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Research Article

Appraisal of groundwater recharge potential using AHP and MIF models: A case study of eastern Balochistan, Pakistan

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Abstract

This study shows an integrated geospatial and multi-criteria decision-making approach to identify Groundwater Recharge Zones (GWRZs) in the semi-arid region of eastern Balochistan, Pakistan. Using remote sensing and geographic information systems, two decision-making methods, the analytical hierarchy process (AHP) and multi-influencing factor (MIF), were used to assess and rank seven important thematic layers. These layers include lithology, land use and land cover, slope, lineament density, rainfall, drainage density, and soil type. Each layer was carefully assigned weight and then combined to produce spatial maps showing recharge potential. The results from the analytical hierarchy process show that about 6 percent of the area has very high recharge potential, while the multi-influencing factor method shows a wider range, with around 13 percent marked as very high. A sensitivity analysis using map removal sensitivity analysis was also carried out to understand how each parameter affects the results, especially because field validation data was not available. The results revealed that lithology, land use and land cover, and slope were the most influential factors in both models. Overall, the findings show that both approaches are reliable and consistent for mapping recharge zones and can be effectively used in dry and data-scarce regions. This combined method can support better decision-making for sustainable groundwater management and planning of artificial recharge in areas facing serious water shortage.

Keywords: Groundwater Recharge, Analytical Hierarchy Process (AHP), Geospatial Analysis, Remote Sensing and GIS, Eastern Balochistan, Sustainable Water Management.

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Introduction

Groundwater, stored beneath the surface in geological formations, is an important resource in dry and semi-arid regions such as Pakistan, where rainfall is seasonal, and surface water is limited. Even though groundwater is widely available. it does not always match the demand in terms of location, amount, or quality [1]. Its occurrence depends on several factors such as geology, climate, hydrology, and physical landscape features [2]. In many regions, groundwater plays a key role in meeting domestic, agricultural, and economic needs; however, its potential can change greatly even over short distances [3].

Evaluating groundwater in remote and rough areas requires the study of different parameters including geology, rainfall, slope, drainage density, lineament density, soil, and land use and land cover [4]. Traditional methods are often not effective because these areas are difficult to access and data is limited. With the help of modern technologies such as remote sensing and geographic information systems, it is now possible to map and analyze groundwater more efficiently and cost-effectively [5]. When combined with multi-criteria decision analysis, these tools have been widely used in different studies through methods like AHP, MIF, fuzzy logic, and frequency ratio models. Among these, the analytical hierarchy process and multi-influencing factor are commonly used because they are simple, reliable, and suitable for spatial decision-making [6]. Analytical hierarchy process uses expert opinion to assign weights through pairwise comparison, while multi-influencing factor considers both major and minor factors. These approaches are useful for identifying groundwater zones, especially before carrying out expensive field investigations [7].

Remote sensing provides large-scale and updated data, especially in areas that are hard to reach, while geographic information systems help in storing, integrating, and analyzing spatial data related to hydrogeological factors [8]. However, many earlier studies do not include sensitivity analysis, which is important to understand how each factor influences the identification of recharge zones [9].

This study identifies groundwater recharge zones in the eastern part of Balochistan, including Sibi, Talli, Lahri, Bhag, Bukhtiarabad Domki, and Kohlu regions where complex interactions between alluvial plains and foothill areas affect groundwater behavior. Using both decision methods, within a geospatial framework, seven important thematic layers were studied to evaluate recharge potential. This approach helps fill a gap in previous research by adapting the method for dry regions and includes sensitivity analysis even though there is limited well data available for validation.

Materials and Methods

This study maps groundwater recharge zones in the semi-arid eastern region of Balochistan by using Remote Sensing, Geographic Information Systems and Multi Criteria Decision Analysis. The AHP and MIF methods were applied to important factors including lithology, slope, land use, drainage density, and rainfall to create a recharge potential map that can support sustainable water resource management.

Study area

The study area shown in yellow (Figure 1) is located in the eastern part of Balochistan, Pakistan, and includes Sibi, Talli, Lahri, Bhag, Bukhtiarabad Domki, and some parts of Kohlu district between 67°30′E to 69°00′E, and 28°30′N to 30°00′N. This region is diverse and geologically rich with a mix of alluvial plains and rough foothill areas shaped by both mountain and valley landscapes. The landforms of the area are influenced by tectonic activity, which has created structural basins and anticlines that are important features of the local terrain. The geology of the area mainly consists of sedimentary rocks such as sandstone, limestone, and shale, along with large quaternary deposits spread across the alluvial plains. These deposits play a key role in storing and moving groundwater in the region. The climate is dry to semi-dry, which increases the reliance on groundwater for daily use, agriculture, and livestock. Seasonal changes in rainfall and evaporation, along with naturally low recharge rates, make water management more difficult. Land use in the area is strongly affected by the semi-arid conditions, with a large part of the land used for agriculture, including irrigated farming and grazing for animals. Urban settlements are mainly found in Sibi and Bukhtiarabad Domki, while most of the surrounding land has low population and is used for basic farming and rangeland. Identifying groundwater recharge zones in such a complex setting is very important for long-term water sustainability, especially as population growth, expansion of agriculture, and changes in climate continue to increase pressure on water resources.

Data sources

Geospatial and environmental data were collected and prepared to ensure uniform resolution, projection, and format. The datasets were standardized using UTM Zone 42N of the WGS 1984 system. Important data sources include (Figure 2):-

- DEM with 30-meter resolution from SRTM was used for slope and drainage analysis.
- Landsat-8/9 OLI images from USGS were used for land use and land cover classification and lineament mapping after applying radiometric and geometric corrections.
- Rainfall data from 2015 to 2024 were obtained from ERA5 provided by ECMWF and were interpolated using inverse distance weighting in ArcGIS.
- Soil and geological data were collected from HWSD and the Geological Survey of Pakistan and then digitized to prepare lithology and soil classification maps.

