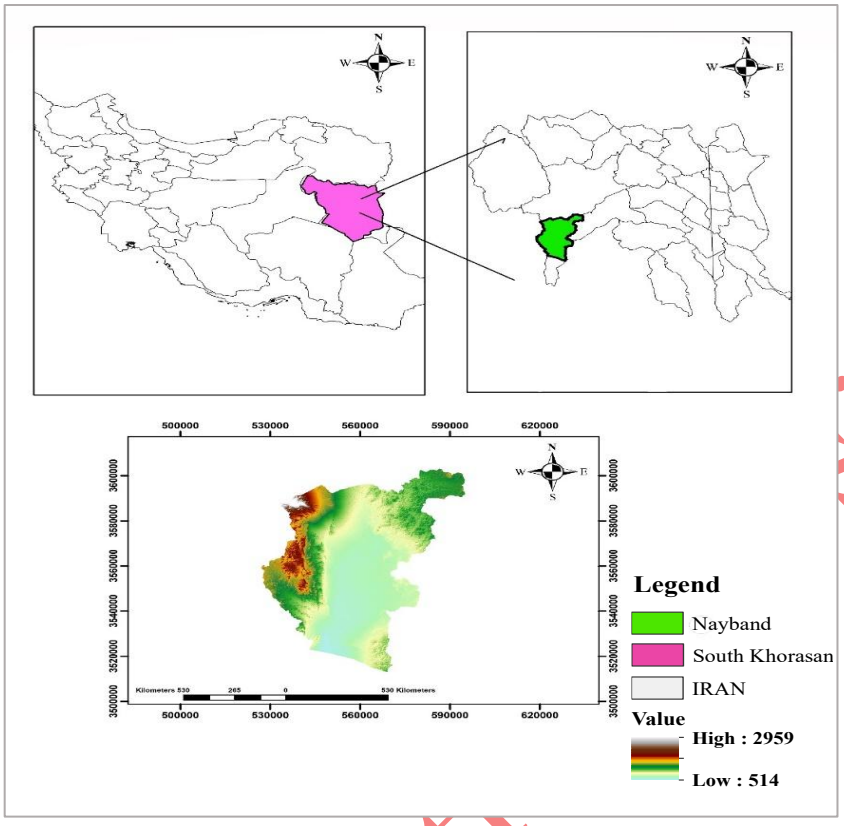


Fig 1. Topography and elevation map of the study area

Materials and Methods

Accurate site selection for groundwater potential requires collecting diverse spatial data from multiple sources, which are organized into thematic layers within a Geographic Information System (GIS) environment. In this study, satellite imagery from the Landsat ETM sensor for the year 2020 with a spatial resolution of 30 m was used and pre-processed in ENVI software, including geometric and radiometric corrections. Land cover maps were generated using a supervised classification approach. Digital Elevation Model (DEM) and Shuttle Radar Topography Mission (SRTM) datasets were used to derive slope and topographic features. Geological maps at a scale of 1:100,000 were employed to extract lithology and fault information. Precipitation data over the past 20 years (2000–2020) were obtained from local meteorological stations and interpolated using the Kriging method in ArcMap, accounting for spatial autocorrelation. Cross-validation was performed to assess interpolation accuracy, ensuring reliable representation of spatial distribution. Drainage network maps were digitized and incorporated. All thematic layers were standardized and integrated to ensure spatial consistency and accuracy for groundwater potential mapping using Fuzzy-AHP.

Seven key hydro-environmental factors were considered in this study, based on expert knowledge and available data:

1. Slope of the land
2. Geomorphology: geological features of the land surface
3. Soil characteristics
4. Lineament density (faults and fractures)
5. Land cover: vegetation and surface cover
6. Precipitation: amount and distribution of rainfall

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7. Drainage pattern density

Drainage Pattern Density and Proximity to Surface Water

Drainage pattern characteristics, particularly density and permeability, play a crucial role in groundwater recharge. High drainage density often enhances aquifer permeability, improving water storage and movement. Therefore, drainage analysis is essential for evaluating groundwater potential and optimizing resource management. Distance from drainage networks was also considered using the Distance tool in ArcGIS. The study area was categorized into five proximity classes: very close, close, moderate, weak, and very weak, reflecting varying distances from drainage patterns (Manikandan, Kiruthika, & Sureshbabu, 2014).

Land Slope

Land slope controls surface runoff and groundwater infiltration, making it a primary factor influencing recharge. Gentle slopes facilitate water infiltration into soils and rocks, enhancing groundwater storage, while steep slopes increase runoff and reduce recharge potential. Slope maps were generated from DEM data in ArcMap software (Elubid et al., 2020).

Geomorphology

Geomorphological features affect groundwater flow and storage, especially in karst and fractured terrains. Analysis of satellite imagery enabled identification of surface features, including elevation, landform shape, and rock density, which influence groundwater potential. The study area was classified into three geomorphological categories:

- **Plains**: Flat areas suitable for recharge
- **Grasslands with moderate slopes**: Moderately suitable
- **Steep lands**: Less suitable due to increased runoff

Soil

Soil properties, particularly permeability, are critical for determining groundwater potential. Soils with high permeability allow efficient infiltration and recharge of aquifers.

