

Delineation of Groundwater Potential Zones (GWPZs) using remote sensing (RS), geographic information systems (GIS), and Analytic Hierarchy Process (AHP): a Case Study from Selekleka River Catchment, Tigray, Northern Ethiopia

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Delineation of Groundwater Potential Zones using GIS and Analytic Hierarchy Process (AHP) in
Selekleka River Catchment, Northern Ethiopia

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Abstract

This study addresses the delineation of groundwater potential zones (GWPZs) using remote sensing (RS), geographic information systems (GIS), and analytic hierarchy process (AHP) in the Selekleka River Catchment, Tigray, North Ethiopia. In the mapping of groundwater potential zones, eight thematic layers (geology, slope, soil, drainage density, lineament density, rainfall, elevation and landuse landcover) were used. The thematic layers were prepared in vector format in ArcMap 10.4.1. The prepared thematic layers were changed to raster and reclassified in the ArcMap spatial analysis tool. Rating and rank of thematic layers were given using AHP techniques. The weighted overlay analysis (WOA) technique was then used in the ArcGIS environment to integrate all thematic layers and generate a GWPZ map. The results indicated that about 61.2 km² (6.5 %) of the total area, falls under the ‘very poor’ zone, 387.6 km² (48 %) falls under the ‘poor’ zone, 311.9 km² (39 %) falls under the ‘good’ groundwater potential zone, and 24.5 km² (2.6 %) of the study area falls under the ‘very good’ zone. The validation was done by distributing the water points, and most of the wells were concentrated in the very good and good potential zones of the study area. From this, we can easily understand that the integration of RS, GIS and AHP are viable approach for delineation of GWPZs

Keywords: Selekleka River Catchment, Delineation, potential zone, thematic layers, AHP, GIS, GWPZs

1. Introduction

Groundwater is a fundamental component of the hydrological system, which occurs in the subsurface geological formations (aquifers) (Pande et al. 2021). In addition, Mulusew et al. (2024) explained that groundwater is one of Earth's most valuable and significant natural resources for survival, the elixir of life, essential for day-to-day activities and the economic development of any country. Due to growing population density, urbanization, and intensive irrigation practices, groundwater use has increased significantly (Mishra and Singh, 2010). In countries like Ethiopia, groundwater use continues to rise rapidly due to expanding urban populations and economic development (Andualem and Demeke 2019).

According to (Ifediegwu 2022; Chatterjee 2022; Asgher et al. 2022), the occurrence of groundwater depends on the recharge process controlled by several factors such as physiography, lithological composition, drainage pattern, land use and land cover, and climatic factors such as precipitation, temperature, evapotranspiration, etc., and geological setting, including fractures and lineament features. In addition, Rao et al. (2022) stated that the occurrence, distribution, and movement of groundwater at any place on the Earth are not a matter of chance but a consequence of the interaction of climatic, geological, hydrological, hydro-geomorphological, physiographical, and ecological factors. Therefore, groundwater potential varies meaningfully in space and time, sometimes by a few meters, even within the same aquifer (Castillo et al. 2022). This confirms the contrast in groundwater potential found from place to place (Thapa et al. 2017).

Mapping groundwater potential zones is crucial for planning the location of new abstraction wells to meet the growing demand for water management and the development of vital groundwater resources (Rao et al. 2022). A detailed study of groundwater occurrences can be made by surface and subsurface investigation methods, such as geological and geophysical methods (Arulbalaji et al. 2019). However, these are extensive and time-consuming ground measurements that can be used only for large-scale mapping (Shirke et al. 2005).

Researchers (e.g., Carver 1991; Jankowski 1995; Boroushaki and Malczewski 2008) explained that recent advances in digital image processing, combined with multi-criteria analysis of the geospatial environment, have enabled scientists to better identify areas where natural recharge occurs using combinations of quasi-static data such as geology, topography, vegetation, soil characteristics, etc. Numerous studies clarified that various methods are crucial for defining groundwater potential zones. Remote sensing and GIS are two of the most effective techniques for

quickly estimating natural resources (Arulbalaji et al. 2019). Additionally, according to Arulbalaji et al. (2019), groundwater potential zones have been delineated in recent years using a combination of GIS and Analytical Hierarchy Process (AHP) methodologies. AHP is regarded as the primary instrument in the subjective evaluation of qualitative procedures, according to Saaty (1980) and Arulbalaji et al. (2019).

In order to determine a scale of preferences among a group of options, AHP is a multi-objective, multi-criteria decision-making method that uses a pairwise comparison procedure (Saaty 1980; Saaty 1990; Saaty 1994; Yakob et al. 2025; Arulbalaji et al. 2019; Diriba et al. 2024). Furthermore, according to Ayalew et al. (2005), AHP is a popular and well-known GIS technique that is widely used in site selection, suitability analysis, regional planning, landslide susceptibility study, and groundwater potential zone delineation. By allowing stakeholders to divide complicated issues into hierarchical structures using their experiences, values, and knowledge, it promotes group decision-making (Yakob et al. 2025). The Analytic Hierarchy Process (AHP) is due to Saaty (1980) and is quite often referred to as the Saaty method. According to Saaty (1980) and Yalcin et al. (2011), AHP is considered the main tool in the subjective assessment of qualitative methods. These structures are solved step-by-step using AHP methodology (Chowdhury et al. 2010). One of AHP's notable strengths is its systematic consistency checks, which distinguish it from other multi-attribute value processes (Yakob et al. 2025). In this study, pairwise comparison matrices were constructed using AHP techniques for determining the total weight of primary criteria.

To identify appropriate locations for potential groundwater zones using GIS-based AHP analysis, the following five procedural steps, as outlined by Machiwal et al. (2011), cited at Yakob et al. (2025), were employed:

(a) Criteria selection and weighting: Determining and categorizing pertinent factors affecting groundwater potential.

(b) Pairwise comparison and weight normalization: Weights are assigned and normalized using Saaty's methods.

(c) Thematic layer generation: Each parameter and its subclasses are represented by thematic maps.

(d) Integration and overlay: Creating maps of groundwater potential by combining normalized thematic layers.

(e) Validation and consistency analysis: The CR is calculated to guarantee the accuracy of conclusions and outcomes.

Climate, slope, geomorphology, drainage density, land use/land cover, geology, lineament density, vadose zone characteristics, soil characteristics, static water level, aquifer lithology, hydraulic conductivity, and aquifer transitivity in various but suitable combinations were among the sets of parameters selected for the various investigations (Lentswe & Molwalefhe 2020).

Numerous wells have been drilled in the study region for irrigation and drinking purpose. However, due to poor site selection and the lack of a prepared map that illustrates possible zones, some of the wells are not operational. To create groundwater potential zones for appropriate site selection and groundwater extraction in the Selekleka River basin, the combination of RS, GIS, and AHP is a viable approach.

1.1. Description of the study area

The study area is located in Tigray, north Ethiopia (Fig. 1). Geographically, it is located between 430000 – 450000 m E latitude and between 1555800 – 1573000 m N longitude with an aerial coverage of 785.2 km². The area has a semi-arid type of climatic condition with minimum and maximum temperatures of 11.7 and 27.4 C° respectively. It has an annual rainfall of 734 mm. The study area gets rainfall in the summer season. Groundwater is the main water supply of the communities of the catchment, and agriculture is the main crop production for the people of the area.

Topographically, the area is characterized by rugged topography that slopes gently from the south, east, and west towards the north. The elevated areas (2400 m) are found in the east and west directions and the lowest elevated areas are found in the north (1600 m) direction of the study area. The area has a dendritic type of drainage pattern that flows from east, south, and southwest towards the north (Fig. 1). The main rivers in the study area are perennial.

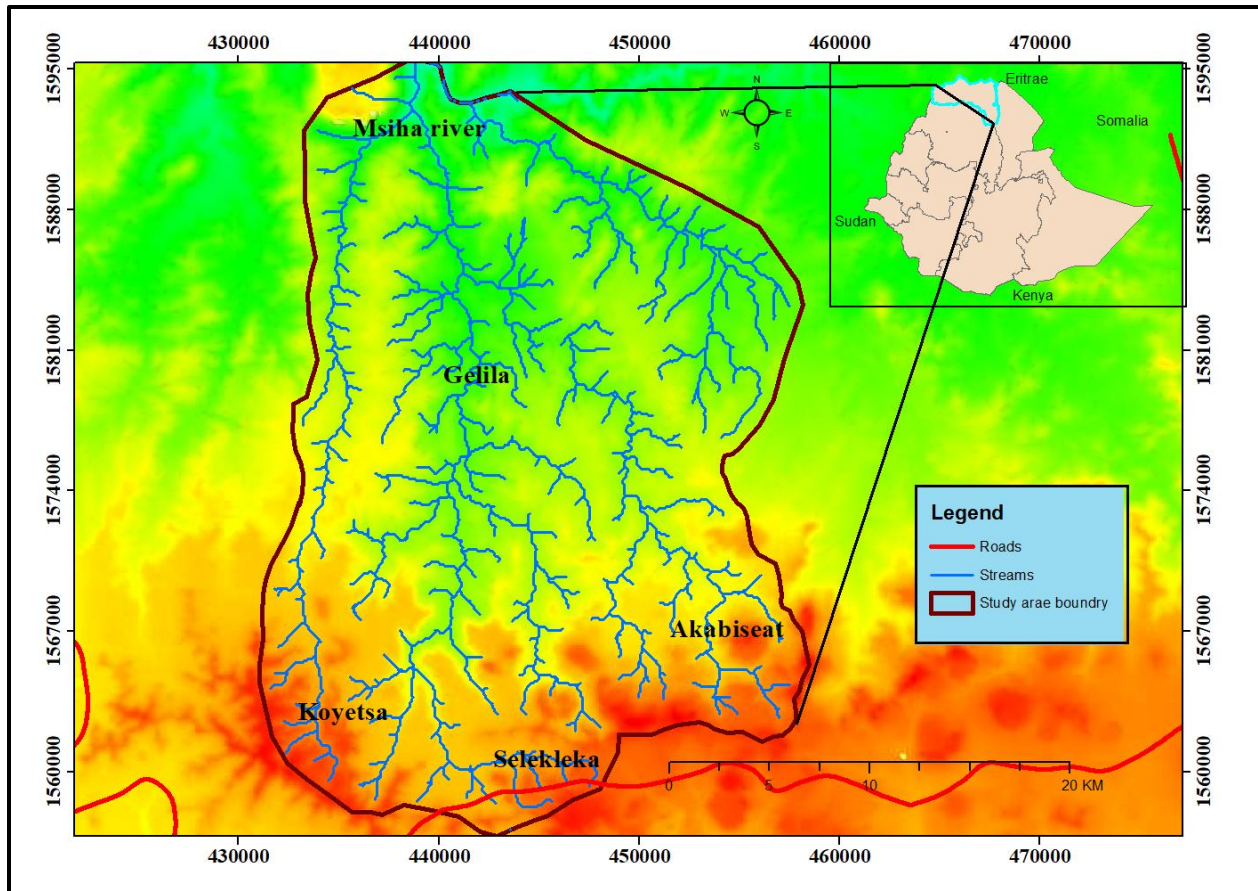


Figure 1: Location map of the study area

1.2. Methodology

1.2.1. Thematic layer preparation

Groundwater potential zone of the study area has been prepared using eight thematic layers (geology, lineament density, land use and land cover, drainage density, rainfall, elevation, slope, and soil). These parameters were selected in this study considering that they have a high impact on the occurrence and distribution of groundwater.

