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ARTICLE

Delineating Groundwater Potential Zones Using Geospatial and Analytical Hierarchy Process Techniques in the Upper Omo-Gibe Basin, Ethiopia

Yonas Hagos[1,2,*], Zelalem Bedaso[1] and Mulugeta Kebede[3]

[1]Department of Geology and Environmental Geosciences, University of Dayton, Dayton, OH 45469, USA

[2]Hanley Sustainability Institute, University of Dayton, Dayton, OH 45469, USA

[3]Institute of Geophysics, Space Science and Astronomy, Addis Ababa University, Addis Ababa, 1000, Ethiopia

*Corresponding Author: Yonas Hagos. Email: hagosy3@udayton.edu

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ABSTRACT

In regions with unpredictable rainfall and limited water supply, it's crucial to pinpoint areas with high potential for groundwater and find the best spots for groundwater resource development. This study utilizes the Analytic Hierarchy Process (AHP) in combination with Geographic Information Systems (GIS) to evaluate the potential groundwater zones in the Gombora watershed within the Omo Gibe basin in Ethiopia. Combining these two tools provided a detailed map showing potential groundwater areas. These zones are determined based on various thematic maps containing information about geology, soil texture, lineament density, slope, land use, and drainage density. The AHP method combines these data layers by assigning weights to each layer based on its importance for groundwater recharge. These weighted layers are then overlaid using a GIS platform to produce a conclusive map of potential groundwater areas. The groundwater potential within the watershed was qualitatively divided into five categories with area coverages of very good (1.6%), good (7.4%), moderate (21.4%), poor (51.6%), and very poor (17.9%) of the watershed area. The accuracy of the groundwater potential zones was evaluated using the receiver operating characteristic (ROC) curve and the area under the curve (AUC), producing good results (AUC = 75.5%). This research has shown that integrating AHP with GIS can effectively pinpoint potential groundwater zones. Additionally, the findings could play a key role in determining suitable locations for new groundwater wells and supplying valuable insights to decision-makers to aid in planning and implementing sustainable strategies for managing groundwater resources in the watershed.

KEYWORDS

Analytic hierarchy process; ArcGIS; groundwater potential zone; MCDA (Multi-Criteria Decision Analysis); weighted index overlay

1 Introduction

Around half of the world's population relies on groundwater as their primary source of freshwater. Agriculture, industry, and ecosystems depend on groundwater [1,2]. Nevertheless, in various regions worldwide, including Ethiopia, groundwater resources face severe threats stemming from overuse, rapid population growth, pollution, and the effects of climate change [3]. Over 80% of Ethiopia's water supply comes from groundwater [4], and with increasing demand and climate change affecting its availability, exploration, and development of groundwater resources are essential to meet these evolving demands and ensure a dependable water supply [5–8]. A crucial aspect of effective groundwater management involves identifying and estimating groundwater potential [9,10]. This process includes evaluating the quantity and quality of groundwater resources and identifying the areas with the highest potential for groundwater development [9]. To ensure the long-term sustainability of groundwater resources, policymakers and stakeholders can use groundwater potential assessment to promote groundwater development and improve effective groundwater management [8,11,12]. Therefore, identifying sites with high groundwater potential in Ethiopia will support groundwater development and help address the critical water shortage for drinking, irrigation, and industry [9,13].

Geospatial technology provides a more efficient and cost-effective method for identifying groundwater potential zones compared with the traditional approaches. Traditional methods rely on ground surveys using geophysical, geological, and hydrogeological tools, which can be expensive, time-consuming [14–18], and often qualitative and subjective [19]. In contrast, geospatial tools allow for quick and affordable data analysis and modeling in various geoscience fields [20,21]. The geospatial mapping of groundwater potential has been used in several regions of the world, including China [22], Ethiopia [23], and India [24]. These techniques involve integrating different thematic layers such as land use, soil texture and depth, rainfall, and slope [25–28] to identify potential groundwater zones. By integrating multiple data sources, geospatial technology generates quantitative results that can be utilized for decision-making [19,25]. This approach is valuable for identifying and mapping potential groundwater zones, which is beneficial for the sustainable management of groundwater resources.

Numerous researchers have definitively utilized various techniques to define and map groundwater potential zones. For instance, some researchers have used machine learning techniques such as random forest (RF) [29–32], maximum entropy (ME) [33,34], probabilistic models such as artificial neural network model [35–39], certainty factor [40], decision tree [41,42], evidential belief function [43–45], frequency ratio [22,33,46–50], logistic regression [51–54], multi-criteria decision analysis [8,55–57], Shannon's entropy [58,59], and weights-of-evidence [43,60,61]. Prior to employing expensive surveying methods, remote sensing, and GIS are used to economically identify potential groundwater locations [62]. To that end, Multi-Criteria Decision Analysis (MCDA) has recently been used in various research to evaluate groundwater potential zones [63–65]. According to Uc castillo et al. [66] and Doke et al. [67], the Analytical Hierarchy Process (AHP) is the most well-known and often applied technique used to define groundwater prospecting zones.

In the study area, the groundwater potential is poorly known and hasn't been well-studied. Thus, the main objective of this study is to map groundwater potential zones in the Gombora watershed using the combination of geospatial and AHP techniques. The study's outcome could provide valuable information for decision-makers, policymakers, and water resource planners to make effective and sustainable groundwater resource management.

2 The Study Area and Methods

2.1 Description of the Study Area

The Gombora watershed is located between 7°22′15″ and 7°41′10″ N latitude and 37°32′30″ and 37°52′40″ E longitude in Ethiopia. It covers an area of 614.7 km^2 and is part of the Omo Gibe basin. The altitude of the area ranges from 998 meters above sea level at the Omo-Gibe River valley to 2817 m above sea level at peak Shonkola. The elevation generally decreases from east to west, with lower elevations in the western part of the watershed and higher elevations in the north and southeastern areas Fig. 1.

