Research Article

Groundwater Potential Zone Assessment Using Remote Sensing, Geographical Information System (GIS), and Analytical Hierarchy Process (AHP) Techniques in Fogera Woreda, South Gondar Zone, Ethiopia

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The study was conducted to identify the groundwater potential zones in Fogera Woreda, South Gondar Zone, Ethiopia. Through the utilization of the analytical hierarchy process (AHP), remote sensing, and geographic information system (GIS), the study identified groundwater potential zones. Ten thematic layers were analyzed to delineate the groundwater potential zones, including land use and land cover (LULC), topographic wetness index (TWI), drainage density, lineament density, geology, slope, rainfall, elevation, and soil texture. By determining the relative importance of each thematic layer through AHP and combining all thematic layers through overlay analysis in a GIS environment, the study revealed a spatial variation in the distribution of groundwater potential zones. The results showed that excellent groundwater potential covers 2.02% of the study area, moderate groundwater potential covers 45.54%, poor groundwater potential covers 51.2%, and extremely poor groundwater potential covers 1.24% of the study area. The study provides valuable information that can be used for decision-making processes and the development of appropriate groundwater management strategies in the region.

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1. Introduction

Water that fills the void spaces in a geological stratum is known as groundwater, and the water-bearing material serves as both a reservoir and a conduit for the permeability of water within it[1]. Groundwater resources are an essential natural resource for use in home, agricultural, and industrial environments[2]. Many factors, including lithology, geological structures, soil, lineament characteristics, slope, drainage pattern, land use/cover, and the interactions between these elements, influence the presence and transport of groundwater in any vicinity[1][3]. Ground surveys are the mainstay of the conventional methods used to prepare groundwater potential zones, but the development of Geographic Information Systems (GIS) and remote sensing technologies has made it easier to map the groundwater potential zones within each lithological stratum of the area[4]. Remote sensing data can be used to evaluate or analyze these factors in GIS[1]. Using geospatial techniques makes it possible to evaluate vast amounts of geospatial data and accurately map various natural resources. Numerous researchers worldwide use remote sensing (RS) and geographical information systems (GIS) to investigate potential zones for groundwater[5][6]. The properties of aquifers, and consequently the groundwater supplies in any region, are primarily influenced by a variety of earthly features, including geology, soil texture, land use and cover, drainage density, lineament density, and distance from rivers/streams[7]. Groundwater studies have shown GIS to be a valuable tool as it offers an excellent foundation for effectively managing massive and complicated spatial data for natural resource management[5]. The study aims to map the groundwater potential of Fogera woreda, South Gondar zone, Ethiopia, using geospatial and Analytical Hierarchy Process methods. With an increasing population, the water demand is rising, making it crucial to evaluate the groundwater potential of the region. By forecasting the groundwater potential areas, we can ensure the efficient utilization of the area's water resources for sustainable development. The study's findings will provide valuable insights into the area's natural resources and guide policymakers in making informed decisions. The aim of this study is to delineate groundwater potential zones using remote sensing, geographical information system (GIS), and Analytical Hierarchy Process in Fogera Woreda, South Gondar zone, Ethiopia.

2. Materials and Methods

2.1. Study area description

The study area is one of the woredas in the Amhara Regional State and is found in the South Gondar Zone. It is situated at 37° 30′ 00″ and 37° 60″ 00″ latitude and 11°40′ and 30″ and 12° 1′ 30″ longitude (Fig 1). Woreta is the capital of the Woreda and is found 625 Km from Addis Ababa and 55 Km from the regional capital, Bahir Dar. Woreta, Alem Ber, and Wanzaye are three major towns in the Woreda. The Woreda has an asphalt road that crosses the town, as well as a gravel road, and it is accessed by vehicle and foot. The area has bimodal rainfall, which receives moderate rainfall from February to April and high rainfall from June to August. As a result, they cultivate rice, beans, and wheat during the Belgian season. The intensity of rainfall is very high in the summer season. Thus, higher precipitation in the study area indicates higher rechargeability of the area. So, the study aims to identify the potential zones of this recharge by combining and analyzing different thematic layers.

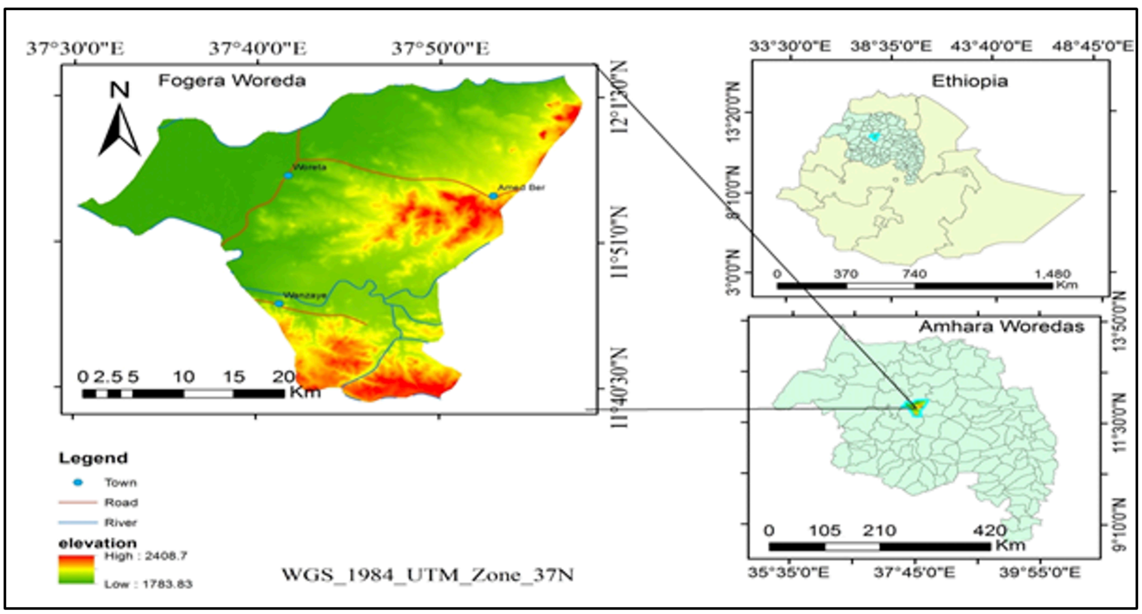

Figure 1. Location map of the study area

2.2. Data used and methods of data analysis

The availability of the data used in this is listed below in Table 1.