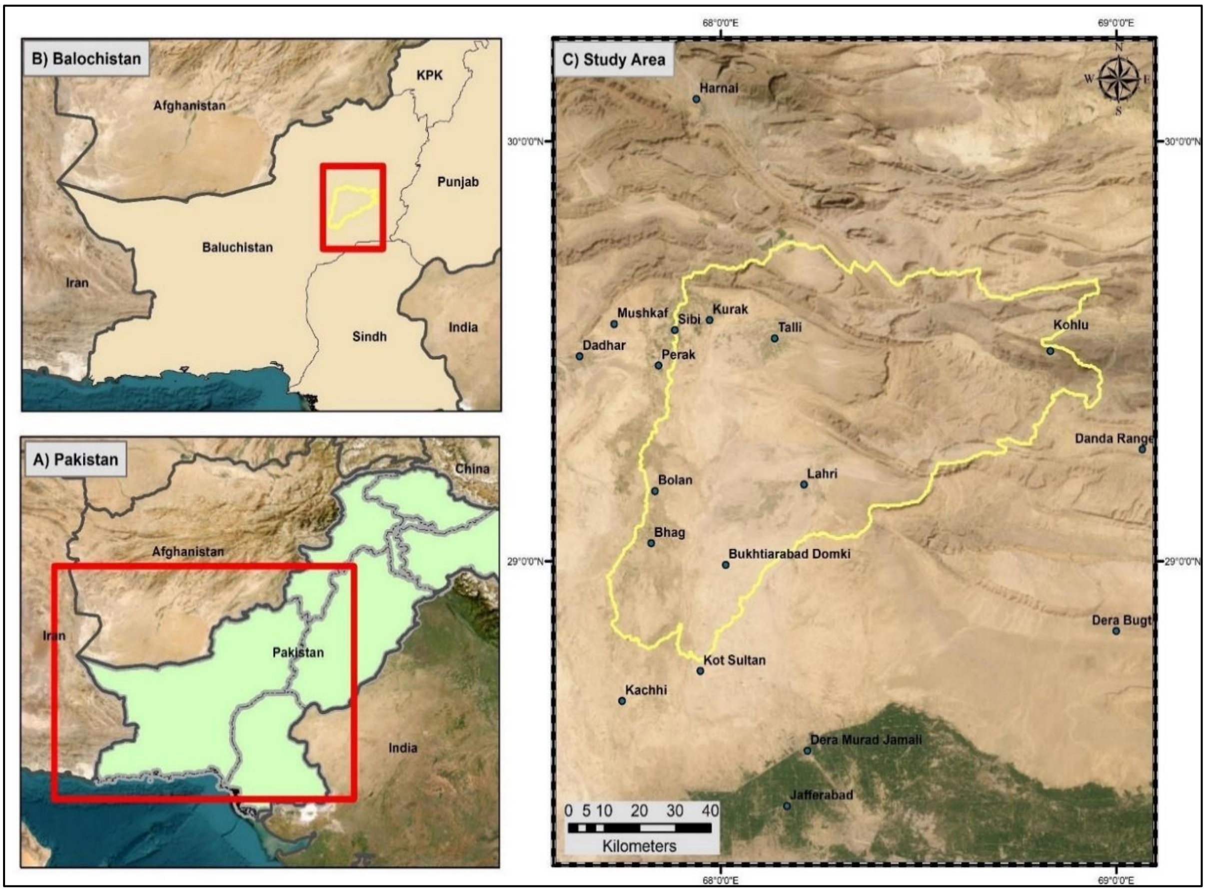

Figure 1: Study area map.

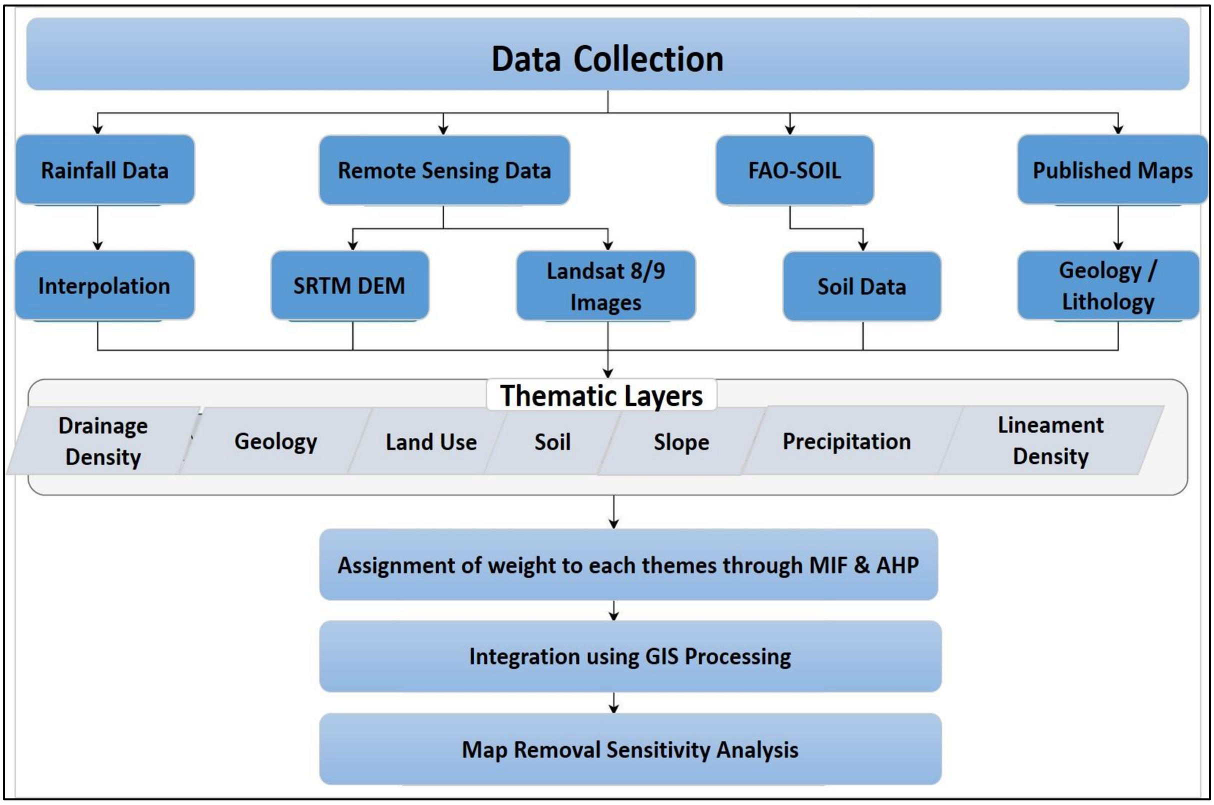

Figure 2: Methodological flowchart.