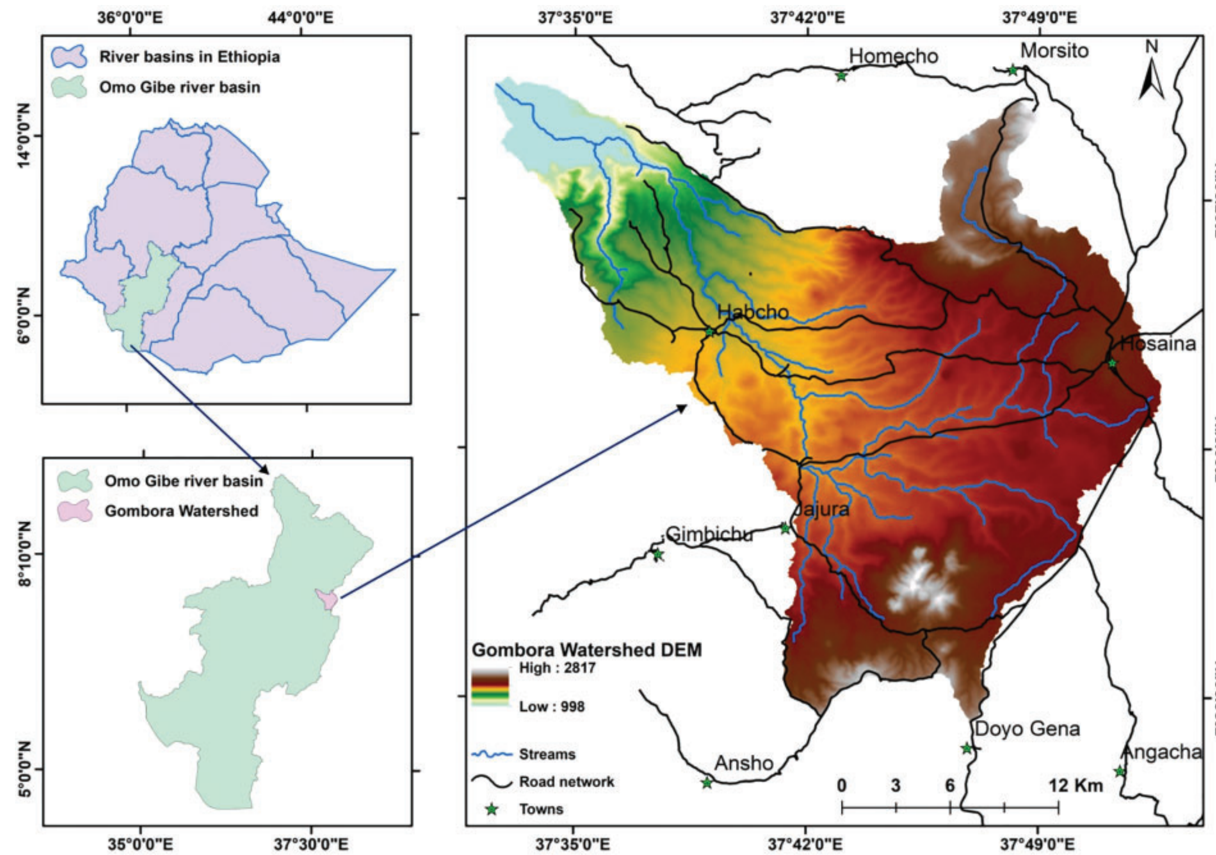

Figure 1: Location of the study area in relation to river basins in Ethiopia and the Omo-Gibe River basin

In the study watershed, there are four different geological units: Ignimbrite, Rhyolite and Ignimbrite, Pumice, tuff and ignimbrite, and Pre-rift volcanics, which cover 52.7, 125.1, 397.1, and 39.8 km^2, respectively. With an aerial extent of 456.3 km^2, light clay (Humic Nitisols) dominates the soil texture/type, followed by sandy clay loam (Chromic Luvisols), which covers 120.0 km^2, and clay loam (Lithic Leptosols), which covers 38.3 km^2 of the watershed. Cropland (392.9 km^2) built area (155.0 km^2), rangeland (34.6 km^2), and forest land spanning an extent of 32.1 km^2 of the total area make up the four land-use groups that characterize the research region. So far, the study area has been distinguished by slope gradients ranging from 0–409.5 in percent rise. The drainage density of the watershed ranges from 0 to 1.7 km/km^2.

In the Gombora watershed, groundwater is primarily used for residential purposes, though occasionally, farmers use it to make up the difference in irrigation needs in various areas of the watershed. Even though several wells have been dug to help meet domestic water needs, a severe water shortage still requires immediate action. Thus, assessment of groundwater potential is essential to alleviate the water shortage and meet significant growing needs for irrigation and residential use.

2.2 Materials and Methods

The investigation utilized a variety of data and software (Table 1). A digital elevation model (DEM) with a resolution of 12.5 m was used to outline the study watershed boundary and produce slope and drainage density maps using ArcGIS. The lineament density map of the study area was generated using a Landsat 8 Operational Land Imager (OLI) satellite image obtained from the USGS website. Lineaments were automatically extracted using the line module of PCI Geomatica. The Geological Survey of Ethiopia provided the geological information, and the data from the Ministry of Water and Energy (MoWE) and Harmonized World Soil Database (HWSD) were used to prepare a soil map of the research area. The 10 m resolution land use/cover map for 2022 was acquired from https://livingatlas.arcgis.com/landcover/ (accessed on 24 July 2023). Finally, to validate the model's output water well and spring location, the water well yield of the existing wells was collected from the zonal, regional, and federal water resources offices.

The factors impacting groundwater occurrence and flow were given weight after the thematic maps were created using ArcGIS 10.3.1 software. Engineers, geologists, hydrologists, and GIS experts provided input for the reclassification of factors and their sub-criteria in ArcGIS, and it was based on that input as well as previous literature [8,12,57,68,69]. Then, using weighted index overlay analysis, a groundwater potential map was created (Fig. 2).

Table 1: Data sources used in this study

Data type	Original format sources	Source of data	Derived map
Geological map	Vector	Geological Survey of Ethiopia	Geological map
DEM	Raster	https://search.asf.alaska.edu/ (accessed on 24 July 2023)	Slope map, drainage density map
Soil map	Vector	MoWE/HWSD V: 1.2	Soil texture map
Landsat 8 (OLI)	Raster	https://landsatlook.usgs.gov/ (accessed on 24 July 2023)	Lineament density map
LULC data	Raster	[70] https://livingatlas.arcgis.com/landcover/ (accessed on 24 July 2023)	Land use/cover map
Well locations	Point	Site Visit and Regional and Zone Water Resource Offices	Borehole, spring locations

Note: DEM: Digital Elevation Model; LULC: Land Use/Land Cover; MoWE: Ministry of Water and Energy of Ethiopia; HWSD: Harmonized World Soil Database Version 1.2.

