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COMPARATIVE ANALYSIS OF MULTI-CRITERIA DECISION-MAKING TECHNIQUES FOR GROUNDWATER POTENTIAL MAPPING IN HIGHLAND OF ERITREA

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Abstract: This study employs an approach that integrates geospatial techniques with the Analytical Hierarchy Process (AHP) and Fuzzy-AHP to identify groundwater potential zones in Debarwa. Seven environmental parameters significantly influencing groundwater potential were selected for analysis: geology, soil, lineament density, rainfall, land use/land cover, drainage density, and slope. A comparative study between the two methods was employed using Geographic Information System (GIS) and Remote Sensing (RS) tools. The thematic layers for each parameter were created and subsequently weighed through pairwise comparisons based on the AHP and Fuzzy-AHP methodology. Consistency tests were conducted to ensure the reliability of the assigned weights. The final weighted overlay map classified the groundwater potential into four categories: poor, good, very good, and excellent. The spatial distribution of the area coverage for the potential zone of AHP and Fuzzy-AHP fall under the good and very good zones. The results for good and very good use of AHP are 74.68% and 24.88%, respectively, with 80.12% and 19.87% for Fuzzy-AHP. While both methods produce comparable results, Fuzzy-AHP exhibits a slight advantage in refining classification accuracy by incorporating degrees of membership rather than rigid classifications. For future work the research recommends incorporating other methods to validate the accuracy and robustness of the outcome. Finally, the preliminary resulting outcome provides a valuable tool for Eritrea water resource department to prioritize areas for detailed groundwater exploration and management.

Keywords: *Groundwater potential, Analytical Hierarchy Process (AHP), Fuzzy-AHP, Geographic Information System (GIS), Water resource management, Eritrea*

1. INTRODUCTION

Groundwater, a vital global water resource, is stored within soil and rock pores following rainwater infiltration through permeable zones (Upwanshi et al., 2023). Unlike surface water, groundwater is often less vulnerable to environmental contamination. It is a crucial source, contributing to 34% of the world's water supply, particularly for agricultural and industrial purposes (Verma and Patel, 2021), with approximately 2.5 billion people worldwide depending on groundwater (Swarnim et al., 2023). Its significance cannot be overstated, especially in arid and semi-arid regions where low rainfall and climate change exacerbate demand (Tegegne et al., 2024). Therefore, assessing this precious resource is essential in coping with the world's high demand.

The objective of this research is to identify groundwater potential zones in the central region of Eritrea around Debarwa city. However, identifying groundwater recharge zones poses challenges due to temporal and spatial variations in recharge rates (Moeck et al., 2020). Consequently, a comprehensive understanding of groundwater dynamics is essential for accurate potential zone mapping. While various exploration methods exist, including geophysical, remote sensing, and geological techniques (AL Deep et al., 2021; Araffa et al., 2023; El-Sayed and Elgendy, 2024), their application may be limited by time and cost considerations, particularly in low-income countries (Agogue Feujio et al., 2024). To address this, researchers have increasingly turned to integrated approaches combining Geographical Information Systems (GIS), Remote Sensing (RS), AHP and Fuzzy-AHP approaches for rapid and accurate assessments (Y. Liu et al., 2020; Sajil Kumar et al., 2022; Shelar et al., 2023; Swarnim et al., 2023). These approaches are also widely used in other disciplines to delineate dam sites and landslides (Bastola et al., 2024; Ksantini et al., 2024; Y. Liu et al., 2020). GIS has become a suitable mapping tool due to its capability to integrate, visualize, model, and manage large amounts of data. Combining data layers in GIS and analyzing them with RS-derived information allows potential recharge zones to be mapped effectively (Kpiebaya et al., 2022).

This study focuses on delineating Groundwater Potential Zones (GWPZ) in the Debarwa catchment area using RS, geospatial, AHP, and Fuzzy-AHP approaches. Where this method is tested for the first time in the study area that will fill the existing traditional exploration methods. Integrating these methodologies with hydrological, topographical, and geological parameters has yielded promising results in various regions (Gidafie et al., 2024; Mohammed et al., 2024). For instance, in the Murredu watershed in India, AHP combined with Fuzzy-AHP found higher area potential with a moderate zone of 73.53% for AHP and 76.55% for Fuzzy-AHP (Raja Shekar and Mathew, 2023). Similarly, in Tunisia's Regueb region, the AHP approach, alongside literature-derived weights, produced comparable results (Hassini et al., 2023). Furthermore, integrating Fuzzy-AHP with GIS-RS mapping in Sevathur region in Tamil Nadu, India, proves good technique for potential groundwater exploration (Prapanchan et al., 2024). Therefore, this method has sound acceptance worldwide.

The urgency of this research came from the critical need for proper groundwater management in Debarwa catchment area. Overexploitation, variable rainfall patterns, and geological factors have led to rapid groundwater depletion, impacting the socio-economic livelihoods of communities reliant on groundwater use for agriculture. Moreover, the study area has a knowledge gap for the scientific assessment of groundwater potential. Therefore, the gap is believed to be solved by employing such research. Seven environmental features have been selected for investigation: geology, soil, lineament density, land use/land cover, rainfall, drainage density, and slope. The outcome of this study produces a map showing different potential groundwater zones. These maps are expected to show preliminary information on the potential zones to the decision-making bodies and water resource departments. In addition, the approach of the scientific result will contribute to overcoming the challenges of groundwater exploration.

2. STUDY AREA

The study area encompasses Debarwa, situated within the administrative zone of the Southern region (Debub local name) in Eritrea *(Figure 1)*.