Lineament Density (Faults)

Fault zones and fractures facilitate groundwater movement and accumulation. High lineament density generally enhances recharge and distribution of groundwater (Haridas, Aravindan, & Girish, 1998). Fault density and fracture patterns were mapped and analyzed to inform groundwater management strategies.

Land Cover

Vegetation cover influences water infiltration and reduces surface runoff. Maintaining or enhancing vegetative cover supports both the quantity and quality of groundwater.

Precipitation

Precipitation data over the past 20 years (2000–2020) were interpolated using Kriging in ArcMap, chosen for its ability to account for spatial autocorrelation and provide unbiased estimates. The interpolation accuracy was evaluated using cross-validation, confirming that the resulting map reliably represents the spatial distribution of precipitation.

Weighting of Information Layers

To integrate the thematic layers and generate the groundwater potential map, the Fuzzy Analytical Hierarchy Process (Fuzzy AHP) was employed. The Fuzzy AHP method, introduced by Van Laarhoven

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and Pedrycz (1983), enhances the traditional Analytical Hierarchy Process (AHP) by addressing limitations such as scale inconsistencies, uncertainty in pairwise comparisons, and the difficulty of capturing the nuances of human decision-making. Fuzzy AHP incorporates triangular fuzzy numbers into the pairwise comparison matrices and applies the least squares logarithmic method to derive weights (Van Laarhoven & Pedrycz, 1983).

Fuzzy AHP provides a mathematical framework to model uncertainty in decision-making. Decision-makers can express preferences with uncertainty represented by fuzzy numbers. Pairwise comparisons between criteria are expressed using triangular fuzzy numbers, and the geometric mean method is applied for weighting and prioritization. This approach allows extension to fully fuzzy contexts and ensures a unique solution from the pairwise comparison matrix.

In this study, a structured Pairwise Comparison Questionnaire was prepared based on the criteria described in the previous section. The survey collected inputs from 20 local experts, including 8 hydrogeologists, 6 water resource engineers, and 6 local planners from the South Khorasan Regional Water Company and the University of Birjand, each with ≥10 years of field experience. These experts ranked the importance of each criterion, and the resulting data were processed using the Fuzzy AHP technique to assign weights to each information layer, followed by normalization. The fuzzy scale used for pairwise comparisons is presented in Table 3 . Finally, the weighted layers were integrated using a linear combination approach within a GIS environment to produce the groundwater potential map (Machiwal, Jha, & Mal, 2011).

Table 3. Fuzzy spectrum equivalent to nine-hour scale in AHP technique (Van Laarhoven & Pedrycz, 1983)

Fuzzy Inverse	Fuzzy Numbers	Comparative Verbal Phrase I Compared To J
(1,1,1)	(1,1,1)	Preferred Equally
(0.333,0.5,1)	(1,2,3)	
(0.25,0.333,0.5)	(2,3,4)	Preferred moderately
(0.2,0.25,0.333)	(3,4,5)	
(0.166,0.2,0.25)	(4,5,6)	Preferred Strongly
(0.142,0.16,0.2)	(5,6,7)	
(0.125,0.142,0.166)	(6,7,8)	Very strongly preferred
(0.111,0.125,0.142)	(7,8,9)	
(0.111,0.111,0.111)	(9,9,9)	Extremely Preferred

The fuzzy hierarchical method applies these weights to each criterion, combining them to generate the final groundwater potential map. Pairwise comparisons were organized in Microsoft Excel, and the comparison matrices are visualized in Figs. 2 and 3, which illustrate the relative importance of each criterion in forming the groundwater potential map. The integration of expert opinions with fuzzy logic ensures a robust weighting scheme that accounts for uncertainty and subjective judgments in spatial decision-making.

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	Slope	Geomorphology	Soil	Fault	Land cover	Rainfall	Proximity to surface water	Fuzzy	Normalized weight
Slope	1	(0.333,0.5,1)	(0.333,0.5,1)	(0.333,0.5,1)	(0.25,0.333,0.5)	(0.142,0.16,0.2)	(0.25,0.333,0.5)	(0.0235,0.042,0.096)	**0.054**
Geomorphology	(1,2,3)	1	(0.25,0.333,0.5)	(0.333,0.5,1)	(0.25,0.333,0.5)	(0.111,0.125,0.142)	(0.25,0.333,0.5)	(0.0253,0.043,0.084)	**0.051**
Soil	(1,2,3)	(2,3,4)	1	1	(1,1,1)	(0.25,0.333,0.5)	(0.25,0.333,0.5)	(0.049,0.091,0.175)	**0.106**
Fault	(1,2,3)	(1,2,3)	1	1	(0.166,0.2,0.25)	(0.25,0.333,0.5)	(0.25,0.333,0.5)	(0.037,0.0713,0.142)	**0.084**
Land cover	(2,3,4)	(2,3,4)	(1,1,1)	(4,5,6)	1	(0.333,0.5,1)	(0.333,0.5,1)	(0.071,0.130,0.271)	**0.158**
Rainfall	(5,6,7)	(7,8,9)	(1,2,3)	(1,2,3)	(1,2,3)	1	(1,2,3)	(0.130,0.277,0.529)	**0.313**
Proximity to surface water	(2,3,4)	(2,3,4)	(2,3,4)	(2,3,4)	(1,2,3)	(0.333,0.5,1)	1	(0.094,0.199,0.403)	**0.233**