Analytical hierarchy process (AHP)

To identify groundwater recharge zones in eastern Balochistan, the AHP was used. This method assigns weights to different factors such as slope, lineament density, drainage density, soil, and land use based on their influence on groundwater potential. It uses expert judgment through pairwise comparison and checks consistency by using a judgment matrix [7, 10 - 11].

Selection of factors affecting ground-water recharge zones

In AHP, the factors that influence groundwater recharge were compared by using Saaty's scale from 1 to 9, where 1 shows equal importance, and 9 shows strong dominance (Table 1). These comparisons convert expert opinion into a numerical matrix, which is then used to calculate consistent weights for each factor.

Pairwise comparison matrix (PCM):

The AHP converts expert judgment into numerical values by using Saaty's scale from 1 to 9. A pairwise comparison matrix or PCM is then created where the diagonal values are set to 1, and the other values are filled with the given scores or their reciprocal values.

$$X = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1n} \\ X_{21} & X_{22} & \cdots & X_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ X_{n1} & X_{n2} & \cdots & X_{nn} \end{bmatrix} \quad (1)$$

Table 1: Saaty's [10, 13] relative class rate scale for analytic hierarchy process (AHP).

Importance	Equal	Very Weak	Weak	Moderate	Moderate Plus	Strong	Strong Plus	Very Strong	Extreme
Scale	1	2	3	4	5	6	7	8	9

This matrix is used to calculate normalized weights and eigenvectors, which show the relative importance of each factor in groundwater recharge.

The pairwise comparison matrix (Table 2), where factors such as lithology, land use and land cover, slope, and others are ranked. Lithology appears as the most influential factor with high comparison values; for example, 7.00 against soil and 5.00 against drainage. The column totals were used to normalize the matrix and to calculate weight values for the overlay analysis.

Normalization and weight derivation

Weights were assigned using expert judgment by normalizing the pairwise comparison matrix. Each element of the normalized pairwise comparison matrix was calculated by dividing it by the total of its column (Equation 2; Table 3). The standard weight for each factor was then obtained by dividing the normalized values by the total number of criteria, as given in Equation 3).

$$Xij = \frac{Cij}{Lij} \quad (2)$$

$$Wi = \frac{\sum Xij}{N} \quad (3)$$

$$\lambda = \sum(CijXij) \quad (4)$$

Where X_{ij} is the normalized pairwise matrix value at i_{th}row and j_{th} column, C_{ij} is the value assigned to each criterion at i_{th}row and j_{th}column and $L_{ij}$is the total value in each column of the pairwise matrix, W_i is the standard weight, and λ is the consistency vector.

Eigenvector and eigenvalue calculations (Table 4) were used to find the relative weights of the thematic layers. The eigenvector obtained from the column-normalized values indicates the influence of each factor, while the main eigenvalue λ_{max} equal to 7.21 confirms the consistency of the matrix [12 - 16].

Table 2: Pair-wise comparison matrix.

Parameter	**Abbreviations**	**RN**	**LD**	**LI**	**SL**	**DD**	**SLO**	**LULC**
Rainfall	RN	1	0.33	0.17	2	0.5	0.25	0.2
Lineaments Density	LD	3	1	0.25	4	2	0.5	0.33
Lithology	LI	6	4	1	7	5	3	2
Soil	SL	0.5	0.25	0.14	1	0.33	0.2	0.15
Drainage Density	DD	2	0.5	0.2	3	1	0.33	0.25
Slope	SLO	4	2	0.33	3	3	1	0.5
Land Use / Land Cover	LULC	5	3	0.5	4	4	2	1
TOTAL		**21.5**	**11.08**	**2.59**	**24**	**15.83**	**7.28**	**4.43**

Table 3: Standardized pairwise comparison matrix and weight factors influencing recharge.

Parameter	Abbreviations	RN	LD	LI	SL	DD	SLO	LULC	Eigen Vector	Influence (%)	AHP Weight
Rainfall	RN	0.1	0	0.1	0.1	0	0.03	0.05	0.05	4.78	0.05
Lineaments Density	LD	0.1	0.1	0.1	0.2	0.1	0.07	0.07	0.11	10.88	0.11
Lithology	LI	0.3	0.4	0.4	0.3	0.3	0.41	0.45	0.36	35.63	0.36
Soil	SL	0	0	0.1	0	0	0.03	0.03	0.03	3.21	0.03
Drainage Density	DD	0.1	0	0.1	0.1	0.1	0.05	0.06	0.07	7.23	0.07
Slope	SLO	0.2	0.2	0.1	0.1	0.2	0.14	0.11	0.15	15.17	0.15
Land Use / Land Cover	LULC	0.2	0.3	0.2	0.2	0.3	0.27	0.23	0.23	23.1	0.24
TOTAL		**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**100**	**1**

Table 4: The principal eigenvalue calculation to rank influence parameter.

Thematic Map	Total Relative Weight of Each Factor (1)	Eigenvector Value of Each Factor (2)	Eigenvalues (1) ×
Rainfall	21.5	0.05	1.03
Lineaments Density	11.11	0.11	1.21
Lithology	2.59	0.36	0.92
Soil	24.06	0.03	0.77
Drainage Density	15.86	0.07	1.15
Slope	7.28	0.15	1.1
Land Use / Land Cover	4.43	0.23	1.02
Principal Eigenvalue (λ_{max})			**7.21**

Assessing matrix consistency

Uniformity is assessed using the Consistency Index (CI) and Consistency Ratio (CR) [17 - 21]. The CI is calculated as:

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (5)$$

Where λ_{max} is the highest eigenvalue, and n is the number of variables, and CI below 0.1 is acceptable [12, 22]. In this study, the CI was 0.035, within the acceptable range. The Consistency Ratio (CR) is calculated as:

$$CR = \frac{CI}{RI} \qquad (6)$$

For a matrix with eight variables, the Random Index (RI) is 1.32 (Table 5). The CR was 0.026, indicating that the pairwise comparisons and weights for GIS thematic layers were consistent [10, 13, 23].

