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Original Article

Groundwater potential mapping using GIS and remote sensing with multi-criteria decision-making in Shinile sub-basin, eastern Ethiopia

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Abstract

The main challenge for water resources development as well as food security in arid and semi-arid regions of Ethiopia is the hydroclimatic variability. Groundwater resources are largely the main sources of water supply in such regions, alleviating the pressure of hydroclimatic variability on water resources. The present study delineated the potential groundwater zones in the Shinile sub-basin by using geospatial techniques. The criteria used were: geology, geomorphology, slope, soil, lineament density, drainage density, land use land cover, topographic wetness index, topographic roughness index, and rainfall. The relative weights were given by the analytic hierarchy process. A validation was done using the area under the curve (AUC=0.941) of the receiver operating curve (ROC) from borehole data. The study region was partitioned to low, moderate, and high potential groundwater zones having respectively 1.5%, 43%, and 55% of the total area. The high potential areas are concentrated in the central part where alluvial and lacustrine sediment is the dominant geologic unit. The validation results suggest that the geospatial identification of groundwater potential zones effectively performed well in the study area. This study is very important for water management experts as well as for stakeholders and policymakers in the study region.

Keywords: geographic information system, satellite imagery, groundwater potential site, multi-criteria decision-making, Shinile sub-basin

1. Introduction

Groundwater is sub-surface water that fills the pore space of soil, and is globally one of the main sources of water supply. It is a precious resource challenged by population growth, intensive agriculture, rapid industrialization, and climate change (Manap, Sulaiman, Ramli, Pradhan, & Surip, 2013). Ground-based hydro-meteorological observations are often limited in developing nations like Ethiopia, due to a lack of resources. Ethiopia has a lot of surface water potential, but developing its water resources is difficult due to the uneven distribution and topographic complexity. Most of the surface water resources are unevenly concentrated relative to the population density (Berhanu, Seleshi, & Melesse, 2014; Mengistu, Demlie, & Abiye, 2019). According to literature, southern, southwest, and southeast regions would experience up to a 20% decrease in rainfall as a result of climate change (Hailemariam, 1999; Seleshi & Zanke, 2004).

Due to the lack of surface water in the study area, groundwater is the best option for satisfying the water demand. A groundwater investigation is a fundamental theme to research in the region because it is the only source of water supply (Devereux, 2010; Gebrewahid, Kasa, Gebrehiwot, & Adane, 2017). The potential and characteristics of groundwater are poorly understood, despite the study area's dependence on its groundwater resources. Identification of

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groundwater potential sites is therefore a crucial undertaking that improves the management of water resources in the semi-arid region in general, and in the Shinile sub-basin in particular, in order to reduce the impacts of recurrent droughts.

The primary objective of this research was to use GIS and remote sensing techniques to define the groundwater potential zones in the Shinile sub-basin. Ten variables that relate to the subbasin's groundwater potential were used in the study. The layers are arranged in categories by geology, geomorphology, rainfall, land use and land cover (LULC), slope, soil, lineament density, drainage density, topographic wetness index (TWI), and topographic roughness index (TRI). The results of this research will give a basic understanding of how various hydro-climatological factors affect the regional groundwater resources. Additionally, this methodology is applicable to other arid and semi-arid regions.

2. Previous Works

Groundwater is a hidden resource and its exploration by drilling tests and stratigraphy analysis methods are either costly or time consuming, and also often require skilled manpower (Kumar, Herath, Avtar, & Takeuchi, 2016). These methods are not feasible for developing nations like Ethiopia. The best and most cost-effective solutions to these problems are using remote sensing (RS) and geographical information system (GIS) for assessing and managing the groundwater resources (Mallick, Singh, Al-wadi, Ahmed, Rahman, Shashtri, & Mukherjee, 2014).

Exploring water resources in general, and a groundwater study in particular, can benefit greatly from the use of GIS and remote sensing. Many studies have employed GIS and remote sensing techniques in geological mapping (Mohamed, Al-Naimi, Mgbeojedo, & Agoha, 2021; Yamusa, Danbatta, & Najime, 2018). The most common applications include groundwater resource assessment, recharge and discharge site identification, pollution investigation, and groundwater quality studies (Dandge & Patil, 2022; Senthilkumar, Gnanasundar, & Arumugam, 2019).