Fig 2. Pairwise comparison of criteri

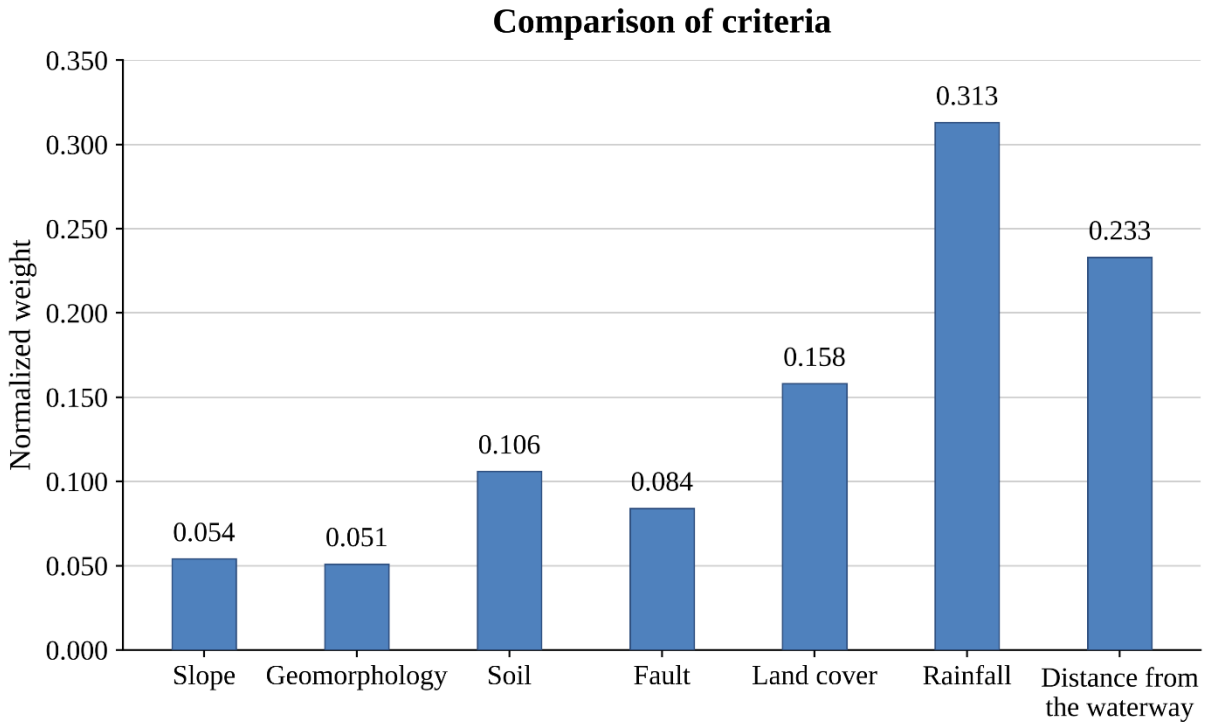


Fig 3 .Pairwise comparison chart of criteria based on normalized weights

Through the comparison of criteria, it was determined that the precipitation criterion, with a normalized weight of 0.313, exerts the greatest influence on groundwater potential. Conversely, the geomorphology criterion, with a weight of 0.051, has the least impact. In other words, the fuzzy-AHP analysis indicates that precipitation is the most critical factor for determining groundwater resource potential in this study. A flowchart outlining the steps followed in this work is presented in Fig .

