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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). It is located 25 km south of Asmara, the capital city of Eritrea at a geographic coordinate of 38°50'E and 15°10'N. The study area has a total of 506 km² 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 lowgrade 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.

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Figure 1 Location map of the study area in Eritrea

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 (Eq. (2))

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

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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

			Saat	ty's ratio ind	lex for differ	ent n values
Ν	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 decisionmaking (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 3AHP 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

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Class Soil es		LD			Rainfall		LI	LULC		Slope		DD		Geology			Weight %					
Geol ogy	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
Rain fall	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
LUL C	0 2 5	0 3	0 5	0 2 5	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 2 5	0 3	0 5	0 2 5	0 3	0 5	0. 2 5	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 2 5	0 3	0 2	0 2 5	0.3	0. 2 5	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

Fuzzy- AHP Pairwise comparison matrix

Table 4

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 km² 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 km² using the natural breaks classification methods which identifies best arrangement values (Figure 5a). The collective influence of these environmental parameters underscores

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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.



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.



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.



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

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Factor	Weight (%) AHP	Weight(%) Fuzzy-AHP	Rank
Geology		1. 400 / 1111	1 st
Low grade metamorphic rocks (basic metavolcanics,	1		4
chlorite schist, etc) Very low-grade metamorphic rocks (carbonaceous rocks	-		
phyllites, and acid volcanics)	29.3	27.95	3
Trap series plateau basalt			2
Syntectonic granite and granodiorite			1
Soil			2^{nd}
Loam	21.8	21.53	2
Clay (light)	2110	1100	1
Lineament density (km/km ²)			3 rd
(6.15 - 7.67)			5
(4.61 - 6.14)			4
(3.08 - 4.6)	17.8	18.19	3
(1.54 - 3.07)			2
(0 - 1.53)			1
Rainfall (mm)			4 th
(43 - 47.3)			3
(38.7 - 42.9)	12.4	12.95	2
(34.3 - 38.6)			1
Landuse/landcover			5 th
Water			7
Trees			6
Rangeland			5
Flooded vegitation	8.1	8.38	4
Crops			3
Built area			2
Bare grounds			1
Slope (degree)			6 th
(0 - 4.15)			5
(4.16 - 9.03)			4
(9.04 - 15.6)	6.1	6.22	3
(15.7 - 24.4)			2
(24.5 - 62.2)			1
Drainage density (km/km ²)			7 th
(0 - 0.645)			5
(0.646 - 1.29)			4
(1.3 - 1.93)	4.6	4.76	3
(1.94 - 2.58)			2
(2.59 - 3.22)			1

 Table 5

 The groundwater parameters are ranked in descending order





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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