Identification of groundwater Potential Areas Using GIS and MCDM in arid and Semi-Arid Regions (Case Study: Nayband in Iran)

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Abstract

Groundwater is an important and essential resource in dry and semi-arid regions, as well as in areas with restricted access to surface waters. Global water demand has increased significantly in recent years, largely due to industrial growth, population growth, and shifts in lifestyle and consumption habits. At present, groundwater is a primary source of freshwater, making up around 34% of the total annual global water supply. Water harvesting is a critical and essential part in infrastructure and economic projects, requiring significant investment. Therefore, it is vital to assess this issue for the sustainable management of groundwater systems. Since groundwater operates dynamically, it is essential to employ Geographic Information System (GIS) in the development and management of groundwater. Multi-Criteria Decision Making (MCDM) analysis including commonly used types such as AHP, is an effective technique in this regard. The main objective of this study is to locate potential groundwater areas in Nayband Plain, Tabas County, using GIS and multi-criteria decision-making analysis. The fuzzy-AHP method was employed to create the groundwater potential map. Various features such as slope, geomorphology, soil characteristics, lineaments, land cover type, precipitation and river distance were used to generate the groundwater potential map. Pairwise comparison of criteria and expert opinions were utilized to assign scores and weights to each groundwater potential criterion. Subsequently, the criteria were categorized, and weights were assigned to each category. Using these weights, final maps were generated using ArcMap 10.8 software. The level of groundwater access in the region was qualitatively classified into five categories: very good, good, moderate, poor, and very poor. To validate the generated map, data from 10 wells, 3 qanats, and 4 springs in the Nayband region were utilized. In conclusion, the comparison of the final map with the distribution of wells, springs, and qanats indicates that this method exhibits high accuracy in this area and contributes to the analysis of the groundwater potential of the region.

Introduction

Groundwater plays a vital role in maintaining the global hydrological balance and holds significant importance in water resource management approaches. Additionally, these resources are recognized as a substantial natural source for ensuring food security, preserving human health, protecting ecosystems, and contributing to the economic and social well-being of global communities (Mussa et al., 2020). Groundwater is perceived as a primary source of freshwater globally, constituting the largest reservoir of fresh water on Earth after glaciers and large ice-covered areas. General assessments of water resources globally indicate that approximately 31% of the total freshwater resources worldwide are attributed to groundwater (Zohrabi et al., 2013).

Groundwater, characterized by attributes such as freshness, lower cost, stable chemical composition, constant temperature, low contamination coefficient, and higher reliability, is particularly recognized in dry and semi-arid regions. However, the significant increase in global water demand in recent years, due to industrial growth, population increase, and changes in consumption patterns and lifestyles, can lead to a considerable shortage in groundwater resources (Pinto et al., 2017). Nevertheless, the excessive exploitation of global groundwater resources has significantly increased in recent decades, imposing substantial pressure on these resources. Finding the potential groundwater zones can assist in optimal utilization of groundwater and surface water resources to address water shortages (Subba Rao, 2006). The growing demand for freshwater in various sectors, especially for drinking water and agriculture, necessitates the identification of areas with groundwater potential (Bhattacharya, 2010; Hoffmann & Sander, 2007).

There are extensive regions characterized by dry and semi-arid climates in Iran, faces significant water scarcity challenges. Groundwater in this country is considered a fundamental water source for various valuable purposes. Since groundwater resources are hidden phenomena, then the assessment through indirect analysis based on factors such as geology, geomorphology, land structure, and hydrogeological characteristics is feasible (Abdalla, 2012). The widespread use of Geographic Information Systems (GIS) and Remote Sensing (RS) in natural resource management is common. Remote sensing enables the provision of multispectral and repeatable data from the Earth's surface using various sensors. Given the dynamic nature of groundwater, the integration of GIS and RS in studies related to the development and management of groundwater resources proves to be highly effective (Jhariya et al., 2016).

The Analytic Hierarchy Process (AHP) has been successfully and extensively used for MCDM in recent decades (Kaliraj, Chandrasekar, & Magesh, 2014). Examining various criteria that impact a subject is a common decision-making method across different fields. Among the MCDM methods, fuzzy-AHP has been utilized in various fields over the past few decades including the evaluation of groundwater quality (2019); (2018), seismic analysis (2019), investigation of ecosystem and environmental vulnerability (2009), and analysis of groundwater vulnerability (2017). These studies generally indicate that fuzzy-AHP models based on Geographic Information System (GIS) can provide more realistic results.

Many researchers have extensively utilized GIS for identifying areas with suitable potential for groundwater in various regions. Rezaei Moghadam et al. (2016) examined the groundwater potential of the watershed that leads to the Tabriz Plain using the network potential analysis method. The research results indicated that precipitation and geology have the most significant impact on the groundwater potential of the area, and regions with high groundwater potential are characterized by Quaternary sediments and low elevations. Unfortunately, in this study, the impact of faults and fracture conditions in the region was not thoroughly investigated.

Ghorbani Nezhad et al. (2017) utilized a frequency ratio-based model in the Geographic Information System (GIS) environment for effective groundwater resource potential mapping in the Azna-Aligudarz plain. This model was employed as a reliable tool in determining the potential of groundwater resources in this area.

Oh et al. (2011) analyzed the potential of groundwater resources in the Pohang city of Korea using Geographic Information System. According to the findings, the analysis yielded a map accuracy of over 77%, revealing the soil characteristics as the most influential factors affecting the potential of groundwater resources in the region while the elevation had the least impact.

Agarwal et al. (2013) studied the groundwater productivity in the Onaoi region of India using Analytic hierarchy process. The results of this research showed that about 25% of the area has very good and good potential in terms of groundwater resources.

Allafta et al (2020) identified 9 influential parameters on groundwater potential, including lithology, precipitation, geomorphology, slope, drainage density, soil, land use/land cover, distance from rivers, and lineament density. They performed appropriate weighting to these parameters using pairwise comparison matrices and ultimately produced a final map of areas susceptible to groundwater.

Makounyo and Msabi (2021) utilized Geographic Information System (GIS) and Multi-Criteria Decision Analysis (MCDA) to investigate the groundwater potential in the fractured aquifer of the semi-arid Mianeh-Mara mountainous region. They employed the Analytical Hierarchy Process (AHP) technique to evaluate and weight eight influential factors. These factors included aquifer lithology, slope, land use/land cover (LULC), soil types, drainage density, geological lineament density, stream accumulation, and Topographic Wetness Index (TWI). They weighted these factors using AHP and ultimately integrated the data using the Weighted Linear Combination (WLC) method in ArcGIS Pro software. The research findings classified the areas into five recharge potential groups, namely very high, high, moderate, low, and very low..