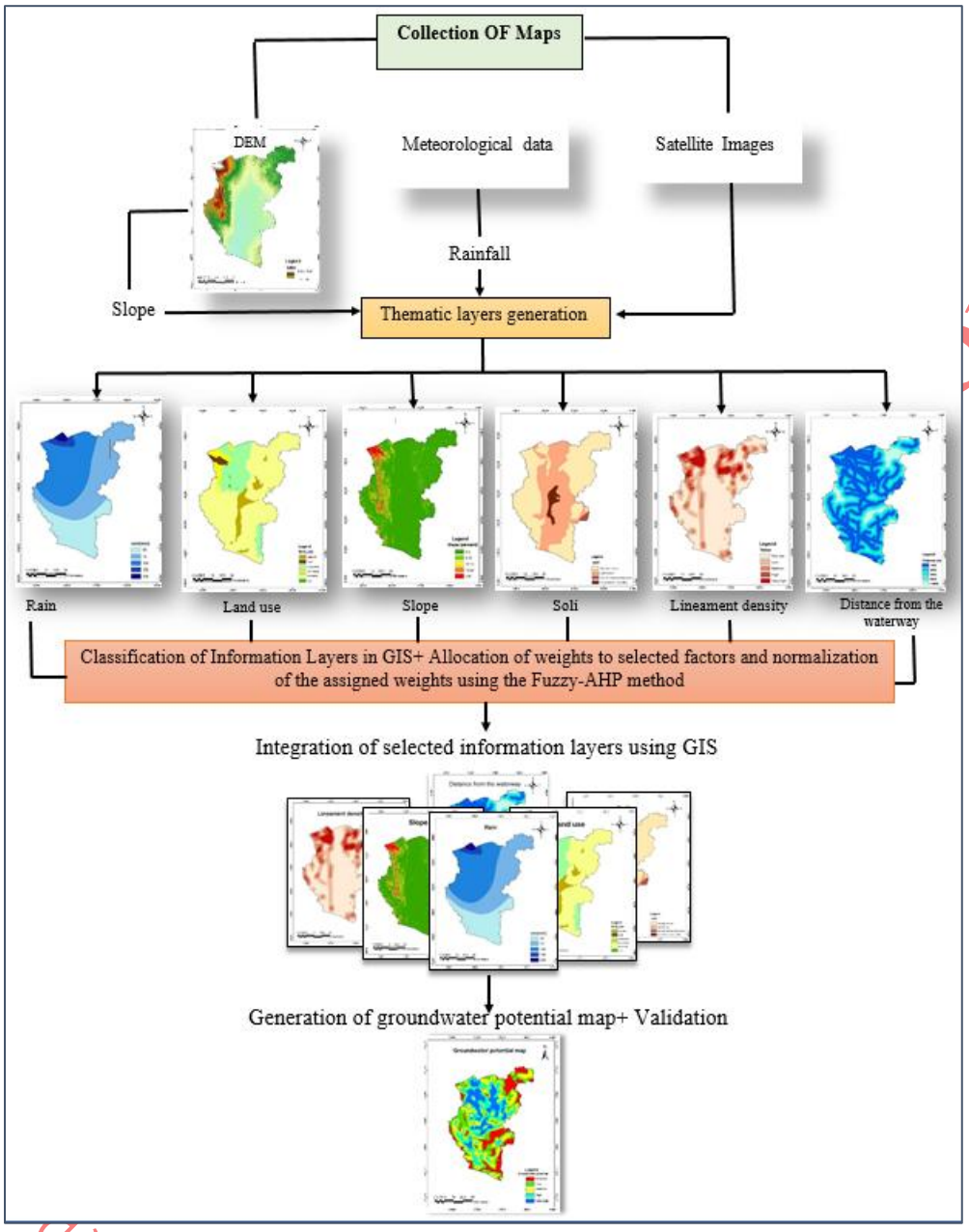


Fig 4.The generated flowchart for producing groundwater potential maps

Calculation of Inconsistency Rate

The inconsistency rate quantifies the degree of agreement among pairwise comparisons made by experts or specialists. It indicates how consistent these comparisons are with each other. A low inconsistency rate suggests a high level of agreement, which enhances the reliability of the results. In contrast, a high inconsistency rate may reveal significant disagreements within the study group, which could introduce uncertainty into the outcomes.

For the weight assignments to be considered valid, the consistency ratio (CR) must not exceed 10%. If the CR is higher than this threshold, the assigned weights should be revisited and adjusted to reduce inconsistencies, ensuring more reliable and accurate results (Saaty, 1990).

The inconsistency rate of each matrix can be determined through the following steps:
1.Form the pairwise comparison matrix A.
2.Determine the weight vector (W).
3.Calculate the maximum eigenvalue of A (λ_{max}).
Estimate the values of λ_{max} by dividing the values obtained for λ_{max}.W by the corresponding W.
In the analysis, the value of λ_{max} was found to be 8.95%.
4.The consistency index (CI) is calculated according to the following formula.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (1)$$

In which λ_{max} represents the maximum eigenvalue, and n is the number of criteria. Therefore, for this analysis, CI is equal to:

$$CI = \frac{8.95 - 8}{8 - 1} = 0.136 \quad (2)$$

5.The Consistency Ratio (CR) is calculated according to the following formula:

$$CR = \frac{CI}{RI} \quad (3)$$

In which RI is the Random Index, obtained from Table corresponding to the number of criteria. In this study, since the number of parameters is 8, RI will be 1.41. Therefore, CR is calculated as follows:

$$CR = 0.096 \quad (4)$$

The Consistency Ratio (CR) is a key metric used to assess the reliability of pairwise comparisons. If the CR exceeds 0.1, it suggests that the judgments are inconsistent, indicating potential errors in the comparison process. Conversely, when the CR is less than or equal to 0.1, it indicates an acceptable level of consistency in the pairwise comparisons (Saaty, 1990). In this study, the calculated Consistency Ratio for the assigned weights is 0.096, signifying a high level of agreement among the participants regarding the relative importance of the criteria. In the Table , n represents the number of elements in the pairwise comparison table, and R is the Consistency Index. And in Fig 2, the maps are displayed in fuzzy form.

Table 4. Consistency Index (Saaty, 1990)

n	1	2	3	4	5	6	7	8	9	10
R	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.45

Results and Discussion

Finally, maps of all factors were standardized and classified to generate groundwater potential layers. Table 5 and Fig. 5 present the classification scheme and resulting maps for the study area.

