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Assessment Of Groundwater Potential Zones Using Remote Sensing, GIS, And AHP In Sohawal Block, Satna District, Madhya Pradesh, India

Sandeep Kumar Shukla[1], Pushpendra Kumar Tiwari[2], Ashish Kumar Mishra[3], Anurag Dwivedi[4]
(Department Of Geology, Pradhanmantri College Of Excellence Govt. Model Science College, Rewa-486001(MP), India)

Abstract:
The overexploitation of groundwater resources and the impacts of climate change have placed significant strain on global water reserves. Sustainable groundwater management is essential for ecological balance, human well-being, and economic development. This study utilizes remote sensing, Geographic Information System (GIS), and the Analytical Hierarchy Process (AHP) to delineate groundwater potential zones (GWPZs) in Sohawal Block, Satna District, Madhya Pradesh, India. Seven thematic layers—drainage density, slope, soil, geomorphology, geology, land use/land cover, and lineament density—were analysed to assess groundwater potential. The AHP method was applied to assign weighted values to these thematic layers based on their significance in groundwater recharge. The final GWPZs were categorized into five classes: very low (10.81 sq. km, 1.45%), low (7.02 sq. km, 0.94%), moderate (237.72 sq. km, 31.94%), high (374.42 sq. km, 50.30%), and very high (114.33 sq. km, 15.36%). The study highlights that the majority of the region exhibits moderate to high groundwater potential. Receiver Operating Characteristics (ROC) analysis validated the results, confirming that the AHP technique achieved an accuracy of about 80% in identifying GWPZs. This study demonstrates the effectiveness of GIS and AHP methodologies in groundwater potential assessment and mapping. The findings provide a valuable reference for sustainable groundwater management in Sohawal Block and can serve as a model for similar hydrogeological studies globally.

Keywords: *Groundwater Potential Zones, Remote Sensing, Geographic Information System (GIS), Analytical Hierarchy Process (AHP), Sustainable Groundwater Management, Sohawal Block, Satna District*

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I. Introduction:

Groundwater serves as a critical resource for sustaining life, agricultural activities, and industrial development, particularly in regions experiencing irregular rainfall and surface water scarcity (Gleeson et al., 2020; Kalaivanan et al., 2019). Sohawal Block of Satna District falls under semi-arid regions. With over 79% of the district's rural population relying on agriculture and groundwater contributing to 70% of irrigation needs, sustainable management of this resource is imperative (CGWB Report). The dependence on groundwater has increased in recent years, leading to concerns regarding its depletion and contamination (Kumar et al., 2022; Datta et al., 2020). These challenges necessitate identification of groundwater potential zones (GWPZs) to balance extraction and recharge. Flatter slopes and alluvial soils typically indicate higher infiltration potential, while dense drainage networks may suggest reduced groundwater retention (Gautam et al., 2023; Ifediegwu, 2022).

Remote sensing and Geographic Information System (GIS) techniques, integrated with multi-criteria decision-making approaches such as the Analytical Hierarchy Process (AHP), have proven effective in delineating groundwater potential zones (Tiwari et al., 2024; Andualem and Demeke, 2019; Arulbalaji et al., 2019; Kolandhavel et al., 2019; Agarwal and Garg, 2016). The application of GIS and remote sensing in groundwater studies enables the analysis of various hydrogeological, topographical, and climatological factors that influence groundwater occurrence and recharge (Arefin, 2020; Benjmel et al., 2020; Ghosh et al., 2020). The use of the AHP technique facilitates systematic weighting and ranking of these factors, allowing for an objective assessment of groundwater potential zones (Bera et al., 2022; Das and Mukhopadhyay, 2018). This integrated approach has been widely applied across diverse geographical settings, including crystalline terrains, alluvial regions, and semi-arid basins, demonstrating its effectiveness in groundwater exploration and management (Kannan et al., 2019; Bayewu et al., 2017). However, indiscriminate groundwater extraction, coupled with limited recharge, poses challenges for sustainable water resource management in the region (Hadi et al., 2021; Mallick et al., 2019; Misi et al., 2018). Previous studies have highlighted the effectiveness of geospatial and hydrogeophysical techniques in groundwater assessment (Prapanchan et al.,2024; Upadhyay et al., 2023; Senapati and Das, 2022; Raj et al., 2022; Mahmud et al., 2022; Kardan Moghaddam et al., 2022; Gaikwad et al., 2021; Arya et al., 2020; Eyankware et al., 2020; Jamal et al., 2020), but a comprehensive evaluation of groundwater potential zones in Sohawal Block remains unexplored. The AHP method, validated through receiver operating characteristic (ROC) curves, provides a structured framework to assign weights to these parameters based on their hydrogeological significance (Kodihal and Akhtar, 2024; Islam et al., 2023).

This study aims to delineate groundwater potential zones by combining satellite-derived datasets with field-based hydrological measurements to create a spatially explicit groundwater potential model. By analysing key influencing factors such as geomorphology, geology, soil type, land use/land cover, slope, drainage density, and lineament density. This research seeks to provide valuable insights for sustainable groundwater management. The findings of this study will aid policymakers, water resource managers, and local stakeholders in making informed decisions for groundwater conservation and utilisation.

