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GEOSPATIAL ANALYSIS AND ANALYTICAL HIERARCHY PROCESS FOR DELINEATING GROUNDWATER POTENTIAL ZONES: A CASE STUDY IN DEBARWA CATCHMENT, ERITREA

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Abstract
Groundwater is a crucial water resource worldwide, particularly in arid and semi-arid regions such as Eritrea. This study employs an approach that integrates geospatial techniques with the Analytical Hierarchy Process (AHP) to identify groundwater potential zones within the Debarwa catchment area in southern Eritrea. Seven key parameters significantly influencing groundwater recharge were selected for analysis: geology, soil, lineament density, rainfall, land use/land cover, drainage density, and slope. Using Geographic Information System (GIS) tools, thematic layers for each parameter were created and subsequently weighted through pairwise comparisons based on the 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 these categories revealed that 0.01% of the area fell into the 'poor' potential zone, 80.9% into the 'good' potential zone, 19.1% into the 'very good' potential zone, and 0.002% into the 'excellent' potential zone. These results indicate that most of the Debarwa catchment area has good to very good potential for groundwater resources. This delineation provides a valuable tool for decision-makers to prioritize regions for detailed groundwater exploration and management. The study's innovative combination of GIS and AHP methodologies offers a systematic and objective framework for groundwater potential assessment. However, further validation studies are recommended to evaluate the accuracy and robustness of the proposed groundwater potential zones. Such validation would enhance the reliability of the findings and support sustainable groundwater resource management in the region. This integrative approach can be adapted and applied globally to similar arid and semi-arid areas to optimize groundwater exploration and utilization strategies.

Keywords: *Groundwater potential, Analytical Hierarchy Process (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 & 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.

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 & Elgendy, 2024; Yousif et al., 2018), 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), and AHP for rapid and accurate assessments (Sajil Kumar et al., 2022; Shelar et al., 2023; Swarnim et al., 2023; Upwanshi et al., 2023). 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 a geospatial and AHP approach. Integrating these methodologies with hydrological, topographical, and geological parameters has yielded promising results in various regions. For instance, in southeastern Bihar, India, AHP combined with weighted overlay resulted in 51.62% good and 47.08% fair zones (Sharma & Pandey, 2023). Similarly, in Tunisia's Regueb region, the AHP approach, alongside literature-derived weights, produced comparable results (Hassini et al., 2023). Furthermore, groundwater potential assessments in South Africa's Buffalo City Metropolitan Municipality (Adesola et al., 2023) and Hungary's Debrecen area (Mohammed et al., 2024) also underscored the effectiveness of AHP.

The urgency of this research stems from the critical need for proper groundwater management in Debarwa's arid and semi-arid setting. Overexploitation, variable rainfall patterns, and geological factors have led to rapid groundwater depletion, impacting the socio-economic livelihoods of communities reliant on groundwater for agriculture. The study area has a knowledge gap for the scientific assessment of groundwater potential. Seven environmental parameters, Geology, soil, lineament density, land use/land cover, rainfall, drainage density, and slope, have been selected for investigation. While this methodology is not entirely novel, its application in the study area represents a pioneering effort since it is tested for the first time. 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. Materials and methods

2.1. Description of the study area

The study area encompasses Debarwa, situated within the administrative sub-zone of the Debub region in Eritrea *(Figure 1)*. It is located 25 km south of Asmara, the capital city of Eritrea, with a coverage area of 506 km^2 and an elevation of 1,926 m above mean sea level. Debarwa experiences distinct climatic conditions, with July marking the wettest month and December the driest. 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. 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 the tension or shear fractures. 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 with the exception of some privately owned agricultural well. So, field measurement of water level in the well field site was difficult.

As a historic market town in central Eritrea, Debarwa boasts a population of approximately 84,150 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.