Table 5. Assigned Values to Each Layer

Layer	**Distance(m)**	**Rank**
Distance from the waterway	1000-0	5
	2000-1000	4
	3000-2000	3
	4000-3000	2
	4000<	1
Layer	range	**Rank**
Slope	5-0	5
	10-5	4

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Layer	Distance(m)	Rank
	15-10	3
	20-15	2
	20<	1
	class	**Rank**
Geomorphology	plain	3
	Pastures with moderate slope	2
	Lands with steep slopes	1
	soil pattern	**Value**
Soil	Sandy	**4**
	Loamy sand	**3**
	Silty loam	**2**
	Silty clay	**1**
	class (km/km^2)	**Rank**
Lineament density(fault)	0.2-0	**1**
	0.4-0.2	**2**
	0.4-0.6	**3**
	0.8-0.6	**4**
	1.8-0.8	**5**
	class	**Rank**
land use	Salt marshes and barren areas	5
	agriculture	4
	Poor pastures	3
	mid-range	2
	Rock	1
	Precipitation	**Rank**
rainfall	50	1
	75	2
	100	3
	150	4
	200	5

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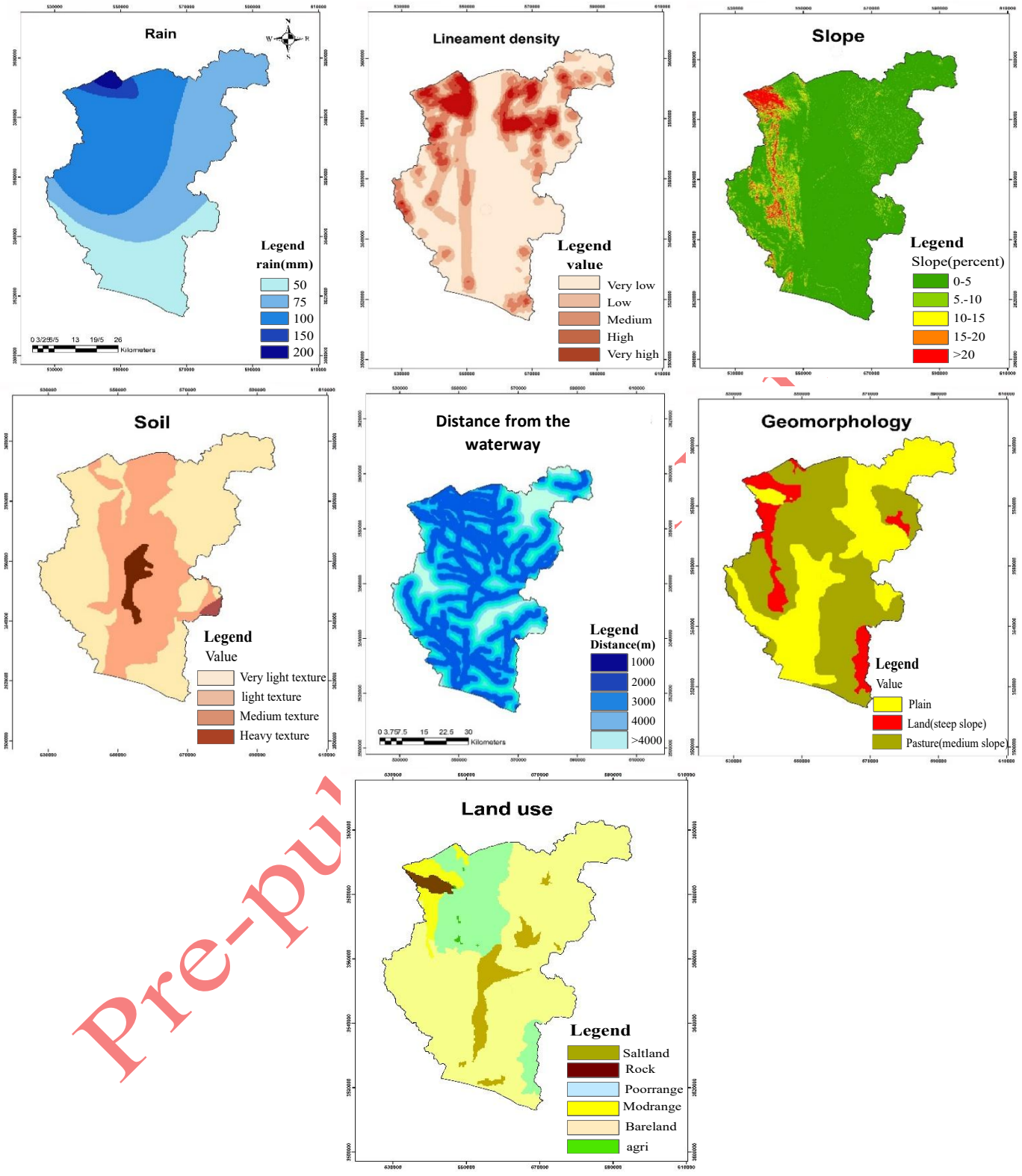