Considering the various studies on the location selection of areas with suitable potential for artificial recharge of groundwater and the evaluation of factors influencing these areas, this study focused on analyzing and weighting the factors to generate a map of areas with groundwater potential in the study area, located in Nayband, South Khorasan province.

Materials and Methods

1- Study Area

Nayband village is situated at approximately 29°54' longitude and 15°32' latitude on the western margin of the Lut Desert in eastern Iran, one of the southernmost points in Tabas County, South Khorasan. The study area is recognized as a desert region with a dry climate. This region is characterized by extreme temperature fluctuations, with high temperatures often exceeding 45°C in summer and dropping to around – 5°C in winter. Rainfall is generally scarce, occurring mostly in winter and early spring. In this area, there are no rivers with constant flow, but seasonal rains can lead to the formation of floods in the rivers. The study area is located at an elevation of approximately 1095 meters above sea level. Regarding the statistics of floods in this region, there is no available information. However, as part of the South Khorasan province, it should be noted that the rivers in this province mostly have seasonal flows, and the occurrence of occasional floods is minimal. The annual surface water flow volume is estimated to be around 400 million cubic meters. These water resources are utilized through traditional methods (South Khorasan Regional Water Authority, 2004). Also the primary source of water resources in this province comes from atmospheric precipitation, totaling over 12 billion cubic meters annually.

About 90% of the total precipitation, roughly 10.6 billion cubic meters, evaporates from the earth's surface, and only 1.4 billion cubic meters or 10% infiltrates in aquifers, contributing to groundwater recharge. Additionally, approximately 2 to 3% of the precipitation, equivalent to 400 million cubic meters, flows as surface water in rivers (South Khorasan Regional Water Authority, 2004). Furthermore, Table 1 and Table 2 present the details respectively regarding the Qantas and springs utilized in this study.

Table 1
Information on the utilized qanats for validation (South Khorasan Regional Water Company, 2022)

Average discharge (L/S)	year	name	city	Qanat
7.76	1398	Nayband	Tabas	Zardgah Nayband
0.09	1398	Nayband	Tabas	Ab Reza
3.51	1398	Nayband	Tabas	Dehnonayband

Table 2
Information on the utilized springs for validation (South Khorasan Regional Water Company, 2022)

Average discharge (L/S)	year	name	city	spring
2.275	1398	Nayband	Tabas	Dig Rostam2
2.15	1398	Nayband	Tabas	Dig Rostam1
0.045	1398	Nayband	Tabas	Ab Reza

2- Data

To conduct the site selection process, it is necessary to first collect diverse spatial information from various sources and then organize them in the form of different information layers within the coverage of GIS-related software. Subsequently, using GIS tools and techniques, analyze this spatial information. These steps ensure that the data is interpreted accurately and logically. Then, based on the results of the analyses, select and determine suitable locations. This method, aided by spatial data and generated maps, contributes to improving decision-making and area management.

In order to prepare the necessary information layers for this research, satellite images of the area were initially collected through the Landsat system. These satellite images then underwent pre-processing stages, including geometric and radiometric corrections. After performing these corrections and pre-processing steps using ENVI software, satellite data were processed and analyzed to extract patterns and information required for the research. This process, from obtaining satellite images to processing data to obtain spatial information and patterns, ultimately contributed to the research.

In this study, remote sensing data were collected from various sources. ETM images with a resolution of 30 meters and SRTM images were the primary sources used. Additionally, geological maps of the region were used to extract information related to lithology and fault lines. SRTM images were also used to create land-use maps. SRTM data were considered as the base data in the research. Slope and topography analyses were obtained from the Digital Elevation Model (DEM) and SRTM Digital Surface Model (DSM) maps.

In this research, eight factors influencing the determination of groundwater potential have been utilized including:

1. Slope of the land.
2. Geomorphology: Geological features of the land surface.
3. Soil: Type and characteristics of the soil in the region.
4. Lineament density (Fault lines): The presence of fault lines or land fractures.
5. Land cover: Type and vegetation cover in the area.
6. Precipitation: Amount and pattern of precipitation in the region.
7. Aquifer density and proximity to surface water: Proximity to rivers or surface water sources.

These factors can have a significant impact on the potential of groundwater resources, and based on the analysis of these factors, maps of groundwater potential have been prepared.

The density of drainage patterns and proximity to surface water:

In studies related to aquifers and groundwater resources, the characteristics of drainage patterns, especially permeability, are of paramount importance. Drainage patterns play a crucial role in nourishing groundwater resources. The density and features of drainage patterns have a significant impact on aquifer permeability. Increasing the density of drainage patterns leads to improved aquifer permeability, signifying enhanced ability for aquifers to draw from sedimentary water. Therefore, analyzing drainage patterns can contribute to a better understanding and management of groundwater resources.

Additionally, a detailed examination of drainage patterns in different regions improves our understanding of the hydrogeological characteristics of groundwater resources, providing more precise information about permeability, yield, and other aquifer properties. This information can be effective in planning and optimizing the management of groundwater resources for various purposes.

In reality, the drainage pattern of a region reveals important features of the land surface and subsurface structures. The competence of groundwater potential is associated with the drainage pattern, as it indicates the distribution of surface runoff and land permeability. The density of the drainage pattern can significantly affect the yield of aquifers. Drainage patterns contribute to the proper distribution and management of surface water resources, guiding rainwater towards aquifers and groundwater. This interaction between drainage patterns and groundwater potential highlights the importance of detailed analysis of drainage patterns and management measures in different regions (Manikandan, Kiruthika, & Sureshbabu, 2014). In this analysis, in addition to drainage pattern density, the distance from drainage patterns has been examined as an essential parameter. Using the "Distance" command in ArcGIS software, the study area has been classified into five categories based on the distance from drainage patterns, including very close, close, moderate, weak, and very weak. This classification reflects the distance of different areas from drainage patterns and their proximity or distance to drainage pattern routes, serving as a basis for analyzing groundwater potential.

Land Slope:

The slope of the land plays a crucial role in controlling surface runoff, groundwater recharge, and the movement of surface water. Indeed, this layer is recognized as one of the fundamental factors influencing groundwater recharge and water movement in different regions. The topography of an area, especially the slope of the land surface, can significantly impact the permeability of water in soils and rocks.

Areas with lower slopes are typically classified as highly suitable for groundwater recharge because a gentle slope can enhance the permeability of soils and rocks, allowing surface water to infiltrate into groundwater. Conversely, areas with moderate slopes are often considered suitable for groundwater recharge due to their relatively stable topography and typically good permeability.

Regions with steeper slopes are generally classified as less favorable for groundwater recharge. These areas have relatively high surface runoff and lower infiltration of surface water into groundwater, resulting in less groundwater storage. Therefore, land slope can be crucial in terms of its impact on groundwater recharge and surface water flow in the region (Elubid et al., 2020). In this study, Digital Elevation Model (DEM) data in the Arc Map software was utilized to generate slope maps for the region.