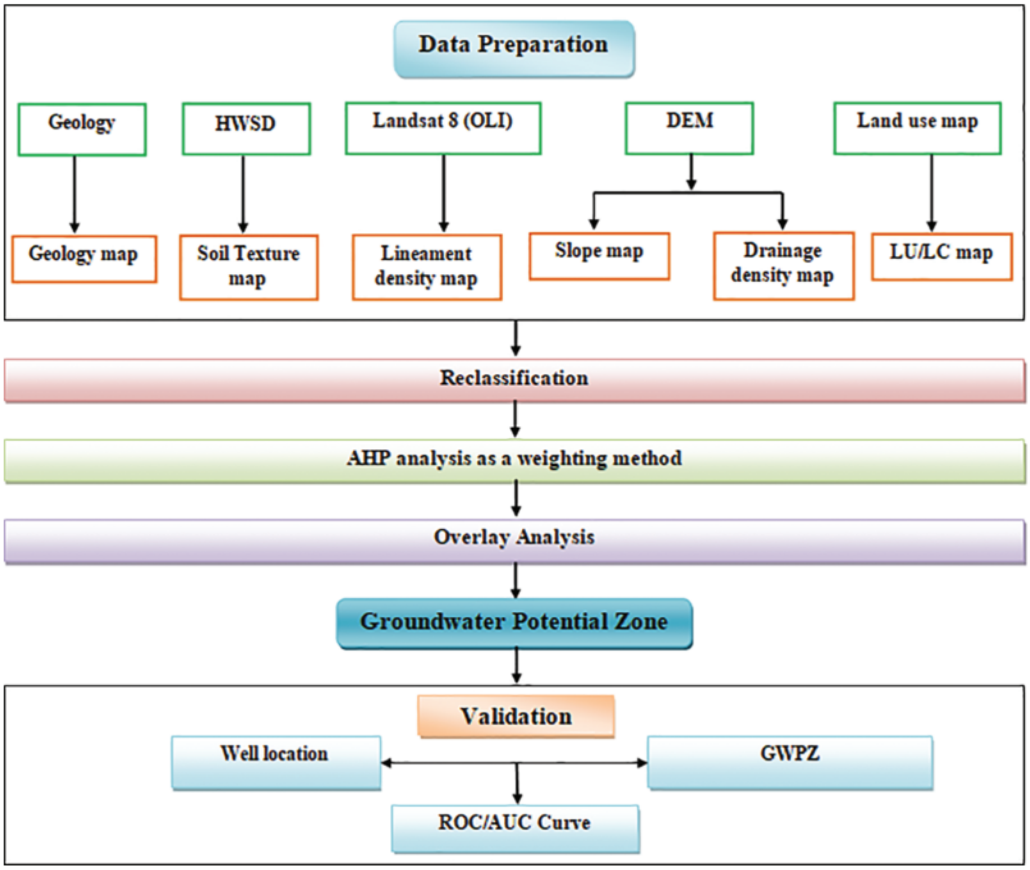

Figure 2: Workflow of groundwater potential zone analysis for Gombora watershed

2.3 Thematic Map Preparation

2.3.1 Geology

The geology of an area is crucial for assessing groundwater potential because it affects the porosity and permeability of rock formations. These factors directly influence the amount of water that can be stored and extracted from an aquifer or underground water source [8,12,71]. The ability of different rock types to hold water and allow its movement depends on their level of permeability and porosity [8,72]. For example, sandstones and fractured limestone are well-suited for groundwater storage and yield higher well outputs due to their high levels of porosity and permeability. Conversely, impermeable rock types such as volcanic rocks, metamorphic rocks, and some sedimentary rocks do not allow water to move through them easily and are therefore unsuitable as aquifers [73]. Identifying the most suitable drilling locations requires utilizing geological data to evaluate groundwater potential [74]. It is essential to have a comprehensive knowledge of geology to identify the most favorable hydrological conditions, reduce drilling costs, and improve sustainability and management practices in the use of groundwater resources [75].

The Gombora watershed is dominated by volcanic rocks (Fig. 3a). Four lithologic units are exposed in the area dominated by the Upper Miocene-Pliocene Nazareth group in the central part of the study area. The Nazareth group comprised of pumice, tuff, ash flows, ignimbrites, rhyolite, and trachyte. The northeastern low-lying areas along the Omo-Gibe River are characterized by alkaline to sub-alkaline Oligocene pre-rift volcanics with basaltic and rhyolitic composition. The northeastern part of the study area is dominated by pyroclastic flow deposits, ignimbrite, composed of a poorly sorted mixture of rock and pumice fragments and crystals in a volcanic ash groundmass. The rocks exposed in the southern part of the study area are mapped as a peralkaline silicic undifferentiated rock with rhyolites and ignimbrites. Generally, Ignimbrites are characterized as low-density and high-porosity rocks. However, their porosity and permeability can vary depending on factors such as the degree of welding and the presence of fractures or faults. Highly welded ignimbrites may have low porosity and permeability, while less welded and highly fractured ignimbrites may have higher porosity and permeability. The central and northeastern parts of the study are mainly comprised of unwelded tuff and pumice deposits, which might lead to high porosity and permeability. The spatial distribution of different rock types could control the degree and nature of groundwater recharge in the study area.

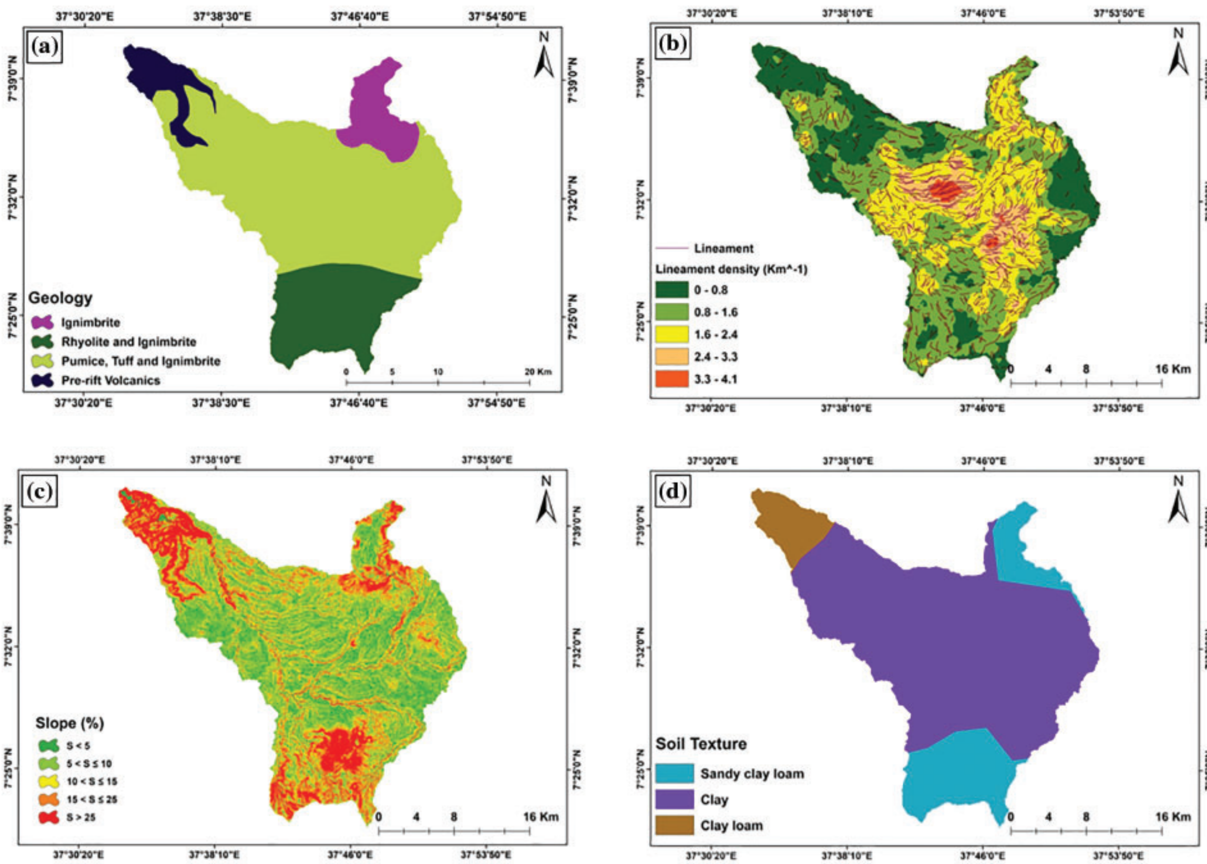

Figure 3: Geology (a); Lineament density (b); Slope (c); and Soil texture (d) maps of the study area

2.3.2 Lineament Density

Lineament density is the quantity of linear geological structures on the surface that are expressions of underlying geological structures, such as faults and fractures, present in each area [76]. These lineaments can act as channels for subterranean groundwater movement, enhancing the likelihood of groundwater availability. In hydrogeological research and decision-making processes related to managing groundwater resources, the density of lineaments can substantially impact groundwater flow and potential assessment [8]. Due to the presence of natural fractures that allow water to pass through rocks and soils, areas with high lineament density have enhanced permeability [22,77–80]. Thus, areas with a high lineament density typically have higher rates of groundwater recharge and outflow [8,81,82]. Lineament density has been employed in several studies to evaluate the potential and vulnerability of groundwater [8,12,69].