Studies using GIS and multi-criteria decision-making to investigate groundwater potential zones in Ethiopia are available (Kabeto, Adeba, Regasa, & Leta, 2022; Yihunie & Halefom, 2020). In the study catchment, there is scant research on water resources (Ketema, Lemecha, Schucknecht, & Kayitakire, 2016; Riché, Hachileka, Awuor, & Hammill, 2009). The majority of these studies focus on the effects of climate change and related problems (Devereux, 2006; Girmay, Gebreselassie, & Bajigo, 2018; Solomon, 2013). The main investigation into the groundwater potential of the studied region is that conducted by Ketema and colleagues (Ketema *et al.*, 2016) on hydrogeological characteristics in Shinile woreda. They investigated the subbasin Shinile woreda's hydrogeological aspects. But rather than constrained by a hydrological boundary, their investigation was restricted to the woreda level, i.e., by a political administrative boundary. Furthermore, their study only uses a small number of thematic factors to classify the groundwater potential, which could degrade accuracy of the analysis. Groundwater potential mapping has not received much attention in the past in the region. The current study used remote sensing and GIS to investigate the potential for groundwater in detail.

3. Methodology

3.1 Description of the study area

The Shinile sub-basin is found in the eastern extreme part of the Awash river basin. Geographically the sub-basin is located between $9^{0}24$**’** to $10^{0}55$**’** north and $41^{0}19$**’** to $43^{0}17$ having a 19,963 sq.km areal coverage. The drainage of the sub-basin follows a south-eastern to north-western orientation (Figure 1). The area is characterized by an arid and semi-arid climate and drought occurrence is the main challenge in the region (Berhanu, Melesse, & Seleshi, 2013). The mean annual rainfall ranges within 200-800 mm and the average temperature range is from 28 to 38 ºC. The inhabitants of the area follow a pastoralist and agro-pastoral way of life. Livestock is the backbone of the economy in the region (Hundera, 2010). The majority of the sub-basin, particularly its central part, is covered by the quaternary formation. Tertiary volcanic also covers partly the upper catchment border area and the northeastern stripes (Kebede, 2013).

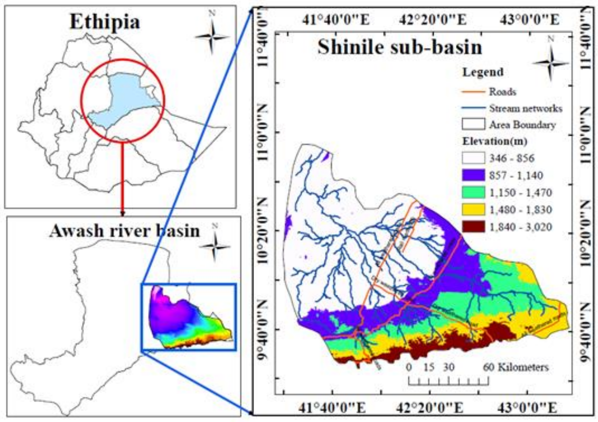

Figure 1. Location map of the Shinile sub-basin

3.2 Input data acquisition

The climatic parameters were obtained from National Meteorological Agency. The topographic and hydrological factors were collected and produced from SRTM digital elevation model (DEM) data on the USGS website. Hardcopy maps of the study area were obtained from the Ethiopian geological survey institute, the ministry of water, and literature. The USGS and Copernicus hub websites were used as a source to download Sentine2 satellite imagery (https://earthexplorer.usgs.gov). The flowchart of the study includes all the thematic parameters with the methodology followed (Figure 2).