Geomorphology:

Geomorphology and the identification of surface features in a region are of special importance in studying groundwater and karsts. Geomorphology refers to the shapes and structures of the Earth's surface that can have a significant impact on the flow and storage of groundwater. Satellites and satellite images can provide useful information about these features (Asgari Moghaddam et al., 2007). By analyzing satellite images and identifying surface features in the area, regions with high groundwater potential can be determined. Features that may be examined in satellite images include elevations, shape and nature of the land surface, the presence of karst structures, changes in vegetation density, and rock and sediment density.

Using this information, researchers can identify areas with favorable conditions for groundwater storage and recharge and utilize these resources for exploration and optimal management. This data can contribute to improving water resource plans and decision-making processes (NRSC, 2010). In this study, the region has been divided into three categories using the geomorphology map:

i. Plains: These areas are typically flat with a low to nearly zero slope. The low slope can make these areas suitable for groundwater recharge.
ii. Grasslands with moderate slope: This category includes areas with a moderate slope, usually grasslands and meadows. These areas may also be suitable for groundwater recharge.
iii. Lands with steep slope: This category includes areas with a steep and mountainous slope. These types of lands are generally not suitable for groundwater recharge because a steep slope can lead to surface runoff and a decrease in the density of water channels.

With this classification, more information about the geomorphological features of the study areas is available, and this information can be useful in potential assessment and groundwater resource management.

Soil:

Soil is a fundamental parameter in groundwater potential and can significantly impact permeability and groundwater recharge. In this regard, two important soil characteristics are discussed as follows:

Permeability: Permeability, or soil transmissivity, indicates the soil's ability to allow water to pass and infiltrate underground. Soils with high permeability can easily feed water to aquifers. Therefore, soils with high permeability are generally considered good for groundwater recharge.

Lineament density (Faults):

In summary, the presence of faults and fault zones can play a crucial role in the distribution and recharge of groundwater. These areas may have a high density of faults, contributing to the accumulation of groundwater. This information can be utilized in planning and managing groundwater resources in the region (Haridas, Aravindan, & Girish, 1998).

These maps and analyses aid in understanding the factors influencing surface water infiltration and groundwater distribution. The density of faults and the rock fracture system are among the critical factors that can play a fundamental role in the recharge and distribution of groundwater. The information derived from these analyses assists water resource managers and decision-makers in planning and managing water resources, aiming to enhance efficiency and address water scarcity issues. The fault density map for the Naein Dasht basin was prepared and classified into five categories. The northwestern part of the region exhibits a higher fault density compared to other areas.

Land Cover:

The presence of vegetation cover can have significant positive effects on water resource management. This vegetative cover not only prevents soil erosion and surface runoff but also facilitates water infiltration and absorption, contributing to the improvement of groundwater quality and quantity. Therefore, preserving and increasing vegetation cover is of great importance in water resource conservation. The Naein Dasht region map was classified into six categories: barren areas, saline lands, agricultural lands, poor pastures, foothills, and rocky areas.

Precipitation:

Groundwater sources are often recharged through subsurface rainfall, where water infiltrates into underground layers and nourishes them. Factors such as topography (land slope), lithology (rock characteristics), vegetation cover, and soil properties play crucial roles in controlling this process. These factors can regulate how water is absorbed and permeates into the soil and subsurface layers, thereby exerting different effects on groundwater resources. Information obtained from studying these factors can be highly significant for better water resource management and determining the potential of areas for groundwater storage and supply.

Therefore, the precipitation layer of the region is one of the influential layers in groundwater potential assessment. This map was prepared using Kriging tools in ArcMap, based on the total precipitation over the past 20 years. The precipitation map of the Naein Dasht region was divided into 5 classes based on the amount of precipitation, and higher scores were assigned to areas with higher precipitation.

Distance map from ground water level:

The Distance map from ground water level map was obtained from the groundwater level data of the South Khorasan province. Then, using the Euclidean Distance tool in ArcMap 10.8, a map of the distance from the groundwater level was created and classified into 5 categories. The scoring criterion was based on the idea that the farther the distance from the groundwater level, the lower the score assigned.

In continuation, maps have been classified based on these values, as shown in the Table 3 and Fig. 2.

Table 3
Assigned Values to Each Layer

Layer	**Distance(m)**	**Value**
Distance from the waterway	1000-0	**5**
	2000 – 1000	**4**
	3000 – 2000	**3**
	4000 – 3000	**2**
	4000<	**1**
Layer	range	Value
Slope	5 – 0	**5**
	10 – 5	**4**
	15 – 10	**3**
	20 – 15	**2**
	20<	**1**
Geomorphology	class	Value
	plain	**3**
	Pastures with moderate slope	**2**
	Lands with steep slopes	**1**
Soil	soil pattern	Value
	very light	4
	style	3
	Medium (loamy silty).	2
	heavy (silty clay)	1
	class (km/km^2)	Value
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	Value

Layer	Distance(m)	Value
land use	Salt marshes and barren areas	**5**
	agriculture	**4**
	Poor pastures	**3**
	mid-range	**2**
	Rock	**1**
	Precipitation	Value
rainfall	50	**1**
	75	**2**
	100	**3**
	150	**4**
	200	**5**

Weighting of Information Layers:

As mentioned, in this study, the Fuzzy Analytical Hierarchy Process (Fuzzy AHP) method has been utilized. Fuzzy AHP was introduced by two Dutch researchers, Van Laarhoven and Pedrycz (1983). They presented this method as an improved approach to address the problems existing in the Analytical Hierarchy Process (AHP), including scale inequalities, uncertainty, difficulties in precise pairwise comparisons, and incomplete understanding of human thought elements. This method, using fuzzy numbers in a triangular form in the pairwise comparison matrices and employing the least squares logarithmic method, has been developed (Habibi et al., 2014; Anabestani and Vasal, 2016).

Fuzzy-AHP is a mathematical theory designed to model uncertainty in decision-making processes related to human decision-makers. This method allows decision-makers to freely choose their preferred values. The uncertainty of decision-makers is expressed using fuzzy numbers, so Fuzzy-AHP uses a range of values to represent this uncertainty. This method uses fuzzy numbers for comparing options and employs the geometric mean method for weighting and prioritization. It can easily be extended to fuzzy cases and helps determine a unique solution for the pairwise comparison matrix.