Study Area

The study area is part of Satna district of Madhya Pradesh. Sohawal Block falls between 24°30'N and 24°50'N latitude and 80°33'E and 81°03'E longitude. It has a total area of about 760 km^2. According to digital elevation model (DEM), the elevation of basin varies from 276 m to 435 m. It falls in parts of Survey of India toposheet numbers 63D/09, D/10, 63D/13 and D/14. The study area is characterised by formation of the Vindhyan Supergroup: Ganurgarh shale, Nagod limestone, Sirbu shale and Upper Rewa sandstone. The land slopes towards the northeast, while the study area has a flat terrain. Simrawal river is main source of surface water which flows east, draining into the Tons River. The region has a dendritic pattern drainage system. The study area's climate features hot summers and overall dryness, except during the southwest monsoon season. study area receives an average annual rainfall of about 1,046 mm, with the majority occurring during the southwest monsoon period.

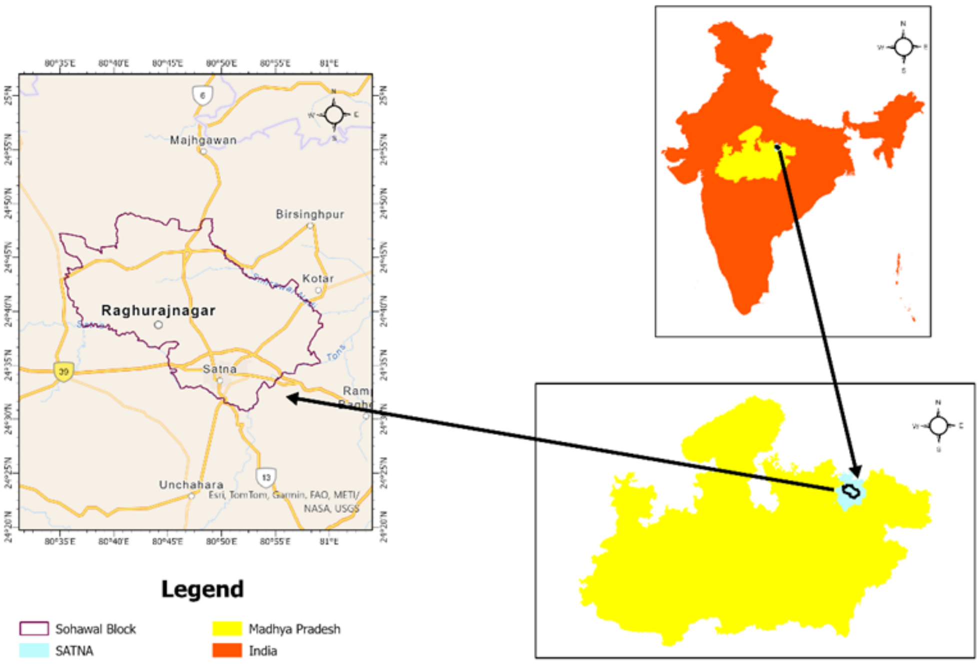

Figure 1. Location Map

II. Methodology

In this study, watershed delineation was conducted using the SRTM-DEM (30-meter resolution) obtained from the USGS Earth Explorer. ArcGIS 10.8 was used to generate and analyse the drainage density and slope maps. Geology and soil maps were created using data from the Central Ground Water Board (CGWB), while geomorphology data was sourced from Bhukosh, and land use/land cover (LULC) information was acquired from the USGS. Thematic maps were assigned weightages based on their influence on groundwater recharge potential, and features were ranked with values ranging from 1 (lowest) to 5 (highest). To generate groundwater potential zone maps, all thematic layers were processed using GIS software, and an overlay analysis was performed, categorising the area into five classes. The results were validated using data from 60 wells through the AUC-ROC tool.

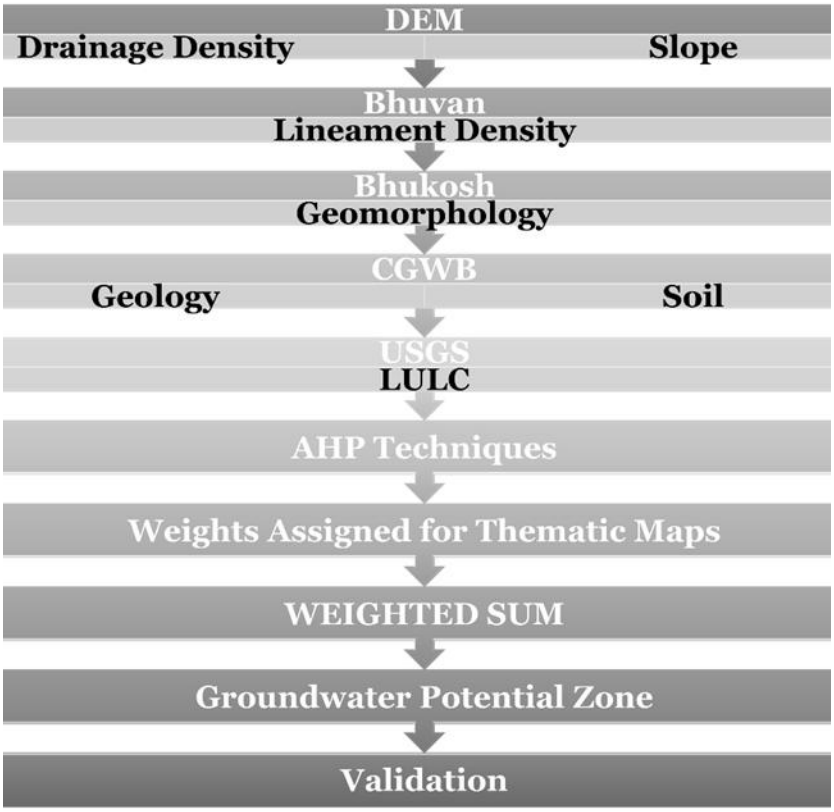

Figure 2. Flowchart of the methodology.