3.3 Groundwater influencing factors

For delineating the groundwater potential zone, the study applied as influencing factors geology, geomorphology, rainfall, land use land cover (LULC), slope, soil, lineament density, drainage density, topographic wetness index (TWI), and topographic roughness index (TRI). For common projection, all the thematic maps were converted and geo-

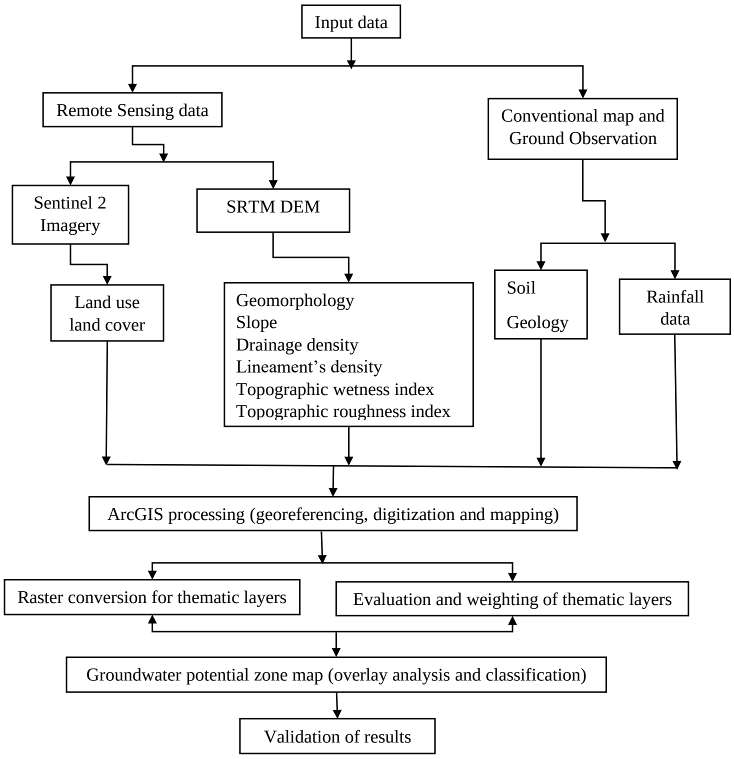

Figure 2. Methodology flowchart of the study

referenced to the same projection. ArcGIS 10.3 software was the main manipulation environment in thematic map preparations. Additionally, the Rockwork 16, ERDAS Imagine, and Surfer software were used in this study for data processing.

3.4 Multi-criteria decision making (MCDM) approach

The study applied the analytic hierarchy process in the multi-criteria decision-making. The AHP is a matrix-based technique and works according to Saaty's scale 1-9 to measure the relative weights of criteria (Saaty, 1987, 2002; Zhang, Sekhari, Ouzrout, & Bouras, 2014). The pairwise comparison matrix (Table 1) indicates the relative weight of each criterion with the AHP technique for MCDM. The sum of each column in the pairwise matrix multiplied by each weight gives the normalized pairwise matrix. To get the weight of each criterion, the average of the normalized pairwise matrix was calculated.

3.5 Consistency examination

The agreement of the calculated weight of each criterion should be checked before using it for overlay analysis. So, the hesitation that can occur in the ranking and weight giving was checked using consistency index and consistency ratio values.

$$Consistency\ ratio(CR) = \frac{consistency\ index(CI)}{Random\ consitency\ Index(RCI)}, CI = \left(\frac{\lambda_{max} - n}{n-1}\right) \quad (1)$$

Here λ_{max} is the maximum eigenvalue (the product between each element of the priority matrix table and sum total) λ_{max} =10.709; and n is the matrix size (number of criteria used, n=10). So, the consistency index becomes (CI=0.078). Taking the value of random consistency index from the table values for n=10, RCI =1.49 (Saaty & Katz, 1990; Tummala, V. M, Ling, & Ling, 1996). So, the consistency ratio of the analysis CR=0.078/1.49=0.053<<0.1 and this is acceptable for groundwater potential mapping.

3.6 Delineation of groundwater potential map

The groundwater potential zoning map was prepared using a weighted overlay of the spatial analyst tool in ArcGIS. The groundwater potential index (GWPI) is defined as:

$$\boldsymbol{GWPI} = \sum_{i=1}^{n} (W_i * R_i) \quad (2)$$

Here *Wi* is the weight of each thematic layer and Ri is the rank of the sub-classes of each thematic layer. The results of the study were validated using the water point data of the field and their distribution (B. Das & Pal, 2020; Fashae, Tijani, Talabi, & Adedeji, 2014).