A geological map of the study area was prepared by a detailed field description, integrating with existing regional geological maps. The prepared lithology map was converted to raster format using ArcGIS 10.4.1 spatial analyst tools to analyze and classify lithological units for the study area.

Slope and elevation maps of the study were prepared from the digital elevation model (DEM) of Ethiopia. The DEM was sourced from the website USGS. To prepare the slope map, the DEM of the study area from the Global Mapper 12 was transferred to the Arc GIS 10.4.1 in the grid system.

Then it was prepared and classified into five classes by the Jenks natural break (Jenks) classification system in the GIS environment.

To prepare the rainfall map, daily rainfall data of the study area were collected from 1992 to 2024 in three stations (Aksum, Shire and Selekleka) from the Ethiopian National Meteorological Agency (ENMA) Mekelle Branch. Through spatial analysis in ArcGIS 10.4.1, the rainfall data were interpolated using the Inverse Distance Weighting (IDW) method to generate a detailed rainfall map of the catchment. Yasin et al. (2024) stated that the IDW interpolation method is chosen for this type of study because of its computational efficiency, deterministic nature, and ability to provide localized estimates without requiring assumptions about spatial autocorrelation, making it suitable for datasets with irregular rainfall distributions.

The land use/land cover map of the study area was prepared from Google Earth. First, the internet connection was activated, and Google Earth was opened. Secondly, the study area was employing the highest possible resolution within which blurred images could be enhanced. Thirdly, the different earth features were selected and delineated by polygons with their names in Google Earth. Then, the selected features in Google Earth were exported to the Global Mapper using the KML file format. Next, the features were subsequently imported and converted into shapefiles using ArcGIS 10.4.1 software. Finally, the shape file was converted to a raster and reclassified in ArcGIS 10.4.1.

In the preparation of the soil map of the study area, the first FAO soil classification system was collected from the USGS. Then it was converted to the textural classification from literature. Finally, the soil map was prepared in vector format and changed to raster and reclassified in the spatial analysis tool in ArcGIS 10.4.1.

A drainage density map of the study area was prepared from the DEM of Ethiopia. In this preparation, the DEM of Ethiopia was opened in Global Mapper 12. In the global mapper, from the file section, the watershed generation was selected, and the stream cell count was set to 50. Then the generated watershed was opened in the ARCGIS 10.4.1, in the spatial analysis tool, to extract the density and line density.

In lineament density preparation, the DEM of the study area was added to the ARCGIS10.4.1, in the spatial analysis tool, and in surface hill shade was extracted. In the extracted hill shade, the lineament density was digitized using a polyline, and line density was extracted.

1.2.2. Normalized weights of thematic layers by the AHP method

Arulbalaji et al. (2019) specified that multi-criteria decision analysis using Analytical Hierarchical Process (AHP) is the most common and well-known GIS-based method for delineating groundwater potential zones. The AHP method is used to generate and integrate all thematic layers based on their importance and influence on groundwater potential (Gebbru et al. 2020). Eight thematic layers were considered in this study, taking into account parameters that significantly contribute to the occurrence and distribution of groundwater. A parameter with a high weight indicates a layer with significant impact, while a parameter with a low weight indicates a minimal impact on groundwater potential (Arulbalaji et al. 2019).

The weightages of each parameter were assigned according to Saaty's scale (1–9) of relative importance value (Table 13). Furthermore, the weights were assigned with consideration of past studies and field experience. The weights of each parameter are assigned according to Saaty's scale (1–9) of relative importance value. Saaty's scale of relative importance value reveals that a value of 1 indicates equal, 2 weak, 3 moderate, 4 moderate plus, 5 strong importance, 6 strong plus importance, 7 very to extreme importance, 8 very, very strong importance, and 9 extreme importance (Arulbalaji et al. 2019), Table 1. As per the classification, weights are assigned to the thematic layers based on their importance and water-holding capacity.

Table 1: Saaty scale of relative importance (Saaty 2005)

Scale	Numerical rating	Reciprocal
Equal importance	1	1
Equal to moderate importance	2	1/2
Moderate importance	3	1/3
Moderate to strong importance	4	1/4
Strong importance	5	1/5
Strong to very strong importance	6	1/6
Very strong importance	7	1/7
Very strong to extreme importance	8	1/8
Extreme importance	9	1/9

1.2.3. Pairwise Comparison Matrix

The pairwise comparison method is used to assign a weight for the criteria layers (Andualem and Alemie 2025). It is the process of summing the proportions of all the parameters and dividing the total by the number of parameters that yields the principal eigenvalue (λ_{max}) and the random consistency index (RI) values corresponding to different matrix sizes (n), which vary according to the number of layers used for groundwater potential assessment (Table 3).

$$\lambda_{max} = \sum_{i=1}^n TW_i * NW_i \text{-----Eq. 1}$$

Where λ_{max} is for the largest eigenvalues, TW_i for the total weight and NW_i for the Normalized weight of the thematic layers.

The AHP result shows that the eigenvalue (λ_{max}) is 8.25 (Table 12). The principal eigenvalue should be equal to or exceed the total number of parameters within the matrices; if this condition is not met, the matrices require reconstruction (Saaty 1980). In this study, the principal eigenvalue of 8 by 8 matrices was employed to determine the consistency index (CI), as shown in Table 12. According to Saaty (1980), a pairwise comparison matrix is consistent only if the principal eigenvalue (λ_{max}) is greater than or equal to the number of parameters investigated (n); otherwise, a new matrix is required.

1.2.3. Assessing Matrix Consistency

AHP offers a useful method to guarantee the consistency of the decision-maker's assessments. The following formula is used to calculate the CI, a statistic for assessing consistency (Saaty 1980):

$$CI = \frac{\lambda_{max} - n}{n - 1} \text{ Eq. 2}$$

where CI represents the consistency index, (λ_{max}) denotes the principal eigenvalue, and n refers to the number of thematic layers. Saaty proposed evaluating the CI with the corresponding RI. According to Saaty (1980), the CR must not exceed 0.1 to affirm the acceptability of the judgments; otherwise, the evaluation requires revision.

$$CI = \frac{8.25 - 8}{8 - 1} = 0.035$$

To identify inconsistencies and derive optimal weights within the pairwise comparison matrix, the CR was computed following the completion of pairwise comparison and the determination of element weights. AHP analysis is considered valid and can proceed if the CR of 0.1 or lower (Saaty

2008). Conversely, if the CR exceeds this threshold, the analysis procedure is regarded as varying, rendering the AHP approach unreliable for producing accurate conclusions (Saaty 2008).

The CR serves as a metric for evaluating the reliability of the relative weights resulting from the matrix. It is calculated as the ratio of the CI to the RI using the following equation:

$$CR = \frac{CI}{RI} \dots\dots\dots \text{Eq. 3}$$

where CR signifies the consistency ratio, CI represents the consistency index, and RI signifies the RI. The value of RI for different 'n' values is given in Table 2.

Table 2: Random consistency index (Saaty 1980)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

$$CR = \frac{0.035}{1.41} = 0.025 \text{ (2.5\%)}$$

Where RI is the average of the resulting consistency index depending on the order of the matrix given by (Saaty 1980).

Based on the AHP methodology (Table 12), the assigned weights for the parameters were as follows: Lt (34%), Rf (23%), S (16%), LULC (7%), LD (10%), DD (2%), ST (5%), Ele (3%) and (Table 12). Lithology emerged as the most influential parameter in the catchment area, as determined by the weighted vector analysis.

Conversely, Ele and DD were ranked with the lowest priority. The weighted values for each thematic layer class were subsequently applied to reclassify and assign weights to the respective classes using ArcGIS 10.4.1.

1.2.3. Identification of Groundwater Potential Zones (GWPZs)

GWPZs are unitless values that can be determined based on the GWP zone in a specific location (Yakob et al., 2025). After preparing all the thematic layers, a GIS overlay analysis was conducted to generate the GWPZs map. To delineate the GWP zones, different researchers (e.g., Malczewski 1999; Shekhar & Pandey 2015) expressed this precisely by the following equation:

$$GWPZ = \sum_{i=1}^n W_i * R_i \dots\dots\dots \text{Eq. 4}$$

Where GWP is groundwater potential zone; W_i is the weight for each thematic layer, R_i is the rate for the classes within a thematic layer, and n is the number of parameters.

For each grid, the GWP was computed according to the equation:

$$GWPZ = LtwLtr + RfwRfr + SwSr + DDwDDr + STwSTr + LULCwLULCr + LDwLDr + ELwELr$$

Where Lt, lithology; Rf, rainfall; S, slope; DD, drainage density; ST, soil; LULC, land use/land cover; EL, elevation; and LD, lineament density.