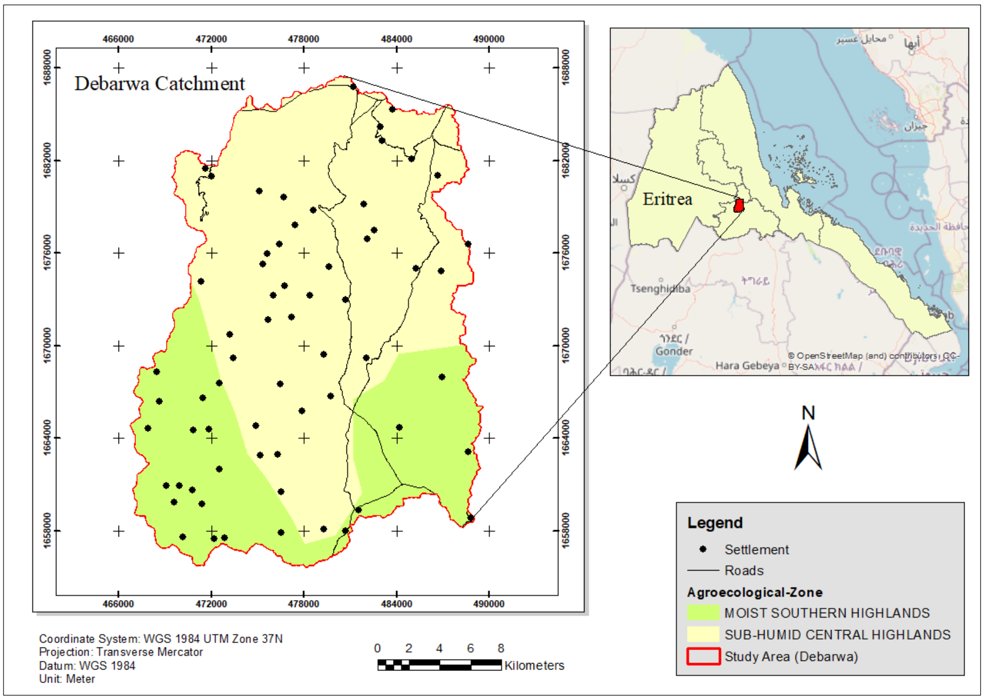

***Figure 1.** Study area location*

2.2. Methodology

The methodology for identifying groundwater potential zones involves some significant steps. These include the selection of parameters influencing groundwater recharge processing and layer analysis in the GIS environment. Then, a pairwise comparison between selected parameters was performed using the AHP method. Finally, the weighted overlay method produces the groundwater potential zone. Based on the available data, the critical influential groundwater controlling parameters selected in this study are geology, soil, lineament density, drainage density, slope, rainfall, and land use/land cover.

The data collection process for the study area involved different sources. Geological data were obtained from the Ministry of Mining and Energy in Asmara, Eritrea, at a spatial resolution of 30 m. The soil was acquired from the Asmara Agricultural Department, whereas rainfall was collected by the Asmara International Airport metrological station from 1992 to 2022. For spatial data, drainage density, lineament density, and slope were derived from Digital Elevation Models (DEM) with a resolution of 30 meters SRTM, accessed from the United States Geological Survey (USGS) website (https://earthexplorer.usgs.gov/). This dataset provides detailed terrain information necessary for groundwater potential analysis. Land Use and Land Cover (LULC) data were downloaded from Sentinel-2 satellite imagery with a resolution of 10 meters. Utilizing satellite data ensures comprehensive coverage and up-to-date information on land use dynamics within the study area. By integrating data from these diverse sources, the study ensures reasonable information for groundwater potential assessment, facilitating good analysis for decision-making processes.

This research determines the weights of the selected parameters influencing groundwater recharge through the AHP, a widely adopted method across various disciplines worldwide (Kassa et al., 2023). The AHP facilitates calculating each criterion's weight or rank based on priority by pairwise comparisons of the datasets (Saaty & 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 controlling parameters were compared through expert judgment and literature review. The consistency test was conducted to ensure the judgment matrix, as recommended by previous studies (Sharma & Pandey, 2023). Following Saaty's principle, the consistency ratio was calculated using the ratio of consistency index and random index *(Equation 2)*. The values depend on the number of selected parameters *(Table 2)*. In this study, seven factors were chosen as groundwater controlling 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

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

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

Subclass ranking was assigned based on percolation rates to contribute water to underground storage, drawing insights from various literature reviews and expert judgments (Kassa et al., 2023; Popalzai et al., 2023; Shelar et al., 2023). The final weight was determined by multiplying each subclass's rank with the feature's weight *(Table 4)* (Thanh et al., 2022). The weighted overlay tool from the spatial analysis toolbox of ArcGIS 10.7 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.