Table 1. AHP weights thematic map layers and ranking of their features.

Factors	Weight	Rank	Over All Weightage
Geomorphology			
Abandoned Channel		4	152
Active Quarry		1	38
Channel Island		4	152
Gullied Tract		2	76
Homocline		1	38
Pediment		2	76
Pediplain		3	114
WatBod - Others		3	114
WatBod- Pond		5	190
WatBod -River	38	5	190
Lineament Density			
Very High		5	95
High		4	76
Moderate		3	57
Low		2	38
Very Low	19	1	19
Geology			
Upper Rewa Sandstone		2	24
Nagod Limestone		4	48
Sirbu Shale		1	12
Ganurgarh Shale	12	1	12
Slope			
276-305		5	50
300-335		4	40
335-365		3	30
365-400		2	20
400-435	10	1	10
Soil			

Clayey Soil		5	40
Loamy Soil		5	40
Sandy Soil	8	3	24
LULC			
Agriculture		4	26.4
Barren Land		2	13.2
Built Up		1	6.6
Forest		4	26.4
Mines		2	13.2
Vegetation		3	19.8
Water Bodies	6.6	5	33
Drainage Density			
Very High		1	6.4
High		2	12.8
Moderate		3	19.2
Low		4	25.6
Very Low	6.4	5	32

III. Result And Discussion

In order to determine the groundwater potential zone, this study uses seven key factors: geology, geomorphology, lineament density, slope, drainage density, soil, land cover, and land use.

Geomorphology

Geomorphology plays a crucial role in groundwater potential zone mapping by influencing infiltration, storage, and movement of groundwater (Arefin, 2020). According to analysis, pediments dominate the study area (88.76%, 673.73 sq. km), suggesting moderate groundwater potential due to their relatively higher permeability and infiltration capacity. Homoclines (8.07%, 61.25 sq. km) contribute to groundwater recharge but may have variable permeability based on lithological composition. Water bodies (ponds, rivers, and others) collectively cover 1.58% of the area, acting as important recharge zones. Pediplains (0.73%, 5.58 sq. km) are potential groundwater reservoirs due to their flat terrain and fine-grained sediments. Gullied tracts (0.36%, 2.74 sq. km) and active quarries (0.48%, 3.63 sq. km) may have limited groundwater potential due to high surface runoff and disturbed geological formations. Channel island and abandoned channels (0.01% each) indicate remnants of past fluvial activities, which might store localised groundwater. The predominance of pediments suggests that groundwater availability is primarily dependent on structural features and infiltration dynamics, necessitating targeted recharge strategies for sustainable water resource management (Figure 3).

Table 2. Area and percentage of geomorphological features.

Geomorphology	Area (in sq km)	Percentage
Pediment	673.73	88.76
Homocline	61.25	8.07
WatBod - Pond	7.39	0.97
Pediplain	5.58	0.73
WatBod - River	3.84	0.51
Active Quarry	3.63	0.48
Gullied Tract	2.74	0.36
WatBod - Others	0.78	0.10
Channel Island	0.04	0.01
Abandoned Channel	0.04	0.01

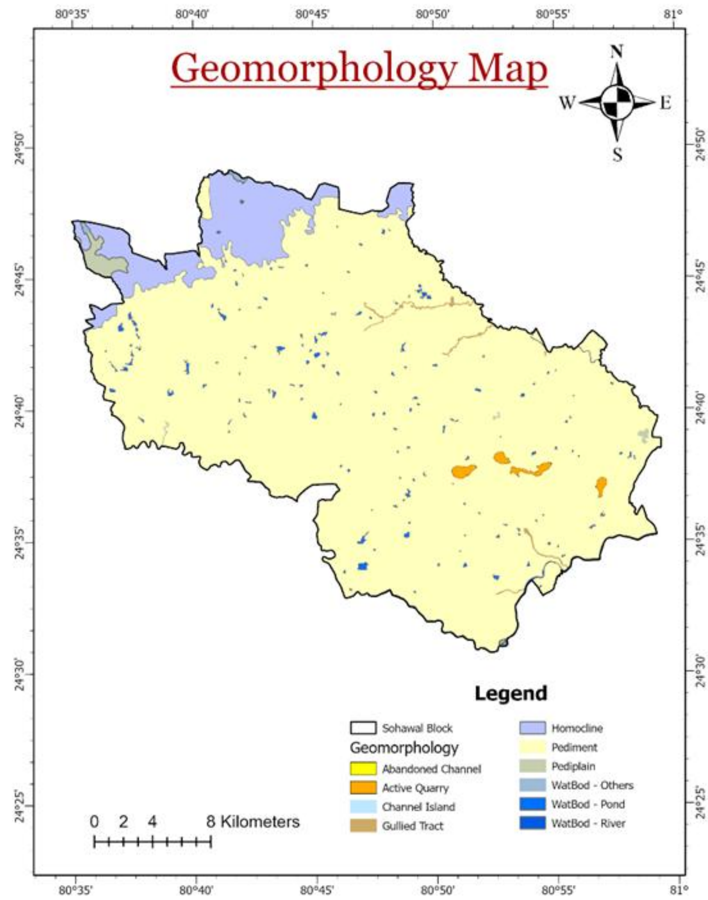

Figure 3. Geomorphology map

Lineament Density

Lineaments are visible linear features on Earth's surface, often indicating fractured bedrock zones with increased porosity and permeability, potentially enhancing groundwater well yields (Tiwari and Kushwaha, 2021). Automatic lineament extraction ensures uniformity across images, speeds up processing, and detects lineaments invisible to the human eye (Benjmel et al., 2020).