The symbol 'w' expresses the weight of a thematic layer, and the symbol 'r' expresses the rating of subclasses (the rank) in each layer

Eight classified thematic maps in raster format were utilized as input datasets in this study. The relative weight of each contributing factor was systematically assigned based on its significance.

Finally, the overlay analysis was conducted within the ArcGIS environment, employing the formula outlined in Equation (5).

$$GWPZ = (0.34 * Lt) + (0.23 * Rf) + (0.16 * S) + (0.02 * DD) + (0.07 * LULC) + (0.03 * EL) + (0.1 * LD) + (0.05 * ST) \text{-----Eq. 5}$$

1.2.4. Validation of Groundwater Potential Zones (GWPZs)

Previous studies (e.g., Andualem & Alemie 2025) stated that the distribution of water points is one of the techniques for the validation of groundwater potential zones. Accordingly, the identified potential groundwater zones of the current study area were validated using water point inventory data of boreholes and springs.

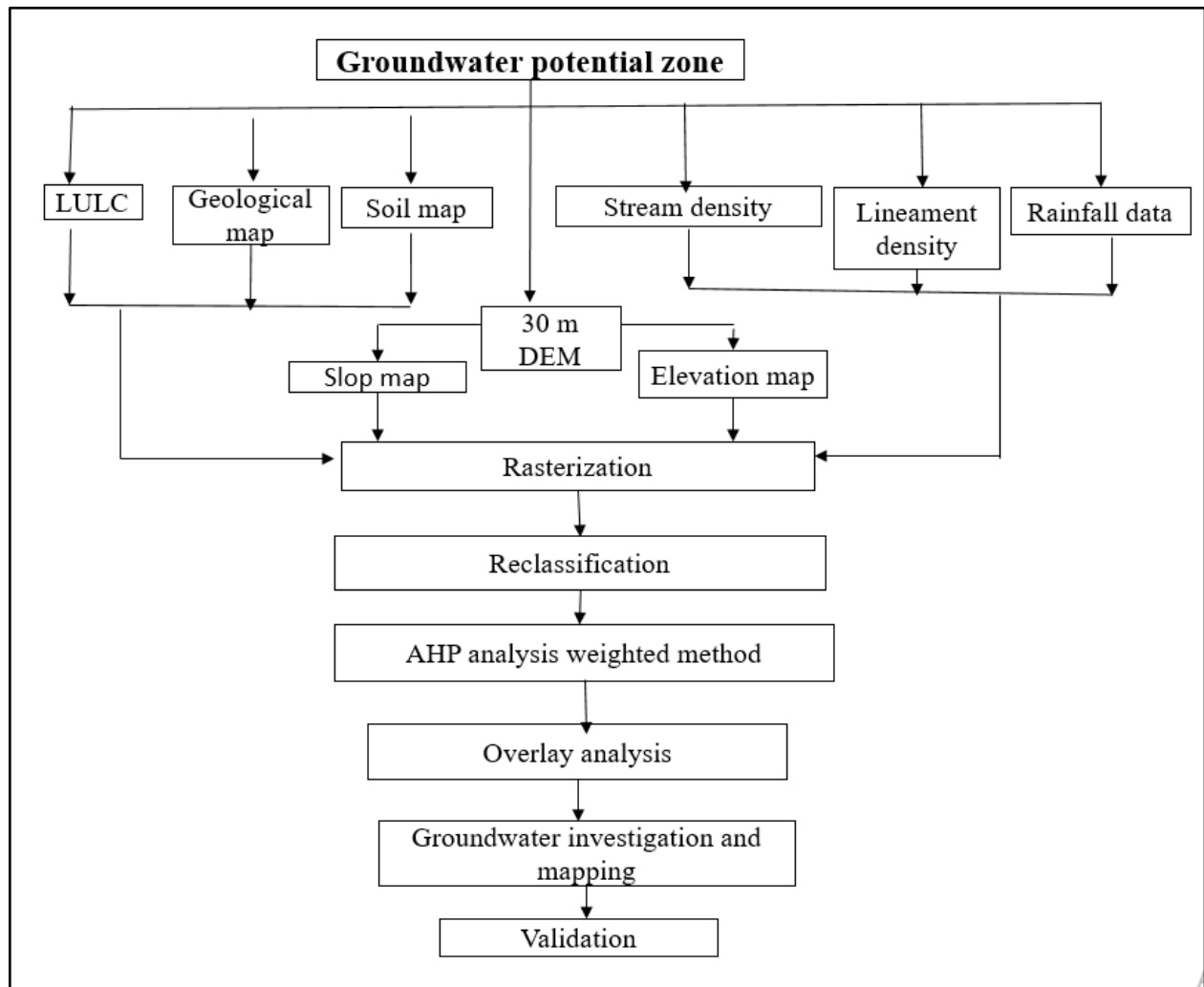


Figure 2: Flow chart of methodology used for Groundwater Potential Zones Mapping

2. Result and discussion

2.1. Geology

The spatial distribution, occurrence and quality of groundwater are greatly influenced by the characteristics of the prominent lithological formation in the area of interest ([Ramamoorthy & Rammohan 2015](#); [Taye et al. 2021](#); [Eshetu et al. 2024](#); [Zewdie et al. 2024](#); [Yeh et al. 2016](#); [Aju et al. 2021](#)). Lithology is a primary determinant in GWPZ delineation, as it governs water storage, infiltration, and movement within an aquifer system ([Yakob et al. 2025](#); [Diriba et al. 2024](#)). The type of lithology present affects the recharge of groundwater ([Shaban et al. 2006](#)) and explains that geology controls the percolation.

The geology of the study area is part of northern Ethiopian geology, which has the stratigraphic sequence of the Northern Ethiopian Highlands ranging from the Precambrian to the Holocene (Merla and Minucci 1938). The lithological units exposed in the study area are trachyte, basalt, sandstone, granite, phyllite, schist and metavolcanics.

Granite: occurs as a ridge and hill forming intrusive rocks in the eastern, central and northern parts of the study area. This rock type has pinkish and greyish fresh color, a yellowish weathered color and a medium to coarse-grained size. It consists of quartz, K-feldspar, and pyroxenes. It covers 193.5 km² (27.7%) of the study area. This has a massive nature and has a low possibility of the occurrence of groundwater in the study area.

Phyllite: The phyllite rocks, originating from sedimentary rocks, are fine-grained, slightly foliated, and composed of graphite, micas (sericite), and small amounts of fine-grained chlorite, feldspar, and quartz. This rock type is particularly noticeable in the central part of the study area and displays a color range including light gray, dark gray, green, and brown/red. Crenulation cleavage is evident in certain areas. The unit also exhibits composite fabrics, including primary and secondary foliation, with primary foliation marked by variations in layer thickness, composition, and color. The phyllite in the study area varies; one is phyllite and quartzite with calcareous bands, and the second one is phyllite, quartzite, and graphitic schist. It covers 165.6 km² (21.1%) of the study area.

Metavolcanics: A metavolcanic is part of the Precambrian stratigraphy of northern Ethiopian geology. This is a hard rock formation in the study area. This rock type is outcropped in the Northern part of the river catchment (Fig. 2). It has greenish and gray fresh and weathered colors, respectively. Development of alterations such as epidotisation and chloritisation are common in this rock type. This is in contact with granite and schist rock types. This covers 112.3 km² (14.3%) of the total study area.

Schists: Schists are exposed in the north-central region of the study area, covering 6.6 km² (2.8%) of the total area (Fig. 2). These rocks are greenish and exhibit a fine- to medium-grained texture. This is composed of schist and schist with a marble band in the study area (Fig. 2). This covers 53.6 km² (7.8%) of the total study area.

Siliceous and Ferruginous Sedimentary Beds: The sedimentary rock is part of the Mesozoic-Palozoic sedimentary deposits deposited above metamorphic terranes. They are mainly composed of conglomerate, reddish sandstone, siltstone, chert, and thin lateritic iron at the top. They occurred as flat plateaus with hills and ridges, and at places as remnant outcrops capping the granites. In this section, the lower part is a thickly bedded white, sometimes purplish white, siliceous mudstone, and it is often weathered and kaolinised. The topmost exposed layer is a dark brown lateritic horizon approximately 2 m thick. The layer contains some widely spaced (over 50 cm) fractures, but its iron-oxide-rich crusted surface renders it to have poor porosity. 42.5 km² (5.4%)

Basalt unit: This unit, corresponding to Tertiary volcanic rocks found elsewhere in the region, is the most widespread outcrop in the study area. Three distinct basaltic layers are identified: fine-grained, olivine- or plagioclase-phyric basalt primarily in the lower section; vesicular and scoriaceous basalt interlayered with thick brownish paleosoil in the middle section; and very fine-grained, aphanitic basalt in the upper section. The unit is heavily weathered, exhibiting exfoliation and spheroidal weathering, and features multiple minor and major fracture systems, both vertical and horizontal. Compared to siliceous sedimentary rocks, the basaltic unit has narrower fracture openings and closer spacing, particularly in thin lava flow layers, resulting in higher fracture intensity in these areas and lower intensity in massive layers. These secondary features significantly enhance the unit's porosity and permeability. Additionally, well-developed columnar joints are present in the upper section. Consequently, the basalt unit is considered the most favorable for groundwater flow and storage compared to other units. This covers 182.2 km² (23.2%) of the study area.

Trachyte-phonolite Plugs: The trachyte plugs occur either as sub-circular bodies or elongated ridges in the west-southwest and east of the Selekhlakha town. The total area coverage of the trachyte/phonolite is only about 35.5 km² (4.5% of the total area). The cross-cutting relationship with the basaltic unit seems to suggest that the plugs are younger than the basaltic flows. In some places, however, for example, along the Selekhlakha-Semema road, trachyte/phonolite outcrops in the form of flows and large blocks overlie the Mesozoic sediments. The rock is usually fresh, light grey, and has a medium-grained texture. It is generally massive but contains vertical columnar joints as well. Because of the compact nature of the rock, less weathering, as well as wide fracture spacing, fracture intensity is considered low compared to the basaltic unit.