Fig 5. Spatial Variation of Factors Affecting Groundwater Resources

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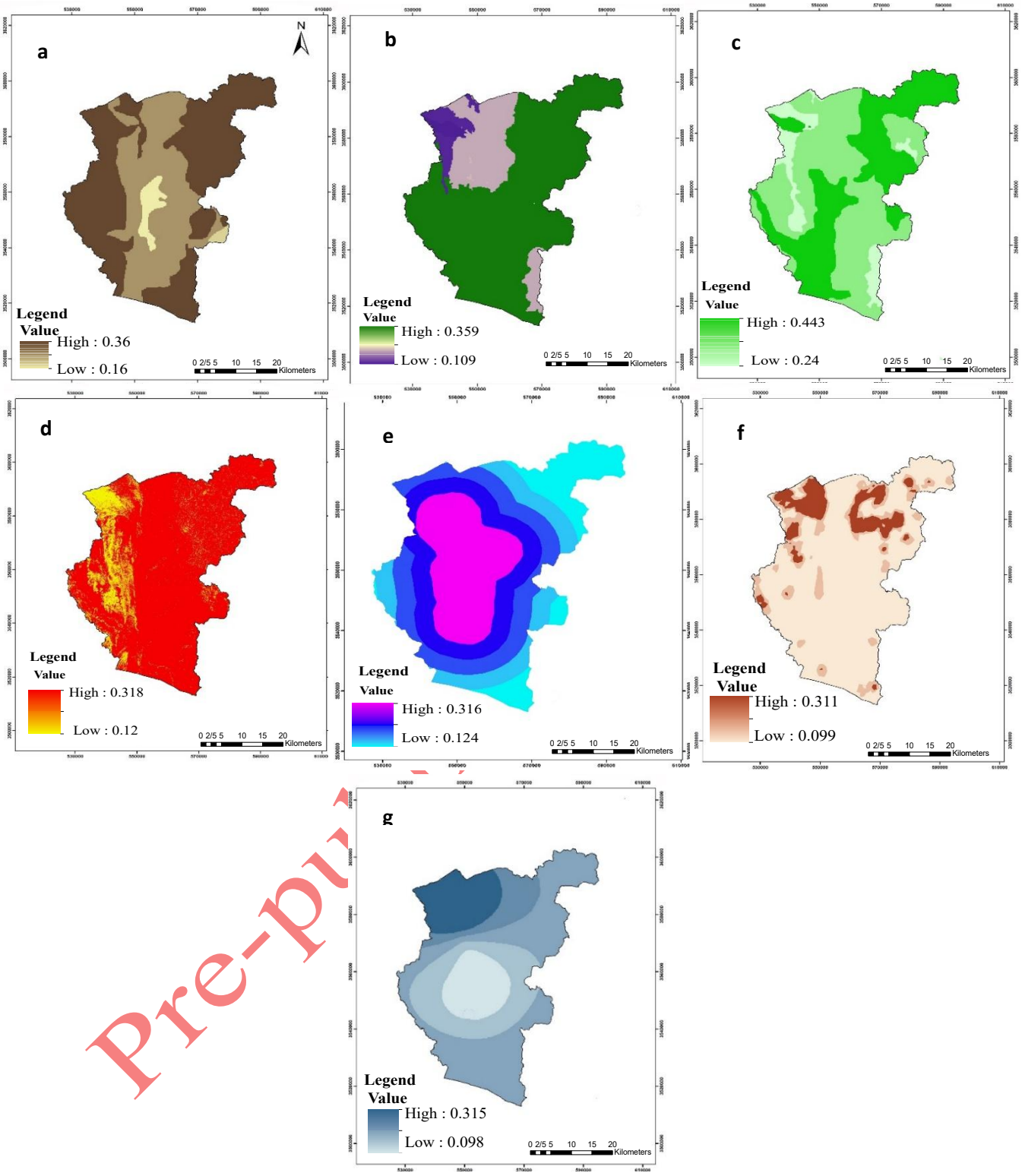


Fig 2. Fuzzy maps of various criteria: a) Soil, b) Land cover, c) Geomorphology, d) Slope, e) Distance from waterways, f) Fault, g) Precipitation

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Combining Information Layers and Creating Groundwater Potential Map

To generate the groundwater potential map, individual maps for each sub-criterion were first prepared based on their normalized weights. These weighted layers were then integrated within a GIS environment to produce the final groundwater potential map.

Table 3. Weights Assigned to Groundwater Potential Criteria and Sub-Criteria Based on Fuzzy-AHP, and Final Weights

Final Weight	Fuzzy-AHP Sub-Criteria Weight	Criterion Weight	Sub- Criteria	Criterion
0.026	0.098	0.313	50	Rainfall
0.040	0.152		75	
0.052	0.195		100	
0.064	0.240		150	
0.084	0.315		200	
0.063	0.319	0.233	1000	Distance from the waterway
0.050	0.253		2000	
0.034	0.172		3000	
0.027	0.137		4000	
0.023	0.120		>4000	
0.032	0.360	0.106	Very light texture	Soil
0.024	0.270		Light texture	
0.019	0.210		Medium texture	
0.014	0.160		Heavy texture	
0.014	0.318	0.054	0-5	Slope
0.010	0.228		5-10	
0.009	0.198		10-15	
0.006	0.137		20-15	
0.005	0.120		>20	
0.007	0.099	0.084	0.2-0	Fault
0.010	0.140		0.4-0.2	
0.012	0.172		0.4-0.6	
0.020	0.278		0.8-0.6	
0.022	0.311		1.8-0.8	
0.048	0.359	0.158	Barren and salt marsh areas	Land use
0.027	0.207		agriculture	
0.026	0.199		Poor pastures	
0.016	0.125		mid-range	
0.014	0.109		Rock	
0.019	0.443	0.051	plain	Geomorphology
0.013	0.317		Medium slope pastures	
0.010	0.240		Steep land	