To create the lineament density map, we utilized a Landsat 8 (OLI) satellite image captured on 19 February 2022. The line module of PCI Geomatica was employed to generate the lineament map [69]. Lineament density (Ld), which was estimated (Eq. (1)) to generate a lineament density map, is defined as the total length of lineaments per unit area [8,12,69,83].

$$L_d = \frac{\sum_{i=1}^{n} L_i}{A} \tag{1}$$

where $\sum_{i=1}^{n} L_i$ represents the total length of lineaments (L), A represents a unit area (L^2), and n stands for the number of lineament networks in the watershed. The lineament density of the study area was classified into five classes (Fig. 3b). Lineaments with densities ranging from $1.6 \geq L_d > 0.8$ km^{-1} dominated the study area with an area coverage of 39.1%. Areas having a lineament density with $L_d > 3.3$ km^{-1} were considered excellent groundwater prospective zones covering about 1.1% of the watershed area. Whereas, about 25.5% of the study area has $L_d < 0.8$ km^{-1}, which is considered as a very poor groundwater prospect zone.

2.3.3 Slope

Considering its significant impact on various aspects such as rainfall infiltration, runoff speed, and groundwater potential, the land slope is a crucial factor in assessing groundwater potential [71,73,74,81,84]. Due to limited infiltration and recharge, a high-slope location would have poor recharge prospects and weak groundwater potential [85]. On the other hand, gentle slopes provide great potential for groundwater recharging and high levels of precipitation infiltration [86]. The slope of an area impacts infiltration capacity, runoff retention on the soil surface, and runoff speed [87]. Flat lands are excellent for groundwater recharge capacity because they favor high infiltration rates and less surface runoff generation. On the contrary, there is less time for stormwater to penetrate in places with steep slopes, and rainfall is easily converted to runoff and runs down the slope quickly [88]. As a result, these locations have low groundwater potential.

The slope percentage map of the study area (Fig. 3c) was prepared from DEM with 12.5 m resolution using a spatial analysis tool in ArcGIS 10.3.1. The slope percentage of the study area varies between 0 and 409.5 %. The area under examination has been divided into five slope categories. About 21.8% of the landscape is under the gentle slope (S < 5%) category. In contrast, the moderate (5% < S ≤ 10%), moderately steep (10% < S ≤ 15%), very steep slope (15% < S ≤ 25%), and escarpment (S > 25%) covers about 29.4%, 18.8%, 18.3%, and 11.7% of the total area of the watershed, respectively.

2.3.4 Soil Texture

It is crucial to consider soil texture when assessing groundwater potential [7,8,71,89]. The distribution of soil particles, including sand, silt, and clay, significantly affects groundwater recharge and storage. Clay soils have low porosity, which hinders rain percolation and increases surface runoff, while sandy soils, with their high porosity and permeability, allow water to percolate quickly [71]. Additionally, the composition, structure, and other physical characteristics of soil directly influence groundwater potential by affecting the retention and transmission of water [74].

Thus, soil plays a crucial role in determining groundwater potential due to its impact on water retention, infiltration, and transmission rates [12,71,74]. The research area features three primary soil types: sandy clay loam (Chromic Luvisols) prevalent in the southern and northern regions, clay loam (Lithic Leptosols) in the central low-lying areas, and light clay (Humic Nitisols) in the western part (see Fig. 3d). These soils demonstrate varying levels of infiltration, categorized as low to moderate based on the USDA-Soil Conservation Service classification system [90] and the Environmental Research Agency standards [91].

2.3.5 Land Use/Cover

Land utilization and coverage play a vital role in assessing the potential of groundwater [57,92–95]. Land use and cover pertains to the utilization of land area in a specific region, encompassing forests, grasslands, urban areas, agricultural lands, and bodies of water [96,97]. Different types of land use and land cover (LULC) can have varying effects on groundwater recharge rates [94,98–100]. This link between groundwater availability and land use/cover is important for two main reasons. The amount of rainfall that percolates into the soil and replenishes groundwater aquifers is first affected by vegetation and ground cover [101]. Infiltration and groundwater recharge are promoted and enhanced by dense vegetation and ground cover [102]. Second, human activities can affect groundwater recharge, including land clearing and construction of infrastructures and facilities like roads, industrial parks, and storage sites [99,103].

The land cover map with a 10 m resolution was downloaded from the https://livingatlas.arcgis.com/landcover/ website for January 2022, accessed on 24 July 2023. The study area comprises four different types of land covers (Fig. 4a), with forestland, rangeland, farmland, and built area covering, respectively, 5.2%, 5.6%, 63.9%, and 25.2% of the total area.

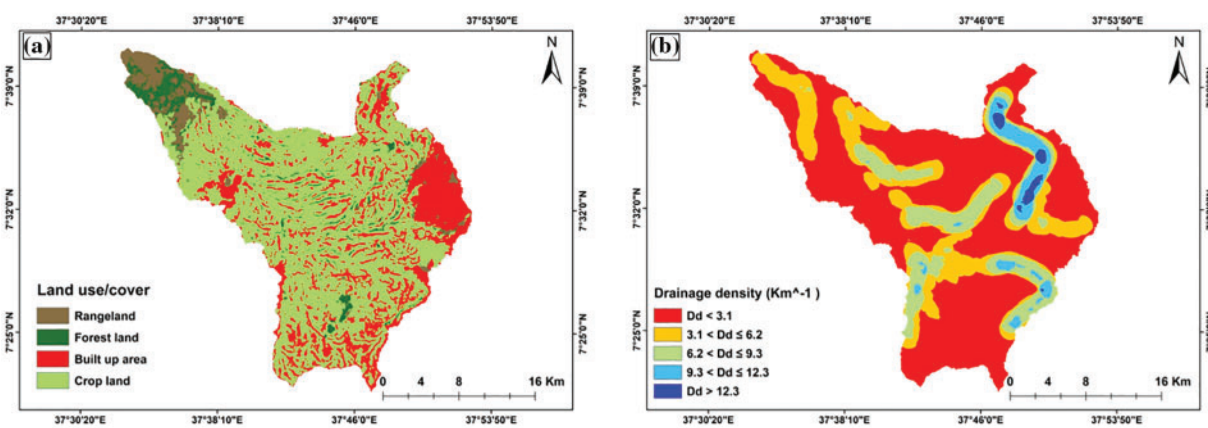

Figure 4: Land use/cover (a) and drainage density (b) maps of the study area

2.3.6 Drainage Density

The density and distribution of stream channels in a watershed are known as drainage density. It is calculated as the total length of the stream channels per unit area of a drainage basin [24,57]. Drainage density controls the flow of water over the ground surface, influencing surface runoff, infiltration, permeability, and subsequent recharge to the underlying aquifer [84,104,105]. Consequently, when evaluating groundwater potential zones, drainage density is taken into consideration [23,56]. Drainage density is inversely related to the permeability of a landscape and determines water movement. Thus, the groundwater recharge rate is higher for areas with low drainage density, whereas it gets lower with increasing drainage density [80]. Al-Ozeer et al. [106] and Raikwar et al. [107] show zones with low drainage density to have good groundwater potential, whereas Raikwar et al. [107] show areas with high drainage density to experience higher runoff.

To determine the drainage density of the Gombora watershed, we utilized a digital elevation model with a 12.5 m resolution on the ArcGIS 10.3.1 platform. As per Horton [108], drainage density was calculated by dividing the total length of the channels in a drainage basin by the size of the watershed (Eq. (2)).

$$D_d = \frac{\sum_{i=1}^{n} L_i}{A} \tag{2}$$

where D_d is the drainage density, n is the number of streams, L is the stream length (km), and A is the drainage basin (km).