Data type	Source	Spatial resolution	Projection	Application
DEM	Alaska satellite facility	12.5×12.5 m	UTM	Slope, Lineament Density, Drainage Density, Elevation Distance from River
Sentinel 2 image	Copernicus open-access hub	10m	UTM	LULC
Geological map	GSE	Scale: 1:250,000	UTM	Geological map
Soil	MWME	Scale: 1:250,000	UTM	Soil texture map
Rainfall	CRU		UTM	Rainfall map

Table 1. Data types and sources. The available data usage is presented in tabular form.

The most popular and widely used GIS-based technique for defining groundwater potential zones is multi-criteria decision analysis with the Analytical Hierarchical Process (AHP). This process aids in the integration of every theme layer. For this study, ten distinct theme layers were taken into account. The area's water flow and storage are intended to be managed by these ten themed layers. Expert opinion and groundwater occurrence are taken into account when assigning weights to these influencing elements. A high weight value represents a highly impactful layer, while a low weight parameter represents a minimal impact on groundwater potential. Every parameter was given a weight based on Saaty's relative relevance scale (1–9). The thematic layers are given weights based on the classification. The study utilized various sources of data to prepare thematic maps for the analysis of groundwater potential in the study area. The Geological Survey of Ethiopia provided the geological map, which was digitized in ArcGIS software. The Food and Agriculture Organization of the United Nations provided the soil map, while 10-year (2011–2022) block-wise rainfall data was downloaded from CRU-TS-4.03 by the Climatic Research Unit. The digital elevation model (DEM) was downloaded from the Alaska satellite facility to prepare soil, slope, lineament density, drainage density, rainfall, distance from the river, elevation, and TWI, while the

Sentinel 2 image was downloaded from the Copernicus open access hub for preparing the LULC map. All these sources were used to generate 10 thematic maps, including lithology, soil, slope, lineament density, drainage density, rainfall, distance from river, TWI, LULC, and elevation, which were analyzed to assess the groundwater potential in the study area (Fig. 2).

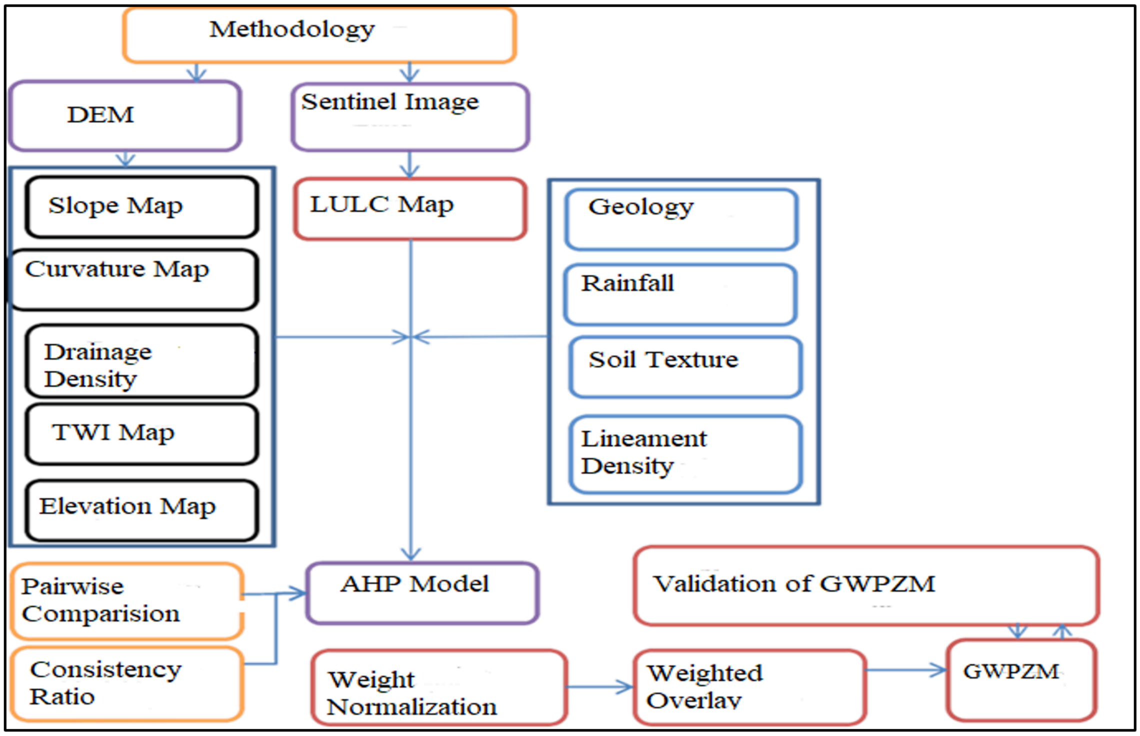

Figure 2. Flow chart for assessing the groundwater potential of the study area

3. Results and Discussion

3.1. Thematic layers

Ten thematic layers were prepared to demarcate the groundwater potential zones of the study area.

3.1.1. Lithology

The geological units of the area control the rate of infiltration and movement of groundwater, which has a significant impact on the occurrence and distribution of groundwater[8]. The study area contains four different types of lithological units: plateau basalt, alkaline basalt, lacustrine deposit, and alluvial deposit

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(Fig. 3). Alluvial deposits have been given more weight than lacustrine deposits, plateau basalt, and alkaline basalt.