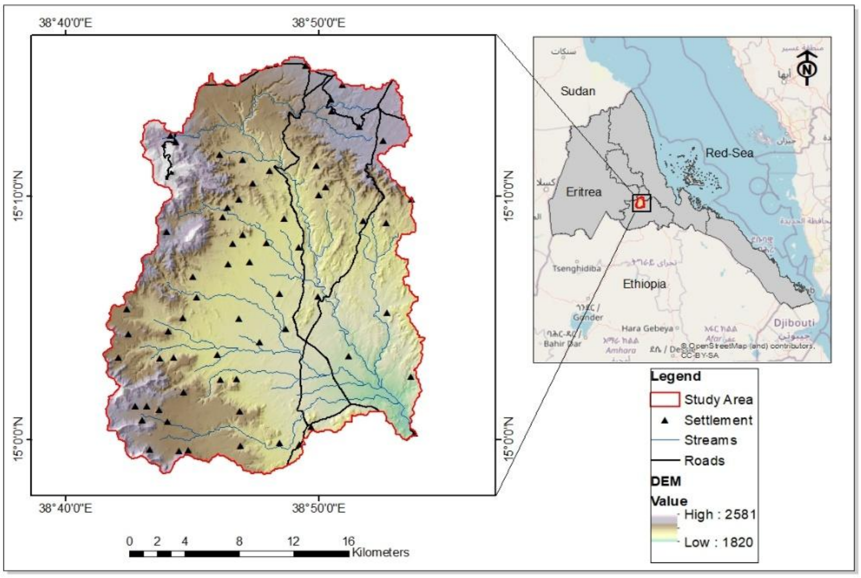

Figure 1
Location map of the study area in Eritrea

It is located 25 km south of Asmara, the capital city of Eritrea at a geographic coordinate of $38^0$50'E and $15^0$10'N. The study area has a total of 506 km^2 area coverage with an elevation of 1926 m above mean sea level. Debarwa experiences distinct climatic conditions, with July marking the wettest month and December the driest, whereas January typically emerges as the coldest month. The region exhibits a variable rainfall pattern, with an average annual precipitation of 53.36 mm and a mean temperature of 23.21 °C (https://weatherandclimate.com/eritrea/debub#t1). The area geology comprises deeply eroded/weathered and strongly lateritized Neoproterozoic low-grade volcanic units underlying tertiary flood basalts and granite-type rocks (Teklay, 2006). The occurrence and movement of groundwater in the area are primarily controlled by nature, spatial distribution, orientation, and penetration depth of secondary permeability, which are tension or shear fractures (Solomon and Quiel, 2006). Recharge may occur to the groundwater system directly from rainfall and indirectly from surface flows over the area drained by the Mereb River drainage system. Most of the wells in the area are protected and inaccessible except for some privately owned agricultural wells. Thus, measuring the well's water level in the field site is difficult.

As a historic market town in central Eritrea, Debarwa boasts a population of approximately 25,000 residents. The local economy predominantly revolves around agriculture, with residents cultivating crops such as teff, finger millet, maize, and barley. However, the agricultural sector faces significant challenges due to climate change impacts and the overexploitation of groundwater resources, leading to water scarcity issues. These challenges underscore the critical importance of effective water resource management strategies in sustaining agricultural production and livelihoods within the region.

3. MATERIALS AND METHODS

There are different methods for assessing groundwater potential mapping (GWPM), but none have been used in the study area. Therefore, this research focused on a comparative analysis of AHP and Fuzzy-AHP in combination with GIS and RS for the assessment of GWPM. These methods can integrate expert judgment with quantitative data and handle subjective decisions (Burayu et al., 2025). The study area, the Debarwa catchment, has a complex geological and environmental factor that requires expert analysis judgment. Where the three experts who have participated in the judgment have a sound knowledge of the study area with geological and hydrogeological background. The methodology for identifying groundwater potential zones involves significant steps in both methods. These include the selection of parameters influencing groundwater recharge processing and layer analysis in GIS environment (Kouaied et al., 2025). Then, a pairwise comparison between selected parameters using the AHP and Fuzzy-AHP. Finally, the weighted overlay method produces the groundwater potential zone map. Based on the available data, the critical influential groundwater controlling parameters selected in this study are geology, soil, lineament density, rainfall, land use/land cover, slope and drainage density. All those parameters have a direct and major contributing factor for groundwater recharge which is categorized as a main input figures in many similar studies.

The selected environmental parameters were processed using the ArcGIS Pro software and reclassified based on classes within the catchment area. All selected environmental parameters with 30-meter resolution were projected to the WGS 1984 UTM Zone 37N coordinate system to align with the local coordinate. Parameters derived from DEM are drainage density, lineament density, and slope, and were classified into five distinct classes based on expert judgment. Geology, rainfall, and soil classifications were based on the specific characteristics of the study area. The land-use and land cover data were downloaded from Sentinel-2 10 m land use/land cover time series. This systematic classification ensures that each parameter is appropriately represented and standardized for subsequent analysis, facilitating the accurate delineation of groundwater potential zones within the Debarwa catchment area.

The data were collected from different sources as discussed below. Geological data were obtained from the Ministry of Mining and Energy in Asmara, Eritrea, at a spatial resolution of 30 m in shapefile format. Soil is another important parameter used to contribute to groundwater occurrence where its data is brought from Asmara Agricultural Department. The lineament is traced manually from the digital elevation model (DEM) hillshade from Shuttle Radar Topographic Mission (SRTM) and generates new map (Asghede et al., 2025). The data was downloaded from Earth Explorer website (https://earthexplorer.usgs.gov/) and converted to line density to make it raster. The Asmara International Airport meteorological station collected rainfall for the period of 1992 to 2022, where the average rainfall data of this period is used in this research.

Many hydrological processes are regulated by land use and land cover, where their importance is crucial (Bhadran et al., 2022). Based on Sentinel-2 satellite imagery classification scheme there are seven classes within the study area. Moreover, the slope map is generated from DEM which was downloaded from the Earth Explorer website. The drainage density parameter has an inversely proportional relationship with the permeability of the underlying rocks (Ifediegwu, 2022). It is generated by creating fill, flow direction, and flow accumulation using the hydrogeological tools in the ArcGIS environment. Then, from the flow accumulation stream order and stream to feature were created. Finally, to convert to raster line density was prepared. By integrating data from these diverse sources and making a comparison between the methods, the study ensures reasonable information for groundwater potential assessment, facilitating good analysis for decision-making processes.

AHP is a widely adopted method across various disciplines worldwide (Arefin, 2020; Kassa et al., 2023). The AHP facilitates calculating each criterion's weight or rank based on priority by pairwise comparisons of the datasets (Saaty and Katz, 1990). These comparisons are made using the Saaty scale, which ranges from 1 to 9 *(Table 1)*, allowing for a systematic assessment of the relative importance of each parameter in the groundwater potential analysis. The selected environmental control parameters were compared through expert judgment and literature review. The consistency test was conducted to ensure the judgment matrix, as recommended by previous studies (Ozegin et al., 2024; Zenande et al., 2024). Following Saaty's principle, the consistency ratio was calculated using the ratio of the consistency index and random index [Equation (2)]

$$CI = \frac{(\lambda - n)}{(n-1)} \tag{1}$$

$$CR = \frac{CI}{RI} \tag{2}$$

where CI is the consistency index, CR is the consistency ratio, RI is the random index, λ is the maximum principal eigenvalue, and n is the number of compared elements or parameters. The values depend on the number of selected parameters *(Table 2)*. In this study, seven factors were chosen as groundwater control parameters. According to Saaty's guideline, for a parameter with seven factors, the consistency ratio should ideally be less than 0.1 (Agogue Feujio et al., 2024). *Equation (1)* was employed to verify this criterion. Subsequently, the weight of each factor was generated, serving as a basis for prioritizing parameters in the development of the groundwater potential map.