Table 5: Random inconsistency indices.

n	3	4	5	6	7	8	9	10
RI	0.6	0.9	1.1	1.2	1.3	1.4	1.5	1.5

Multi-influencing factor (MIF)

The MIF method is an effective MCDM approach used in environmental management to identify groundwater recharge zones [24 - 26]. It assigns weights to various factors based on their influence on groundwater movement and storage (Figure 3).

Each factor and its classes were ranked and weighted according to their impact on recharge potential. Major influences were assigned a weight of 1.0, while minor influences were assigned 0.5, and factors with no impact received a weight of zero [12, 20]. The total weight of each factor was used to calculate its recharge potential weight [20, 27], with the final percentage weight derived using Equation (7), results are shown in Table 6.

$$\text{Proposed Score} = \frac{\text{Major Effect} + \text{Minor Effect}}{\text{Major Effect} + \text{Minor Effect}} \times 100 \quad (7)$$

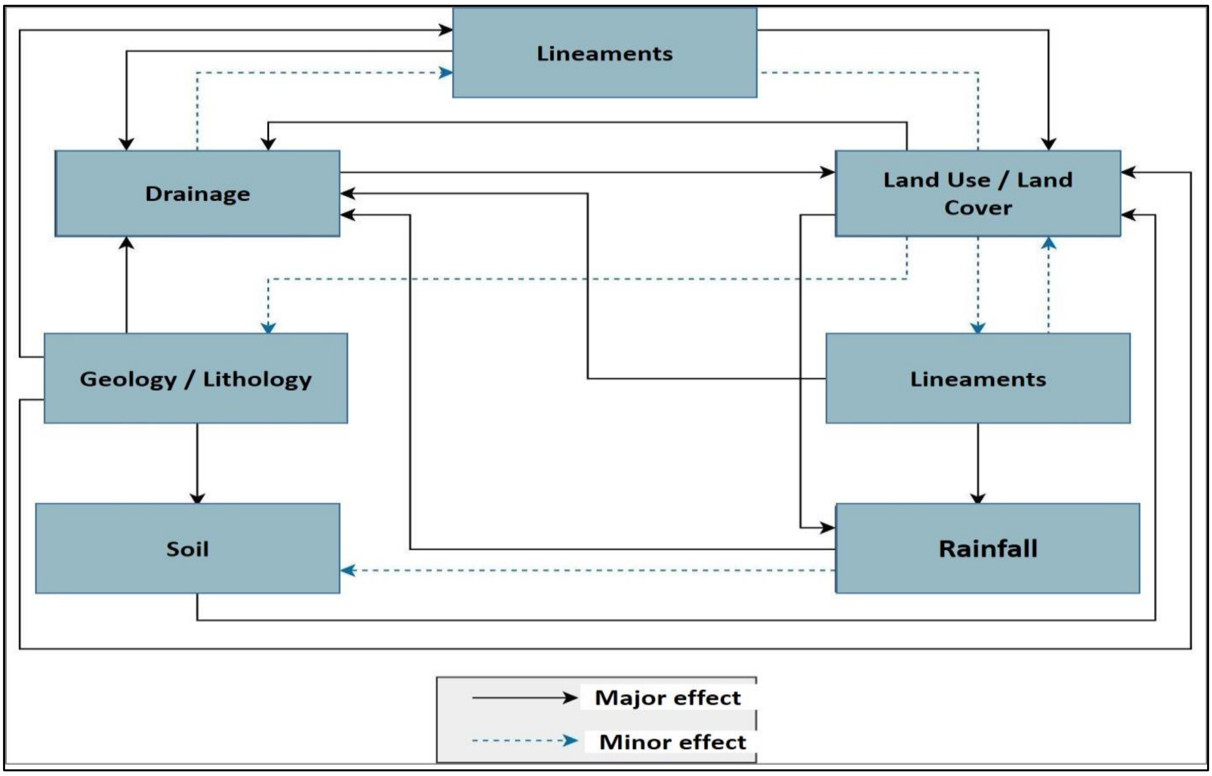

Figure 3: Relationships between multiple factors affecting groundwater recharge.

Table 6: The values of major, minor, relative effects, and proposed weight of influencing factors.

Thematic Map	Major Effect	Minor Effect	Relative Effect	Proposed Weight (%)
Rainfall	1	0.5	1.5	9.38
Lineaments Density	2	0	2	12.5
Lithology	4	0	4	25
Soil	1	0	1	6.25
Drainage Density	1	0.5	1.5	9.38
Slope	2	0.5	2.5	15.63
Land Use / Land Cover	2	1.5	3.5	21.88
Total			**16**	**100**

Figure 4 illustrates the GIS-based procedure used to map groundwater recharge potential. This analysis employed seven thematic layers, each with a weight percentage reflecting its influence on recharge potential [11, 28]. These layers were reclassified using a scale from 1 to 5, where 1 indicates "very good" and 5 indicates "very poor" recharge suitability. The cell values were multiplied by their respective weights and summed to generate the final recharge potential map [29, 30], as shown in Equation (9):

$$GWRZ = \sum ni=0\ Wi \times Ri \quad (8)$$

$$GWRZ = RN_cRN_w + LD_cLD_w + LI_cLI_w + SL_cSL_w + DD_cDD_w + SLO_cSLO_w + LULC_cLULC_w \quad (9)$$

Each thematic layer (e.g., Lithology, Land Use/Land Cover, Slope, Lineament Density, Rainfall, Drainage Density, Soil Cover) was ranked based on its suitability for groundwater recharge, with the ratings multiplied by the layer's weight, derived from the AHP method. This process resulted in a spatial map of groundwater recharge zones.

Sensitivity analysis

The groundwater recharge zone index depends on the weight of each factor and the rating assigned to each class within each layer. A sensitivity analysis was carried out to show how much each thematic layer and its weight influence the resulting map. A map removal sensitivity analysis was used to examine the effect of removing each factor on the final groundwater recharge zone map.

Map removal sensitivity analysis

MRSA was used to find the most and least significant thematic layers for groundwater recharge zones. The sensitivity index, S, was determined using Equation (10).

$$| \underline{GWRZ}\ \underline{GW}RZ' |$$

$$S^{N} = [\ ] \times^{n} 100$$

GWRZ (10)

Where GWRZ and GWRZ' represent the result of the groundwater recharge map index for all theme layers and when one of the thematic layers is deleted, respectively. N is the number of full thematic layers used to compute the GWRZ, whereas n is the number of thematic layers utilized to compute GWRZ'.