Study region is dominated by very low lineament density areas (67.62%, 513.02 sq. km), suggesting limited groundwater infiltration and storage potential due to fewer fractures and structural controls. Low-density zones (13.69%, 103.87 sq. km) may allow some groundwater movement but are still relatively less favourable for recharge. Medium-density areas (14.58%, 110.63 sq. km) provide moderate groundwater potential, as fractures and faults enhance permeability. High-density (3.15%, 23.88 sq. km) and very high-density (0.95%, 7.23 sq. km) zones are the most promising for groundwater recharge and storage, as increased fractures facilitate infiltration and subsurface flow. The limited extent of high and very high lineament density zones indicates that groundwater potential in the study area is largely constrained by structural geology, emphasizing the need for artificial recharge techniques in less fractured regions to enhance groundwater availability.

Table 3. Area and percentage of lineament Density.

Lineament Density	Area (in sq km)	Percentage
Very Low	513.02	67.62
Low	103.87	13.69
Medium	110.63	14.58
High	23.88	3.15
Very High	7.23	0.95

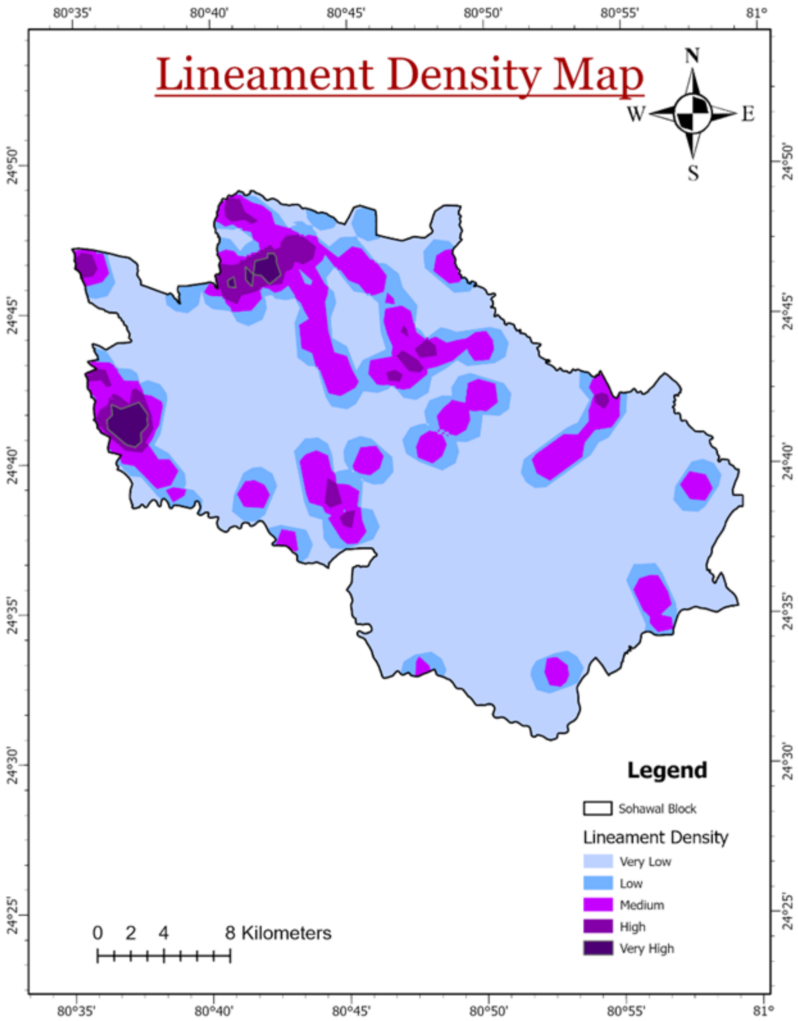

Figure 4. Lineament Density

Geology

Geological formations play a significant role in groundwater potential zone mapping by influencing porosity, permeability, and water retention capacity (Tiwari et al., 2024). The study area falls under Vindhyan supergroup. Nagod Limestone (34.15%, 259.23 sq. km) is the dominant formation, suggesting high groundwater potential due to its porous and permeable nature. Ganurgarh Shale (30.74%, 233.32 sq. km) covers a substantial portion of the area but may have lower groundwater potential due to its fine-grained, less permeable characteristics, restricting infiltration. Upper Rewa Sandstone (18.07%, 137.18 sq. km) is compact in nature, making it less likely to support groundwater availability. Sirbu Shale (17.03%, 129.29 sq. km) may act as an aquitard, limiting groundwater movement due to its low permeability. The predominance of limestone suggests that groundwater availability is largely controlled by lithology, with limestone acting as a key aquifer. However, shale formations may restrict groundwater flow, necessitating effective water resource management.

Table 4. Area and percentage of geological features.