In this study, first, a questionnaire named 'Pairwise Comparison of Criteria (information layers discussed in the previous section)' is designed and prepared. For each of these criteria, the opinions of 20 experts and specialists from the province are collected, and a ranking is assigned for each criterion. Then, using the Fuzzy-AHP technique (Fuzzy Analytical Hierarchy Process), weighting is performed for these information layers, followed by normalization. In the final stage, a linear combination of weighting in a GIS environment is used to integrate thematic maps to produce a groundwater potential map (Machiwal, Jha, & Mal, 2011). In the Table 4, the phase spectrum equivalent to the scale of nine hours in the AHP technique is shown.

Table 4
Fuzzy spectrum equivalent to nine-hour scale in AHP technique (Habibi et al., 2013)

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

In the fuzzy hierarchical method, to achieve the final map of groundwater potential, each criterion is weighted, and then they are combined based on these weights. To compare the criteria and weight them, the opinions of experts and specialists in this field are considered as criteria.

The binary comparison matrix of the criteria is displayed in EXCEL software, and the pairwise criteria comparison chart, which is visible in the Fig. 3 and Fig. 4. This process is carried out to determine the relative importance of the criteria in forming the groundwater potential map.

By conducting the criteria comparison, it was revealed that the precipitation criterion with a normalized weight of 0.313 has the most significant impact, while the geomorphology criterion with a weight of 0.051 has the least impact. In other words, according to the fuzzy AHP analysis, the precipitation criterion is more important than the other criteria in determining the potential of groundwater resources in this study.

Calculation of Inconsistency Rate:

The inconsistency rate is an index that indicates the degree of compatibility between pairwise comparisons. Pairwise comparisons are made by experts or specialists, and if these comparisons are compatible with each other, the results can be trusted. In fact, the inconsistency rate reflects the extent of disagreement or lack of consensus among the members of the study group regarding pairwise comparisons. If the inconsistency rate is very low, it indicates greater agreement among the members on pairwise comparisons, and there is more confidence in the results. However, if the inconsistency rate is high, it may indicate a lack of agreement and significant differences of opinion within the group, which may lead to uncertainty in the comparisons.

Weight assignments will be compatible only when the consistency ratio is equal to or less than 10%; otherwise, weights need to be re-evaluated and estimated to reduce inconsistency (Saaty, 1990).

The assigned weights will be compatible only when the consistency ratio (CR) is equal to or less than 10%. Otherwise, the weights should be re-evaluated and estimated to reduce inconsistency (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 $\lambda_{max}$by dividing the values obtained for λ_{max}.W by the corresponding W.

In this study, the value of $\lambda_{max}$was found to be 8.95%.

1. 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, in this study, CI is equal to:

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

2. 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 4 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 designed in such a way that if CR > 0.1, it indicates in and if CR ≤ 0.1, it shows an acceptable level of consistency in pairwise comparisons (Saberi et al., 2013). The Consistency Ratio for the weights given in this study is 0.096. This ratio indicates the consistency of the comparisons, meaning that the study participants agree on the weighting of the criteria. In the Table 5, n represents the number of elements in the pairwise comparison table, and R is the Consistency Index.

Table 5
Consistency Index (Qudsiehpour, 2008)

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

Combining Information Layers and Creating Groundwater Potential Map:

To generate a groundwater potential map, you need to first obtain maps corresponding to each sub-criterion based on their normalized weights.

Table 6
Weights of Criteria and Sub-criteria, and Final Weights

Fuzzy-AHP			sub- criteria	Criterion
Final weight	sub-criteria weight	Criterion weight		
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 6 shows the weights of criteria, sub-criteria, and the final weight for each. In this table, the final weight for each sub-criterion is obtained 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 combined, and then, using the fuzzy hierarchical method, the map is classified into 5 quantitative categories, ranging from very good to very poor. As a result of this classification, approximately 16% of the area is classified as very poor, 22% as poor, 24% as moderate, 22% as good, and 14% as very good.

Validation

Through the analysis of the locations of wellsqanats, and springs in the area, the results indicate that the region is very good in terms of groundwater potential and possesses significant groundwater resources. These findings demonstrate that the use of remote sensing techniques, Geographic Information System (GIS), and fuzzy-AHP modeling are effective in estimating the potential of groundwater resources and decision-making in water management. According to the information in Fig. 9, there are 10 well rings, 3 qanats, and 3 springs in the region, with a significant portion of the resources derived from groundwater placed in the very good zone in terms of groundwater potential. This reflects the high accuracy of the research results in employing GIS, and fuzzy-AHP techniques in groundwater potential assessment.

Conclusion

Given the high capabilities of ArcGIS software in handling spatial and geographical data, importing relevant information—such as thematic maps, field measurements, or outputs from other software like ENVI—into the GIS environment allows for accurate identification of areas with high groundwater potential. This approach can significantly reduce the need for extensive field visits for well drilling and other groundwater uses, leading to substantial cost and time savings.

This research demonstrates that by utilizing available tools for data collection, like as GIS, in conjunction with multi-criteria decision-making methods, we can estimate groundwater potential at a lower cost while maintaining an acceptable level of accuracy. This approach is applicable in various fields, including water resource management and identifying suitable areas for drilling extraction and recharge wells.

By combining layers affecting groundwater concentration in the study area through their analysis, the potential areas with very good groundwater potential were identified, indicating that approximately 14% of the study area has a very good potential, mostly located in the north and northwest of the region.

It should be noted that the current results are based on the availability of existing data and maps. The most significant limitation in terms of data has been related to geomorphology and soil maps, which had the least accuracy. Given that the role of geomorphology and soil criteria in this study has been proven (especially considering the lack and incompleteness of the mentioned data), the final groundwater potential map may be subject to changes in the regions of the northeastern and southwestern parts of the study area.

Additionally, the uncertainty and limitations of the tools used in this study are highlighted, considering that recommendations have been made in this regard in the suggestions section.

In summary, based on the information provided, it can be concluded that using GIS, along with multi-criteria decision-making methods, groundwater potential estimation can be performed with lower costs, while still maintaining an acceptable level of accuracy. This approach is applicable in various fields, such as water resource management and identifying suitable areas for drilling extraction and recharge wells.

Suggestions for future work include utilizing new libraries within the Python programming language to weight various methods, such as fuzzy-AHP. Additionally, it is recommended to compare the results of this study with other multi-criteria decision-making methods, specifically the Analytic Network Process (ANP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Furthermore, employing applied maps with higher accuracy and better resolution will enhance the generation of a high-precision groundwater potential map.

Declarations

Conflict of interest

All authors declare no conflict of interest.