The Gombora watershed exhibits a drainage density ranging from 0 to 12.3 km^{-1}, as depicted in Fig. 4b. The study area has been categorized into five drainage density classes based on their significance for groundwater storage: very poor ($D_d > 12.3$ km^{-1}), poor ($9.3 < D_d \leq 12.3$ km^{-1}), good ($6.2 < D_d \leq 9.3$ km^{-1}), very good ($3.1 < D_d \leq 6.2$ km^{-1}), and excellent ($D_d < 3.1$ km^{-1}). Approximately 54.5% and 30.5% of the area fall within the excellent ($D_d < 3.1$ km^{-1}) and very good ($3.1 < D_d \leq 6.2$ km^{-1}) drainage density classes, respectively, indicating their significance for groundwater storage.

2.4 Weight Assignment

The data necessary for the study was collected from multiple sources (Table 1), and the potential groundwater zone was determined utilizing the Weighted Overlay tool within the ArcGIS Spatial Analyst Toolbox. This tool is grounded in the principles of Multi-Criteria Decision Analysis (MCDA). MCDA is a systematic approach used to weigh and assess diverse data about a particular issue with multiple criteria, enabling the identification of optimal solutions through comprehensive evaluation [109,110]. The methodology involves a transparent process of appraising and ranking alternatives, facilitating rational, transparent, and justifiable decision-making. The effectiveness of the approach lies in the collaboration of various stakeholders to reach a consensus on the most favorable course of action.

The groundwater potential zone was established and weighted using key parameters [8,12,68,69,111]. Six variables were chosen to define the groundwater potential zones in this study: geology, lineament density, slope, soil texture, land use/cover, and drainage density. These variables have varying effects on the identification of groundwater potential zones. The weight of each factor was determined by its impact on runoff speed, groundwater potential, aquifer recharge potential, and flow direction [8,12,57,69,112]. The reclassified and weighted factor maps are then overlaid to create the final groundwater potential zone map using the Weighted Overlay tool of the Spatial Analyst Toolbox in the ArcGIS 10.3.1 environment.

The analytical hierarchy process, also known as AHP, is an approach used to determine the normalized weights of the distinct themes and their various levels. In addition, it can be used to select the best option from a list of options. It was created in the 1980s by Dr. Thomas Saaty and has since gained widespread acceptance in industries like business, engineering, and social sciences. AHP entails dissecting difficult choices into smaller, more manageable components and methodically weighing the alternatives. It employs mathematical calculations to give decision criterion weights, simplifying alternatives based on the effect of the criteria on the specific case study.

The AHP process entails several processes, such as defining the issue at hand, listing potential solutions, determining evaluation criteria, and allocating weights to the criteria [57,112]. The judgment matrices are then created for each level/class of criteria in AHP, which assign weights to each one and assess each one relative importance using Saaty's scalar from 1 to 9. It is done by reviewing literature, field observation, and expert judgment. On a scale of 1 to 9, the parameters used to zone groundwater potential areas are ranked, with 1 denoting equal importance and 9 denoting that one component is more crucial than the others [113,114]. One is less significant than the other when using the reciprocal of 1 to 9 (1/1 and 1/9) (Table 2). After assigning weights to the selected factors, the fundamental processes of establishing the indicator's weight and consistency ratio (CR) were completed.

Table 2: Satty's scale of relative importance. Adapted with permission from [113]. Copyright © 2006 Springer Science+Business Media, LLC

Importance scale	Definition
1	Equal importance
3	Moderately importance
5	Strongly more important/Much more important
7	Very strongly/Far more important
9	Extremely more important
2, 4, 6, 8	Intermediate values between the two adjacent judgments
Reciprocals	Values for inverse comparison

Step 1-Establishment of judgment matrices (P) by pair-wise comparison.

$$\boldsymbol{P} = \begin{pmatrix} \boldsymbol{P}_{11} & \boldsymbol{P}_{12} & \cdots & \boldsymbol{P}_{1n} \\ \boldsymbol{P}_{21} & \boldsymbol{P}_{22} & \cdots & \boldsymbol{P}_{2n} \\ \vdots & \cdots & \ddots & \vdots \\ \boldsymbol{P}_{n1} & \boldsymbol{P}_{n2} & \cdots & \boldsymbol{P}_{mn} \end{pmatrix} \quad (3)$$

where n denotes the ^{n}th row, and m denotes the ^{m}th column elements of the judgment matrix.

The pairwise comparison between each thematic layer obtained based on the methods employed by several researchers in different case studies (Tables 3 and 4) [23,24,57,74,84,85,112,115,116].

Table 3: Pair-wise comparison of six criterion matrix

Factor	Geology	Lineament density	Slope	Soil Texture	Land use type	Drainage density
Geology	1					
Lineament density	1/2	1				
Slope	1/2	1/2	1			
Soil texture	1/3	1/3	1/2	1		
Land use type	1/4	1/4	1/4	1/2	1	
Drainage density	1/5	1/5	1/4	1/3	1/2	1

Table 4: Pair-wise comparison of six criterion decimal matrix

Factor	Geology	Lineament density	Slope	Soil texture	Land use type	Drainage density
Geology	1.00	2.00	2.00	3.00	4.00	5.00
Lineament density	0.50	1.00	2.00	3.00	4.00	5.00
Slope	0.50	0.50	1.00	2.00	3.00	4.00
Soil texture	0.33	0.33	0.50	1.00	2.00	3.00
Land use type	0.25	0.25	0.33	0.50	1.00	2.00
Drainage density	0.20	0.20	0.25	0.33	0.50	1.00
Sum	2.78	4.28	6.08	9.83	14.50	20.00

Step 2-Calculation of normalized weight

The matrix will be normalized in this stage by adding the values in each column. The column sum is then divided by each entry's normalized score to produce the result. Each column's total is 1 (Tables 5 and 6).

Table 5: Normalized pair-wise matrix calculated

Factor	Geology	Lineament density	Slope	Soil texture	Land use type	Drainage density
Geology	0.36	0.47	0.33	0.31	0.28	0.25
Lineament density	0.18	0.23	0.33	0.31	0.28	0.25
Slope	0.18	0.12	0.16	0.20	0.21	0.20
Soil texture	0.12	0.08	0.08	0.10	0.14	0.15
Land use type	0.09	0.06	0.05	0.05	0.07	0.10
Drainage density	0.07	0.05	0.04	0.03	0.03	0.05

Table 6: Determined relative criterion weights

Factor	Geology	Lineament density	Slope	Soil texture	Land use type	Drainage density	Criteria weight
Geology	0.36	0.47	0.33	0.31	0.28	0.25	0.33
Lineament density	0.18	0.23	0.33	0.31	0.28	0.25	0.26
Slope	0.18	0.12	0.16	0.20	0.21	0.20	0.18
Soil texture	0.12	0.08	0.08	0.10	0.14	0.15	0.11
Land use type	0.09	0.06	0.05	0.05	0.07	0.10	0.07
Drainage density	0.07	0.05	0.04	0.03	0.03	0.05	0.05

$$W_n = \left(\frac{GM_n}{\sum_{n=1}^{ni} GM_n} \right) \quad (4)$$

where the geometric mean of the ^{i}th row of the judgment matrices is calculated as:

$$\boldsymbol{GM}_n = \sqrt[ni]{\boldsymbol{P}_{1n}\boldsymbol{P}_{2n}\cdots\boldsymbol{P}_{mn_i}} \tag{5}$$

Step 3-Calculate a consistency ratio (CR) to verify the coherence of the judgments. The consistency ratio should now be calculated, and its value verified. This is being done to ensure that the initial preference ratings were accurate.

$$CR = \frac{CI}{RI} \tag{6}$$

Consistency index (CI) is denoted as follows:

$$\boldsymbol{CI} = \frac{\boldsymbol{\lambda}_{\max} - \boldsymbol{n}_i}{\boldsymbol{n}_i - \mathbf{1}} \tag{7}$$

where max is the eigen value of the judgment matrix and it is calculated as:

$$\boldsymbol{\lambda}_{\max} = \sum_{n=1}^{n_i} \frac{(\boldsymbol{PW})_n}{\boldsymbol{n}_i\boldsymbol{w}_n} \tag{8}$$

where W is the weight vector (column). Random index (RI) can be obtained from standard tables (Table 7) [114]. In practical terms, a CR of 0.1 or less is thought to be acceptable. Any greater value at any level means that the verdicts need to be reviewed. The consistency ratio in this study is 0.02, which is acceptable (Table 8).