Table 1

Saaty's scale for relative importance (Saaty and Katz, 1990)

Range of importance	Description
1	Equal importance
3	Moderate importance
5	Essential
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between adjacent scale values

Subclass ranking was assigned based on percolation rates to contribute water to underground storage, drawing insights from various literature reviews and expert judgments (Popalzai et al., 2023; Sharma and Singh, 2025). The final weight was determined by multiplying each subclass's rank by the feature's weight. The weighted overlay tool from the spatial analysis toolbox of ArcGIS Pro was utilized to sum all the weighted features and generate the required groundwater potential map. Ensuring uniformity in cell size and projection systems across all layers is imperative to facilitate a smooth analysis process (Thanh et al., 2022).

Table 2

Saaty's ratio index for different n values

N	3	4	5	6	7	8
RI	0.58	0.89	1.12	1.24	1.32	1.41

Fuzzy-AHP method is an extension of the traditional AHP that incorporates fuzzy logic to the expert judgment to handle uncertainty and subjectivity in decision-making (Liu et al., 2020). Based on the expert surveys and literature reviews, pairwise comparisons of parameters were made based on their relative importance. Then, pairwise comparisons of values were converted to fuzzy triangular numbers to account for uncertainty in expert opinions. Using fuzzy logic operations, the fuzzy weight of each parameter is computed. The final weight of each parameter is found by converting the fuzzy weights to crisp values, that is the defuzzification process (Githinji et al., 2022). Finally, criterion weights are obtained after ensuring the consistency ratio. This weight is integrated into the spatial layer of each parameter to generate a groundwater potential map.

4. RESULTS AND DISCUSSION

Both AHP and Fuzzy approaches' results revealed that all the selected environmental parameters have almost similar outcomes *(Tables 3, 4)*. The weights of the parameters are determined in the following descending order based on the expert judgment: geology, soil, lineament density, rainfall, land use/land cover (LULC), slope, and drainage density. The first four parameters contribute more than ten percent of the total weight *(Table 5)*.

Table 3

AHP Pairwise comparison matrix

Parameter	Slope	DD	LD	LU/ LC	Soil	Rainfall	Geology	Normalized principal eigenvector	AHP Weight
Geology	4.0	4.0	2.0	3.0	2	3.0	1	29.3%	0.29
Soil	3.0	4.0	2.0	3.0	1	2.0	0.50	21.8%	0.22
LD	3.0	4.0	1	3.0	0.5	2.0	0.50	17.8%	0.18
Rainfall	3	3	0.5	2	0.5	1	0.33	12.4%	0.12
LULC	2	2	0.33	1	0.3	0.50	0.33	8.1%	0.08
Slope	1	2.0	0.33	0.5	0.3	0.33	0.25	6.1%	0.06
Drainage density	0.50	1	0.25	0.5	0.25	0.33	0.25	4.6%	0.05

Table 4

Fuzzy-AHP Pairwise comparison matrix

Classes	Soil			LD			Rainfall			LULC			Slope			DD			Geology			Weight %
Geology	1	2	3	1	2	3	2	3	4	2	3	4	3	4	5	3	4	5	1	1	1	27.95
Soil	1	1	1	1	2	3	1	2	3	2	3	4	2	3	4	3	4	5	0.3	0.5	1	21.53
LD	0.3	0.5	1	1	1	1	1	2	3	2	3	4	2	3	4	3	4	5	0.3	0.5	1	18.19
Rainfall	0.3	0.5	1	0.3	0.5	1	1	1	1	1	2	3	2	3	4	2	3	4	0.3	0.3	0.5	12.95
LULC	0.25	0.3	0.5	0.25	0.3	0.5	0.3	0.5	1	1	1	1	1	2	3	1	2	3	0.3	0.3	0.5	8.38
Slope	0.25	0.3	0.5	0.25	0.3	0.5	0.25	0.3	0.5	0.3	0.5	1	1	1	1	1	2	3	0.2	0.3	0.3	6.22
DD	0.2	0.25	0.3	0.2	0.25	0.3	0.25	0.3	0.5	0.3	0.5	1	0.3	0.5	1	1	1	1	0.2	0.3	0.3	4.76

The result of the two methods revealed that geology has the highest weight comprising 29.3% for AHP and 27.95% for Fuzzy-AHP of the total weight *(Tables 3, 4)*. The geological classification encompasses four subclasses *(Figure 2a)*: low-grade metamorphic rocks, very low-grade metamorphic rocks, trap series plateau basalt, and granite-type rocks. These geological features are crucial in groundwater recharge dynamics (Moon et al., 2024). Following geology, the soil is ranked as the second-highest contributing factor, weighing 21.8% and 21.53% for AHP and Fuzzy-AHP methods, respectively. The classification includes loam and light clay soils *(Figure 2b)*, indicating favorable conditions for water infiltration and seepage to the saturated zone with minimal hindrance.

Lineament density is another significant factor, weighing 17.8% and 18.19% for AHP and Fuzzy, respectively. The cracks and fissures in the rocks facilitate water percolation, further aiding in aquifer recharge (Daher et al., 2011). These structural features are classified into five categories ranging from 1.53 to 7.67 km per km^2 to standardize and simplify the analysis for use in the multi-criteria evaluation models

(Figure 3a), which enhances groundwater recharge by providing pathways for water movement through the subsurface. Furthermore, rainfall intensity emerges as a critical determinant, particularly in arid and semi-arid regions like the study area. With spatially and temporally limited distribution, the area experiences relatively low average annual rainfall, ranging from 34.3 to 47.3 mm (Figure 3b), based on readings from national meteorological stations. Consequently, rainfall variability is categorized as the fourth contributing factor, representing 12.4% and 12.95% for AHP and Fuzzy-AHP, respectively *(Table 5)*.

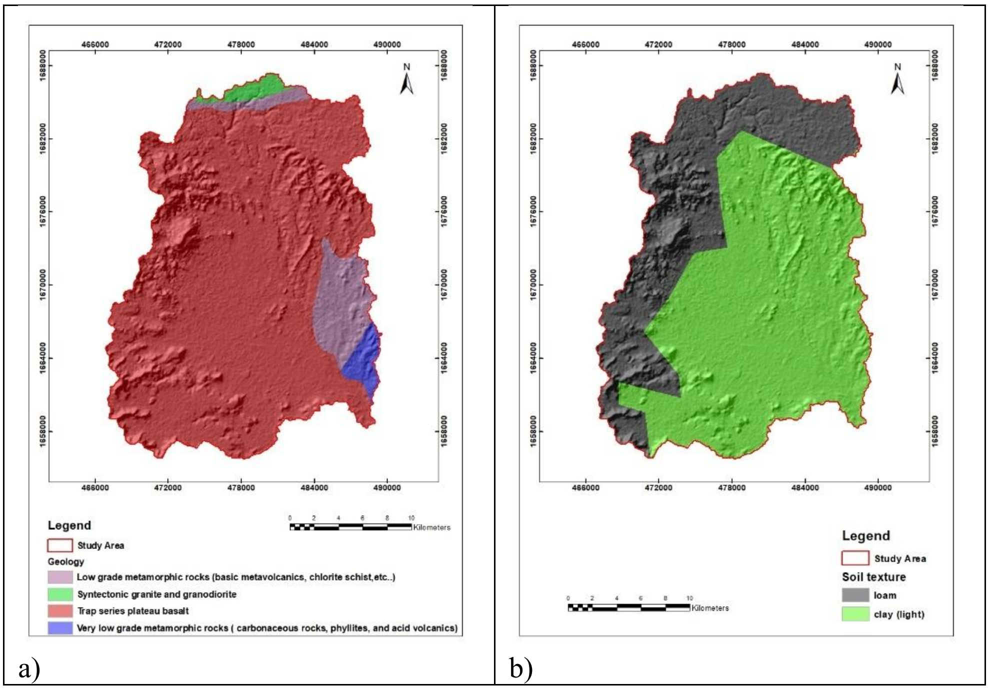

Figure 2

Geology setting (a) and soil map of the study area (b)