Table 3 shows the weights assigned to the criteria, sub-criteria, and the final weight for each. The final weight for each sub-criterion is calculated by multiplying the weight of the main criterion by the weight of the sub-criterion. To generate the groundwater potential map, the maps corresponding to each sub-criterion are integrated. Then, using the fuzzy hierarchical method, the map is classified into five distinct categories, ranging from very good to very poor. The classification results reveal that approximately 16% of the area is classified as very poor, 22% as poor, 24% as moderate, 22% as good, and 14% as very good.Fig 3).

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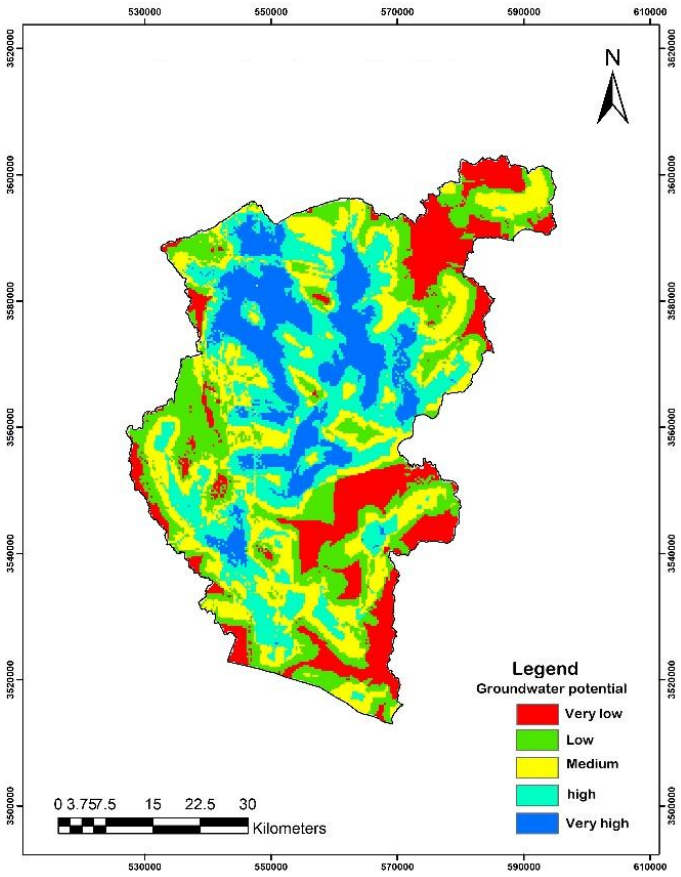


Fig 3. Groundwater Potential Map

Validation

The validation of the groundwater potential map was performed by analyzing the locations of wells, qanats, and springs within the study area. The results indicate a strong spatial correspondence between actual water sources and areas classified as having high groundwater potential. Specifically, 10 wells, 3 qanats, and 3 springs are primarily located within zones identified as very high potential, representing approximately 40% of the region's groundwater resources. This spatial alignment demonstrates the effectiveness of integrating remote sensing, Geographic Information Systems (GIS), and fuzzy-AHP modeling for groundwater resource assessment. While the current validation emphasizes spatial agreement, the methodology provides a solid foundation for future studies, where additional statistical validation techniques could be employed to further enhance model assessment.

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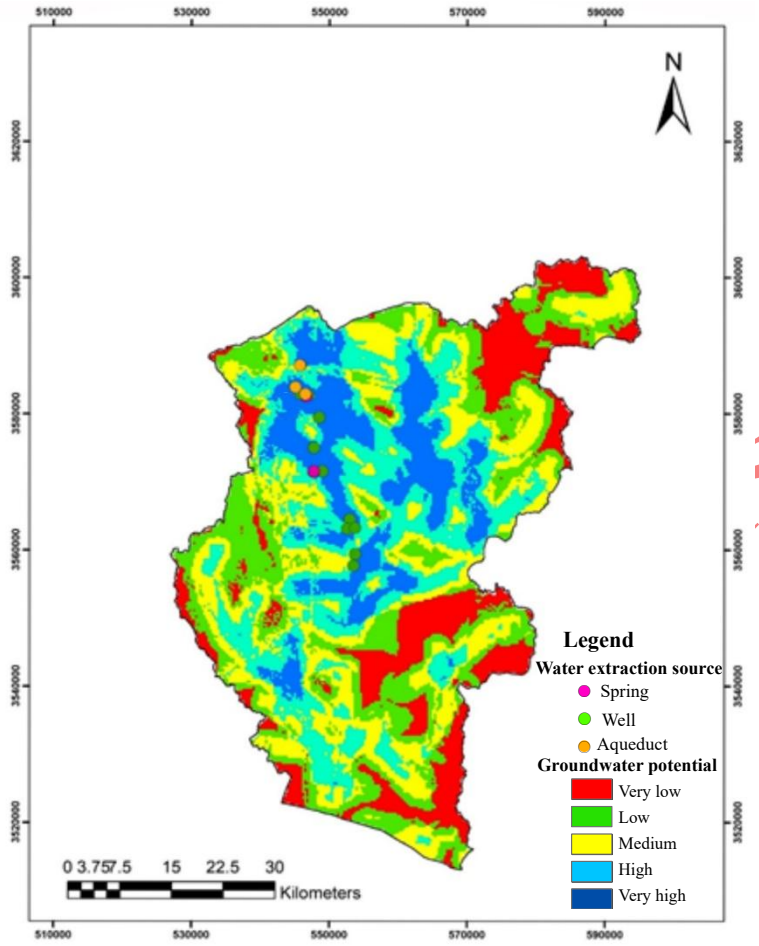