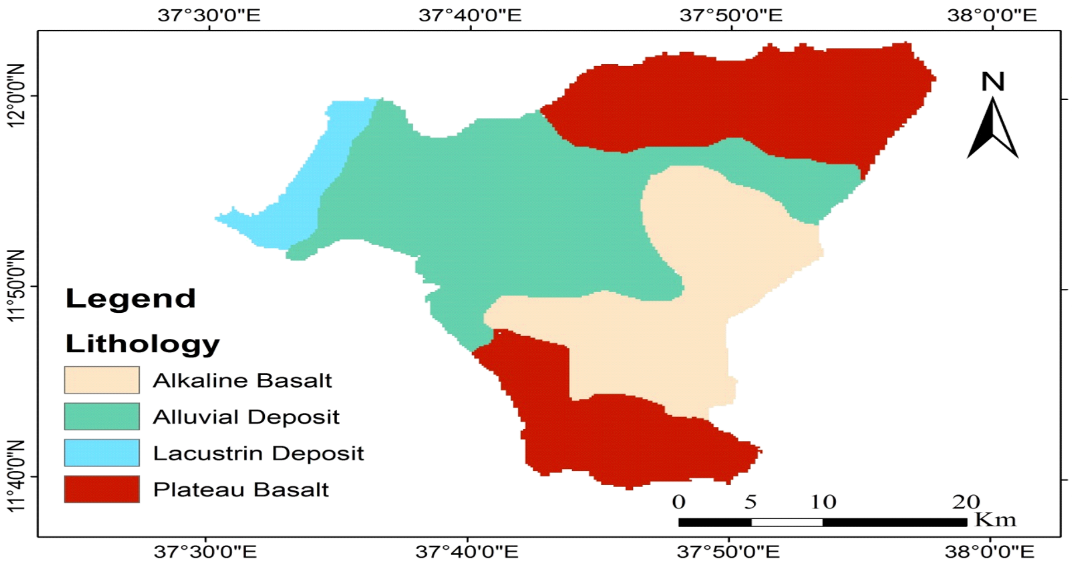

Figure 3. Lithological map of the study area

3.1.2. Soil

The texture of the soil determines the infiltration rate of precipitation and exponentially determines the groundwater potential zone[9][8]. The study area is covered by four soil textures, namely: fine, fine loamy, loamy, and coarse loamy (Fig. 4). The infiltration rate of the soils has been used to determine the rank of the soils in the study area (Table 3). The soil texture maps of the study area have different vulnerability ranks for groundwater potential.

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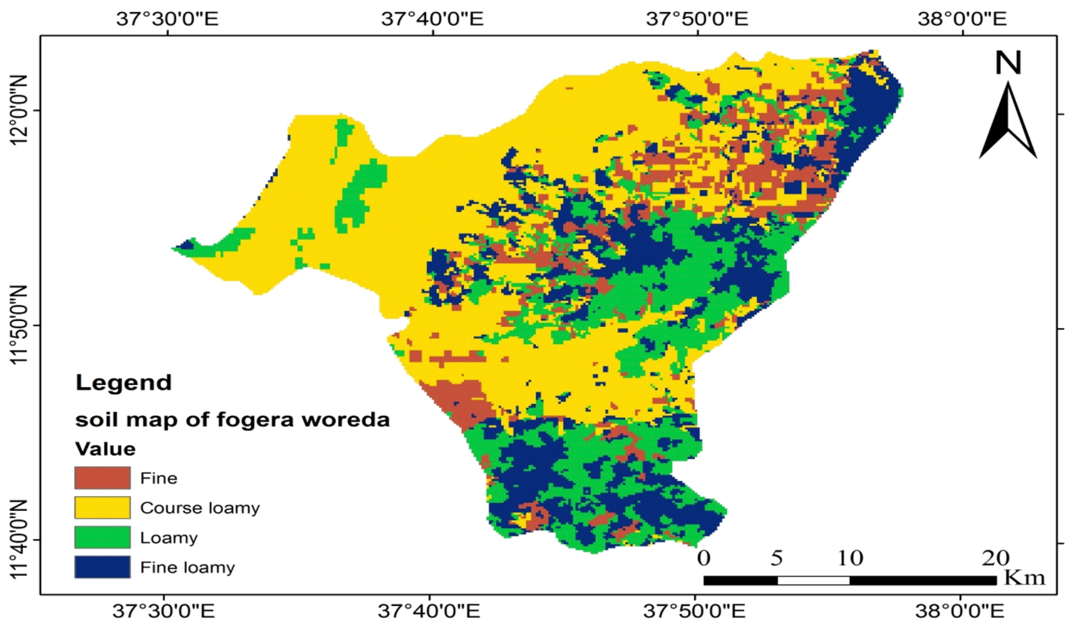

Figure 4. Map showing the distribution of various soil types in the study area.

3.1.3. Slope

The slope of an area has a direct impact on groundwater recharge and infiltration[5]. Gentle slopes have higher groundwater recharge than steep slopes. The slope map of the study area is divided into four slope classes: 0–4.490, 4.5–10.50, 10.60–19.20, and 19.30–76.40 (Fig. 5).

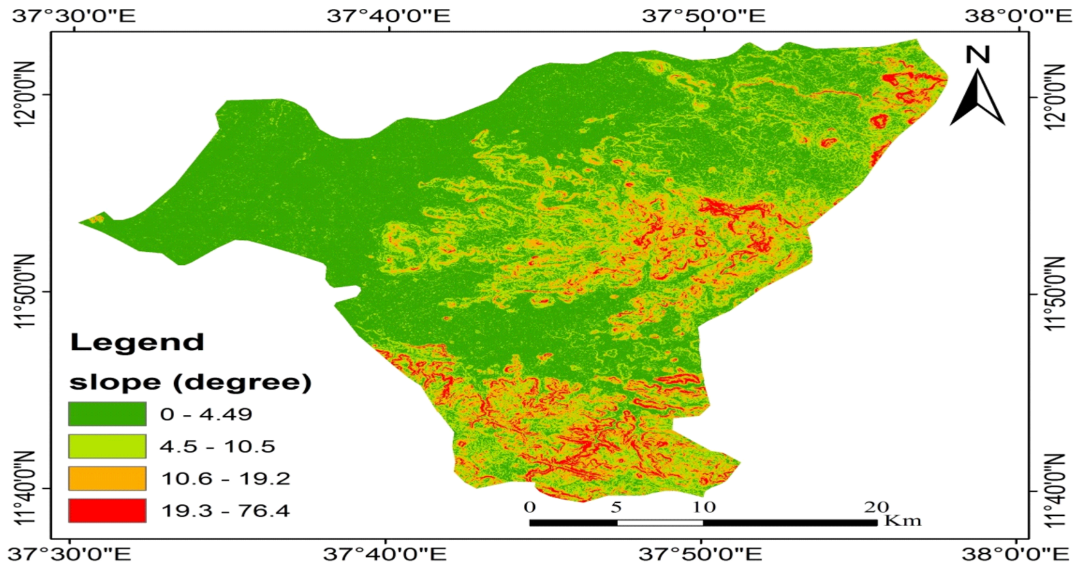

Figure 5. Slope map of the study area.