LULC is categorized into seven classes based on Sentinal-2 classification scheme: water, trees, rangeland, flooded vegetation, crops, built-in areas, and bare grounds *(Figure 4a)*. LULC collectively contributes 8.1% and 8.38% for AHP and Fuzzy-AHP to the total weight of the parameters influencing groundwater potential. Slope variation is identified as another crucial controlling factor for groundwater recharge *(Figure 4b)*. With slope degrees ranging from 4.15 to 62.2, steep slopes contribute to high runoff, limiting water infiltration into the aquifer (Kaliraj et al., 2014). In this study, the slope weight is determined to be nearly 6% for both approaches.

Similarly, drainage density, derived from the DEM using a flow accumulation threshold of 500 cells as the Critical Source Area (CSA), plays a significant role in the groundwater potential analysis. Higher drainage density is generally associated with reduced groundwater recharge, as it promotes surface runoff and limits the infiltration of water into the subsurface (Oikonomidis et al., 2015). The weight assigned to drainage density is found to be 4.6% and 4.76% for AHP and Fuzzy-AHP, with subclass classifications ranging from 0.645 to 3.22 km per km^2 using the natural breaks classification methods which identifies best arrangement values *(Figure 5a)*. The collective influence of these environmental parameters underscores their cumulative effect on the potential groundwater resources of the study area. The overall result for the good groundwater potential zone using AHP and Fuzzy-AHP is 74.68% and 80.12% respectively. The second significant areal coverage is for a very good zone with 24.88% for AHP and 19.87% for Fuzzy-AHP *(Figure 5b)*. The two extreme zones show below 1% results in both methods. As shown in *Figure 6*, the overall groundwater potential zone map coverage area falls under the good zone and some parts of the western and northern parts show very good potential.

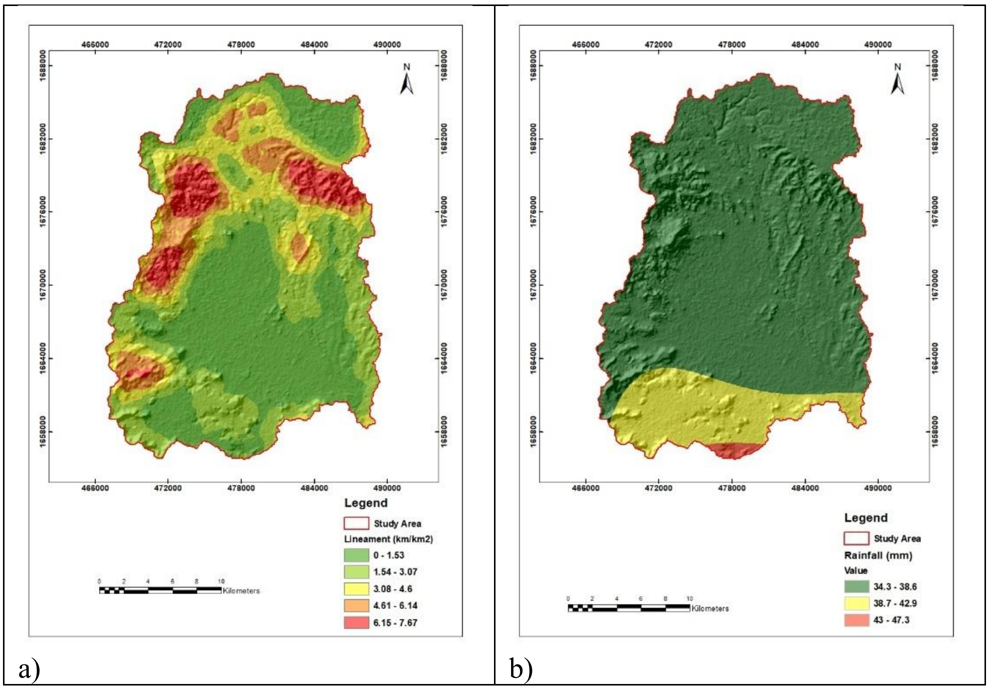

Figure 3
Lineament density map (a) and rainfall map (b)

For future use to allocate resources accurately, it is essential to map the groundwater potential zone (Sarkar et al., 2024). The Debarwa catchment study area encompasses many villages that largely depend on agricultural practices. Identification of groundwater potential zone maps using AHP and Fuzzy-AHP methods will solve the traditional groundwater exploration techniques. The comparative analysis of the AHP and Fuzzy-AHP methods for groundwater potential mapping demonstrates that both approaches yield highly similar results in terms of weight factor distribution and areal coverage classification. Geology emerges as the most influential factor in both methods, with AHP assigning it a weight of 29.3% and Fuzzy-AHP slightly lower at 27.95%. Similarly, soil holds the second-highest weight in both methods, at 21.8% and 21.53% for AHP and Fuzzy-AHP, respectively. The least influential parameter, drainage density, exhibits a negligible difference between the two methods, with values of 4.6% for AHP and 4.76% for Fuzzy-AHP. Both methods rely on pairwise comparisons and expert judgment to determine the relative importance of parameters, where due to this reason could be the weighted factors are closely aligned.