Fig 4. The location of existing wells on the groundwater potential map (South Khorasan Regional Water Company, 2022)

The results of this study indicate that approximately 36% of the Nayband Plain exhibits good to very good groundwater potential, predominantly in the northern and northwestern sectors. These findings are consistent with previous studies in arid and semi-arid regions, where GIS-based multi-criteria methods such as Fuzzy-AHP have successfully delineated groundwater potential zones (Chen et al., 2025; Shinde et al., 2024; Ali et al., 2024; Seraiche et al., 2025). Similar to our study, precipitation has been found to exert a dominant control over groundwater occurrence in data-scarce and arid environments, outweighing geological factors due to limited recharge from surface sources. The relative importance of rainfall over lithology in the Nayband Plain can be attributed to the region's low and highly variable precipitation, sparse vegetation cover, and fractured aquifers, which limit infiltration and emphasize the influence of precipitation patterns. These results highlight the critical role of climate in groundwater availability in arid regions and support the use of Fuzzy-AHP integrated with GIS as a reliable tool for groundwater resource assessment and sustainable management.

While this study provides a robust assessment of groundwater potential, some limitations should be acknowledged. The use of medium-resolution satellite imagery (Landsat ETM, 30 m) may not capture fine-scale land cover variations, potentially affecting infiltration estimates. Precipitation data were interpolated over 20 years, but temporal variations and extreme events could influence groundwater recharge beyond the scope of this analysis. Additionally, the static nature of geological and soil data may not fully reflect dynamic processes such as erosion or sediment deposition that could modify local recharge patterns.

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Despite these limitations, the integrated use of GIS, remote sensing, and Fuzzy-AHP provides a reliable framework for identifying groundwater potential zones, supporting sustainable water resource management. These results can guide policymakers, planners, and local authorities in prioritizing areas for groundwater extraction, artificial recharge, and conservation efforts, while providing a foundation for more detailed, site-specific investigations in the future.

Conclusion

The integration of Geographic Information Systems (GIS) with multi-criteria decision-making (MCDM) methods, such as Fuzzy-AHP, provides a robust framework for delineating areas with high groundwater potential. By integrating thematic maps, field measurements, and remote sensing data within a GIS environment, spatial patterns, trends, and relationships between environmental factors and groundwater availability can be systematically analyzed. This approach enhances decision-making for groundwater extraction and artificial recharge projects, thereby reducing the need for extensive fieldwork and associated costs.

In the Nayband Plain, approximately 36% of the area exhibits high groundwater potential, with 22% classified as good and 14% as very good. The highest potential zones are predominantly located in the northern and northwestern sectors, making them suitable for sustainable groundwater extraction and the installation of recharge wells. These findings are consistent with previous studies in arid and semi-arid regions, where GIS-based MCDM approaches, including Fuzzy-AHP, have effectively delineated groundwater potential zones (Chen et al., 2025; Shinde et al., 2024; Ali et al., 2024; Seraiche et al., 2025). Similar to our study, precipitation has been identified as the dominant factor controlling groundwater occurrence in arid environments. In the Nayband Plain, the low and highly variable rainfall exerts a stronger influence on recharge than geological factors, as fractured aquifers and limited surface water infiltration reduce the effect of lithology on groundwater availability. This observation aligns with other semi-arid studies where climate-driven recharge patterns outweighed the role of geology (Sepahvand et al., 2025).

While the results are robust, their accuracy depends on the quality of input data. Limitations in geomorphological and soil maps, as well as inherent uncertainties in remote sensing and GIS analyses, may introduce variability in certain locations. Temporal factors, such as seasonal precipitation variability and fluctuations in groundwater levels, are not fully captured by static datasets, highlighting the need for cautious interpretation of the results.

Future studies could improve the methodology by incorporating real-time groundwater monitoring, higher-resolution datasets, and advanced computational approaches, including machine learning and alternative MCDM techniques. Expanding spatial and temporal validation datasets, conducting sensitivity analyses, and incorporating dynamic environmental variables would further enhance the accuracy and reliability of groundwater potential assessments. Overall, this research confirms that GIS integrated with Fuzzy-AHP provides a cost-effective, efficient, and reliable tool for sustainable groundwater management in arid and semi-arid regions.

Conflict of interest

All authors declare no conflict of interest.

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