3.1.4. Drainage density

Drainage density is defined as the total number of streams per catchment area. The higher the drainage density, the lower the groundwater zone, and vice versa[10]. Low drainage density areas have high rankings, whereas high drainage density areas have lower ranks in the case of groundwater potential zone mapping. The drainage density of the area is 0–1.19, 1.2–2.28, 2.29–3.57, and 3.58–4.76, and the drainage density is higher in the northern and southern parts of the study area (Fig. 6).

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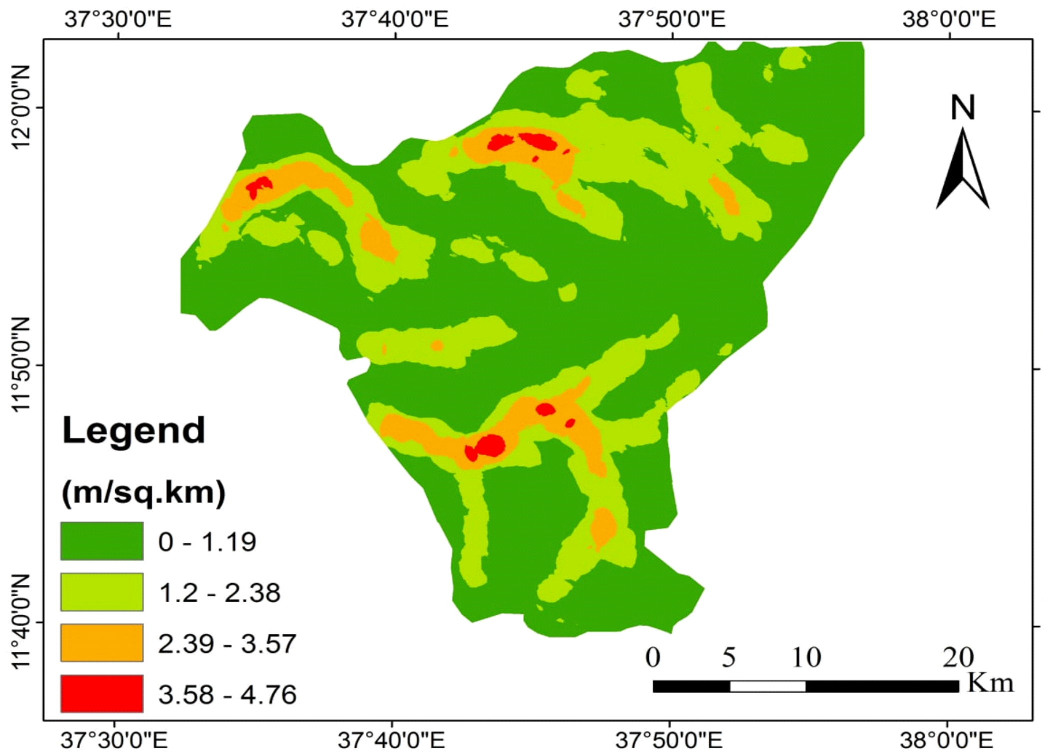

Figure 6. Drainage density map of the study area.

3.1.5. Lineament density

Lineament density is defined as the geological structures/discontinuities in an area[11]. The lineament density of any given area is calculated as below in eq1.

$$\mathrm{d} = \sum_{i=1}^{n} = \frac{\mathrm{Li}}{\mathrm{A}} \qquad \text{(eq1)}$$

High lineament density is favorable for high groundwater potential and gets higher ranks than lower lineament areas. Four intervals of lineament density were identified as 0–0.44, 0.45–0.87, 0.88–1.3, and 1.4–1.7 (Fig. 7). The study area has higher lineament density in the southern, central, and northern parts.

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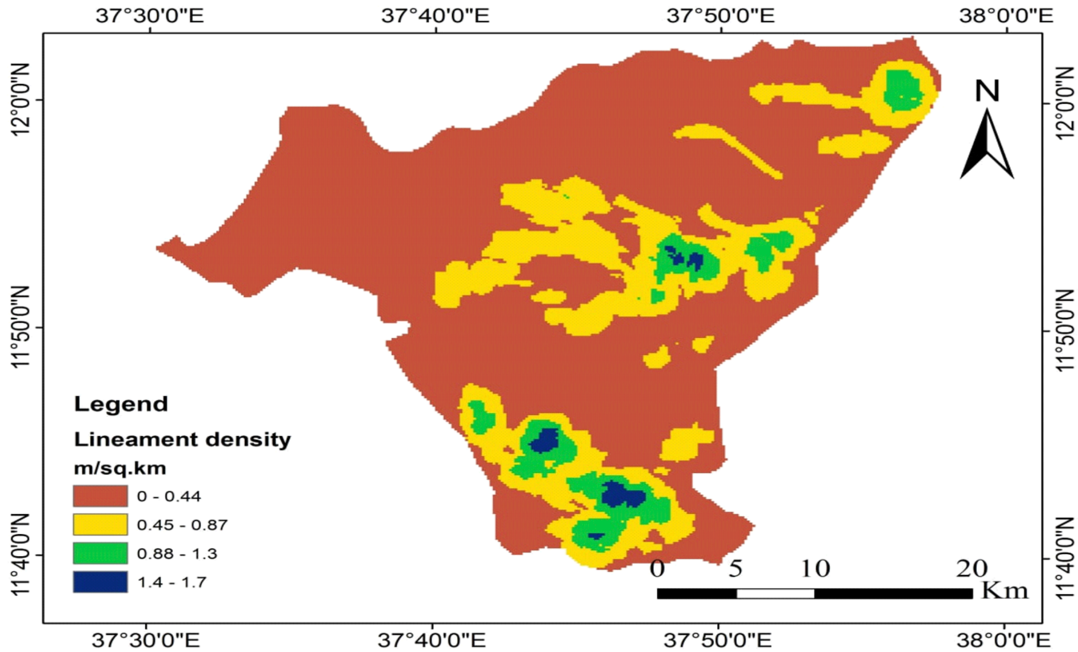

Figure 7. Lineament density map of the study area.