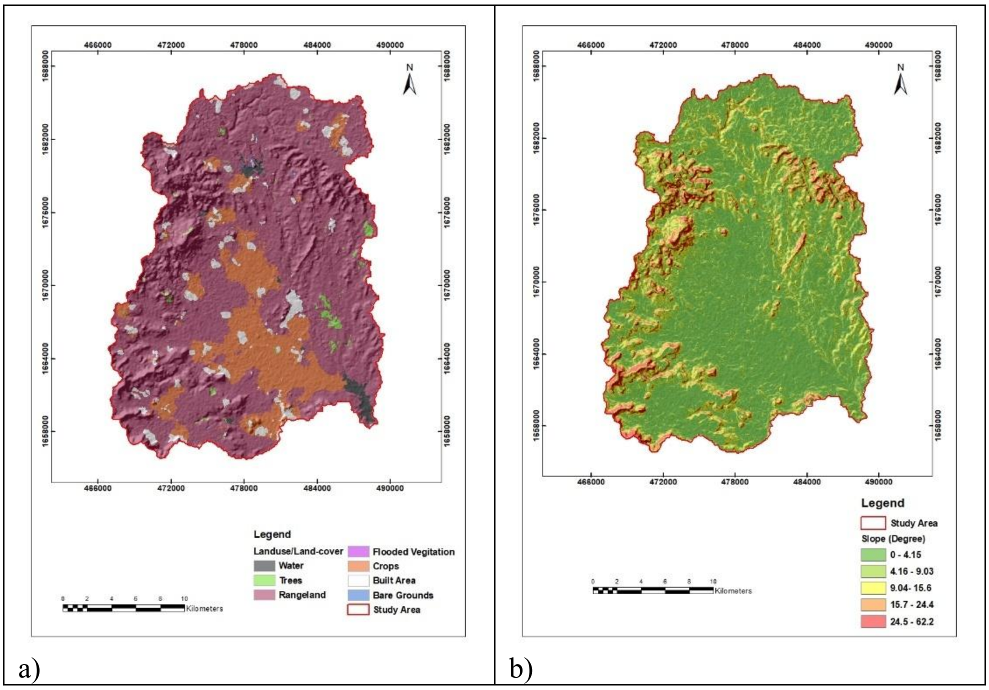

Figure 4

Landuse/Landcover map (a) and slope map (b)

AHP results show that the "good" and "very good" potential zones cover 74.68% and 24.88%, respectively, while Fuzzy-AHP assigns 80.12% to "good" and 19.87% to "very good". Notably, the percentage of areas classified as "poor" and "excellent" is extremely low in both methods, with Fuzzy-AHP producing slightly more refined classifications. The higher percentage of "good" zones in the Fuzzy-AHP approach suggests that this method provides a smoother and more continuous representation of groundwater potential, reducing abrupt transitions between zones. This could be attributed to the ability of fuzzy logic to handle uncertainty and ambiguity more effectively than the crisp decision-making process in AHP. Similar works were observed in different research activities that predict accurate groundwater potential results (Tiwari et al., 2024; Zewdie et al., 2024). For future work, the result of this research can be cross-checked with machine learning and other methods upon having enough ground data as it was tested for the same task accurately in different research areas (Das and Saha, 2022; Lee et al., 2020; R. Liu et al., 2022; Nguyen et al., 2024). Additionally, the concentration of the result around the good potential zone map can open further discussion of research, which can validate its reality with ground truth data for future work. While both methods produce comparable results, Fuzzy-AHP exhibits a slight advantage in refining classification accuracy by incorporating degrees of membership rather than rigid classifications. These findings underscore the importance of the AHP and Fuzzy AHP methods in optimizing groundwater exploration. By utilizing these advanced techniques, decision-makers can significantly shorten the exploration process compared to traditional methods, which are often time-consuming and less efficient. AHP and Fuzzy AHP provide a systematic and data-driven approach, improving accuracy in identifying potential groundwater sources and reducing uncertainties in the exploration phase.

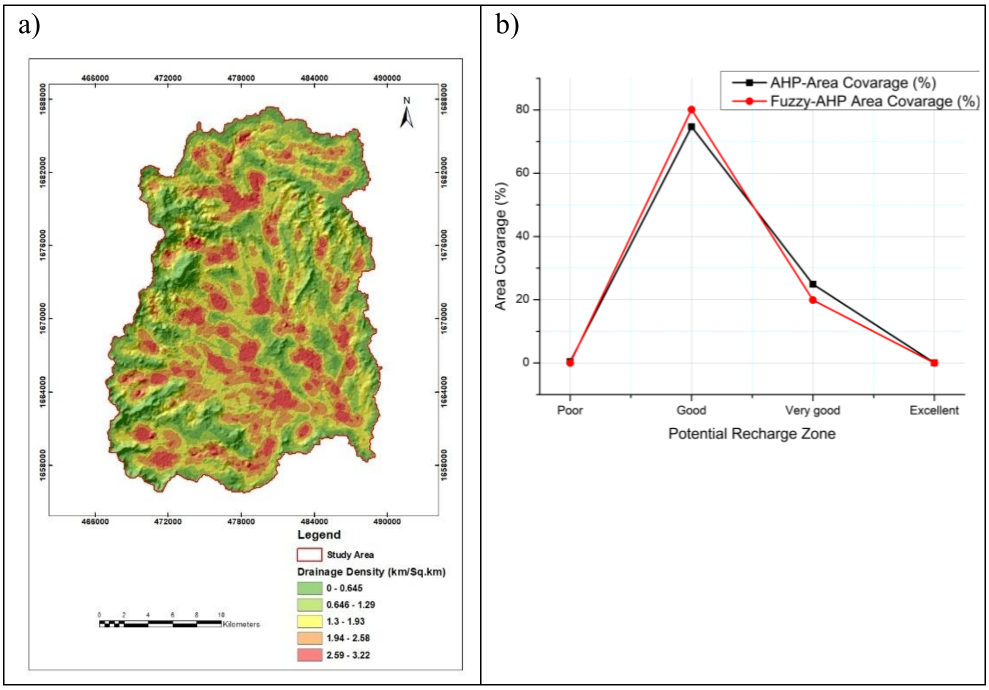

Figure 5

Drainage density map (a) and graphical comparison between AHP and Fuzzy-AHP results (b)

Table 5

The groundwater parameters are ranked in descending order

Factor	Weight (%) AHP	Weight(%) Fuzzy-AHP	Rank
Geology	29.3	27.95	1st
Low grade metamorphic rocks (basic metavolcanics, chlorite schist, etc..)			4
Very low-grade metamorphic rocks (carbonaceous rocks, phyllites, and acid volcanics)			3
Trap series plateau basalt			2
Syntectonic granite and granodiorite			1
Soil	21.8	21.53	2nd
Loam			2
Clay (light)			1
Lineament density (km/km^2)	17.8	18.19	3rd
(6.15–7.67)			5
(4.61–6.14)			4
(3.08–4.6)			3
(1.54–3.07)			2
(0–1.53)			1
Rainfall (mm)	12.4	12.95	4th
(43–47.3)			3
(38.7–42.9)			2
(34.3–38.6)			1
Landuse/landcover	8.1	8.38	5th
Water			7
Trees			6
Rangeland			5
Flooded vegitation			4
Crops			3
Built area			2
Bare grounds			1
Slope (degree)	6.1	6.22	6th
(0–4.15)			5
(4.16–9.03)			4
(9.04–15.6)			3
(15.7–24.4)			2
(24.5–62.2)			1
Drainage density (km/km^2)	4.6	4.76	7th
(0–0.645)			5
(0.646–1.29)			4
(1.3–1.93)			3
(1.94–2.58)			2
(2.59–3.22)			1