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

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

Where:
CI: Consistency index, CR: Consistency ratio, RI: Random index, λ: maximum principal eigenvalue, and n: number of compared elements or parameters.

3. Results

Based on the AHP pairwise comparison matrix results *(Table 3)*, the weights of the parameters are determined in the following descending order: geology, soil, lineament density, rainfall, land use/land cover (LULC), slope, and drainage density *(Table 4)*. The first four parameters contribute more than ten percent of the total weight. Subsequently, the selected parameters were processed using the ArcGIS software and reclassified based on classes within the catchment area. Parameters derived from DEM, such as drainage density, lineament density, and slope, were classified into five distinct classes. Geology, rainfall, and soil classifications were based on the specific characteristics of the study area. The land-use and land cover data were classified according to the Sentinel-2 classification system, which has a resolution of 10 m. 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.

Table 3

Pairwise comparison matrix

Parameter	Slope	Drainage Density	Lineament Density	LU/ LC	Soil	Rainfall	Geology	Normalized principal Eigenvector	Weight
Slope	1	2.0	0.33	0.50	0.33	0.33	0.25	6.1%	0.06
Drainage density	0.50	1	0.25	0.50	0.25	0.33	0.25	4.6%	0.05
Lineament density	3.0	4.0	1	3.0	0.50	2.0	0.50	17.8%	0.18
LULC	2.0	2.0	0.33	1	0.33	0.50	0.33	8.1%	0.08

Parameter	Slope	Drainage Density	Lineament Density	LU/ LC	Soil	Rainfall	Geology	Normalized principal Eigenvector	Weight
Soil	3.0	4.0	2.0	3.0	1	2.0	0.50	21.8%	0.22
Rainfall	3.0	3.0	0.50	2.00	0.50	1	0.33	12.4%	0.12
Geology	4.0	4.0	2.0	3.0	2	3.0	1	29.3%	0.29

According to the classification scheme, the highest weight is assigned to geology, comprising 29.3% of the total weight (*Tables 3* and *4*). The direct correlation between geology and the intensity of permeability within the study area justifies this significant weighting. The geological classification encompasses four subclasses: low-grade metamorphic rocks, very low-grade metamorphic rocks, trap series plateau basalt, and granite-type rocks. These geological features play a crucial role in groundwater recharge dynamics. Following geology, soil is ranked as the second-highest contributing factor, with a weight of 22%. The classification includes loam and light clay soils, indicating favourable conditions for water infiltration and seepage to the saturated zone with minimal hindrance.

Table 4

The groundwater parameters ranked in descending order

FACTOR	**WEIGHT (%)**	**RANK**
GEOLOGY		1st
LOW GRADE METAMORPHIC ROCKS (BASIC METAVOLCANICS, CHLORITE SCHIST, ETC.)	29.3	4
VERY LOW-GRADE METAMORPHIC ROCKS (CARBONACEOUS ROCKS, PHYLLITES, AND ACID VOLCANICS)		3
TRAP SERIES PLATEAU BASALT		2
SYNTECTONIC GRANITE AND GRANODIORITE		1
SOIL		2nd
LOAM	21.8	2
CLAY (LIGHT)		1
LINEAMENT DENSITY (KM/KM2)		3rd
(6.15–7.67)	17.8	5
(4.61–6.14)		4
(3.08–4.6)		3
(1.54–3.07)		2
(0–1.53)		1
RAINFALL (MM)		4th
(43–47.3)	12.4	3
(38.7–42.9)		2
(34.3–38.6)		1
LANDUSE/LANDCOVER		5th
WATER	8.1	7
TREES		6

FACTOR	**WEIGHT (%)**	**RANK**
RANGELAND		5
FLOODED VEGITATION		4
CROPS		3
BUILT AREA		2
BARE GROUNDS		1
SLOPE (DEGREE)		6th
(0-4.15)	6.1	5
(4.16–9.03)		4
(9.04–15.6)		3
(15.7–24.4)		2
(24.5–62.2)		1
DRAINAGE DENSITY (KM/KM2)		7th
(0–0.645)	4.6	5
(0.646–1.29)		4
(1.3–1.93)		3
(1.94–2.58)		2
(2.59–3.22)		1