3.1.6. Rainfall

Rainfall plays a vital role in the hydrologic cycle, and it is a good source of groundwater recharge[3]. Four rainfall zones cover the entire area: 853.7–860.6 mm, 860.1–866.2 mm, 866.3–872.5 mm, and 872.6–878.7 mm. The western part of the area experiences high rainfall, while the center and eastern portions have moderate to low rainfall, as depicted in (Fig. 8).

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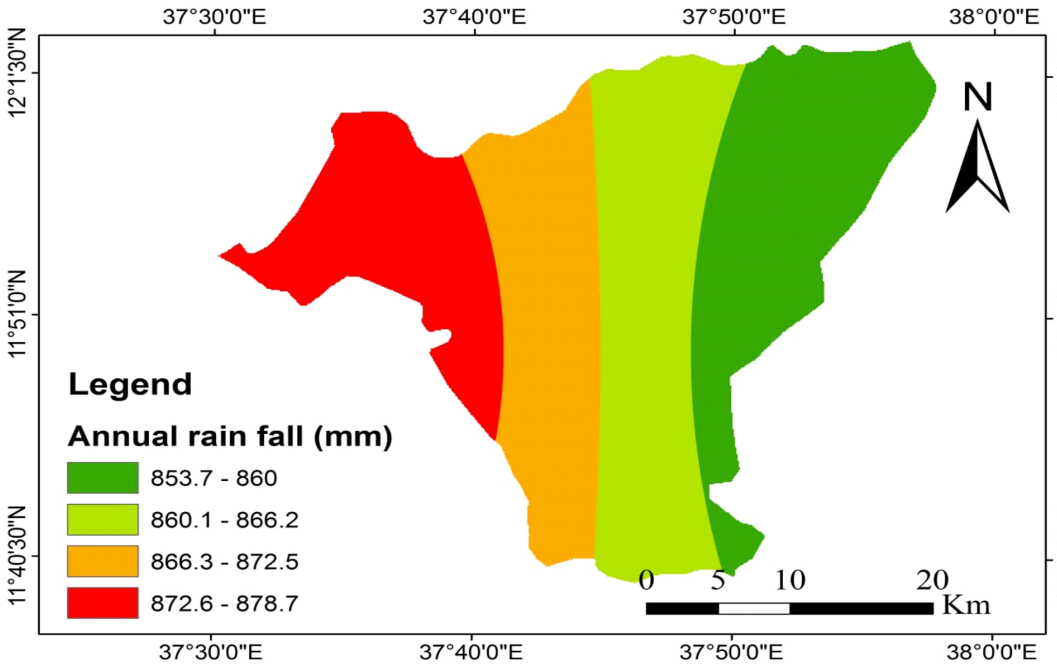

Figure 8. Map showing the distribution of various rainfall classes in the study area.

3.1.7. Distance from River

Groundwater potential is influenced by the distance from the river[12]. Near the river, the groundwater potential is higher than at a location far from the river. The distance from the stream map is classified into five such as < 500, 1000, 2000, 3000, and > 3000 m (Fig. 9). The higher groundwater potential is available at < 500 m, whereas very low groundwater potential is available at 3000-4000 m.

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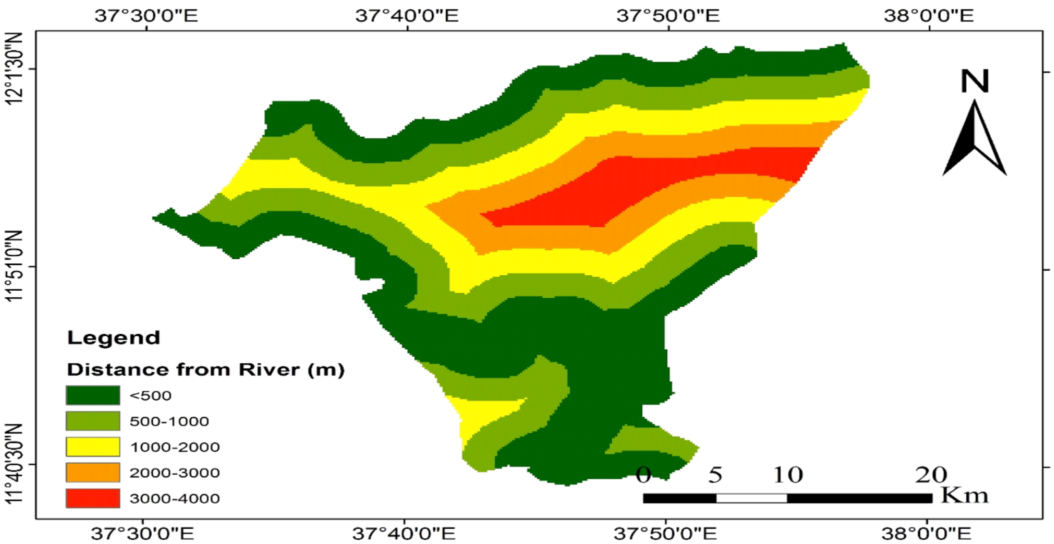

Figure 9. Distance from river map of the study area

3.1.8. Topographic Wetness Index (TWI)

In the hydrogeological system, the topographic wetness index (TWI) plays a vital role in groundwater potential zone mapping[9]. The TWI has been measured by the equation 2 below in Arc GIS 10.8 software :

$$\mathrm{TWI} = \ln \frac{As}{\tan \beta} \qquad \text{(eq2)}$$

TWI, where s and tan β stand for the point's slope angle and specific catchment area, respectively. TWI was divided into five classes (Fig. 10).