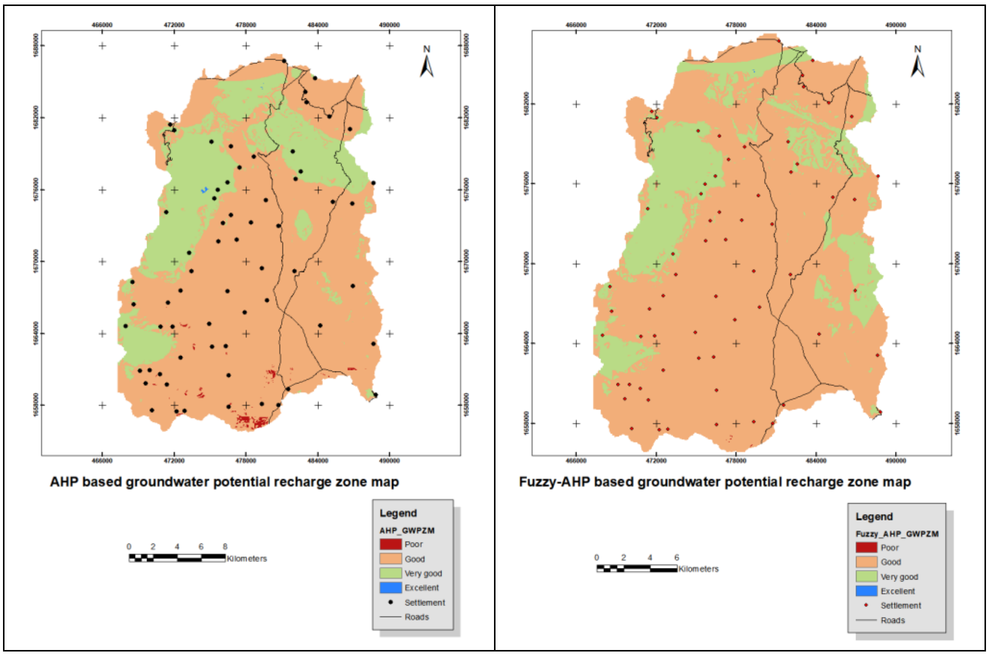

Figure 6

Groundwater classification maps: AHP (a) Fuzzy-AHP (b)

5. CONCLUSIONS

The research addresses a comparative analysis between AHP and Fuzzy-AHP approaches for groundwater potential mapping in the study area. The primary objective was to delineate the groundwater potential zone in the Debarwa catchment area. This delineation will assist in a better groundwater management strategy for the water resource department in Eritrea. The comparative evaluation of AHP and Fuzzy-AHP for groundwater potential mapping indicates that both methods provide nearly identical weight factor distributions and classification outputs, demonstrating their reliability in groundwater assessment. The similarity in results is likely due to the structured nature of AHP, the well-defined relationships among environmental parameters, and the dominant influence of geology and soil. While Fuzzy-AHP provides a more refined transition between classes, the overall impact of fuzzification remains minimal in this study. Despite the close agreement, Fuzzy-AHP slightly enhances classification precision by better handling uncertainties, making it preferable in studies where data ambiguity is a concern. On the other hand, AHP remains a viable and computationally efficient alternative, particularly in cases where a straightforward decision-making process is sufficient. Ultimately, the choice between AHP and Fuzzy-AHP depends on the specific study requirements. The results have some limitations such as a lack of validation, subjective expert input, and potential for bias in parameter weighting. With the availability of enough ground truth data, further research is recommended using other techniques such as frequency ratio and machine learning approaches to fill these gabs. Finally, by providing a comprehensive understanding of groundwater potential zones, this study facilitates informed decision-making and sustainable management practices to optimize groundwater resources within the Debarwa catchment area.

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REFERENCES

Agogue Feujio, D. H., Aretouyap, Z., Tchato, S. C., Ngog II Legrand, C., Djomdi, E., Nague Madadjeu, N., Nguimfack Nguimgo, C., and Ndinchout Kpoumie, A. (2024). Application of analytical hierarchy process to assess groundwater potential for a sustainable management in the Menoua Division. *Heliyon*, 10 (2). https://doi.org/10.1016/j.heliyon.2024.e24310

AL Deep, M., Araffa, S. A. S., Mansour, S. A., Taha, A. I., Mohamed, A., and Othman, A. (2021). Geophysics and remote sensing applications for groundwater exploration in fractured basement: A case study from Abha area, Saudi Arabia. *Journal of African Earth Sciences*, 184. https://doi.org/10.1016/j.jafrearsci.2021.104368

Araffa, S. A. S., Hamed, H. G., Nayef, A., Sabet, H. S., AbuBakr, M. M., and Mebed, M. El. (2023). Assessment of groundwater aquifer using geophysical and remote sensing data on the area of Central Sinai, Egypt. *Scientific Reports*, 13 (1). https://doi.org/10.1038/s41598-023-44737-9

Arefin, R. (2020). Groundwater potential zone identification at Plio-Pleistocene elevated tract, Bangladesh: AHP-GIS and remote sensing approach. *Groundwater for Sustainable Development*, 10. https://doi.org/10.1016/j.gsd.2020.100340

Asghede, K. M., Vágó, J., & Pecsmány, P. (2025). Integrated approach for lineament extraction in assessing groundwater potential: a case study in the highlands of Eritrea. *Acta Geographica Debrecina Landscape & Environment Series*, 19 (1), https://doi.org/10.21120/LE/19/1/1

Bastola, S., Shakya, B., Seong, Y., Kim, B., and Jung, Y. (2024). AHP and FAHP-based multi-criteria analysis for suitable dam location analysis: a case study of the Bagmati Basin, Nepal. *Stochastic Environmental Research and Risk Assessment*. https://doi.org/10.1007/s00477-024-02799-9

Bhadran, A., Girishbai, D., Jesiya, N. P., Gopinath, G., Krishnan, R. G., and Vijesh, V. K. (2022). A GIS based Fuzzy-AHP for delineating groundwater potential zones in tropical river basin, southern part of India. *Geosystems and Geoenvironment*, 1, 93. https://doi.org/10.1016/j.geogeo.2022.10

Burayu, D. G., Karuppannan, S., and Shuniye, G. (2025). Geospatial mapping of groundwater potential zones using multi-criteria decision analysis and GIS fuzzy logic in Dabus Sub-Basin, western Ethiopia. *Quaternary Science Advances*, 18, 100275. https://doi.org/10.1016/j.qsa.2025.100275