Geology	Area (in sq km)	Percentage
Upper Rewa Sandstone	137.18	18.07
Nagod Limestone	259.23	34.15
Sirbu Shale	129.29	17.03
Ganurgarh Shale	233.32	30.74

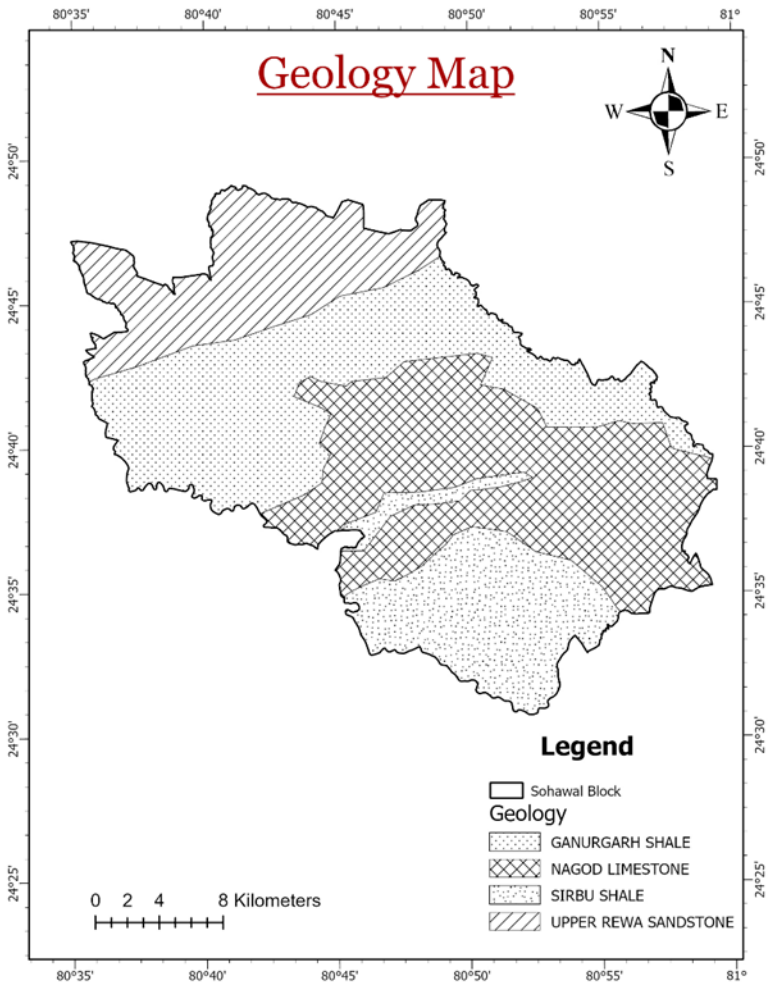

Figure 5. Geology map

Drainage Density

Drainage density (Dd), introduced by Horton (1932), measures landform linear scale in stream-eroded areas. Defined as the total stream length per catchment area (km/km²), it quantifies stream channel spacing and proximity, offering a measurable representation of stream distribution across a basin. Study reveals that very low drainage density areas dominate the study region (32.69%, 247.96 sq. km), indicating favourable conditions for groundwater recharge due to minimal surface runoff and higher infiltration potential. Low (21.31%, 161.65 sq. km) and medium (22.50%, 170.68 sq. km) drainage density zones also support moderate recharge. High (16.64%, 126.25 sq. km) and very high (6.86%, 52.04 sq. km) drainage density areas experience increased surface runoff, reducing infiltration and groundwater recharge potential. The prevalence of low to medium drainage density zones suggests significant groundwater recharge potential in these areas, while high drainage density regions may require artificial recharge techniques to enhance groundwater storage.

Table 4. Area and percentage of drainage Density.

Drainage Density	Area (in sq km)	Percentage
Very Low	247.96	32.69
Low	161.65	21.31
Medium	170.68	22.50
High	126.25	16.64
Very High	52.04	6.86