Table 7: Random inconsistency indices

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.46	1.49

Table 8: Determined consistency ratios (CR)

Factor	Geology	Lineament density	Slope	Soil texture	Land use type	Drainage density	Weighted sum value	Criteria weight	Weighted sum/ weighted criteria
Geology	0.36	0.47	0.33	0.31	0.28	0.25	1.99	0.33	6.23
Lineament Density	0.18	0.23	0.33	0.31	0.28	0.25	1.57	0.26	6.23
Slope	0.18	0.12	0.16	0.20	0.21	0.20	1.07	0.18	6.13
Soil texture	0.12	0.08	0.08	0.10	0.14	0.15	0.67	0.11	6.08
Land use type	0.09	0.06	0.05	0.05	0.07	0.10	0.42	0.07	6.06
Drainage density	0.07	0.05	0.04	0.03	0.03	0.05	0.28	0.05	6.09

(Continued)

Table 8 (continued)

Factor	Geology	Lineament density	Slope	Soil texture	Land use type	Drainage density	Weighted sum value	Criteria weight	Weighted sum/ weighted criteria
Total	1.000	1.000	1.000	1.000	1.000	1.000		CI RI CR CR $<$ 0.1 Consistency is acceptable	0.03 1.24 0.02

According to their significance in determining the groundwater potential zone, weight values were allocated for each factor and their subsequent classes, with the most significant factor having the highest weight and vice versa (Table 3). The weighted average of the factors in this study is 33.1% for geology, 26.2% for lineament density, 17.9% for slope, 11.2% for soil texture, 7.0% for land use, and 4.6% for drainage density (Table 9).

Table 9: The eigenvector weights of each factor obtained after the pairwise comparison

Factor	Normalized weight	Influence (%)
Geology	0.33	33.1
Lineament density	0.26	26.2
Slope	0.18	17.9
Soil texture	0.11	11.2
Land use type	0.07	7.0
Drainage density	0.05	4.6

2.5 Delineation of Groundwater Potential Zones

Weights were assigned to the factors influencing the presence and movement of groundwater after thematic maps were created (Table 10). The groundwater prospective map was created using GIS environment-weighted index overlay analysis. A weighted linear combination approach was used to determine the groundwater potential index [117] (Eq. (9)). In general, the study procedure adopted was shown in the flowchart (Fig. 2).

$$GWPI = G_w G_r + Ld_w Ld_r + Sg_w Sg_r + S_w S_r + Lu_w Lu_r + Dd_w Dd_r \quad (9)$$

where GWPI is the groundwater potential index; G is the score of geology; Ld is the score of lineament density; Sg is the score of slope gradient; S is the score of soil texture; Lu is the score of LULC; and Dd is the score of drainage density, and where the subscripts w and r refer to the weight of a theme and the rate of individual features of a theme, respectively.

Table 10: AHP weights for the parameters of groundwater potential assessment for the Gombora watershed

S. No.	Factor	Sub-factors	Local weight	Average weights	Area coverage (km^2)	Area coverage (%)
1	Geology	Pre-rift volcanics	46.6	33.1	39.8	6.5
		Ignimbrite	27.7		52.7	8.6
		Rhyolite and Ignimbrite	16.1		125.1	20.4
		Pumice, Tuff and Ignimbrite	9.9		397.1	64.6
2	Lineament Density (km^{-1})	Ld > 3.3	50.3	26.2	6.9	1.1
		$3.3 \geq$ Ld > 2.4	26.0		42.8	7.0
		$2.4 \geq$ Ld > 1.6	13.4		168.4	27.4
		$1.6 \geq$ Ld > 0.8	6.8		240.1	39.1
		Ld < 0.8	3.5		156.6	25.5
3	Slope (%)	S < 5	47.4	17.9	134.2	21.8
		$5 < S \leq 10$	28.6		180.5	29.4
		$10 < S \leq 15$	13.6		115.6	18.8
		$15 < S \leq 25$	6.9		112.6	18.3
		S > 25	3.5		71.8	11.7
4	Soil Texture	Sandy clay loam	53.9	11.2	120.0	19.5
		Clay loam	29.7		38.3	6.2
		Clay	16.4		456.4	74.2
5	Land use/ Land cover	Forest land	55.8	7.0	32.1	5.2
		Rangeland	26.3		34.6	5.6
		Cropland	12.2		392.9	63.9
		Built up area	5.7		155.0	25.2
6	Drainage density (km^{-1})	Dd < 0.3.1	46.0	4.6	335.0	54.5
		$3.1 <$ Dd ≤ 6.2	31.4		187.4	30.5
		$6.2 <$ Dd ≤ 9.3	12.7		71.6	11.6
		$9.3 <$ Dd ≤ 12.3	6.5		18.5	3.0
		Dd > 12.3	3.4		2.3	0.4

3 Result and Discussion

According to the GWPI values, the groundwater potential zones can be classified as being either very good, good, moderate, poor, or very poor [56,57,68,118–120]. The outcome of the ArcGIS overlay analysis at the Gombora watershed quantifies the proportion of different groundwater potential zones as 1.6% (very good), 7.4% (good), 21.4% (moderate), 51.6% (bad), and 17.9% (very poor) (Fig. 5).

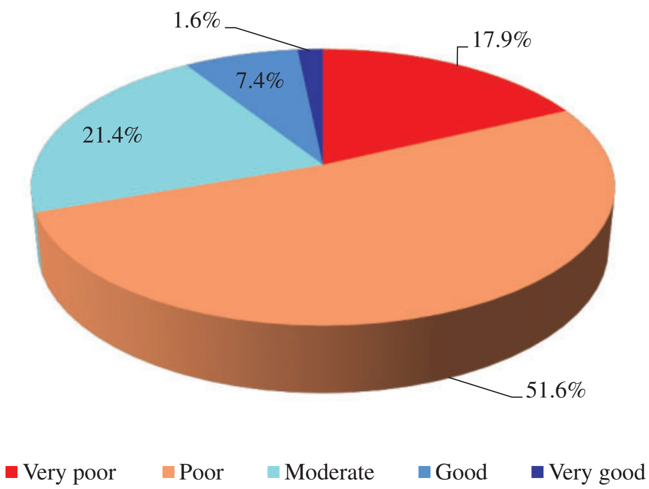

Figure 5: Groundwater potential zones class and their area coverage

As shown in Fig. 6, by giving high relative importance to the geology of the region and less importance to drainage density layers (Table 9), the northwestern, central, and northern part of the watershed is delineated as good and very good groundwater potential zones based on the AHP model. Those areas with good to very good groundwater potential could be due to the high porous and permeable rock media and high liniment density that favor groundwater recharge, storage, and movement. Moreover, these areas are characterized as sandy clay loam and flat slopes, which are the fundamental factors for groundwater potential prospecting. The poor to very poor potential zones are mainly distributed in areas having steep slopes, low lineament density, covered by clay soil, and high drainage density. This study clearly shows the influence of geologic features, lineament density, and slope in the groundwater potential zone delineation.