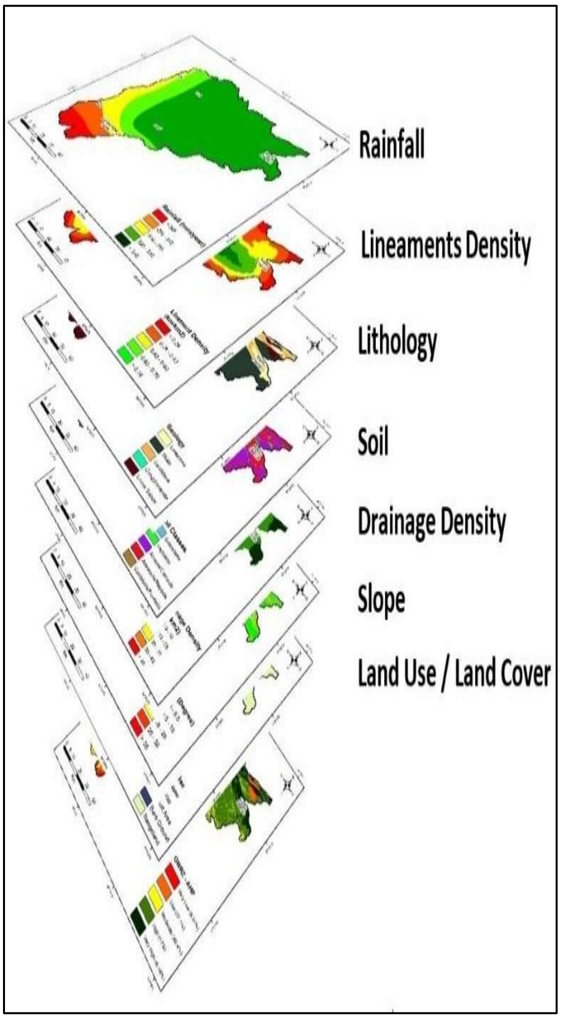

Figure 4: Illustrating the overlay analysis of thematic layers in a Geographic Information System (GIS) to identify groundwater recharge zones (GWRZ).

Results and Discussion

Factors influencing groundwater occurrence and movement

The availability and movement of groundwater in the Sibi region are primarily influenced by a combination of lithological, geomorphological, pedological, and climatic factors. This study evaluates seven key parameters: lithology, slope, land use and land cover, lineament density, drainage density, rainfall, and soil type to assess their relative influence on groundwater recharge and storage potential.

Table 7: Assigned criteria ratings and weights for AHP and Multi-Influencing Factors (MIF) methods.

AHP							MIF	
Factor	**Domain of Effect**	**Rank**	**Weight**	**Weighted Ring**	**Total Weight**	**Weight**	**Weighted Ring**	**Total Weight**
Rainfall	< 295 295 - 310 310 - 325 325 - 340 > 340	1 2 3 4 5	0.05	0.05 0.09 0.14 0.18 0.23	0.68	0.09	0.09 0.19 0.28 0.38 0.47	1.41
Lineaments Density	< 0.24 0.24 - 0.42 0.42 - 0.60 0.60 - 0.78 > 0.78	1 2 3 4 5	0.11	0.11 0.21 0.32 0.43 0.53	1.59	0.16	0.16 0.31 0.47 0.63 0.78	2.34
Lithology	Shale Limestone Sandstone Congulomerate Loose Sands	1 2 3 4 5	0.36	0.36 0.72 1.07 1.43 1.43	5.01	0.25	0.25 0.50 0.75 1.00 1.25	3.75
Soil	Solonchaks Laptosols Acrisols/Calcisols Arenosols/regsols Cambisols/Fluvisols	1 2 3 4 5	0.03	0.03 0.06 0.12 0.09 0.15	0.46	0.06	0.06 0.13 0.25 0.19 0.31	0.94
Drainage Density	0 - 15 15 - 25 25 - 35 35 - 45 > 45	1 2 3 4 5	0.07	0.07 0.14 0.21 0.28 0.35	1.04	0.09	0.09 0.19 0.28 0.38 0.47	1.41
Slope	0 - 8.5 8.5 - 18 18 - 28 28 - 38 >38	5 4 3 2 1	0.15	0.77 0.62 0.46 0.31 0.15	2.31	0.16	0.78 0.63 0.47 0.31 0.16	2.34
Land Use / Land Cover	Water Crop Built Area Bare Ground Rangeland	5 4 3 2 1	0.24	1.18 0.94 0.24 0.47 0.71	3.54	0.22	1.09 0.88 0.22 0.44 0.66	3.28