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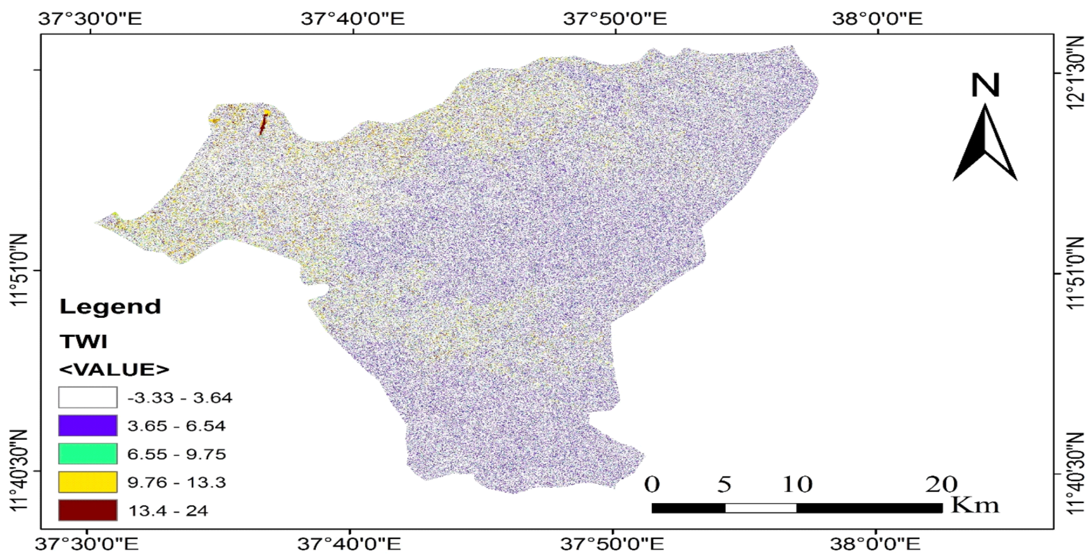

Figure 10. Topographic wetness index map of the study area

3.1.9. Land use/land cover

The major component influencing groundwater recharge and occurrence is land use and cover (LULC)[13]. There are four different forms of land cover in the study area, namely settlement, forest, agricultural land, and water bodies (Fig. 11).

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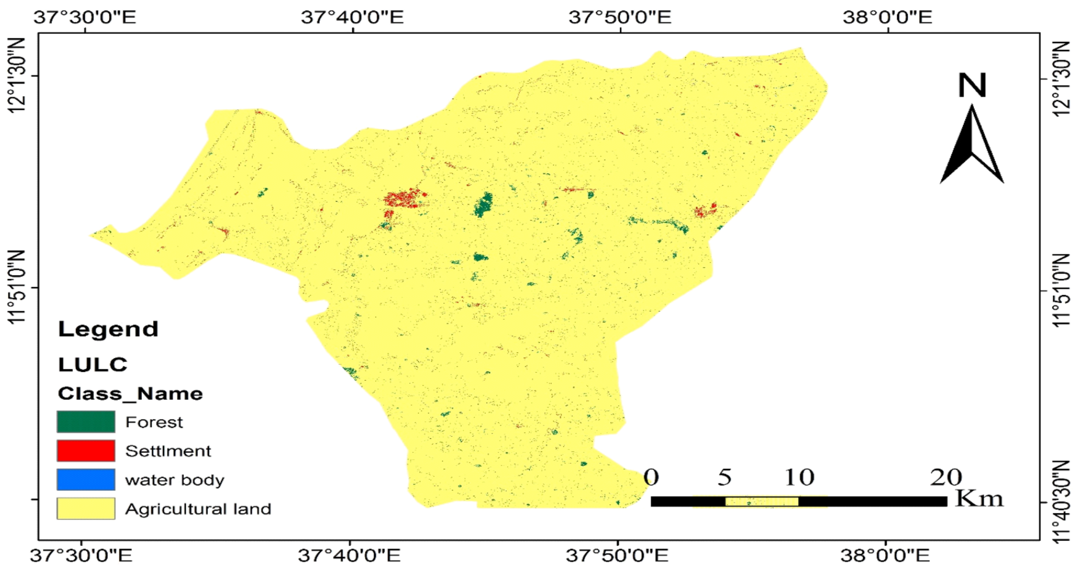

Figure 11. LULC map of the study area

3.1.10. Elevation

Lower topography is where water tends to accumulate, and it is an area of recharge. The groundwater potential increases with decreasing elevation and decreases with increasing elevation[9]. The elevation map of the study area is classified into five classes (Fig. 12). The highest groundwater potential zone susceptibility area has an elevation range from 1778 - 1847 m, and the lowest groundwater potential susceptible class has a range of 2148 - 2414 m.

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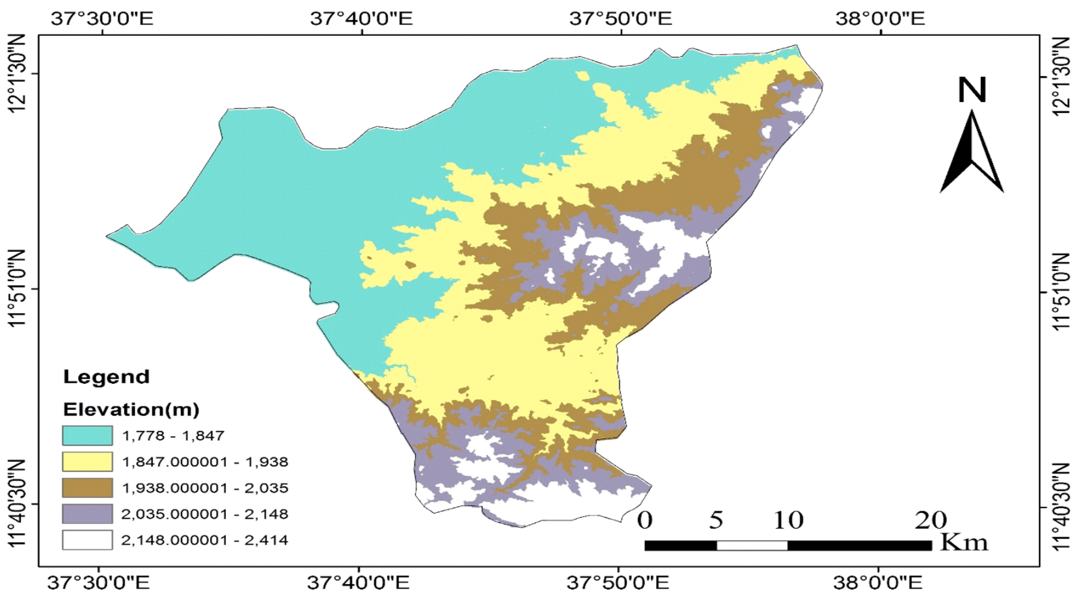

Figure 12. Elevation map of the study area

3.2. Assignment of weights and weights normalization

The analytical hierarchy process (AHP) method was used to derive the weight of the thematic layers that govern groundwater. The pairwise matrix comparison of the ten thematic layers has been done by the AHP Excel sheet as given in Table 2.