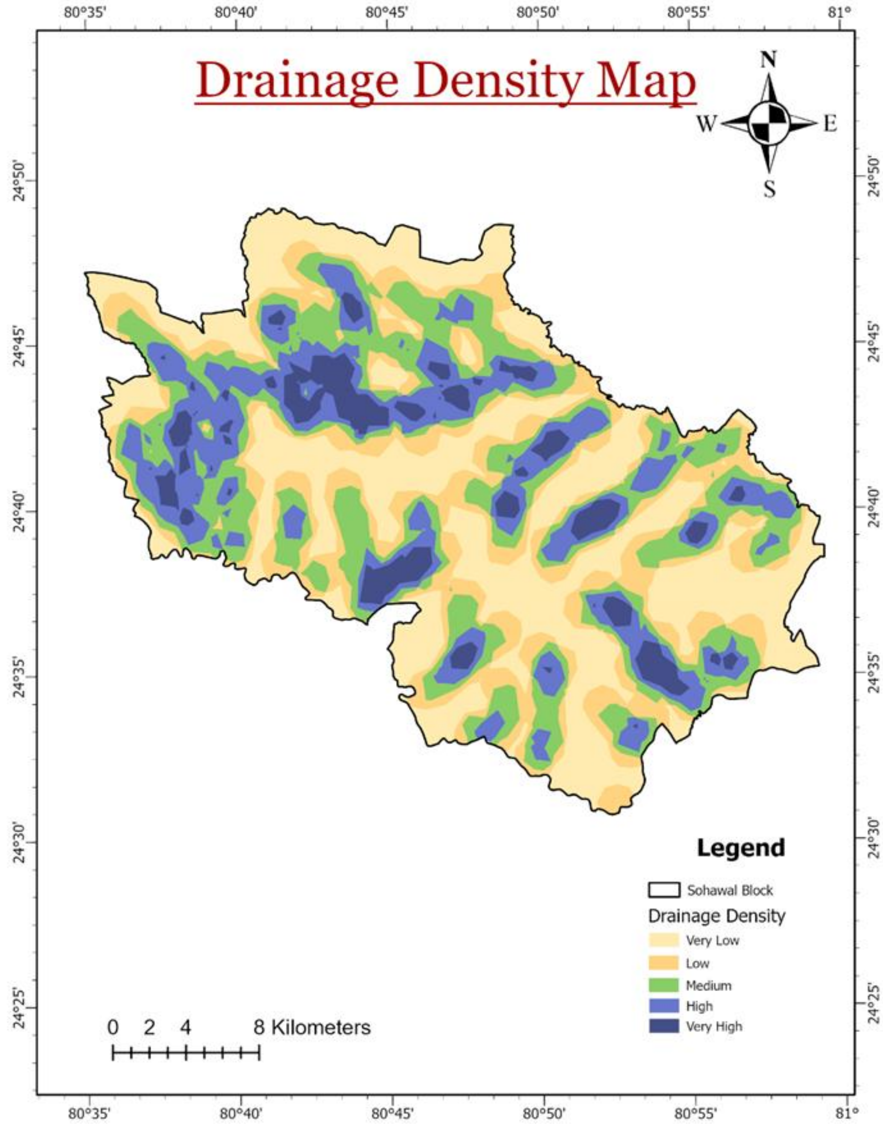

Figure 6. Drainage Density map

Slope

Slope is a key factor in groundwater potential; lower slopes enhance infiltration and recharge, while steep slopes increase runoff, reducing groundwater recharge (Gaikwad et al., 2021). The slope map for area was made using 30m resolution DEM data which was obtained from USGS (Figure 7).

The majority of the study area (64.88%, 492.55 sq. km) falls within the 300–335 m slope range, indicating a predominantly moderate terrain. The 276–305 m category covers 15.16% (115.09 sq. km), while 13.41% (101.81 sq. km) of the area falls within the 335–365 m range. Higher elevation zones, including 365–400 m and 400–435 m, account for 4.49% (34.12 sq. km) and 2.05% (15.58 sq. km) of the total area, respectively. This distribution suggests that the region is characterized by relatively moderate slopes, which can influence groundwater recharge. Lower elevation areas provide better conditions for infiltration and groundwater storage, while steeper regions may contribute to surface runoff. However, with the majority of the land in the 300–335 m range, the area still holds significant potential for sustainable groundwater recharge.

Table 5. Area and percentage of slope.

Slope (in m)	Area (in sq km)	Percentage
276-305	115.09	15.16
300-335	492.55	64.88
335-365	101.81	13.41
365-400	34.12	4.49
400-435	15.58	2.05

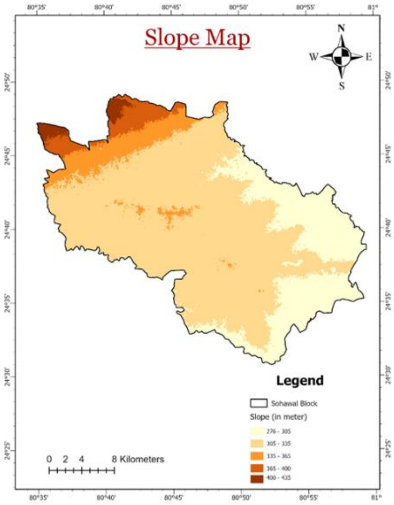

Figure 7. Slope map

Soil

Soil type, thickness, texture, and composition influence infiltration and groundwater recharge, making it an important factor for assessing GWPZ. Permeability, determined by infiltration, runoff, and soil properties, defines groundwater potential (Das and Mukhopadhyay, 2018). Clayey soil dominates the study area (66.69%, 506.20 sq. km), suggesting low permeability and slow infiltration, which may limit groundwater recharge but enhance water retention. Sandy soil covers 25.56% (194.02 sq. km) of the area, offering high permeability and facilitating rapid infiltration. Alluvial soil (7.75%, 58.79 sq. km) is also significant, typically associated with good groundwater potential due to its moderate permeability and ability to store water. The predominance of clayey soil suggests challenges in direct infiltration, but sandy and alluvial soil regions provide promising zones for groundwater recharge.

Table 6. Area and percentage of soil.

Soil	Area (in sq km)	Percentage
Clayey Soil	506.20	66.69
Sandy Soil	194.02	25.56
Alluvial Soil	58.79	7.75