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Figures

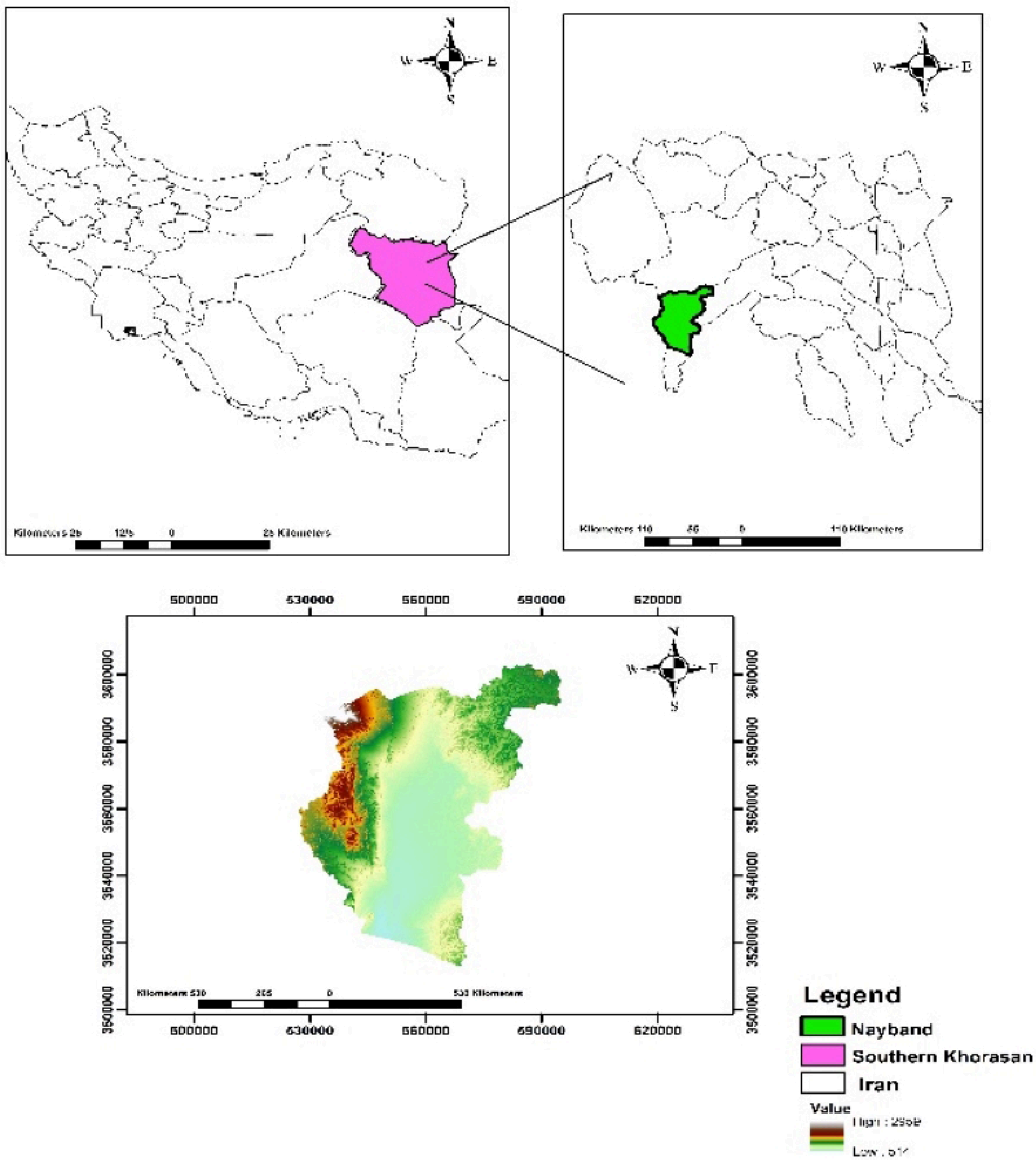

Figure 1

Topography and elevation map of Study Area

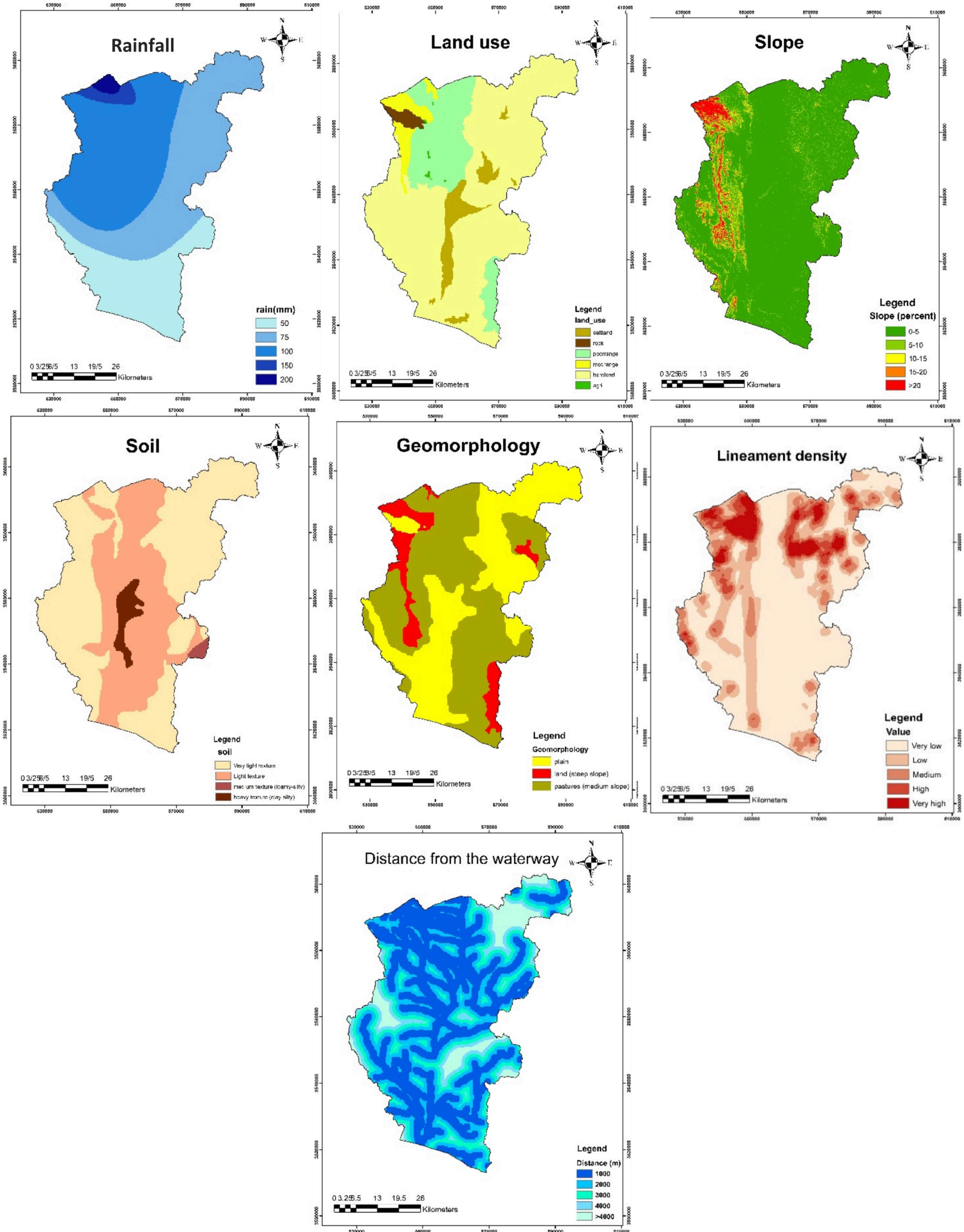

Figure 2

spatial variation of different factors affecting the Groundwater Resources

	slope	Geomorphology	Soil	fault	land cover	rainfall	Distance from the waterway	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**
Distance from the waterway	(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**