Lineament density is identified as another significant factor, with a weight of 18%. The cracks and fissures in the rocks facilitate water percolation, further aiding in aquifer recharge. These structural features are classified into five categories ranging from 1.53 to 7.67 km per km^2, 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, based on readings from national meteorological stations. Consequently, rainfall variability is categorized as the fourth contributing factor, representing 12% of the total weight in this study. This comprehensive classification of parameters underscores their respective contributions to groundwater recharge processes within the Debarwa catchment area, providing a solid foundation for the subsequent delineation of groundwater potential zones.

LULC is categorized into seven classes: water, trees, rangeland, flooded vegetation, crops, built-in areas, and bare grounds, based on the Sentinel-2 classification scheme. Despite rangeland having extensive coverage, water bodies emerge as the highest contributing factor in terms of groundwater recharge. LULC collectively contributes 8% to the total weight of the parameters influencing groundwater potential. Slope variation is identified as another crucial controlling factor for groundwater recharge. With slope degrees ranging from 4.15 to 62.2, steep slopes contribute to high runoff, limiting water infiltration into the aquifer. In this study, the slope weight is determined to be 6%.

Similarly, drainage density plays a significant role, with higher drainage density indicating lower contributions to groundwater recharge. High drainage density leads to increased surface runoff, diminishing the amount of water available for percolation into the ground. The weight assigned to drainage density is found to be 5%, with subclass classifications ranging from 0.645 to 3.22 km per km^2. The collective influence of these environmental parameters underscores their cumulative effect on the potential groundwater resources of the study area. A comprehensive understanding of groundwater dynamics is achieved by considering the interplay of geology, soil, lineament density, rainfall, LULC, slope, and drainage density. This facilitates informed decision-making for sustainable water resource management.

4. Discussion

For future use to allocate resources accurately, it is essential to map the groundwater potential zone (Sarkar et al., 2024). Our findings for mapping groundwater potential reveal a significant variation in the areal coverage across the study area, Debarwa. The map is generated using a weighted overlay analysis of all the contributing parameters. The analysis process produces four layers of potential maps with a range of poor, good, very good, and excellent zones. Such classification was observed in some research throughout the world (Tiwari et al., 2024; Zewdie et al., 2024), which predicts accurate groundwater potential results. In this research, the percentage of area coverage for the zones ranging from poor to excellent are 0.01, 80.9, 19.1, and 0.002 (*Table 5* and *Figure 2*). The work analysis shows that most of the area falls under good zones ranging almost entirely from the study area apart from the range of North-east to North-west and some parts of South-east and South-west.

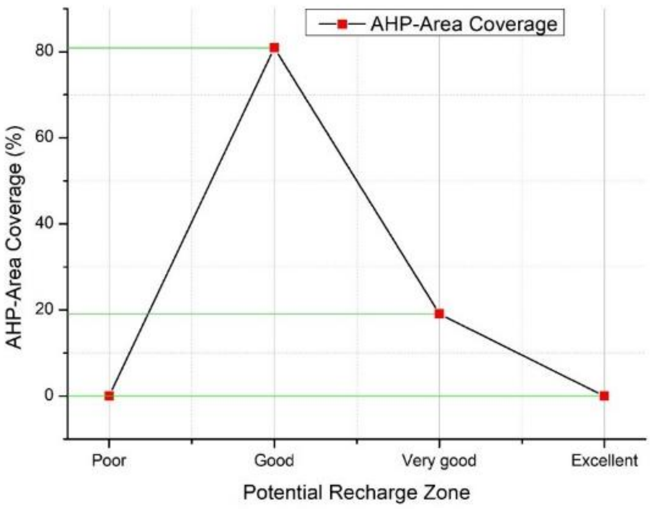

Figure 2. *Groundwater classification graph*

On the contrary, insignificant results were seen in the two extremes (Poor and Excellent), where relative significance was recorded with a very good coverage zone *(Figure 3)*. The result could be cross-checked using the machine learning method as it is tested for the same task accurately in different research areas (Das & Saha, 2022; Lee et al., 2020; Liu et al., 2022; Nguyen et al., 2024; Pourghasemi et al., 2020; Prasad et al., 2020). 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 in the future. Generally, this study's findings may help decision-makers formulate relevant guidelines for water resources sustainably and minimize the overuse of groundwater resources. They can create sustainable water management initiatives and increase resistance to the problems posed by climate change by utilizing accurate groundwater information.