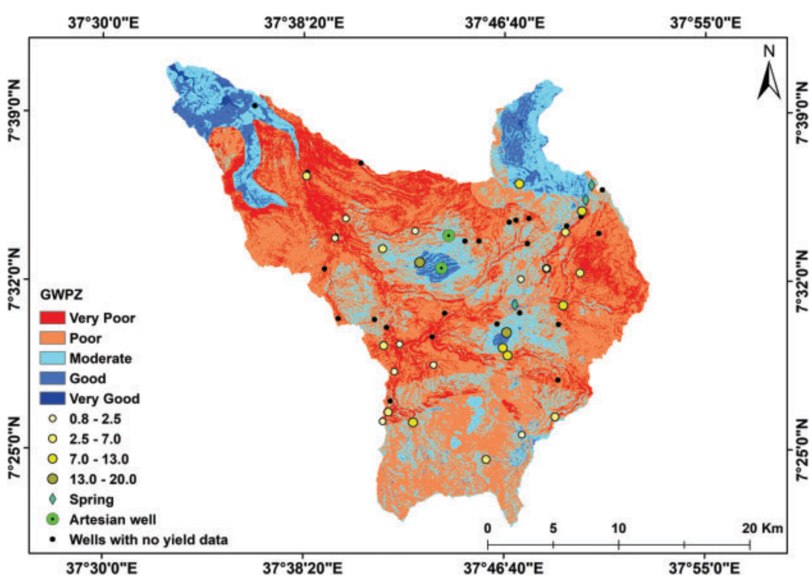

Figure 6: Groundwater potential zones, well yield in l/s, location of existing well and springs of the study area

The results of this study attest to the use of GIS and AHP techniques to delineate groundwater potential zones and provide a cost-effective assessment for further detailed investigation of groundwater development in Ethiopia. Similar geospatial and AHP methods were also successfully used in mapping groundwater potential in other parts of Ethiopia. For example, Duguma et al. [121] in the Guder watershed, Abay basin; Kabeto et al. [8] in the West Arsi Zone; Burayu [23] in the Didessa Sub-Basin, western Ethiopia; Seifu et al. [122] in the Fafen-Jerer sub-basin; Melese et al. [123] in the Muga watershed found that GIS and AHP techniques were efficient and useful in delineating and mapping groundwater potential zone. Overall, these studies show that GIS and AHP techniques are effective in identifying groundwater potential zones in Ethiopia. The results of this study are consistent with the findings of other studies, which have identified very poor to very good potential groundwater zones in different parts of the watershed. However, it is important to note that the methods and results of these studies may vary depending on the study area and the data used. Therefore, it is crucial to conduct site-specific studies to assess groundwater potential zones accurately.

Assessing groundwater potential is crucial for achieving Sustainable Development Goals (SDGs) 6, 12, and 13. Identifying viable groundwater resources allows us to guarantee access to clean water and sanitation (SDG 6), promote sustainable water use, reduce water waste (SDG 12), and improve climate resilience by mitigating the impacts of droughts and floods (SDG 13). This knowledge empowers us to make informed decisions for long-term water security and environmental sustainability. The proper management of water resources can be aided by the identification of groundwater potential zones [122]. The results of this investigation in delineating the groundwater potential zones in the Gombora watershed have significant ramifications for water resource management. Previous related research on Ethiopia's groundwater potential zone mapping indicated that it could help groundwater well location, water management, better planning, and sustainable development [7,124,125]. Identifying groundwater potential zones may also assist in increasing water access. Water resource managers could focus on high groundwater zones and ensure water availability and sustainability of water resources [126]. Communities can obtain clean and safe drinking water, water for irrigation, and other uses by drilling wells in these areas. Furthermore, locating groundwater potential zones might aid in better urban planning. For instance, identifying the groundwater potential zones serves as a valuable tool when selecting suitable sites for new development to support the community and prevent overusing the area's groundwater supplies. Thus, identifying groundwater potential zones would promote sustainable development.

The fundamental constraints of the groundwater potential zone assessment utilizing GIS coupled with AHP are not well outlined in most prior studies; however, the AHP method has some limitations. As an illustration, the AHP is a heuristic method that ranks criteria based on knowledge, which introduces subjectivity and prejudice [67]. Another drawback is that the input data, such as thematic layers and remote sensing data, may vary in quality and resolution, affecting the accuracy of the final map is [71]. AHP is a popular and well-known GIS-based technique for defining groundwater potential zones, but it might not be the most accurate [67], and the result might depend on available input data. This research defined the groundwater potential zone map using only six contributing parameters. To obtain better results, however, additional factors should be considered, including geomorphology, rainfall, curvature, the thickness of aquifers, and other datasets. Additional fieldwork and other relevant investigations, such as geophysical and hydrogeological, should be carried out to understand the area's potential for groundwater overall. Regardless, the outcome of this study demonstrates that integrating GIS and AHP techniques can provide an effective first-order assessment of the groundwater potential zone in the Gombora watershed of the Omo-Gibe basin.

3.1 Groundwater Map Validation

Validating a groundwater map entail confirming the veracity of the data that went into its creation. This is accomplished by gathering field information on well locations, well discharge, and groundwater levels, and comparing it to the information used to produce the map [127]. Validation is done to make sure the groundwater map is accurate and gives decision-makers and stakeholders relevant information (Fig. 7).