Figure 3

Pairwise comparison of criteria

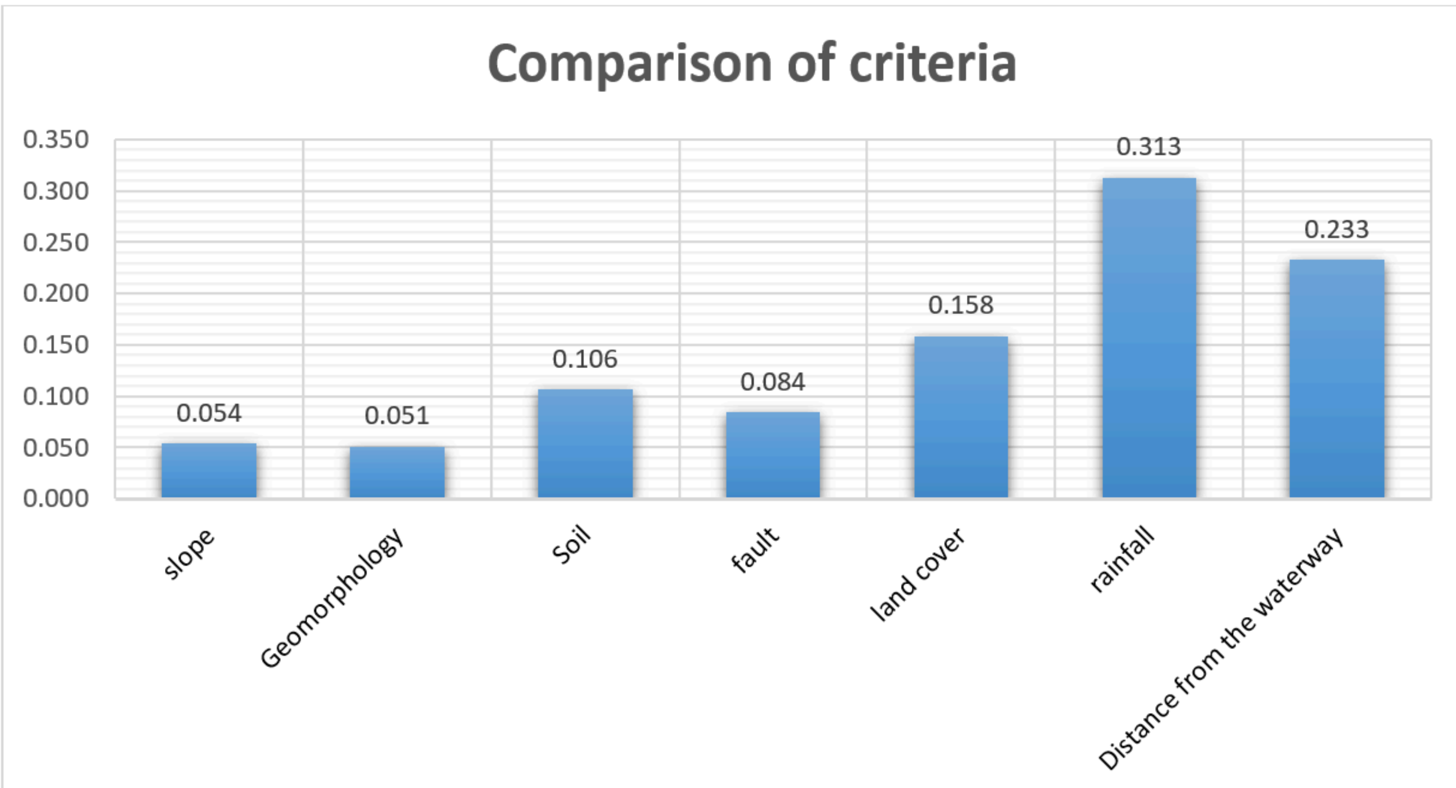

Figure 4

Pairwise comparison chart of criteria based on normalized weights

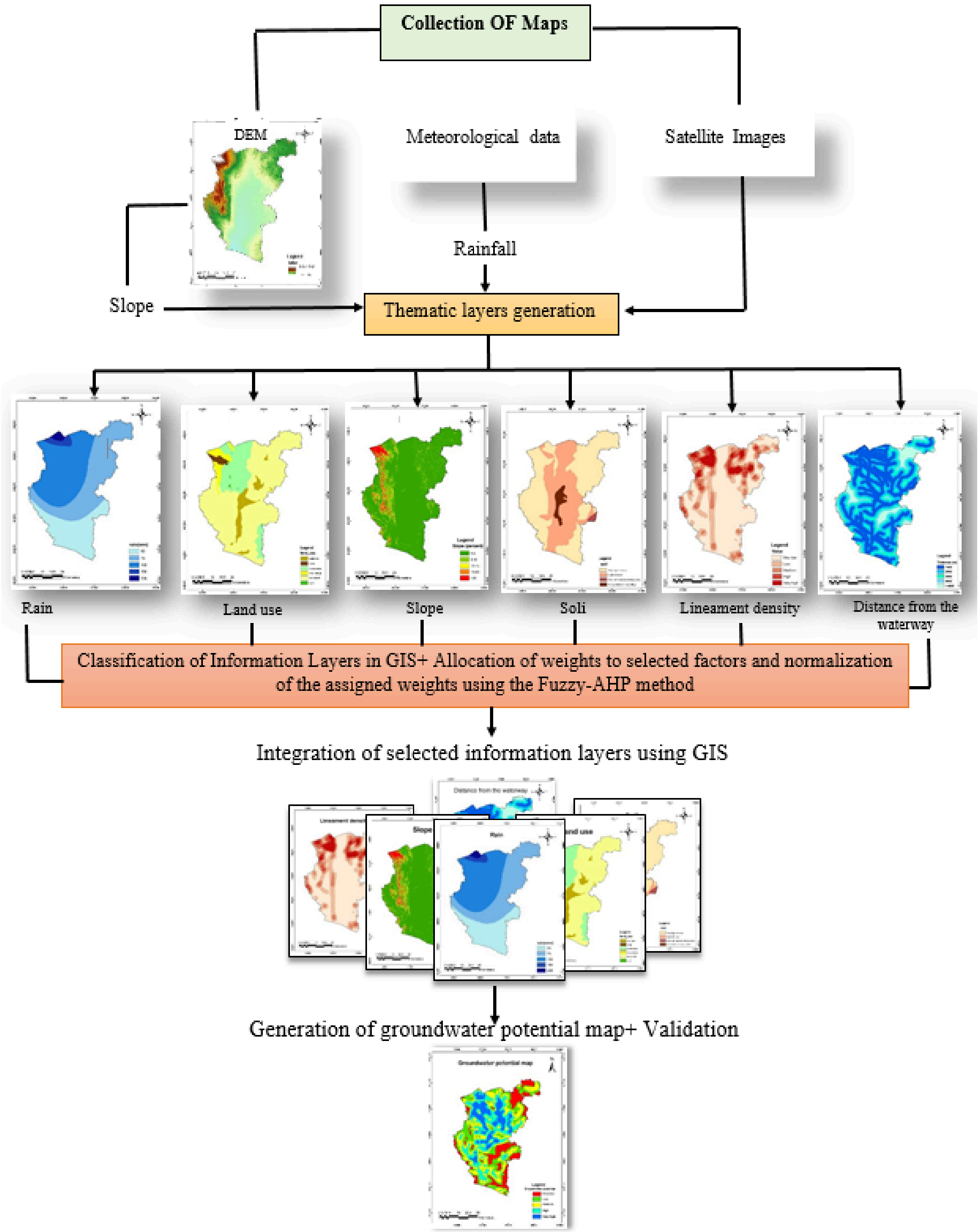

Figure 5