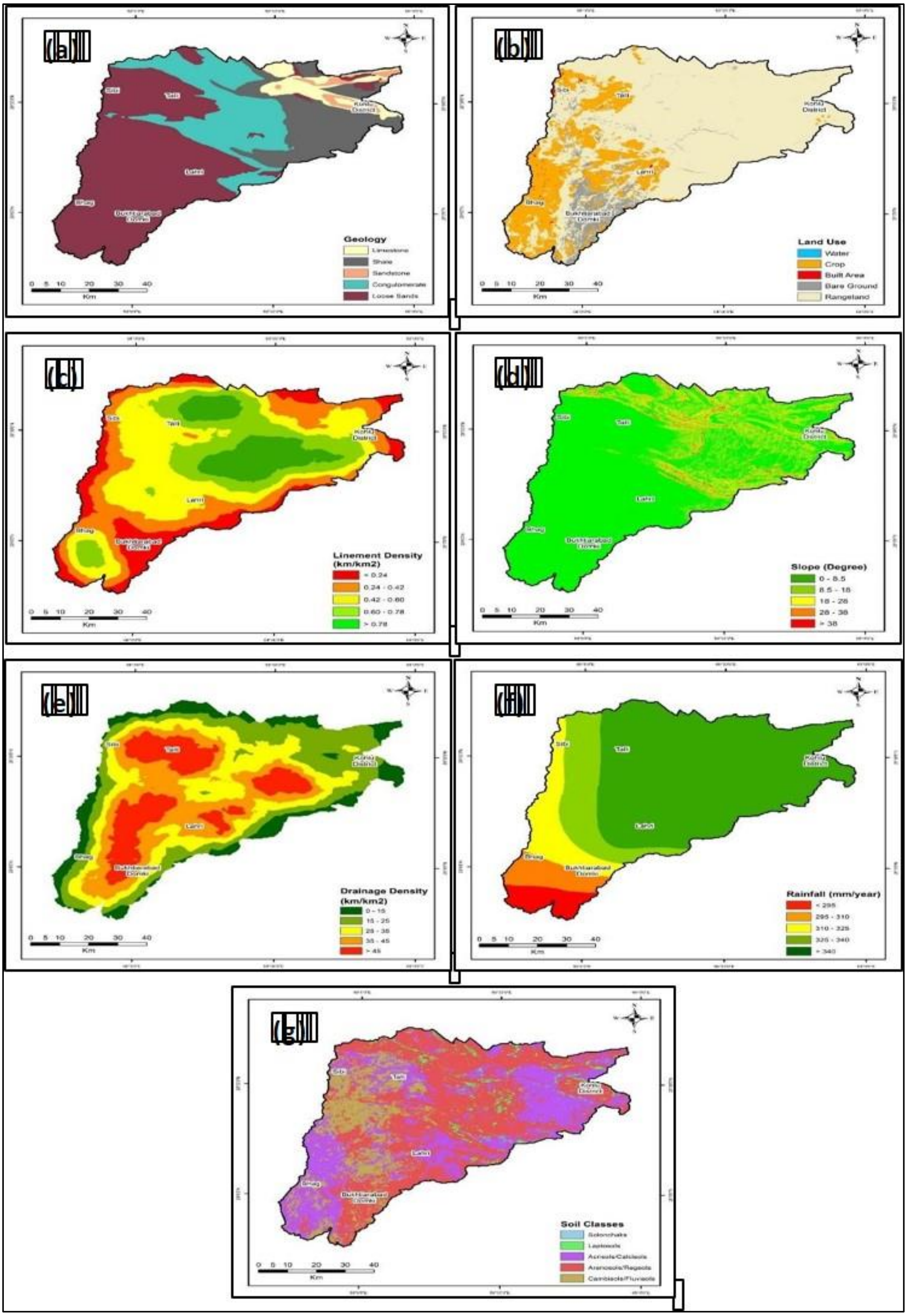

Figure 5: The seven thematic layers used in the multi-criteria decision-making frameworks to map groundwater recharge potential: (a) Geology/Lithology, (b) Land use, (c) Lineament density, (d) Slope, (e) Drainage density, (f) Rainfall, and (g) Soil classes.

Lithology is a major factor controlling recharge potential. The geology of the region includes limestone, shale, sandstone, conglomerates, and loose sands. Fractured limestone and sandstone are highly permeable, allowing greater water infiltration, while conglomerates and sandy alluvial deposits also enhance recharge because of their porous nature. Shale formations, on the other hand, restrict infiltration due to their dense and impermeable structure.

Land use and land cover patterns also affect recharge dynamics. The landscape is mostly covered by rangelands, especially in the northeast, while croplands are more common in the western and southern zones. Vegetated areas promote infiltration and reduce surface runoff, particularly when combined with permeable soils. Bare land and built-up areas in the central and southern regions have impervious surfaces that limit infiltration and increase runoff. The lack of major water bodies makes natural recharge largely dependent on land cover characteristics.

Lineament density reflects structural features such as faults and fractures and has a strong effect on groundwater movement. Areas including central Talli, Lahri, and north-eastern Kohlu have high lineament density, which improves subsurface permeability and encourages deep infiltration. Regions like Bhag and Bukhtiarabad Domki with lower lineament density have fewer structural pathways, which reduces recharge potential.

Slope affects runoff and infiltration rates. Gentle slopes from 0 to 8.5 degrees found in central and southern zones favour percolation by slowing runoff. Steeper slopes from 18 to 38 degrees, mainly in the north-eastern highlands, increase surface runoff and limit water infiltration, reducing recharge.

Drainage density indicates surface permeability. Areas with low drainage density from 0 to 15 km/km2 in the northeast and eastern edges suggest good infiltration and high recharge potential. Higher drainage density zones, especially around Sibi, Talli and Bukhtiarabad Domki, indicate low permeability and reduced recharge due to compact surface conditions.

Rainfall patterns also influence recharge. Annual rainfall ranges from less than 295 mm/yr in the southwest to more than 340 mm/yr in the northeast, including Kohlu and Talli. Moderate rainfall from 295 to 340 mm/yr occurs in areas such as Sibi and Lahri. Higher rainfall combined with favorable landforms and land use conditions significantly enhances recharge despite the overall arid climate.

Soil type controls infiltration through its texture and permeability. Central and southwestern plains with loamy soils such as Acrisols, Calcisols, and Arenosols support high infiltration. In contrast, upland areas near Kohlu and Talli with clay-rich soils, including Cambisols and Solonchaks, have low permeability and limited recharge. Loamy soils in the plains promote water percolation while clayey soils restrict it.

Groundwater potential zonation

Analytical hierarchy process

The groundwater recharge zones were identified by using the ratings and weights assigned to eight thematic layers as defined in (Equation 11).

$$\boldsymbol{GWRZ} = (\boldsymbol{RN} \times \mathbf{0.05}) + (\boldsymbol{LD} \times \mathbf{0.11}) + (\boldsymbol{LI} \times \mathbf{0.36}) + (\boldsymbol{SL} \times \mathbf{0.03}) + (\boldsymbol{DD} \times \mathbf{0.07}) + (\boldsymbol{SLO} \times \mathbf{0.15}) + (\boldsymbol{LULC} \times \mathbf{0.24}) \quad (11)$$

The AHP-derived GWRZ map classifies the study area into five recharge potential classes: very high (6.16%), high (17%), moderate (40.4%), low (27.1%), and very low (9.21%) as shown in Figure 6. Very high and high recharge zones are mostly found in the northeastern area near Kohlu District, where favorable conditions such as quaternary alluvial deposits, gentle slopes and dense lineament networks promote infiltration. Moderate recharge zones dominate central areas like Talli and Lahri, reflecting medium recharge potential due to a mix of topography and lithology. While low and very low recharge zones occur mainly in the western and southern regions, including Sibi Bhag and Bukhtiarabad Domki, where steep slopes, impermeable rock formations, and rugged terrain reduce infiltration.