Table 5
Groundwater potential classification result

Value	Cell count	Area (km^2)	% Percentage	Classes
1	31	0.03	0.01	Poor
2	455591	410.03	80.9	Good
3	107670	96.9	19.1	Very good
4	13	0.01	0.002	Excellent

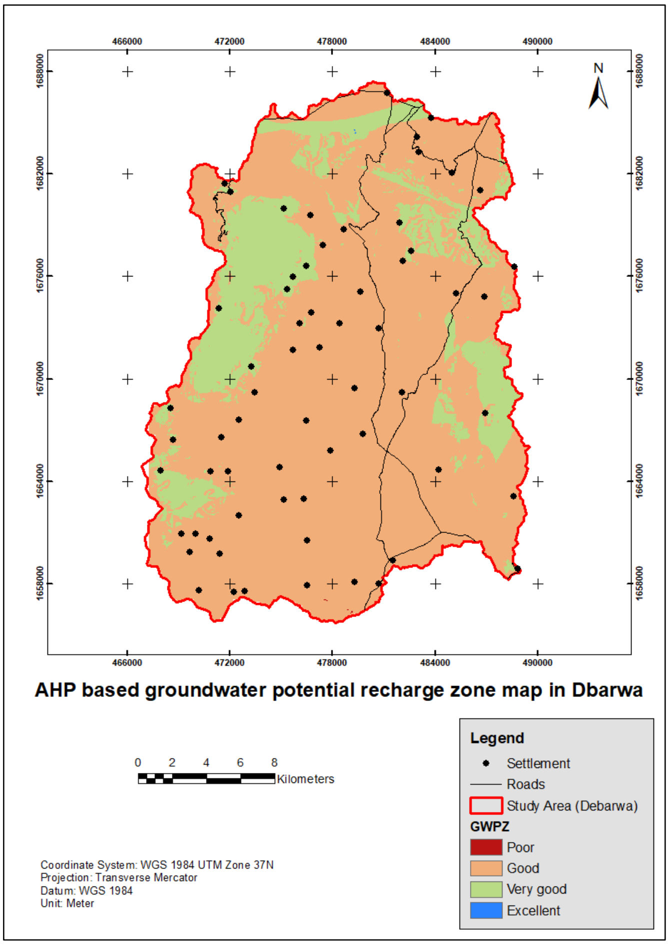

Figure 3. *Groundwater potential map*

5. Summary

The primary objective of this study is to delineate groundwater potential zones within the Debarwa catchment area by employing the Analytical Hierarchy Process (AHP) in conjunction with Geographic Information System (GIS) techniques. Seven key environmental controlling parameters were selected based on available data sources. Geology emerged as the highest priority factor, with a weight factor of 29%, followed closely by soil, with a weight factor of 22%, indicating their significant influence on groundwater recharge dynamics. Lineament density, rainfall, land use/land cover (LULC), slope, and drainage density were also considered, with weight factors of 18%, 12%, 8%, 6%, and 5%, respectively, reflecting their respective contributions to the groundwater potential assessment. The groundwater potential map derived from this analysis revealed four distinct classification zones: poor, good, very good, and excellent, covering percentages of 0.01%, 80.9%, 19.1%, and 0.002%, respectively. These delineations provide valuable insights into the spatial distribution of groundwater resources within the study area, guiding resource allocation and management efforts. Moving forward, this study will be pursued through the integration of alternative techniques, such as AHP-Fuzzy, Frequency Ratio, and Machine Learning approaches. By combining these methodologies, the robustness of the findings can be verified and enhanced, ensuring the reliability of groundwater potential assessments. Ultimately, this research endeavors to support the efforts of the water resource department by streamlining the exploration process for groundwater sources. 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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