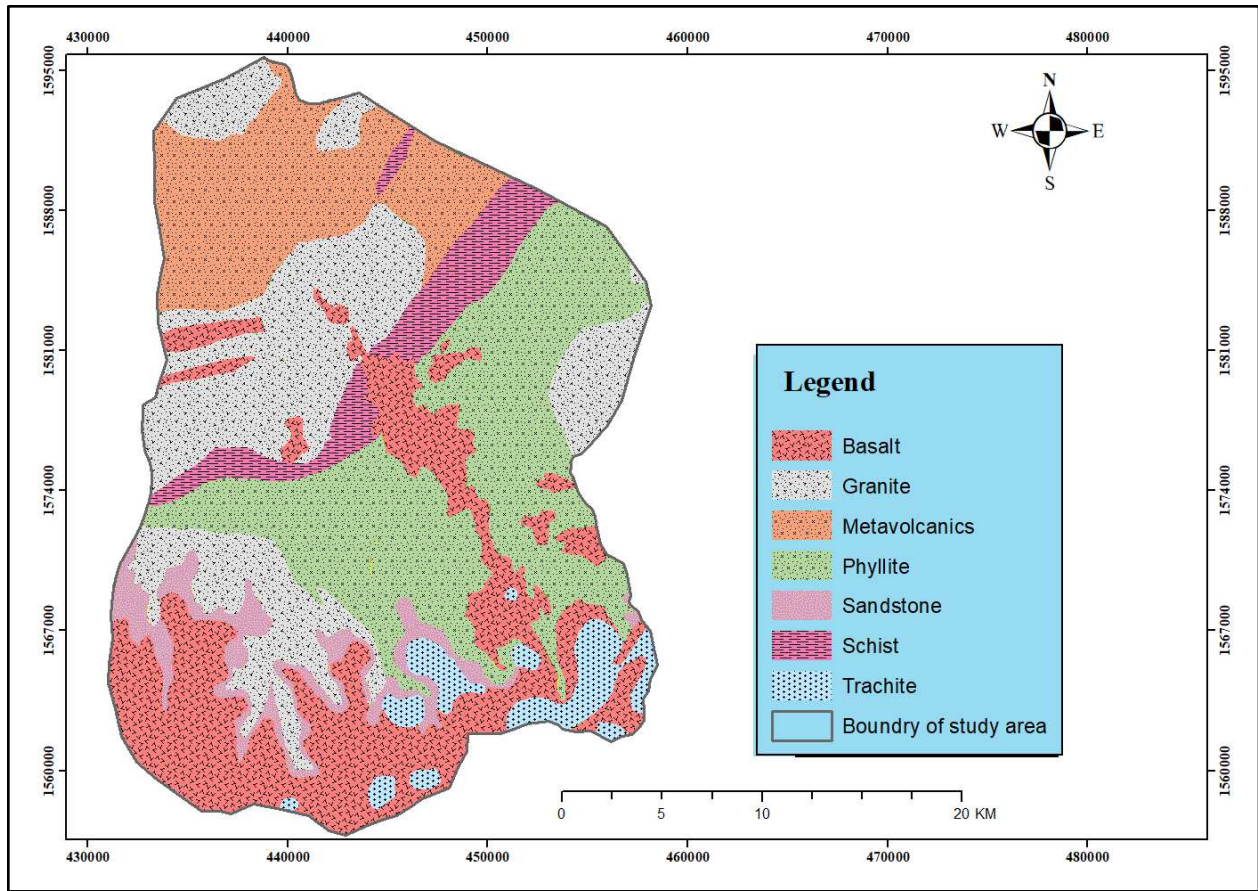


Figure 3: Lithology map of the study area.

Table 3: Normalized weight and comparison matrix of lithology

Geology	[1]	[2]	[3]	[4]	[5]	[6]	[7]	Rate	Rank
[1] Basalt	1	2	3	4	5	7	9	0.36	7
[2] Reddish sandstone	1/2	1	2	3	4	5	7	0.24	6
[3] Phyllite	1/3	1/2	1	2	3	4	5	0.16	5
[4] Schist	1/4	1/3	1/2	1	2	3	4	0.10	4
[5] Granite	1/5	1/4	1/3	1/2	1	2	3	0.07	3
[6] Trachite	1/7	1/5	1/4	1/3	1/2	1	2	0.04	2
[7] Metavolcanics	1/9	1/7	1/5	1/4	1/3	1/2	1	0.03	1
N	RI	CI	CR	CR < 0.1; therefore, consistency is					
7	1.32	0.02	0.015	acceptable					

2.2. Slope

The slope represents the steepness of the ground surface which provides important information on the nature of geologic and geodynamic processes operating at that regional scale (Kumar 2016). It is one of the criteria that helps to delineate groundwater potential zones that directly affect the infiltration and runoff (Jhariya et al. 2021; Magesh et.al. 2012). Besides, Magesh et al. (2013) stated that a higher degree of slope results in rapid runoff and increased erosion rate with feeble recharge potential.

The study area was divided into five slope classes as flat ($<5^\circ$) with “very good” infiltration rate, gentle ($6-10^\circ$) with “good” infiltration rate, moderate ($11-16^\circ$) with “moderate” infiltration, steep ($17-21^\circ$) has “poor” infiltration and very steep ($>21^\circ$) with “very poor” infiltration rate. The map (Fig. 3) shows that the largest part of the study area, mainly the central part is covered by a flat and gentle slope. This shows that the flat and gentle slope has good potential, while the steep slope has low potential in groundwater. So, a high weight is assigned for the flat plain, and a low weight is assigned for the steep slopes (Table 4).

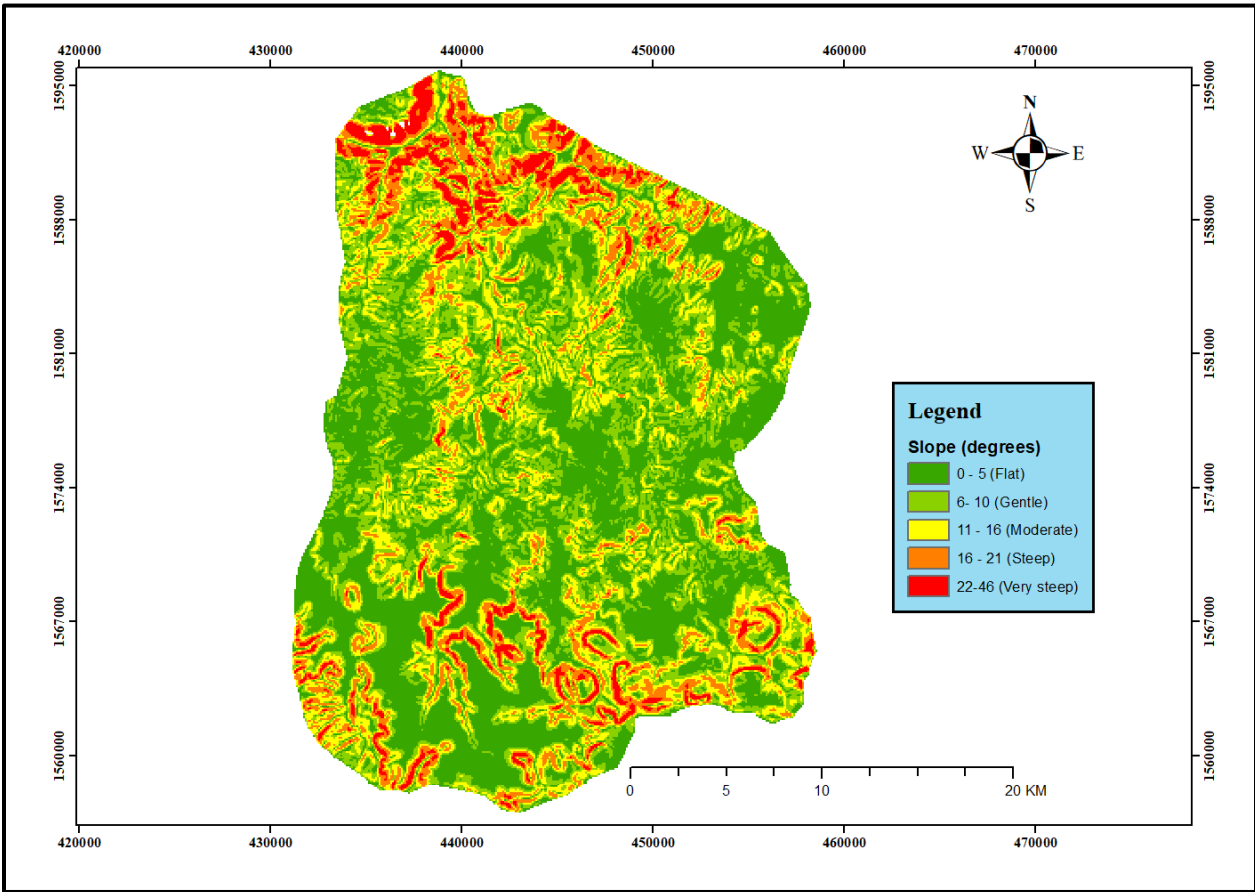


Figure 4: Slope map of the study area.

Table 4: Normalized weight and comparison matrix of slope

Slope(°)	[1]	[2]	[3]	[4]	[5]	Rate	Rank
[1] <5	1	2	5	7	9	0.49	5
[2] 5-11	1/2	1	2	5	7	0.27	4
[3] 11-16	1/5	1/2	1	2	5	0.14	3
[4] 16-21	1/7	1/5	1/2	1	2	0.07	2
[5] >21	1/9	1/7	1/5	1/2	1	0.04	1
N	RI	CI	CR	CR < 0.1; therefore, consistency is			
5	1.12	0.035	0.031	acceptable			

2.3. Drainage Density (DD)

Drainage density is defined as the closeness of spacing of stream Channels (Magesh et al. 2011). It is one of the crucial factors for the occurrence and distribution of groundwater (Ganpuram et al, 2009; Arulbalaji et al. 2019). The drainage density is the result of geology and has an inverse function with permeability (Arulbalaji et al. 2019). Areas with dense drainage networks typically have high surface runoff and low infiltration rates, leading to low groundwater recharge potential. This is often associated with impermeable lithology, steep slopes, and low-porosity soils (Jha et al. 2010; Rahmati et al. 2015). An area that has high drainage density represents and is not more favorable for groundwater potential and low drainage density represents high infiltration, which is more favorable for groundwater (Arulbalaji et al. 2019). Drainage density is the total length of all streams per unit drainage Area (Verma and Ramesh 2021).

$$DD = \frac{LS}{A} \quad \text{..... Eq. 6}$$

where DD is the drainage density, SL is the total stream length, and A is the catchment area.