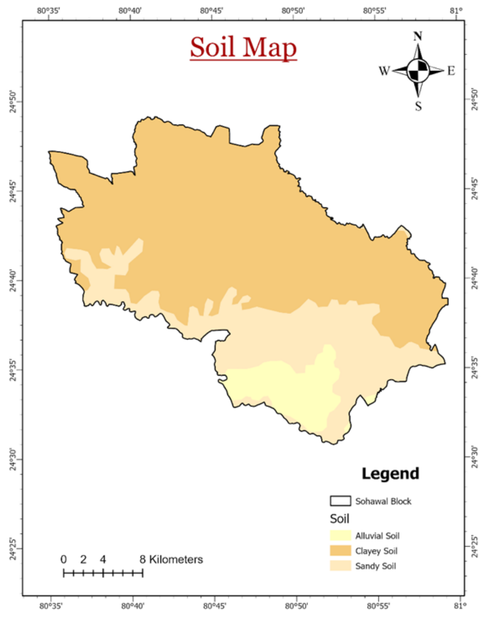

Figure 8. Soil map

Land Use and Land Cover

The LULC map provides precise information on the area's geography and various land use classifications (Bera et al., 2022). LULC significantly impacts groundwater potential by influencing infiltration, runoff, and recharge capacity. Study area is dominated by agriculture (67.94%, 515.60 sq. km), which can enhance groundwater recharge if managed sustainably but may also lead to over-extraction. Barren land (12.42%, 94.24 sq. km) has limited vegetation cover, reducing infiltration and increasing runoff. Built-up areas (9.71%, 73.70 sq. km) contribute to reduced infiltration due to impervious surfaces, limiting groundwater recharge. Vegetation (5.45%, 41.35 sq. km) and forest cover (0.44%, 3.37 sq. km) aid in infiltration and groundwater conservation. Mines (3.18%, 24.13 sq. km) may disrupt natural recharge patterns, potentially lowering groundwater levels. Water bodies (0.86%, 6.53 sq. km) act as crucial recharge zones, supporting groundwater sustainability.

Table 7. Area and percentage of LULC.

LULC	Area (in sq km)	Percentage
Water Bodies	6.53	0.86
Built Up	73.70	9.71
Agriculture	515.60	67.94
Vegetation	41.35	5.45
Barren Land	94.24	12.42
Mines	24.13	3.18
Forest	3.37	0.44

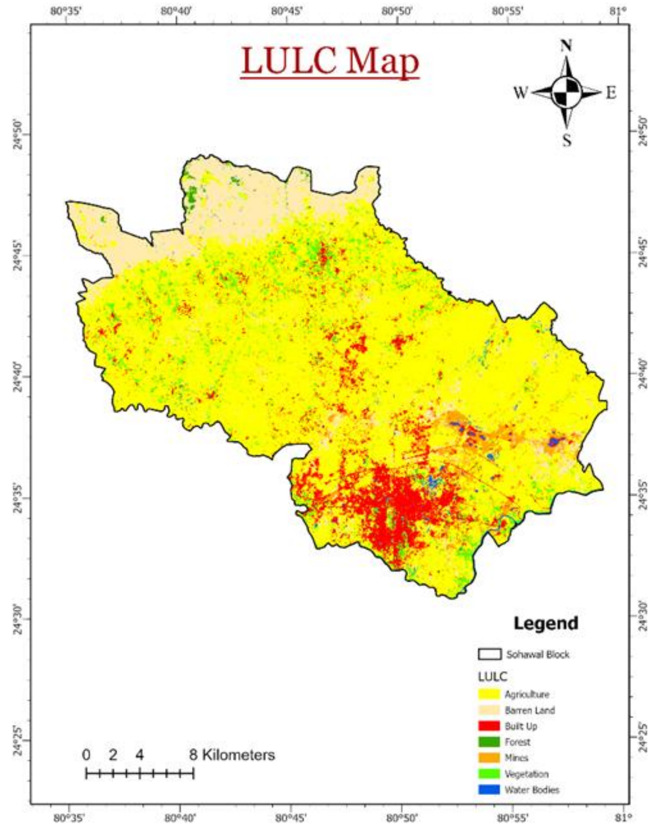

Figure 9. LULC map

Groundwater Potential Zone

Groundwater Potential (GWP) zones are determined through a weighted sum analysis of various thematic layers, including geomorphology, land use/land cover, lineament density, geology, soil, drainage density, and slope. Based on this assessment, the groundwater potential map is categorised into five zones: very high, high, medium, low, and very low (Figure 10). The results indicate that 50.30% (374.42 km²) of the total study area falls under the very high category, while 15.36% (114.33 km²) is classified as high. Approximately 31.94% (237.72 km²) of the region has medium groundwater potential. The low and very low potential zones cover 1.45% (10.81 km²) and 0.94% (7.02 km²), respectively. The very high and high groundwater potential zones are widely distributed across the region, whereas the low and very low zones are concentrated in specific areas. Since the high-potential zones are characterised by high infiltration capacity and permeability, they must be protected from contamination. The relatively flat topography in these areas allows for efficient infiltration of rainwater and surface water into the aquifer. To optimise groundwater recharge during monsoon seasons, structures such as check dams, percolation ponds, and recharge shafts should be constructed. In contrast, groundwater use in low and very low potential zones should be minimised by modifying cropping patterns. Alternative water sources, such as surface water and rainwater, should be prioritized to meet local demands. Strict water management policies must be enforced in these areas to enhance groundwater resources and ensure sustainable water use.

Table 7. Area and percentage of GWPZ.

GWPZ	Area (in sq km)	Percentage
Very Low	10.81	1.45
Low	7.02	0.94
Medium	237.72	31.94
High	374.42	50.30
Very High	114.33	15.36