The generated flowchart for producing groundwater potential maps

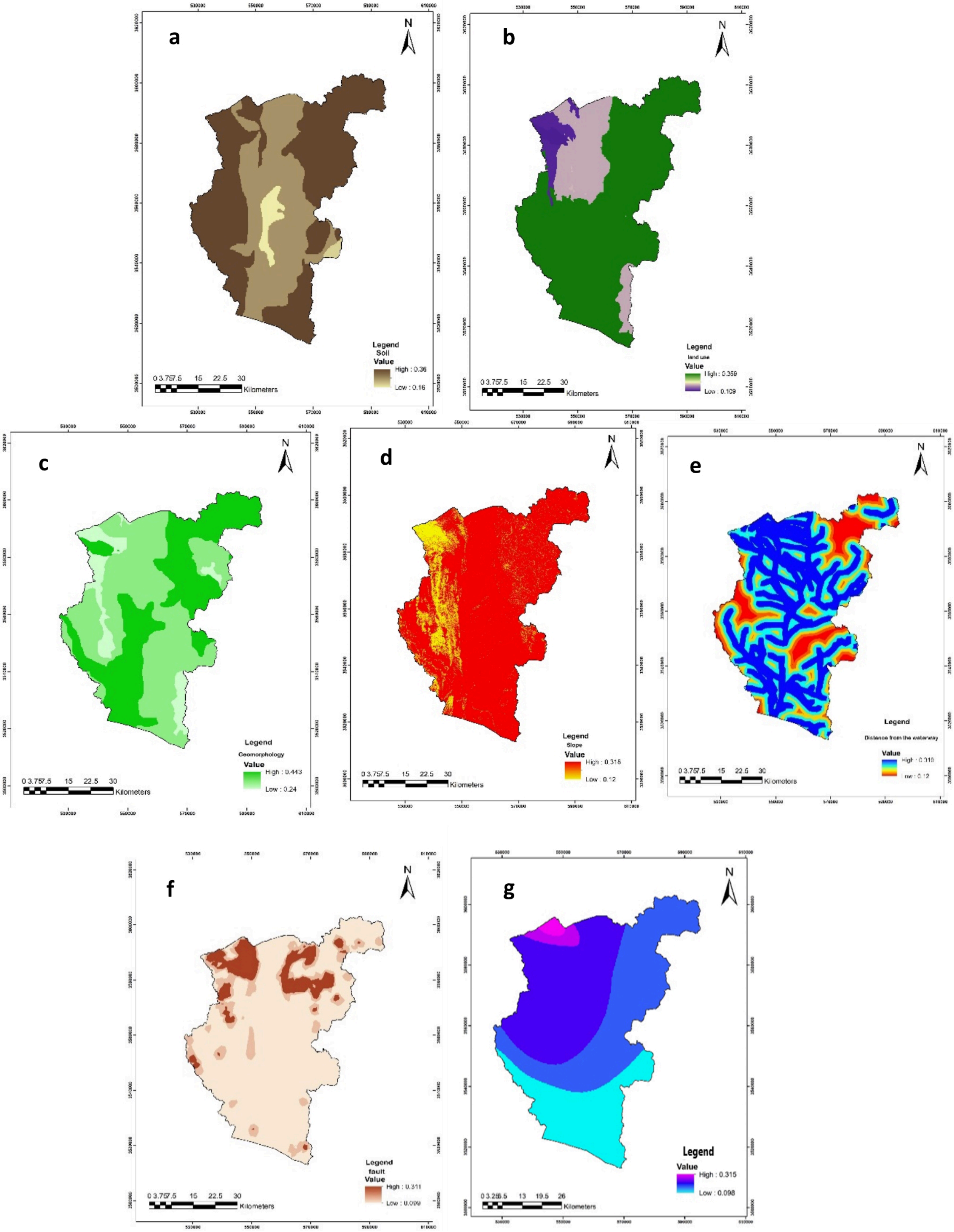

Figure 6

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

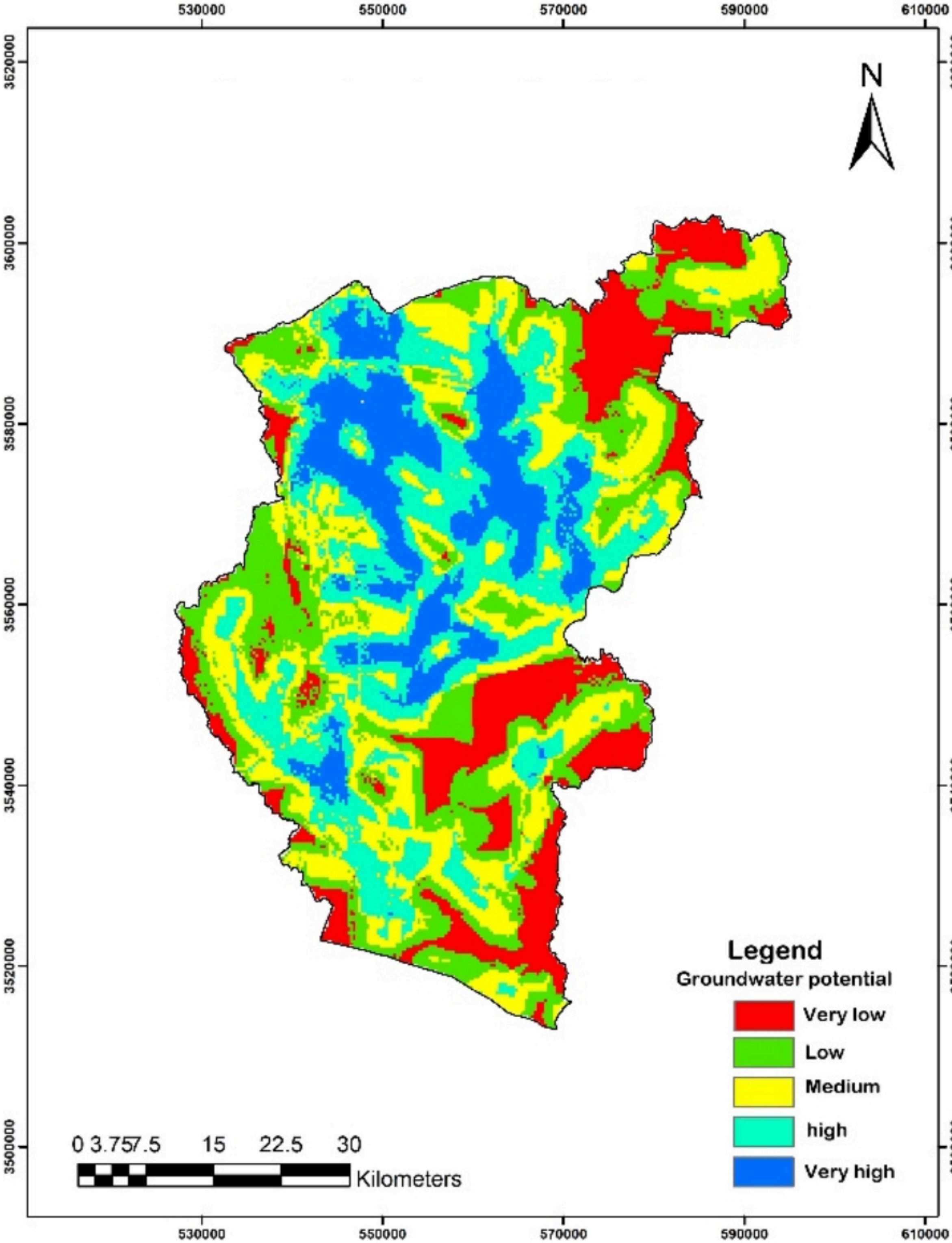