The drainage density of the catchment was reclassified into five very low (0-2.9 km/km²), low (2.9-5.7 km/km²), medium (5.7-8.6 km/km²), high (8.6-11.5 km/km²) and very high (11.5-14. km/km²) (Fig. 5). In the delineation of the groundwater potential zone of the study area, a high weight was assigned for the low drainage density and a low weight was assigned for the high drainage density (Table 5).

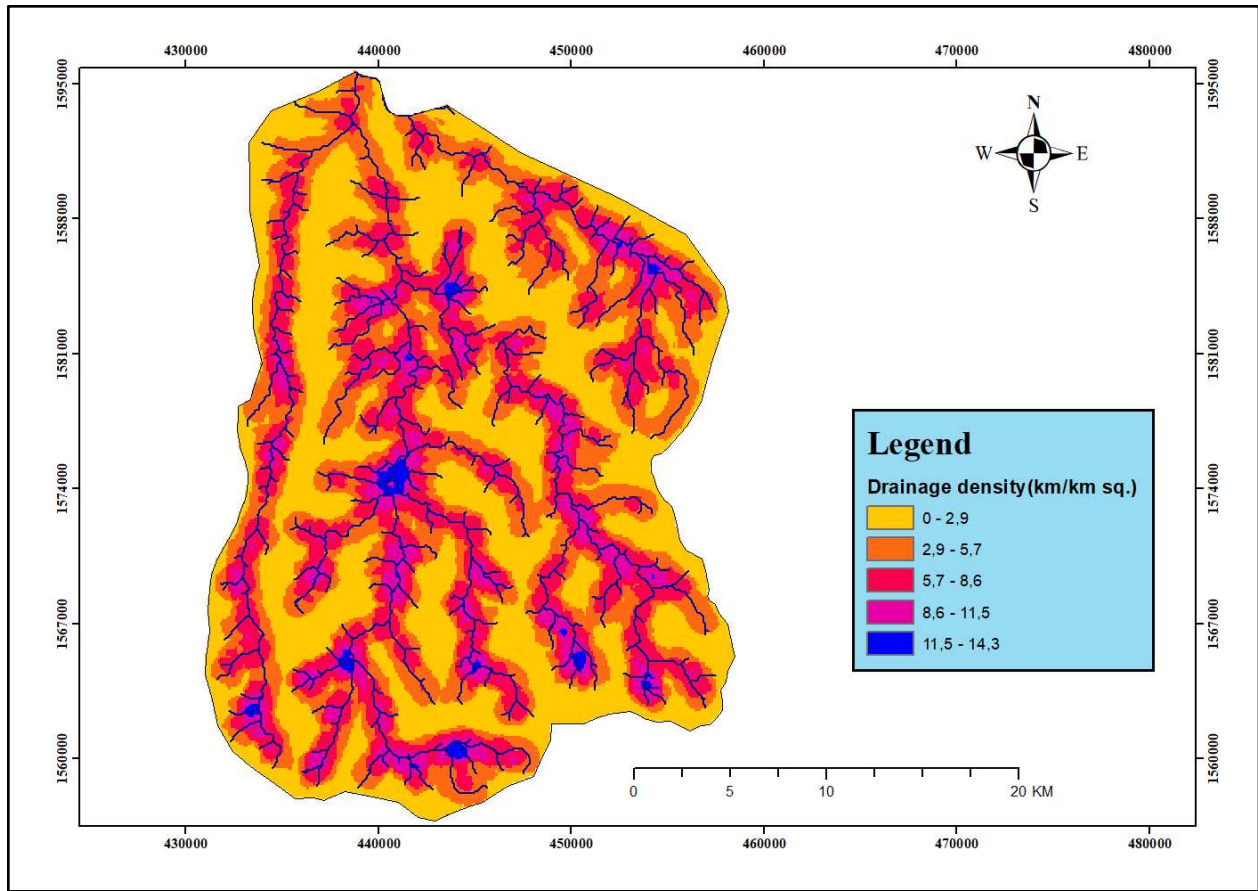


Figure 5: Drainage density map of the study area.

Table 5: Normalized weight and comparison matrix of drainage density

Drainage density (km^{-1})	[1]	[2]	[3]	[4]	[5]	Rate	Rank
[1]0-2.9	1	1/2	1/5	1/7	1/9	0.036	5
[2]2.9-5.7	2	1	1/3	1/5	1/7	0.058	4
[3]5.7-8.6	5	3	1	1/3	1/5	0.136	3
[4]8.6-11.5	7	5	3	1	1/3	0.262	2
[5]11.5-14.3	9	7	5	3	1	0.502	1
N	RI	CI	CR	CR < 0.1 , therefore, consistency is acceptable			
5	1.12	0.0425	0.038				

2.4. Land use land cover map

Consumption of land for different processes also affects the pattern of infiltration within an area (Mesfin et.al. 2022). Land use/Land Cover (LU/LC) is an important indicator of potential

groundwater zones (Verma and Ramesh 2021). Forests, water bodies, and croplands are good repositories of groundwater; built-up land and barren land are poor repositories (Verma and Ramesh 2021). The LULC of the area was categorized into six classes, namely cultivation land, forest land, settlement, shrub land, bare land, and grass, with an aerial coverage of 517 km², 71.4 km², 3.9 km², 130.17 km², 60.9 km² and 2.13 km², respectively (Fig. 6). The cultivation land and settlement are settled in the flat plains, and the forest lands are more common in the hillsides of the mountainous areas. In this study, a high weight was assigned for the grassland and a low weight was assigned for the residential area (Table 6).

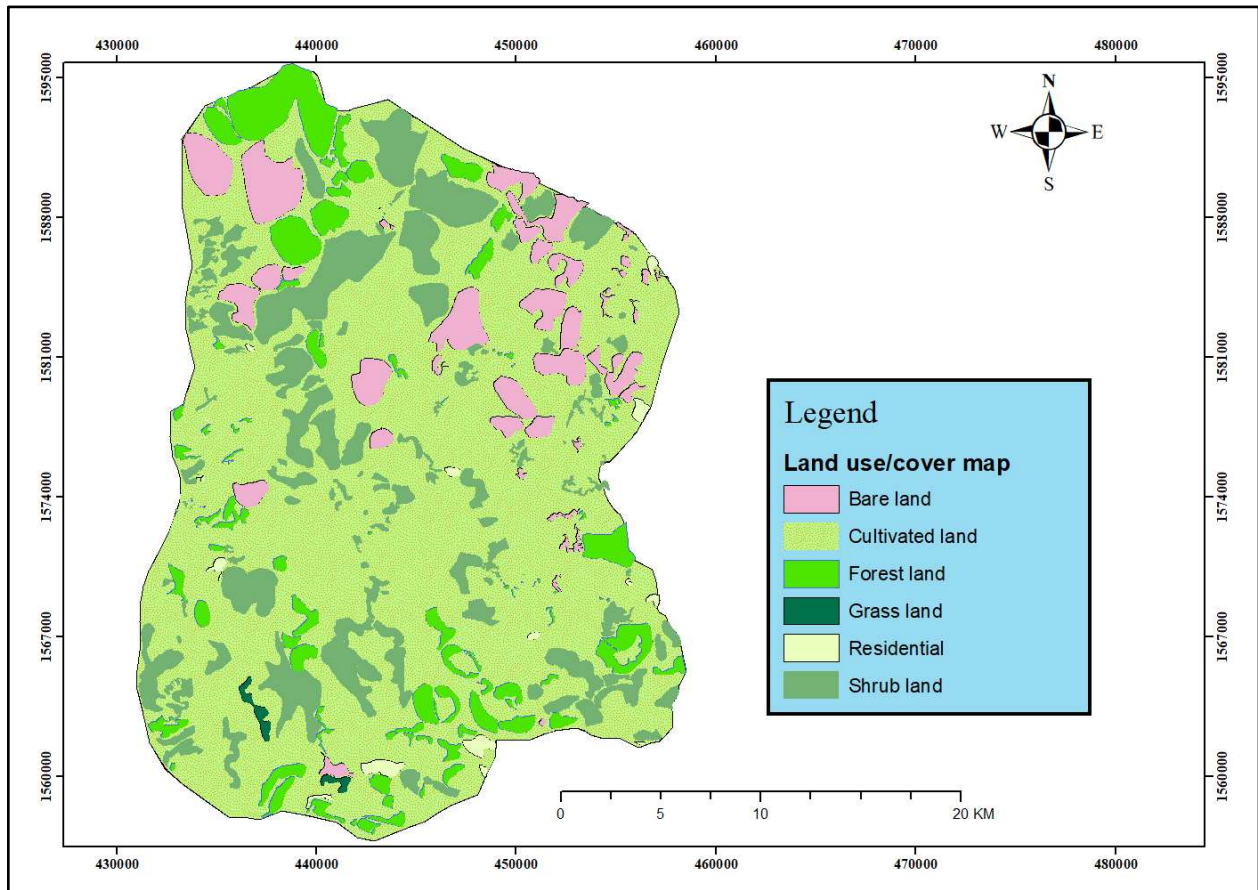


Figure 6: Land-use map of the study area.