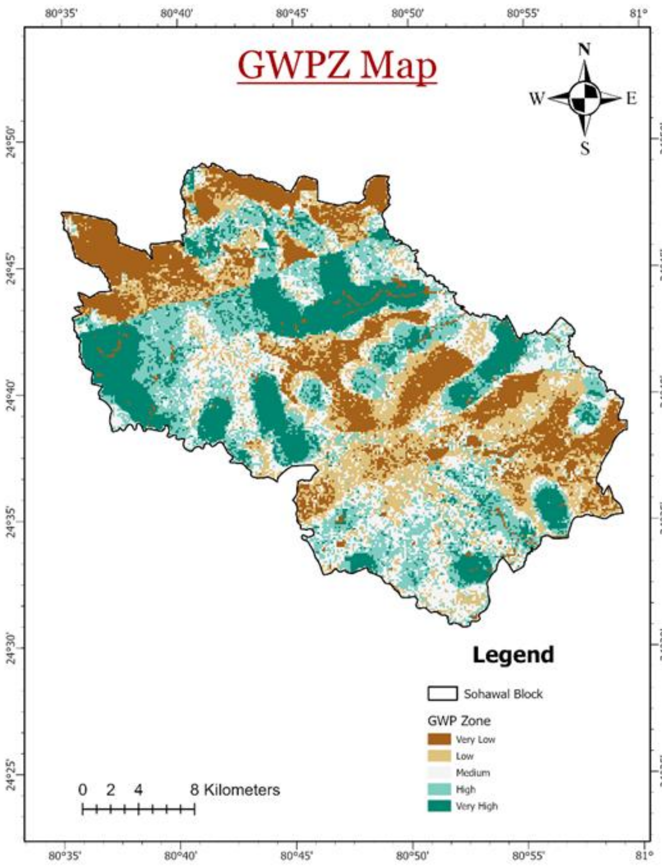

Figure 10. GWPZ map

Validation of Groundwater Potential Map

Validation plays an important role in scientific research. In this study, data from 60 wells were used to validate the final Groundwater Potential Zonation (GWPZ). The Area Under the Curve (AUC) in Receiver Operating Characteristic (ROC) analysis assesses the model's accuracy. The AUC value is classified into five qualitative and quantitative categories: excellent (0.9–1), very good (0.8–0.9), good (0.7–0.8), average (0.6–0.7), and poor (0.5–0.6) (Maity et al., 2022; Makonyo and Msabi, 2021). The results indicate that the Analytical

Hierarchy Process (AHP) model achieved an AUC value of 0.80, signifying very good predictive accuracy for the study area (Figure 11). This suggests that the model effectively differentiates between high and low groundwater potential zones. The strong validation with well data confirms its reliability, making it a valuable tool for sustainable groundwater management in the study area.

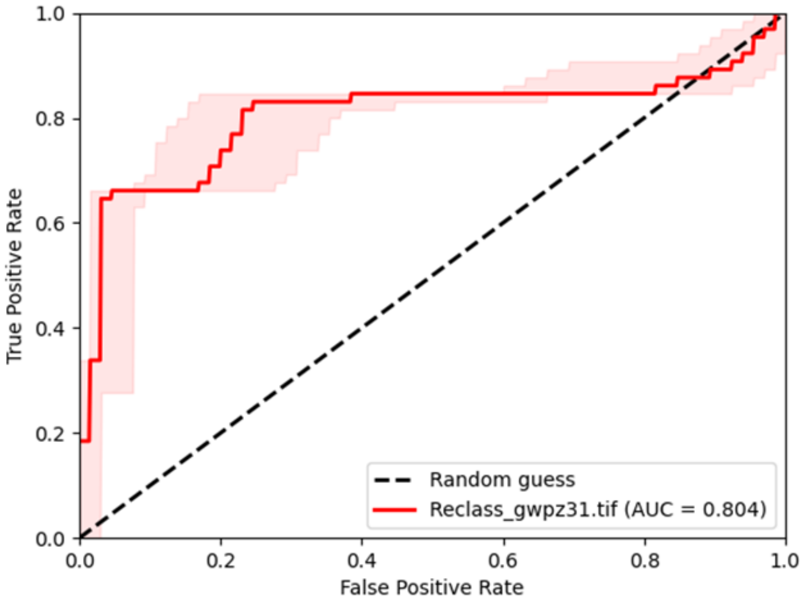

Figure 11. ROC curve for groundwater potential map**.**

IV. Conclusion

The study successfully mapped and evaluated groundwater potential zones by integrating seven key thematic layers. Utilizing remote sensing, Geographic Information Systems (GIS), and the Analytical Hierarchy Process (AHP), the research identified that a significant portion of the study area exhibits promising groundwater potential. Approximately 50.30% (374.42 km²) of the region falls under the very high potential category, followed by 15.36% (114.33 km²) classified as high potential. Medium potential zones account for 31.94% (237.72 km²), while low and very low zones constitute only 1.45% (10.81 km²) and 0.94% (7.02 km²), respectively. This distribution highlights the region's overall suitability for groundwater recharge, primarily driven by predominantly moderate terrain (64.88%, 492.55 sq. km), dominance of permeable geological formations like Nagod Limestone (34.15%), and low to medium drainage density zones conducive to infiltration. The validation of the GWPZ map using data from 60 wells and the Receiver Operating Characteristic (ROC) curve yielded an Area Under the Curve (AUC) value of 0.80, indicating very good predictive accuracy. This confirms the reliability of the AHP model in delineating groundwater potential zones and underscores its applicability as a decision-making tool for water resource management in the Sohawal Block. The study reveals that geomorphology (e.g., pediments covering 88.76%) and geology play pivotal roles in controlling groundwater availability, while factors like clayey soils (66.69%) and high drainage density zones (6.86%) pose challenges to infiltration in specific areas. The extensive agricultural land use (67.94%) further emphasizes the need for sustainable groundwater management to balance recharge and extraction. The integration of remote sensing, GIS, and AHP provides a framework for assessing groundwater potential in the Sohawal Block. The findings highlight the spatial variability of groundwater resources and offer a scientific basis for planning sustainable water management strategies in this semi-arid region of Madhya Pradesh. In areas identified with very high and high groundwater potential, such as those dominated by pediments and limestone formations, artificial recharge structures like check dams, percolation ponds, and recharge shafts should be implemented to maximize rainwater infiltration during the monsoon season.

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