Figure 7

Groundwater Potential Map

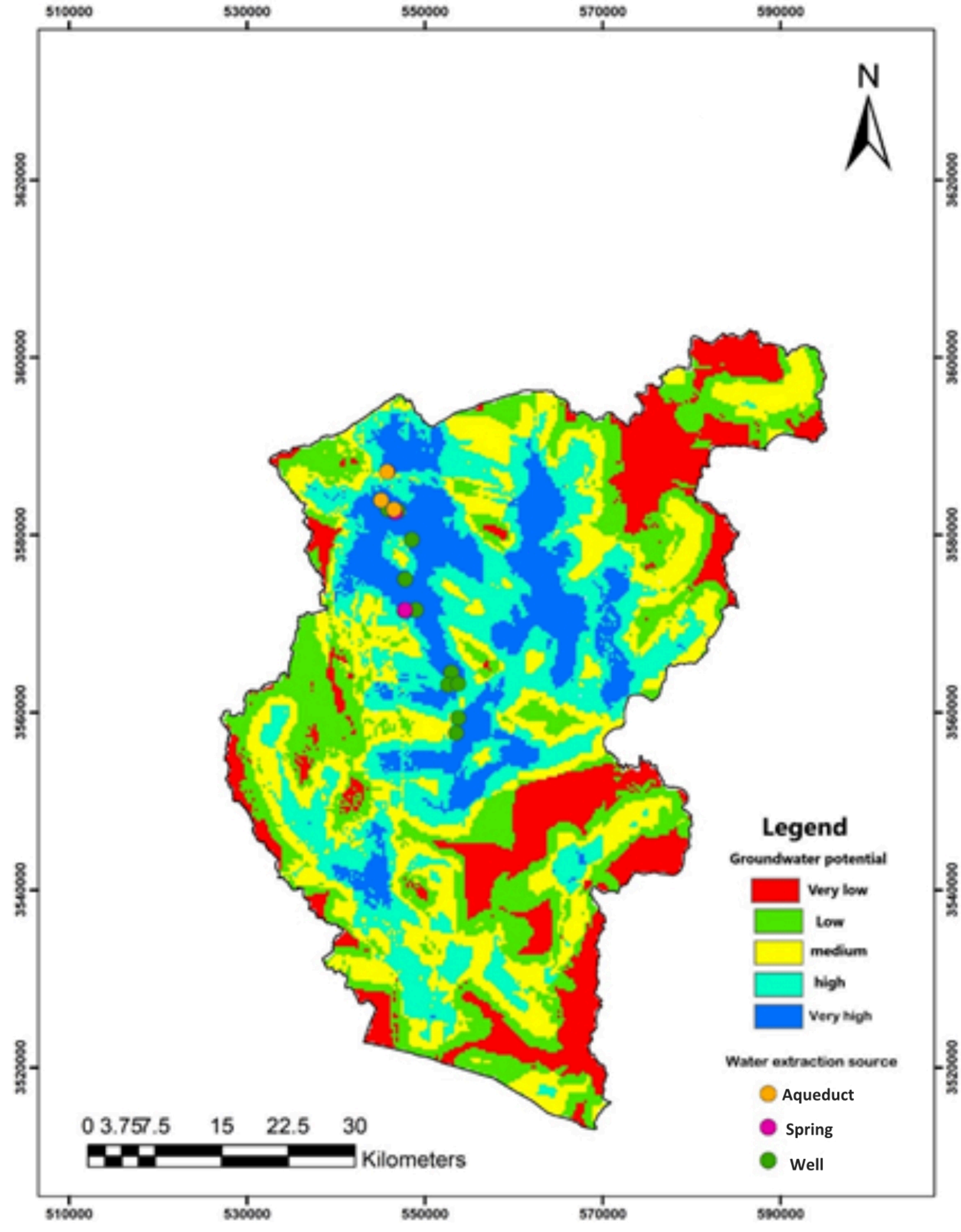

Figure 8

The location of existing wells on the groundwater potential map (South Khorasan Regional Water Authority, 2022)