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Factors	Geol	RF	LD	DD	SL	ST	TWI	CUR	AS	EL
Geol	1									
RF	1/3	1								
LD	1/2	½	1							
DD	1/4	1/3	1/2	1						
SL	1/5	¼	1/3	½	1					
ST	1/7	1/5	1/4	1/3	1/2	1				
TWI	1/6	1/5	1/5	¼	1/3	½	1			
CUR	1/7	0	1/5	¼	1/3	1/3	1	1		
EL	1/7	1/6	1/6	1/5	1/4	¼	1/3	½	1	
LULC	1/8	1/7	1/6	1/5	1/5	¼	1/4	1/3	1/2	1
Sum	3.11	6.08	6.96	11.90	16.78	23.53	27.28	32.08	38.83	45.50

Table 2. Pairwise comparison matrix of 10 groundwater prospecting factors using AHP

The weight normalization is made by literature review and expert-based. Using Saaty's AHP, the weights allocated to the ten thematic layers and their constituent features were standardized (Table 3). As advised by Saaty[14], the normalized weights of the thematic layers and those of their features were checked for consistency. For this aim, Saaty[14] proposed computing the consistency ratio (CR). To calculate the CR for every theme and feature, the subsequent procedures were taken: Step 1: The eigenvector approach was used to calculate the principal eigenvalue (λ). Step 2: Equation 3[14] was used to determine the Consistency Index (CI):

$$CI = \frac{\lambda \max - \mathbf{n}}{\mathrm{n} - 1} \quad \text{(eq3)}$$

Where n is the number of criteria or factors

Finally, CR was calculated as[14]:

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$$CR = \frac{\mathbf{CI}}{\mathrm{RCI}} \quad \text{(eq4)}$$

Where RCI = random consistency index.

The value of CR should be less than 10%[14] for consistent weights; otherwise, the equivalent weights should be re-evaluated to avoid inconsistency. Based on equation 4, the consistency ratio (CR) is 0.0668.

Factors	Geol	RF	LD	DD	SL	ST	TWI	AS	CUR	EL	Normalized Weight (%)
Geol	0.3211	0.4931	0.2874	0.3361	0.2979	0.2975	0.2199	0.2182	0.1803	0.1758	27
RF	0.1070	0.1644	0.2874	0.2521	0.2383	0.2125	0.1833	0.1870	0.1545	0.1538	19
LD	0.1605	0.0822	0.1437	0.1681	0.1787	0.1700	0.1833	0.1558	0.1545	0.1319	15
DD	0.0803	0.0548	0.0718	0.0840	0.1192	0.1275	0.1466	0.1247	0.1288	0.1099	10
SL	0.0642	0.0411	0.0479	0.0420	0.0596	0.0850	0.1100	0.0935	0.1030	0.1099	8
ST	0.0459	0.0329	0.0359	0.0280	0.0298	0.0425	0.0733	0.0935	0.1030	0.0879	6
TWI	0.0535	0.0329	0.0287	0.0210	0.0199	0.0212	0.0367	0.0623	0.0773	0.0879	5
AS	0.0459	0.0274	0.0287	0.0210	0.0199	0.0142	0.0183	0.0312	0.0515	0.0659	4
CUR	0.0459	0.0274	0.0239	0.0168	0.0149	0.0106	0.0122	0.0156	0.0258	0.0440	3
EL	0.0401	0.0235	0.0239	0.0168	0.0119	0.0106	0.0092	0.0104	0.0129	0.0220	2
SUM											100

Table 3. Weight assigning and normalization.

3.3. Delineation of groundwater potential zones

Groundwater potential assessment has been done by an integrated system of geospatial and AHP techniques[8]. Using ArcGIS 10.8 software, the systematic analysis of AHP techniques on weighted thematic layers/ factors resulted in an appropriate groundwater potential zone map for the study area developed (Fig. 13). Each thematic layer is resampled to 30*30 cell size for overlay analysis. The developed groundwater potential zone map was excellent, moderate, poor, and very poor potential zones.

2.02% (21.19 km^2) of the study area showed an excellent groundwater potential zone. 51.2% 536.6 of the area has poor groundwater potential, and 1.24% (12.99 km^2) of it is very poor potential for groundwater. high groundwater potential zones are found in lacustrine and alluvial deposits, nearly level slopes, and cover an area of 21.19 km^2 (table 4). On the other hand, 536.6 km^2 of poor groundwater potential zones are located distant from significant lineaments and over a moderate to steep slope. Zones with extremely low groundwater potential cover a 12.99 km^2 area, and are found in the study area's hilly sections.

By Considering the ten thematic layers, the groundwater potential zone map (GWPZM) is computed as follows in equation 5.

$$\begin{gathered}\mathrm{GWPZ} = \mathrm{LwLr} + \mathrm{EwEr} + \mathrm{SwSr} + \mathrm{LDwLDr} + \mathrm{DDwDDr} + \\ \mathrm{RwRr} + \mathrm{DRwr} + \mathrm{WTWItwir} + \mathrm{Wlulcrlulc} + \mathrm{welrel}\end{gathered} \tag{eq5}$$

Where Lw is the weight of lithology, Lr is its corresponding rank, Sw is the weight of soil, and Sr is its corresponding rank, Ew is the weight of slope, Er is its corresponding rank, LDw is the weight of lineament density, and LDr is its corresponding rank, DDw is the weight of drainage density, and DDr is its corresponding rank, Rw is the weight of rainfall, and Rr is its corresponding rank, DR is the weight of distance from river, and wr is its corresponding rank, WTWI is the weight of topographic wetness index, and twi is its corresponding rank, Wlulc is the weight of LULC, and rlulc is its corresponding rank, Wel is the weight of elevation, and rel is its corresponding rank.