Table 6: Normalized weight and comparison matrix of land use and land cover

LULC (km ²)	[1]	[2]	[3]	[4]	[5]	[6]	Rate	Rank
[1] Grass land	1	2	3	4	7	9	0.41	6
[2] Cultivation land	1/2	1	2	3	4	7	0.25	5
[3] Forest land	1/3	1/2	1	2	3	4	0.15	4

[4] Shrub land	1/4	1/3	1/2	1	2	3	0.10	3
[5] Bare land	1/7	1/4	1/3	1/2	1	2	0.06	2
[6] Residential	1/9	1/7	1/4	1/3	1/2	1	0.41	1
N	RI	CI	CR	CR< 0.1, therefore, consistency is				
6	1.24	0.052	0.042	acceptable				

2.5 . Lineament density

Largely extended faults and joint systems are responsible for the occurrence of GW and are very important for local (perched) aquifer system recharge (Zewdie et al. 2024). In addition, Zewdie et al. (2024) stated that lineaments are structurally controlled linear or curvilinear geological features that represent faulting and fracturing zones developed when the geologic formation is subjected to external pressure and in increased secondary porosity and permeability.

The LD of the river catchment was determined using the equation proposed by Yeh et al. (2016):

$$LD = \frac{LL}{AC} \dots\dots\dots \text{Eq. 7}$$

where LD represents lineament density, LL is the total length of lineaments, and AC is the area of the river catchment.

The lineament density map of the study area is shown in Fig. 6, which is divided into five categories based on its influence on groundwater potential. The map (Fig. 6) reveals that high lineament density is observed in the northern and southern parts of the study area, with a value > 0.88 km/km² linear alignments. In the delineation of the groundwater potential zone, a high weight was assigned for the high lineament density and a low weight was assigned for the low lineament density (Table 7).

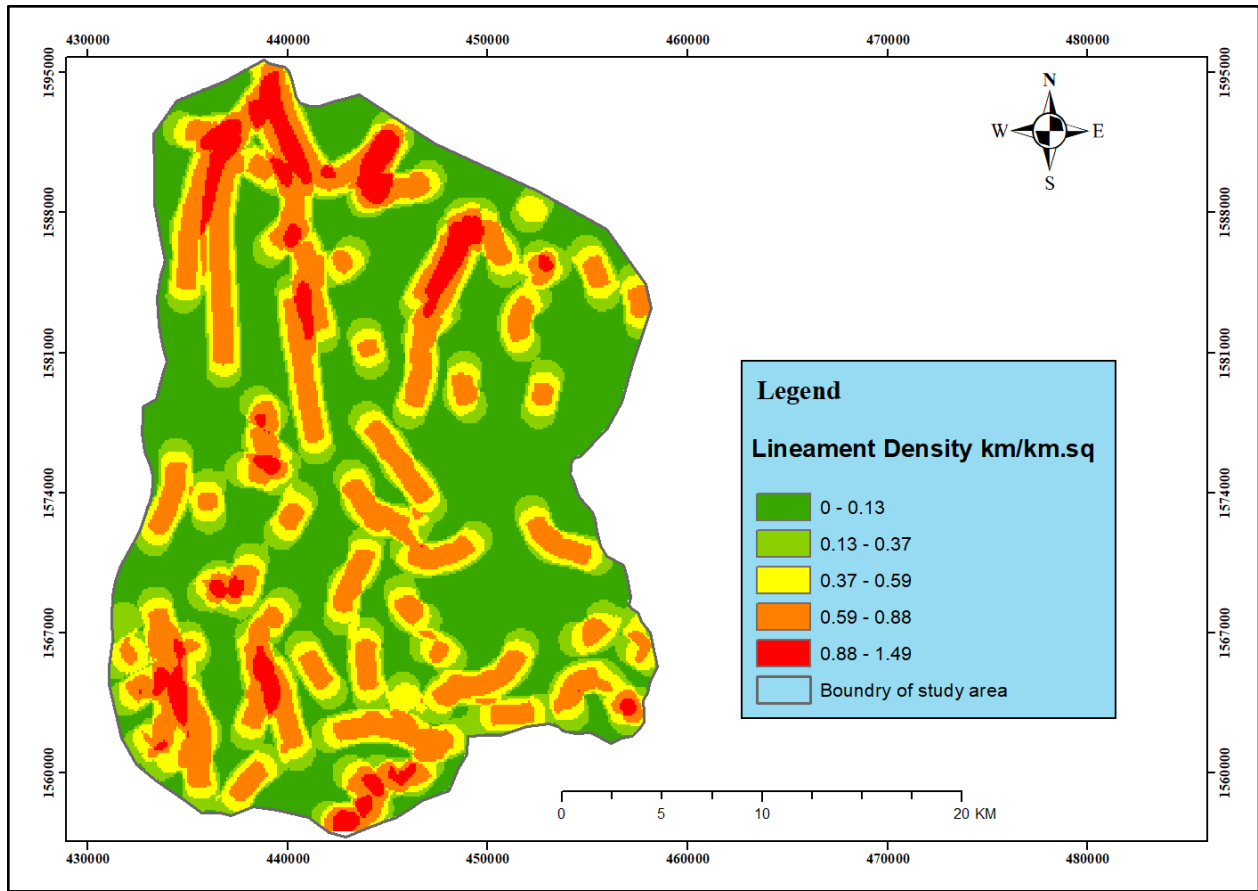


Figure 7: Lineament density map of the study area.

Table 7: Normalized weight and comparison matrix of lineament density

Lineament (km/km ²)	[1]	[2]	[3]	[4]	[5]	Rate	Rank
[1] 0-0.13	1	1/2	1/3	1/5	1/7	0.052	1
[2] 0.13-0.37	2	1	1/2	1/3	1/5	0.089	2
[3] 0.37-0.59	3	2	1	1/2	1/3	0.153	3
[4] 0.59-0.88	5	3	2	1	1/2	0.262	4
[5] 0.88-1.49	7	5	3	2	1	0.444	5
N	RI	CI	CR	CR < 0.1; therefore, consistency is acceptable			
5	1.12	0.005	0.0045				

2.6. Soil

Ibrahim-Bathis & Ahmed (2016) explained that Soil is an important parameter that affects the occurrence and distribution of groundwater, playing a significant role in the infiltration of water

and thereby influencing the recharge of groundwater. The soil map of the study area was classified into six types.

2.6.1. Cambisols:

Cambisols are developed in medium and fine-textured materials derived from a wide range of rocks, mostly in alluvial, colluvial and aeolian deposits (Table 8). It covers 57.7 km² (7.9 %) of the total study area and is exposed in two places of the study area (Fig. 8)

2.6.2. Leptosols:

Leptosols are soils with a very shallow profile depth (indicating little influence of soil-forming processes), and they often contain large amounts of gravel. (Food and Agriculture Organisation (FAO). This soil type covers 74.6 km² (10.1%) of the total area. This soil type is coarse-grained, and it is not suitable for the infiltration of groundwater.

2.6.3. Fluvisols:

Fluvisols are young soils formed from recent alluvial deposits, often found in floodplains, deltas, and coastal areas. This covers 204.6 km² (26.6 %) of the total study area.

2.6.4. Regosols:

Regosols are characterized by shallow, medium- to fine-textured, unconsolidated parent material that may be of alluvial origin and by the lack of a significant soil horizon (layer) formation because of dry or cold climatic conditions. They are usually found under their original natural vegetation or under limited dryland cropping. This covers 265.8.4 km² (34.4 %) of the study area. This soil type contains from sandy to clayey materials.

2.6.5. Luvisols:

Luvisols are moderately weathered soils; they contain less Al-, Fe- and Ti-oxides than their tropical counterparts, the Lixisols, and have an SiO₂/Al₂O₃ ratio in excess of 2.0. Luvisols tend to become richer in swelling and shrinking clays towards the dry end of their climatic zone. Covers 4.4 km² (1.15 %) of the area.

2.6.6. Vertisols:

424 Vertisols are heavy clayey soils enriched with montmorillonite clay minerals that shrink when dry
 425 and swell when wet. Through alternation of dry and wet, deep and wide vertical cracks are
 426 developed on their profiles. This soil type covers 178.2 km² (23.3 %) of the total study area.

427 Table 8: Conversion of agricultural soil to textural soil

Food and Agriculture Organization (FAO) classification	Textural classification
Cambisols	These soils have a fine texture, often loamy (balanced sand, silt, clay) to clayey. Fine grained
Regosols	from sandy to clayey,
Leptosols	These shallow soils often have coarse textures (sandy or loamy) due to their development on hard rock or gravelly material. Coarse grained
Luvisols	leading to a clay loam or clay texture in the B horizon. Medium grained
Fluvisols	They can range from sandy (in high-energy river systems) to silty or clayey
Vertisols	These soils are clay-rich, typically with >30% clay (fine-grained)

428

429 Table 9: Normalized weight and comparison matrix of soil

Soil type	[1]	[2]	[3]	[4]	[5]	[6]	Rate	Rank
[1] Leptosols	1	3	5	7	8	9	0.40	6
[2] Luvisols	1/3	1	3	5	7	8	0.25	5
[3] Fluvisols	1/5	1/3	1	3	5	7	0.16	4
[4] Regosols	1/7	1/5	1/3	1	3	5	0.10	3
[5]Cambisols	1/8	1/7	1/5	1/3	1	3	0.06	2
[6] Vertisols	1/9	1/8	1/7	1/5	1/3	1	0.04	1
N	RI	CI	CR	CR < 0.1; therefore, consistency is				
6	1.24	0.004	0.0032	acceptable				