Multi-influencing factors techniques (MIF)

The GWRZ index was computed using the MIF technique as per the specified Equation 12;

$$\boldsymbol{GWRZ} = (\boldsymbol{RN} \times \mathbf{0.09}) + (\boldsymbol{LD} \times \mathbf{0.16}) + (\boldsymbol{LI} \times \mathbf{0.25}) + (\boldsymbol{SL} \times \mathbf{0.06}) + (\boldsymbol{DD} \times \mathbf{0.09}) + (\boldsymbol{SLO} \times \mathbf{0.16}) + (\boldsymbol{LULC} \times \mathbf{0.22}) \quad (12)$$

The GWRZ map derived using the MIF technique categorizes the study area into five recharge potential zones: very high (13.1%), high (30.7%), moderate (25.5%), low (22%), and very low (8.5%). Very high and high recharge zones are mostly found in the northeastern area near Kohlu District, where favorable conditions such as quaternary alluvial deposits, gentle slopes, and dense lineament networks promote infiltration. Moderate recharge zones dominate central areas like Talli and Lahri, reflecting medium recharge potential due to a mix of topography and lithology. Low and very low recharge zones occur mainly in the western and southern regions, including Sibi, Bhag, and Bukhtiarabad Domki, where steep slopes, impermeable rock formations, and rugged terrain reduce infiltration.

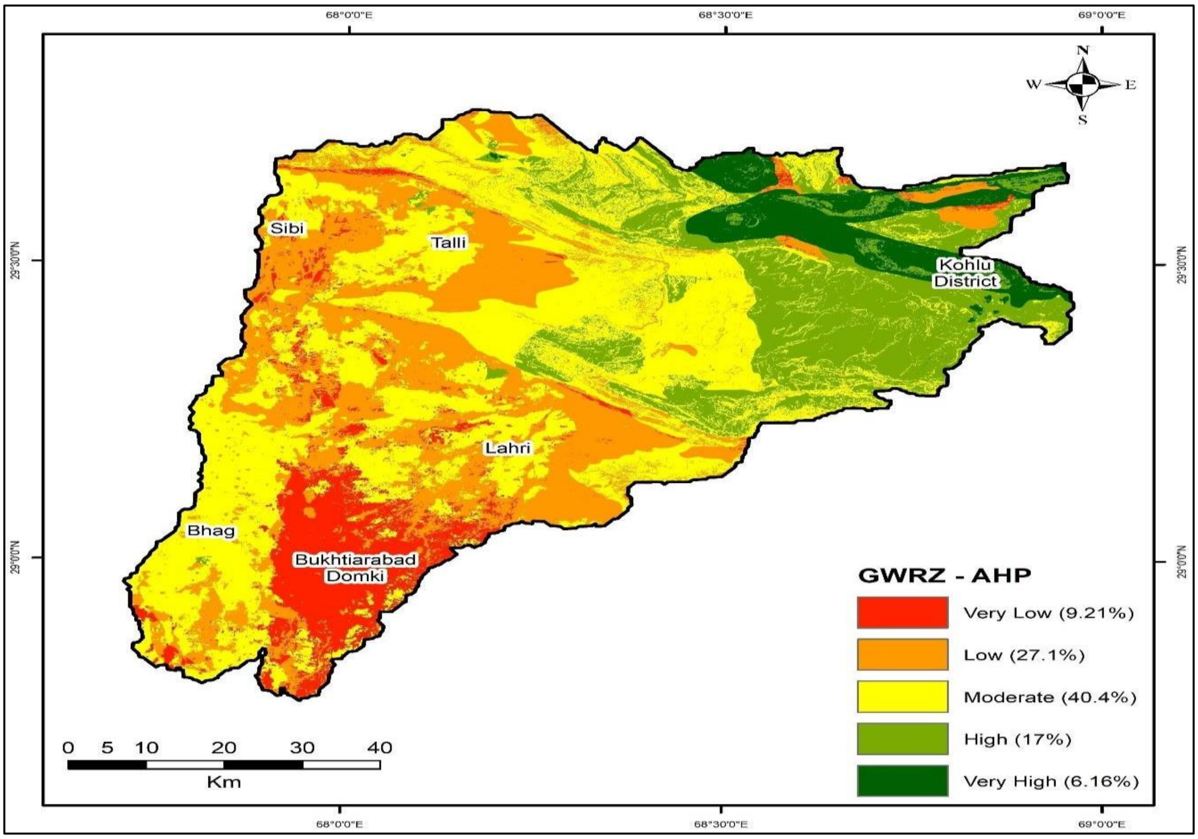

Figure 6: Potential ground water recharge zones using AHP.