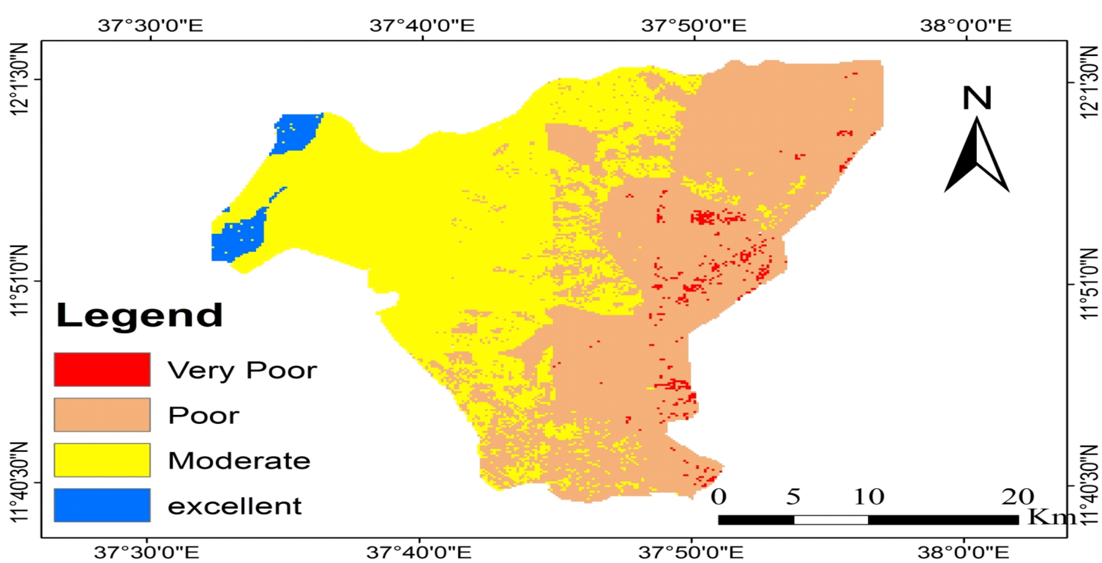

Figure 13. Map showing the groundwater potential zone

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GWPZ	Area km^2	Percentage of the area
Excellent	21.19	2.02
Moderate	477.29	45.54
Poor	536.6	51.2
Very poor	12.99	1.24

Table 4. Classification of groundwater potential zones

3.4. GWPI validation

Based on the well yield data, the groundwater potential map was verified. Upon superimposing the final output map of groundwater prospect zones with Amhara Water Works and Supervision Enterprise's well yield data, it was observed that the high to moderate groundwater potential zones identified in this study through RS and GIS tools and the AHP technique corresponded with the high well yield zones. In contrast, the regions demarcated as poor to very poor groundwater potential displayed low well yield (Fig. 14).

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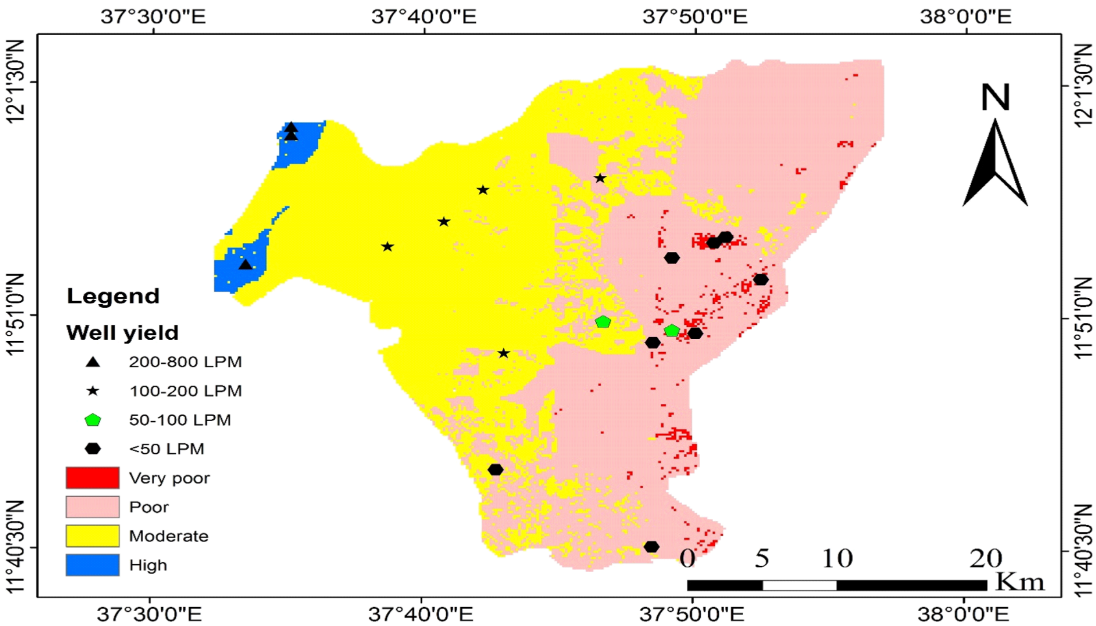

Figure 14. Groundwater potential map and its validation of the study area.

4. Conclusions

The groundwater potential zonation utilizes the use of geospatial and Analytic Hierarchy Process (AHP) techniques. The study area is analyzed using weighted overlay analysis applied to ten thematic layers. These layers are independently prepared from disparate spatial resolutions and are subsequently resampled to a uniform spatial resolution. For the purpose of overlay analysis, each thematic layer is subjected to reclassification and resampling to a 30m × 30m spatial resolution. The study area is divided into four potential zones, namely, excellent potential, moderate potential, poor potential, and extremely poor potential. The results indicate that only 2.02% (21.19 km2) of the study area has outstanding groundwater potential, whereas 45.54% (477.29 km2) has moderate groundwater potential, 51.2% has low groundwater potential, and 1.24% has very poor groundwater potential. The use of geospatial techniques has proven to be a cost-effective and time-efficient means of identifying potential groundwater zones. Therefore, the application of geospatial techniques and AHP in groundwater potential mapping is a crucial tool for future investigations.

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Statements and Declarations

Availability of data and materials

On reasonable request, the corresponding author will provide the datasets used and/or analyzed during the current work.

Competing interests

There are no competing interests declared by the authors.

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Authors' contributions

Both authors contributed to data gathering or acquisition. The 1st author contributed the most to data processing, interpretation, and drafting of the paper. The second author prepared the manuscript and conducted detailed proofreading of the manuscript. The work has been refined by both writers, and both have given their approval for it to be published.

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