Daher, W., Pistre, S., Kneppers, A., Bakalowicz, M., and Najem, W. (2011). Karst and artificial recharge: Theoretical and practical problems. A preliminary approach to artificial recharge assessment. *Journal of Hydrology*, 408(3–4), 189–202. https://doi.org/10.1016/j.jhydrol.2011.07.017

Das, R., and Saha, S. (2022). Spatial mapping of groundwater potentiality applying ensemble of computational intelligence and machine learning approaches. *Groundwater for Sustainable Development*, 18. https://doi.org/10.1016/j.gsd.2022.100778

El-Sayed, H. M., and Elgendy, A. R. (2024). Geospatial and geophysical insights for groundwater potential zones mapping and aquifer evaluation at Wadi Abu Marzouk in El-Nagila, Egypt. *Egyptian Journal of Aquatic Research.* https://doi.org/10.1016/j.ejar.2023.12.008

Gidafie, D., Nedaw, D., and Azagegn, T. (2024). Integrated remote sensing and geographic information system overlay analysis for groundwater potential evaluation using AHP and fuzzy AHP: Southern sections of the western Afar rift margin and associated rift floor. *Groundwater for Sustainable Development*, 26. https://doi.org/10.1016/j.gsd.2024.101310

Githinji, T. W., Dindi, E. W., Kuria, Z. N., and Olago, D. O. (2022). Application of analytical hierarchy process and integrated fuzzy-analytical hierarchy process for mapping potential groundwater recharge zone using GIS in the arid areas of Ewaso Ng'iro – Lagh Dera Basin, Kenya. *HydroResearch*, 5, 22–34. https://doi.org/10.1016/j.hydres.2021.11.001

Hassini, E., Hassini, S., Hamdi, M., and Hamed, Y. (2023). Satellite remote sensing and GIS-based multi-criteria analysis for assessing the groundwater recharge potential zones in the Regueb basin (central Tunisia). Applied Geomatics, 15 (1), 29–43. https://doi.org/10.1007/s12518-022-00478-4

Ifediegwu, S. I. (2022). Assessment of groundwater potential zones using GIS and AHP techniques: a case study of the Lafia district, Nasarawa State, Nigeria. *Applied Water Science*, 12(1). https://doi.org/10.1007/s13201-021-01556-5

Kaliraj, S., Chandrasekar, N., and Magesh, N. S. (2014). Identification of potential groundwater recharge zones in Vaigai upper basin, Tamil Nadu, using GIS-based analytical hierarchical process (AHP) technique. *Arabian Journal of Geosciences, 7(4), 1385–1401*. https://doi.org/10.1007/s12517-013-0849-x

Kassa, A. K., Tessema, N., Habtamu, A., Girma, B., and Adane, Z. (2023). Identifying groundwater recharge potential zone using analytical hierarchy process (AHP) in the semi-arid Shinile watershed, Eastern Ethiopia. *Water Practice and Technology*, 18(11), 2834–2850. https://doi.org/10.2166/wpt.2023.168

Kouaied, A., Msaddek, M. H., Zghibi, A., Barrek, A., Pistre, S., and Chenini, I. (2025). Groundwater recharge zone mapping in a coastal mediterranean aquifer applying fuzzy and analytical hierarchy process and frequency ratio: A case study of northeast Tunisia. *In Journal of African Earth Sciences* (Vol. 224). Elsevier Ltd. https://doi.org/10.1016/j.jafrearsci.2025.105537

Kpiebaya, P., Amuah, E. E. Y., Shaibu, A. G., Baatuuwie, B. N., Avornyo, V. K., and Dekongmen, B. W. (2022). Spatial assessment of groundwater potential using Quantum GIS and multi-criteria decision analysis (QGIS-AHP) in the Sawla-Tuna-Kalba district of Ghana. *Journal of Hydrology: Regional Studies*, 43. https://doi.org/10.1016/j.ejrh.2022.101197

Ksantini, F., Sdiri, A., Aydi, A., Almeida-Ñauñay, A. F., Achour, H., and Tarquis, A. M. (2024). A comparative study based on AHP and fuzzy logic approaches for landslide susceptibility zoning using a GIS-based multi-criteria decision analysis. *Euro-Mediterranean Journal for Environmental Integration.* https://doi.org/10.1007/s41207-024-00552-w

Lee, S., Hyun, Y., Lee, S., and Lee, M. J. (2020). Groundwater potential mapping using remote sensing and GIS-based machine learning techniques. *Remote Sensing*, 12 (7). https://doi.org/10.3390/rs12071200

Liu, R., Li, G., Wei, L., Xu, Y., Gou, X., Luo, S., and Yang, X. (2022). Spatial prediction of groundwater potentiality using machine learning methods with Grey Wolf and Sparrow Search Algorithms. *Journal of Hydrology*, 610. https://doi.org/10.1016/j.jhydrol.2022.127977

Liu, Y., Eckert, C. M., and Earl, C. (2020). A review of fuzzy AHP methods for decision-making with subjective judgements. *In Expert Systems with Applications*, Vol. 161. https://doi.org/10.1016/j.eswa.2020.113738

Moeck, C., Grech-Cumbo, N., Podgorski, J., Bretzler, A., Gurdak, J. J., Berg, M., and Schirmer, M. (2020). A global-scale dataset of direct natural groundwater recharge rates: A review of variables, processes and relationships. *Science of the Total Environment*, 717. https://doi.org/10.1016/j.scitotenv.2020.137042

Mohammed, M. A. A., Mohammed, S. H., Szabó, N. P., and Szűcs, P. (2024). Geospatial modeling for groundwater potential zoning using a multi-parameter analytical hierarchy process supported by geophysical data. *Discover Applied Sciences*, 6(3). https://doi.org/10.1007/s42452-024-05769-6

Moon, S. H., Park, C., Kim, H. C., Kim, Y., Kee, W. S., Lee, C. M., and Kim, S. (2024). Groundwater productivity analysis with geology in the Geumgang River region, Korea. *Geosciences Journal.* https://doi.org/10.1007/s12303-024-0047-8

Nguyen, H. D., Nguyen, Q. H., Dang, D. K., Nguyen, T. G., Truong, Q. H., Nguyen, V. H., Bretcan, P., Șerban, G., Bui, Q. T., and Petrisor, A. I. (2024). Integrated machine learning and remote sensing for groundwater potential mapping in the Mekong Delta in Vietnam. *Acta Geophysica.* https://doi.org/10.1007/s11600-024-01331-5

Oikonomidis, D., Dimogianni, S., Kazakis, N., and Voudouris, K. (2015). A GIS/ Remote Sensing-based methodology for groundwater potentiality assessment in Tirnavos area, Greece. *Journal of Hydrology*, 525, 197–208. https://doi.org/10.1016/j.jhydrol.2015.03.056

Ozegin, K. O., Ilugbo, S. O., and Akande, O. N. (2024). Leveraging geospatial technology and AHP for groundwater potential zonation in parts of South and North-Central Nigeria. *Sustainable Water Resources Management*, 10(4). https://doi.org/10.1007/s40899-024-01124-0