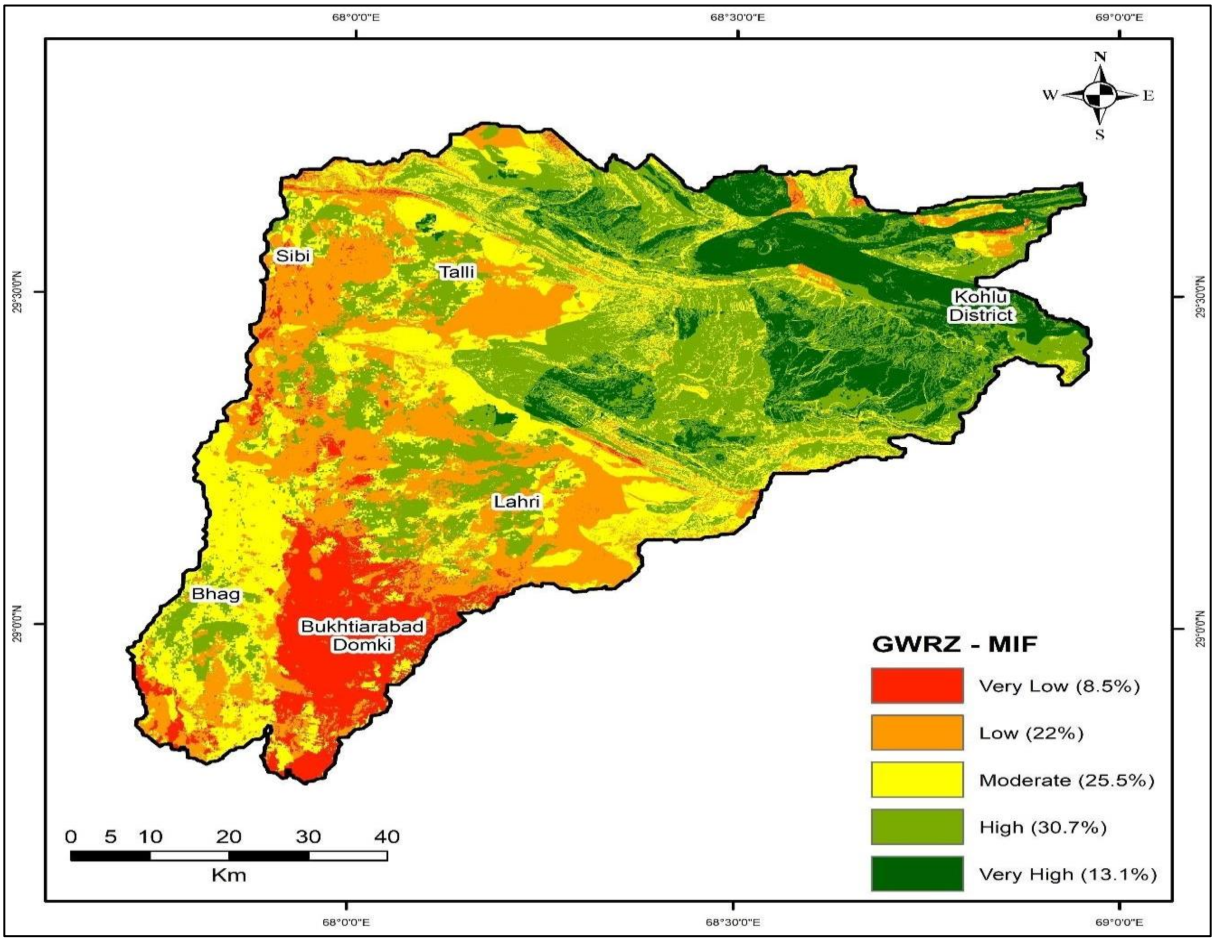

Figure 7: Potential Ground Water Recharge Zones using MIF.

Sensitivity analysis results

In the map removal sensitivity analysis for both analytical hierarchy process and multi-influencing factor methods, each thematic layer was removed one by one to evaluate its effect on the identification of groundwater recharge zones. The Sensitivity Index (S) values (Table 8), show the relative importance of each factor. The most influential factor in both methods is geology/lithology with the highest mean variation index values of 1.83 for AHP and 1.64 for MIF. This is followed by land use and land cover with values of 1.42 and 1.56, and slope with values of 1.46 and 1.52, respectively. These high sensitivity values indicate that these layers play a major role in controlling recharge potential.

Lineament density and rainfall also have an important contribution, with lineament density showing values of 1.02 for AHP and 1.06 for MIF, while rainfall has values of 1.01 and 0.97. Although their influence is slightly lower, they are still important for recharge mapping. Drainage density shows a moderate effect with values of 0.88 and 0.99. In contrast, soil has the lowest sensitivity in the Analytical Hierarchy Process with a value of 0.70 but shows slightly higher importance in the Multi-Influencing Factor with a value of 1.06, which indicates that the influence of factors can vary depending on the method used.

The sensitivity ranking of layers for the AHP method is Geology/Lithology > Slope > LU/LC > Lineament Density > Rainfall > Drainage Density > Soil

For the MIF method, the ranking shows a slight difference: Geology/Lithology > LU/LC > Slope > Lineament Density = Soil > Drainage Density > Rainfall

Table 8: Statistics of the sensitivity analysis index numbers.

Layer Removed	Sensitivity Analysis Index (S)							
	Minimum		Maximum		Mean Variation Index		Standard Deviation	
	AHP	MIF	AHP	MIF	AHP	MIF	AHP	MIF
Rainfall	0.13	0	2.91	3.23	1.01	0.97	0.38	0.64
Lineaments Density	0	0.01	3.78	4.32	1.02	1.06	0.87	1.1
Geology / Lithology	0	0.01	8.53	6.38	1.83	1.64	2.44	1.55
Soil	0.88	0	2.65	2.93	0.7	1.06	0.19	0.41
Drainage Density	0.01	0	2.95	3.18	0.88	0.99	0.59	0.6
Slope	0	0	4.56	4.5	1.46	1.52	0.82	0.72
Land Use / Land Cover	0	0	5.79	5.7	1.42	1.56	1.47	1.28

These results show that some layers have a strong and consistent influence in both models, while small differences in weights and their interactions cause variation in their relative sensitivity. Overall, the map removal sensitivity analysis confirms that all selected thematic layers play an important role in identifying groundwater recharge zones in the Balochistan region and should be included for reliable recharge mapping.

Conclusions

This study used two multi criteria decision making techniques, analytical hierarchy process and multi influencing factor, within a geographic information system framework to identify groundwater recharge zones in the eastern region of Balochistan, Pakistan. Important thematic layers such as lithology, land use and land cover, slope, lineament density, rainfall, drainage density, and soil type were combined to evaluate recharge potential. The groundwater recharge map based on analytical hierarchy process classified the area into very high 6.16% high 17% moderate 40.4% low 27.1% and very low 9.21% zones. In comparison, the map based on multi-influencing factors showed 13.1% of the area as very high, 30.7% as high, 25.5% as moderate, 22% as low, and 8.5% as very low recharge zones.

Model validation was carried out using map removal sensitivity analysis instead of field-based data. The results of this analysis show that both the analytical hierarchy process and multi-influencing factors respond differently when individual layers are removed, which reflects the internal consistency and strength of the decision-making framework. The analysis also shows that geology/lithology, land use and land cover, and slope are the most influential factors in mapping groundwater recharge zones. These results highlight the importance of sensitivity analysis in understanding model performance and improving the reliability of groundwater recharge zone mapping. This approach can support better groundwater management in arid and semi-arid regions.

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