430

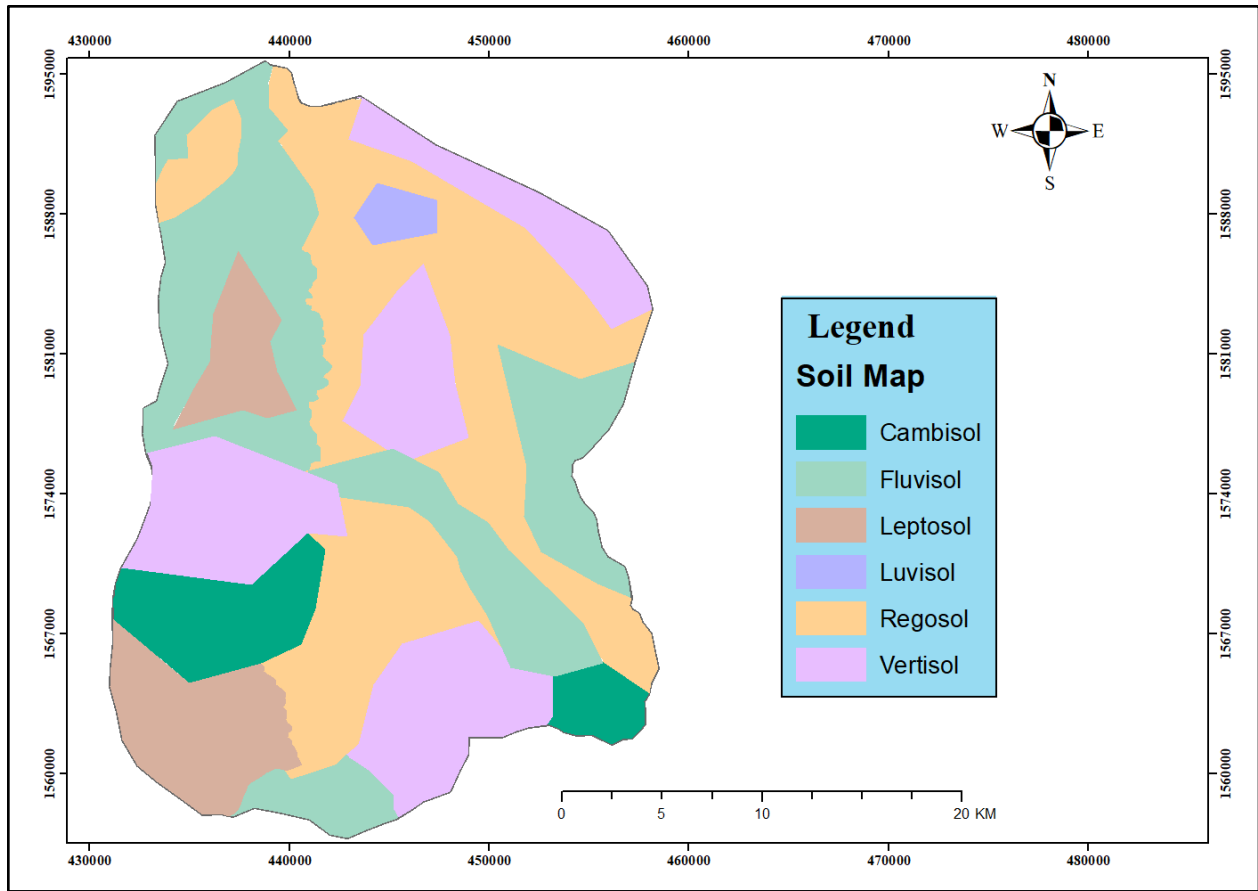


Figure 8: Soil map of the study area.

2.7. Rainfall

Rainfall is the most important water source in the hydrological cycle and the primary leading factor in the groundwater of an area (Arulbalaji et al. 2019). The southwestern part of the river catchment receives low precipitation, while the northeastern part receives relatively high precipitation (Fig. 9). Diriba et al. (2024) explained that the intensity of rainfall directly affects groundwater recharge, with higher intensity leading to increased recharge and vice versa. The mean annual precipitation of the study area ranges from 760 to 1095 mm/year, with an average value of 913 mm/year. The precipitation distribution in the basin can be grouped into five classes as 760 to 825 mm, 825 to 895 mm, 895 to 960 mm, 960 to 1025 mm and 1025 to 1095 mm/year (Fig. 9). The area with low precipitation is assigned a low weight (Table 10) and the area with high precipitation is assigned a higher weight.

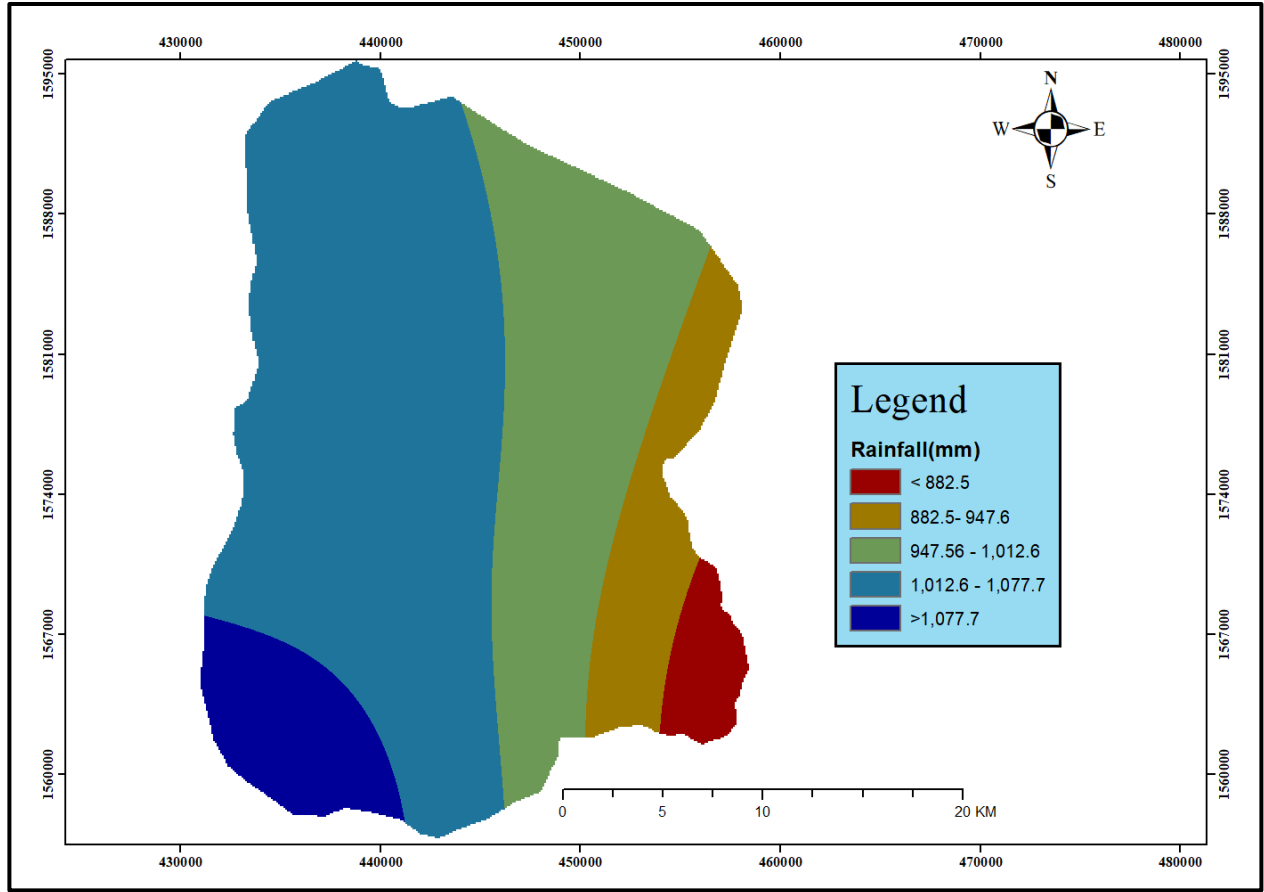


Figure 9: Rainfall map of the study area.

Table 10: *Normalized weight and comparison matrix of rainfall*

Rainfall (mm)	[1]	[2]	[3]	[4]	[5]	Rate	Rank
[1]> 1077.7	1	3	5	7	9	0.46	5
[2] 1012.6-1077.7	1/3	1	3	5	7	0.25	4
[3] 947.6-1012.6	1/5	1/3	1	3	5	0.20	3
[4] 882.5-947.6	1/7	1/5	1/3	1	3	0.06	2
[5] <882.5	1/9	1/7	1/5	1/3	1	0.03	1
N	RI	CI	CR	CR< 0.1; therefore, consistency is acceptable			
5	1.12	0.05	0.044				

2.8. Elevation

The occurrence of groundwater is significantly impacted by elevation (Diriba et al. 2023)

According to Thepa et al. (2017) cited in (Diriba et al. 2024), groundwater tends to flow from high

elevation to low elevation and high-pressure areas to low-pressure, with minor exceptions for surface irregularities. Elevation of the river catchment ranges from 1457 to 2063 m and is divided into five categories (Fig. 10). The northern parts of the river catchment have lower elevations (1457 m), while higher elevations are found in southern areas (2063 m). According to Waikar and Nilawar 2014) cited in (Diriba et al. 2024) plainer regions with lower elevations have a longer water retention time, resulting in more significant infiltration and recharge of water and areas with higher elevations experience more runoff and less infiltration. Based on that, lower elevated zones in the northern part of the river catchment are assigned higher weight, while highly elevated areas in southern part of the river catchment are assigned lower weight (Table 11).