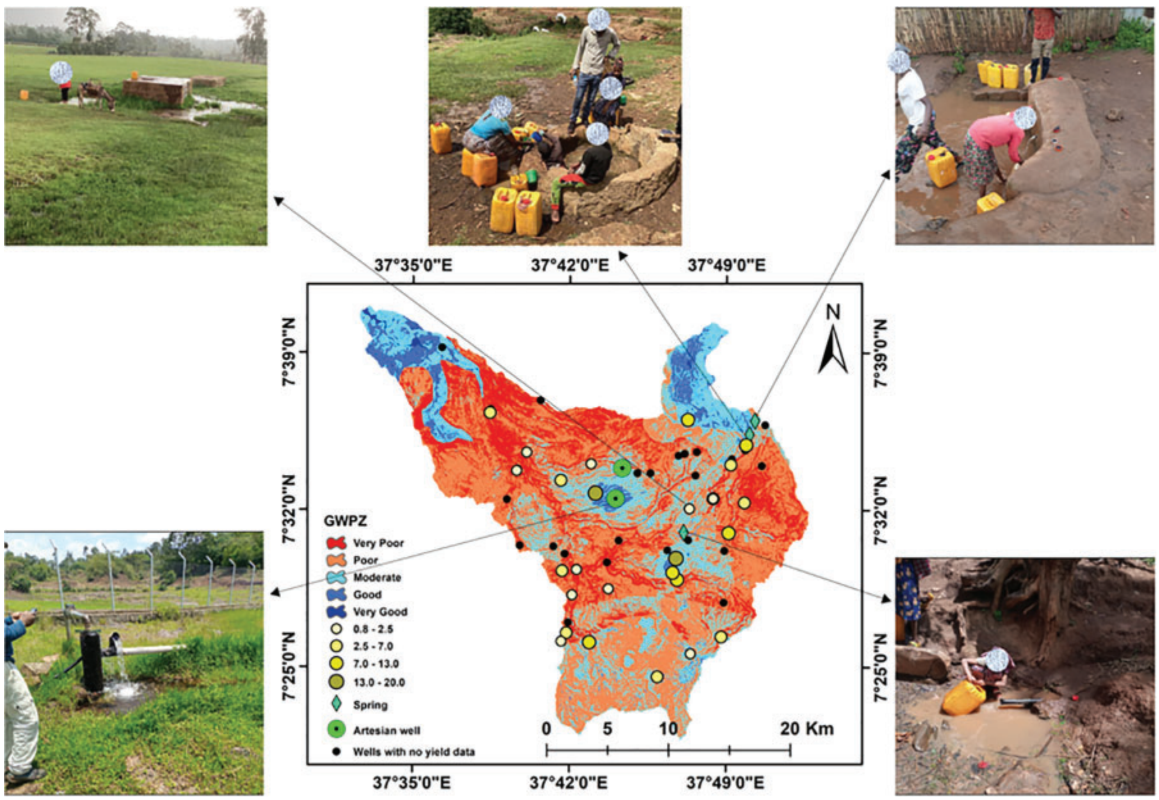

Figure 7: Image of some Artesian well and springs around the Gombora watershed (Source taken by authors during field work)

Receiver Operating Characteristic (ROC) curve analysis was used in this study of groundwater potential zone assessment in the Gombora watershed to compare the locations of existing groundwater wells and validate the model output created by integrating GIS and MCDA [20]. The classification performance of a binary classifier is depicted graphically by the ROC curve. At various classification thresholds, it plots the true positive rate (TPR) along the y-axis and the false positive rate (FPR) along the x-axis. ROC curves are frequently employed in statistics, machine learning, and medical imaging applications. They assist academics and industry professionals in evaluating the performance of several models, choosing the best thresholds, and determining which model is best suited for a particular categorization challenge (Fig. 8).

The total performance of the classifier is frequently summarized using the area under the curve (AUC) measure. According to Naghibi et al. [59], the relationship between AUC and prediction accuracy is as follows: Excellent (0.9–1), Very Good (0.8–0.9), Good (0.7–0.8), Satisfactory (0.6–0.7), and Unsatisfactory (0.5–0.6) are all acceptable grades. A higher AUC implies better performance.

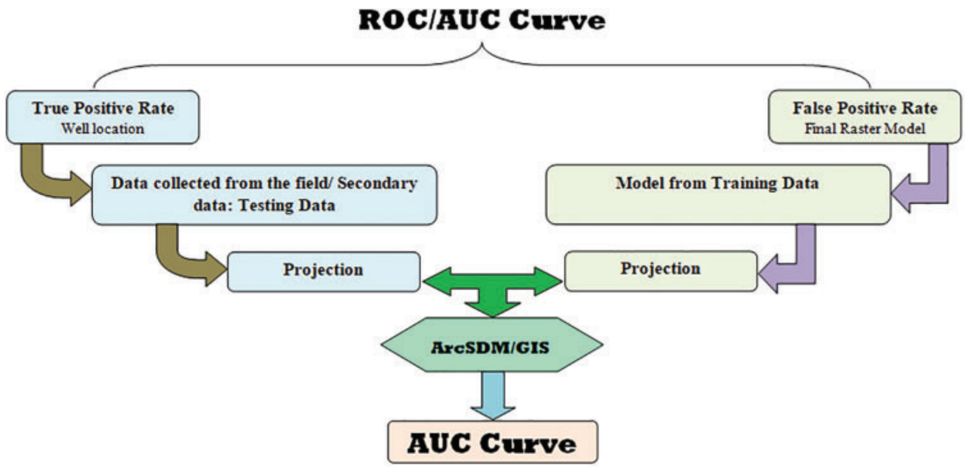

Figure 8: ROC curve used for validation

The ROC's area under the curve (AUC) for this study is 0.747, which is a good performance (Fig. 9). In addition to the AUC curve value, we use the ground truth locations of high yield artesian wells and springs to validate the model output with the actual condition (Fig. 7).

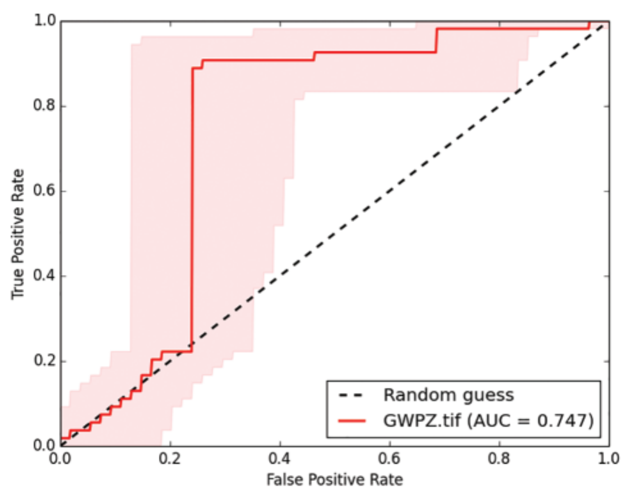

Figure 9: ROC curve used for validation

4 Conclusion

The utilization of GIS combined with AHP for assessing groundwater potential zones has grown in popularity due to its efficiency in terms of time and cost-effectiveness as well as reduced labor-intensive requirements. This integration of AHP and geospatial technology has improved the precision and effectiveness of Groundwater potential zone identifications. The identification of groundwater potential zones can aid in more effective water resource management, better planning, increased water access, and sustainable development. In this study at the Gombora watershed, Omo Gibe basin, Ethiopia, a qualitative analysis was conducted to evaluate the groundwater potential zones using GIS and AHP techniques. Geology, lineament density, slope, soil texture, land use/cover, and drainage density were some of the six influencing thematic layers used to construct the delineated groundwater potential zone. Geology, with a weight of 33.1%, was found to be the most crucial factor in identifying a groundwater potential zone, followed by lineament density, slope, soil texture, land use, and drainage density, which had weights of 26.2%, 17.9%, 11.2%, 7.0%, and 4.6%, respectively.

A groundwater potential zones map was created after the obtained data were analyzed using the analytical hierarchy method and mapped using geographic information system techniques. According to the output of the model for groundwater potential zones, 1.6%, 7.4%, 21.4%, 51.6%, and 17.9% of the watershed are, respectively, in very good, good, moderate, poor, and very poor groundwater potential zones. The AUC value for this study was discovered to be 0.745, indicating good prediction capability of the AHP approach. Therefore, groundwater development activities can be carried out to increase the productivity of supplemental irrigation and household usage in such high groundwater prospect zones of the landscape. The methodology used in this study, which can be applied in other regions of the country, offers valuable insights for water resource planners in identifying possible groundwater development areas. To increase the accuracy of the groundwater potential evaluation, future research should add more data layers such as geomorphology, rainfall, curvature, and aquifer thickness. Additionally, the application of machine learning algorithms such as random forest and support vector machines may increase the accuracy of the groundwater potential evaluation. Furthermore, future studies could compare alternative weighting methods to identify which method offers the most accurate groundwater potential assessment, as well as study the impact of climate change on groundwater potential.

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Availability of Data and Materials: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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