Popalzai, A., Ahmadi, H., Rahmani, A. B., and Pekkan, E. (2023). Delineation of Groundwater Potential Zones Using Multi-Criteria Decision Analysis: *The Case of Balkh Province, Northern Afghanistan*, 41. https://doi.org/10.3390/iecg2022-14817

Pourghasemi, H. R., Sadhasivam, N., Yousefi, S., Tavangar, S., Ghaffari Nazarlou, H., and Santosh, M. (2020). Using machine learning algorithms to map the groundwater recharge potential zones. *Journal of Environmental Management*, 265. https://doi.org/10.1016/j.jenvman.2020.110525

Prapanchan, V. N., Subramani, T., and Karunanidhi, D. (2024). GIS and fuzzy analytical hierarchy process to delineate groundwater potential zones in southern parts of India. *Groundwater for Sustainable Development*, 25. https://doi.org/10.1016/j.gsd.2024.101110

Prasad, P., Loveson, V. J., Kotha, M., and Yadav, R. (2020). Application of machine learning techniques in groundwater potential mapping along the west coast of India. *GIScience and Remote Sensing*, 735–752. https://doi.org/10.1080/15481603.2020.1794104

Raja Shekar, P., and Mathew, A. (2023). Assessing groundwater potential zones and artificial recharge sites in the monsoon-fed Murredu river basin, India: An integrated approach using GIS, AHP, and Fuzzy-AHP. *Groundwater for Sustainable Development*, 23. https://doi.org/10.1016/j.gsd.2023.100994

Saaty, T. L., and Katz, J. M. (1990). How to make a decision: The Analytic Hierarchy Process. *European Journal of Operational Research*, Vol. 48.

Sajil Kumar, P. J., Elango, L., and Schneider, M. (2022). GIS and AHP Based Groundwater Potential Zones Delineation in Chennai River Basin (CRB), India. *Sustainability (Switzerland)*, 14(3). https://doi.org/10.3390/su14031830

Sarkar, S. K., Alshehri, F., Shahfahad, Rahman, A., Pradhan, B., and Shahab, M. (2024). Mapping groundwater potentiality by using hybrid machine learning models under the scenario of climate variability: a national level study of Bangladesh. *Environment, Development and Sustainability.* https://doi.org/10.1007/s10668-024-04687-2

Sharma, A., and Singh, K. (2025). Determining prospective zones for groundwater recharge using remote sensing, GIS, and AHP modelling techniques: an investigation of the Mandi district in Himachal Pradesh, India. *Environmental Earth Sciences*, 84(5). https://doi.org/10.1007/s12665-025-12137-z

Sharma, B., and Pandey, A. A. (2023). Application of geospatial techniques and analytic hierarchy process in delineating ground water potential zones: a case study from the Southeastern part of Bihar, India. *International Journal of Energy and Water Resources.* https://doi.org/10.1007/s42108-023-00260-1

Shelar, R. S., Nandgude, S. B., Pande, C. B., Costache, R., El-Hiti, G. A., Tolche, A. D., Son, C. T., and Yadav, K. K. (2023). Unlocking the hidden potential: groundwater zone mapping using AHP, remote sensing and GIS techniques. *Geomatics, Natural Hazards and Risk*, 14(1). https://doi.org/10.1080/19475705.2023.2264458

Solomon, S., and Quiel, F. (2006). Groundwater study using remote sensing and geographic information systems (GIS) in the central highlands of Eritrea. *Hydrogeology Journal*, 14 (5), pp. 729–741. https://doi.org/10.1007/s10040-005-0477-y

Swarnim, Tripathi, J. N., Sonker, I., and Tiwari, S. P. (2023). Groundwater potential mapping in Trans Yamuna Region, Prayagraj, using combination of geospatial technologies and AHP method. *Environmental Monitoring and Assessment*, 195 (11). https://doi.org/10.1007/s10661-023-11934-y

Tegegne, A. M., Lohani, T. K., and Eshete, A. A. (2024). Groundwater potential delineation using geodetector based convolutional neural network in the Gunabay watershed of Ethiopia. *Environmental Research*, 242. https://doi.org/10.1016/j.envres.2023.117790

Teklay, M. (2006). Neoproterozoic arc-back-arc system analog to modern arc-back-arc systems: Evidence from tholeiite-boninite association, serpentinite mudflows and across-arc geochemical trends in Eritrea, southern Arabian-Nubian shield. *Precambrian Research*, 145 (1–2), pp. 81–92. https://doi.org/10.1016/j.precamres.2005.11.015

Thanh, N. N., Chotpantarat, S., Trung, N. H., Ngu, N. H., and Muoi, L. Van. (2022). Mapping groundwater potential zones in Kanchanaburi Province, Thailand by integrating of analytic hierarchy process, frequency ratio, and random forest. *Ecological Indicators*, 145. https://doi.org/10.1016/j.ecolind.2022.109591

Tiwari, R. N., Kushwaha, V. K., and Sharma, B. (2024). Delineation of suitable sites for water conservation structures and groundwater potential zones using integration of remote sensing and GIS: a case study of Central India. *Arabian Journal of Geosciences*, 17 (5). https://doi.org/10.1007/s12517-024-11949-w

Upwanshi, M., Damry, K., Pathak, D., Tikle, S., and Das, S. (2023). Delineation of potential groundwater recharge zones using remote sensing, GIS, and AHP approaches. *Urban Climate*, 48. https://doi.org/10.1016/j.uclim.2023.101415

Verma, N., and Patel, R. K. (2021). Delineation of groundwater potential zones in lower Rihand River Basin, India using geospatial techniques and AHP. *Egyptian Journal of Remote Sensing and Space Science*, 24 (3), pp. 559–570. https://doi.org/10.1016/j.ejrs.2021.03.005

Yousif, M., Sabet, H. S., Ghoubachi, S. Y., and Aziz, A. (2018). Utilizing the geological data and remote sensing applications for investigation of groundwater occurrences, West El Minia, Western Desert of Egypt. *NRIAG Journal of Astronomy and Geophysics*, 7 (2), pp. 318–333. https://doi.org/10.1016/j.nrjag.2018.07.002

Zenande, N., Adesola, G. O., Madi, K., and Gwavava, O. (2024). Groundwater potential assessment in the Eastern Cape, South Africa, using analytical hierarchical process (AHP) technique. *Sustainable Water Resources Management*, 10 (6). https://doi.org/10.1007/s40899-024-01166-4

Zewdie, M. M., Kasie, L. A., and Bogale, S. (2024). Groundwater potential zones delineation using GIS and AHP techniques in upper parts of Chemoga watershed, Ethiopia. *Applied Water Science*, 14 (4). https://doi.org/10.1007/s13201-024-02119-0