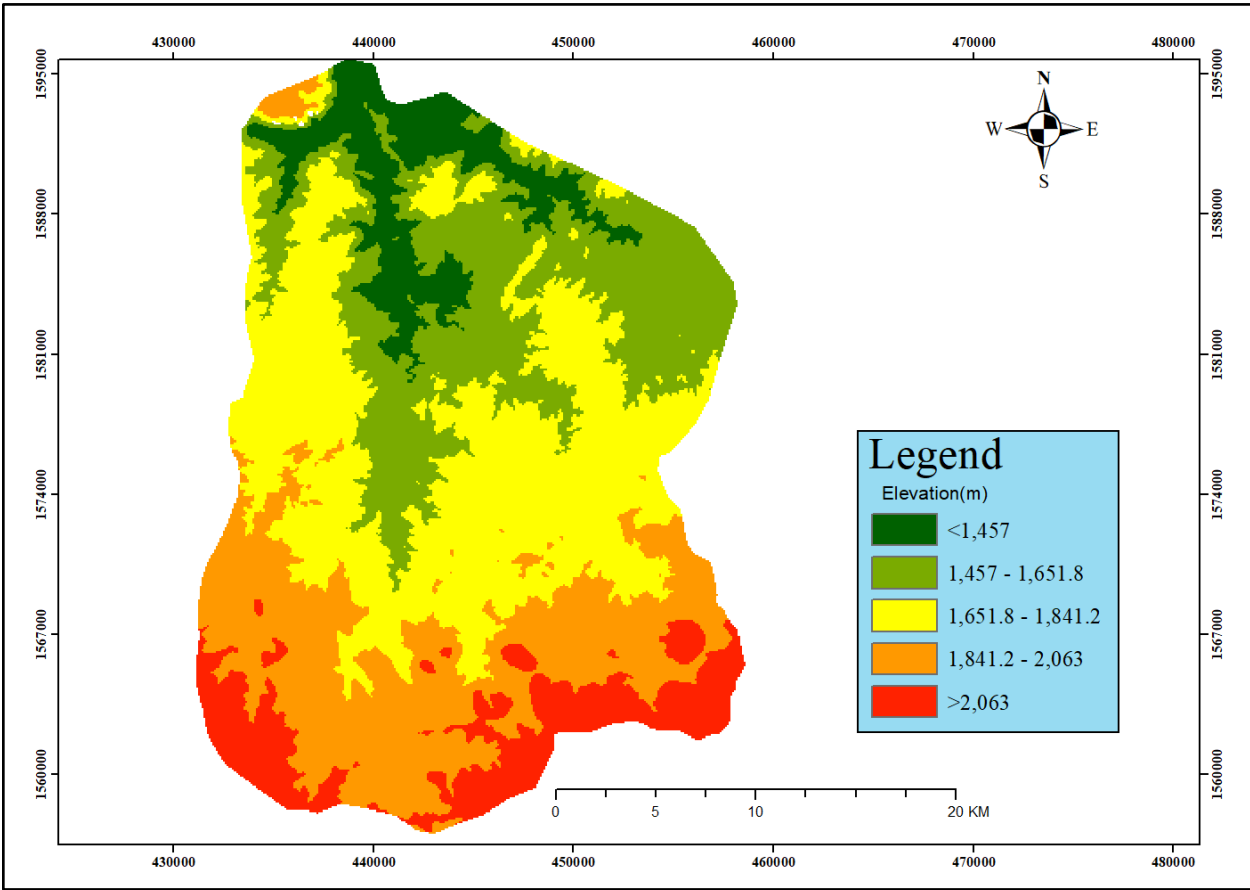


Figure 10: elevation map of the study area

Table 11: Normalized weight and comparison matrix of rainfall

Elevation(m)	[1]	[2]	[3]	[4]	[5]	Rate	Rank
[1] <1457	1	2	3	5	7	0.44	5

This indicates this zone has a high possibility due to the basalt formation, precipitation and slope effect. Arulbalaji et al. (2019) stated that very high and high groundwater potential zones are confined generally to high rainfall regions, which in turn have high infiltration potential. Similarly, the good groundwater potential zone is found in the southern and central part of the study area in the gentle slope in the foliated metamorphic rock (phyllite) and basalt rock formation. The very low groundwater potential zone is mainly concentrated in the northern and southeastern parts of the area. This is exposed in the low precipitation, very steep slope, metavolcanics and close drainage density area (Fig. 11).

Table 13: Class of thematic layers with normalized weights

Themes	% Influence	Individual class/features	Normalized weight	Rank
Geology	34	Basalt	0.31	8
		Reddish sandstone	0.23	7
		Phyllite	0.16	6
		Schist	0.12	5
		Granitoids	0.07	4
		Granite	0.05	3
		Trachite	0.04	2
		Metavolcanics	0.02	1
Rainfall	23	> 1077.7	0.46	5
		1012.6-1077.7	0.25	4
		947.6-1012.6	0.20	3
		882.5-947.6	0.06	2
		<882.5	0.03	1
slope	16	<5	0.49	5
		5-11	0.27	4
		11-16	0.14	3
		16-21	0.07	2
		>21	0.04	1
Lineament density	10	0-0.13	0.052	1
		0.13-0.37	0.089	2
		0.37-0.59	0.153	3
		0.59-0.88	0.262	4

		0.88-1.49	0.444	5
LULC	7	Grass land	0.41	6
		Cultivation land	0.25	5
		Forest land	0.15	4
		Shrub land	0.10	3
		Bare land	0.06	2
		Residential	0.04	1
soil	5	Leptosols	0.40	1
		Luvisols	0.25	2
		Fluvisols	0.16	3
		Regosols	0.10	4
		Cambisols	0.06	5
		Vertisols	0.04	6
Elevation(m)	3	1572-1742	0.44	5
		1743-1911	0.26	4
		1912-2080	0.15	3
		2081-2250	0.09	2
		>2250	0.05	1
Drainage density	2	0-2.9	0.036	5
		2.9-5.7	0.058	4
		5.7-8.6	0.136	3
		8.6-11.5	0.262	2
		11.5-14.3	0.502	1

The groundwater potential map of the study area is validated with the concentration of borehole and springs (Fig. 12). The result indicates that most of the water points, which serve for irrigation and drinking purposes, are concentrated in the very good and good groundwater potential zones (Fig. 12).

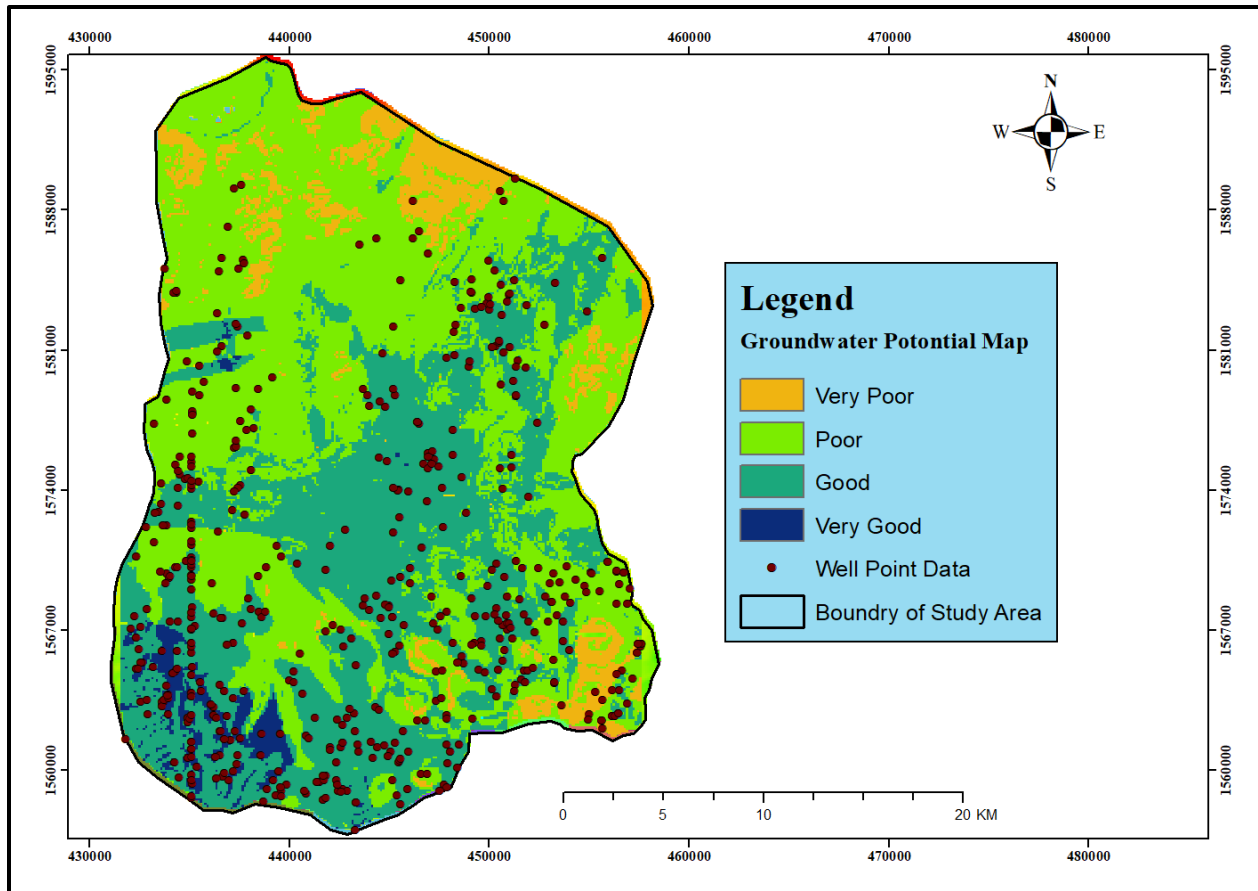


Figure 11: Groundwater potential zone map

4. Conclusion

In this study integrated RS, GIS, and AHP approach was successfully utilized to delineate the GWP zones of the Selekleka River catchment. Eight parameters were considered (rainfall, elevation, drainage density, soil types, lineament density, lithology, slopes, and LUL) in the study to produce a GWP zones map. To assign suitable weights to each factor, the AHP approach was employed, considering their varying contributions to groundwater occurrence to ensure accuracy. Finally, all thematic layers were integrated using a WOA in the ArcGIS environment. The result of the GWP zones map indicated the distribution of different GWPZs in the river catchment. The classification showed that 61.2 km² (6.5 %) of the total area falls under the 'very poor' zone, while 387.6 km² (48 %) falls under the 'poor' zone. Good GWPZ covers 311.9 km² (39%) of the total area, and 24.5 km² (2.6%) of the study area falls under the 'very good' zone. Therefore, the study suggests prioritizing the development of groundwater resources in these favorable GWPZs to

enhance the productivity of agriculture and domestic water supply in the catchment. As the study indicated, lithology is the area's most dominant factor regulating groundwater potential zones.

To validate the result, the different water points were distributed in GWP zones map. The validation result approves that most of the water points are concentrated in the “good” and “very good” GWP zones of the study area. The study recommended that to determine the aquifer characteristics, such as porosity, permeability and the extent of the aquifer, detailed aquifer characterization studies should be conducted by future researchers. This will optimize the groundwater abstraction methods and supply crucial information for effective groundwater resource management.

Declaration

We authors confirm that there is no conflict of interest.

Data availability

Data will be available on request.

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Consent for publication: Not applicable, as the manuscript does not contain any identifying information or images of study participants.

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