4. Results and Discussion

In this part of the study, the results of thematic maps developed for overlay analysis and a discussion are presented. Table 2 presents the weights of each thematic layer and the ranks given for the sub-classes of the thematic layer.

Table 1. Pairwise comparison matrix

	G	Gm	RF	Slope	LD	LULC	DD	Soil	TWI	TRI
G	1	3	3	3	3	5	5	6	5	7
Gm	0.333	1	3	3	3	5	5	5	6	7
RF	0.333	0.333	1	1	3	3	5	5	5	7
Slope	0.333	0.333	1	1	1	2	3	3	5	5
LD	0.333	0.333	0.333	1	1	1	3	3	5	5
LULC	0.200	0.200	0.333	0.5	1	1	1	3	3	5
DD	0.200	0.200	0.200	0.333	0.333	1	1	1	3	3
Soil	0.167	0.200	0.200	0.333	0.333	0.333	1	1	3	3
TWI	0.200	0.167	0.200	0.200	0.200	0.333	0.333	0.333	1	1
TRI	0.143	0.143	0.143	0.200	0.200	0.200	0.333	0.333	1	1

Note: G: geology; Gm: Geomorphology; RF: rainfall; LD: Lineament Density; LULC: Land use/Land cover; DD: Drainage Density; TWI: topographic wetness index; and TRI: topographic roughness index

Table 2. Thematic maps and their weighting with the assigned ranks for each subclass

No	Thematic layer	Weight	Sub-class	Rank	Overall weight
1	Geology	26	Alluvial and lacustrine deposits(Q)	5	130
			Undifferentiated alluvial, lacustrine and beach sediments (Qh)	5	130
			Basalt flows, spatter cones and hyaloclastites (Qb)	4	104
			Jessoma Formation (Pj)	3	78
			Hamanlei Formation (Jh)	3	78
			Adigrat Formation (Ja)	2	52
			Ashangi Formation(P2a)	2	52
			Afar Series (Na)	4	104
			Amba Aradom Formation (Ka)	3	78
			Chilalo Formation (Nc)	2	52
			Dalaha Formation (Ndb)	2	52
			Alghe Group (ARI)	1	26
2	Geomorphology	21	Valley	5	105
			Open slope	4	84
			Plain area	4	84
			Hills	2	42
			High ridge and Mountains	1	21
3	Rainfall	14	426-521	1	14
			522-585	2	28
			586-631	3	42
			632-676	4	56
			677-798	5	70
4	Slope	10	Level to gentle slope	5	50
			Moderate sloping	4	40
			Strong slope	3	30
			Moderate steep	2	20
			Steep to very steep	1	10
5	Lineaments Density	9	0-0.146	1	9
			0.147-0.292	2	18
			0.293-0.438	3	27
			0.439-0.584	4	36
			0.585_0.73	5	45
6	LULC	7	Forest Land	5	35
			Agricultural land	5	35
			Shrub land	3	21
			Build up area	2	14
			Rock out crop	1	7
			Grass Land	4	28
			Bare land	1	7
7	Drainage density	5	0-0.18	5	25
			0.181-0.359	4	20
			0.36-0.539	3	15
			0.54-0.719	2	10
			0.72-0.898	1	5

Table 2. Continued

No	Thematic layer	Weight	Sub-class	Rank	Overall weight
8	Soil	4	Clay	1	4
			Loam	3	12
			Loamy sand	5	20
			Sandy loam	4	16
9	Topographic wetness index	2	2.67-7.02	1	2
			7.03-8.79	2	4
			8.8-11.3	3	6
			11.4-14.7	4	8
			14.8-25.3	5	10
10	Topographic roughness index	2	0.111-0.364	5	10
			0.365-0.471	4	8
			0.472-0.566	3	6
			0.567-0.675	2	4
			0.678-0.889	1	2

4.1 Geology

The geological features of the area collected from Ethiopia geological survey institute in “pdf” and “jpg” formats were used by georeferencing and digitizing in ArcGIS software. According to a geological survey report (Geological Survey of Ethiopia, 1996), the quaternary formation covers a major area of the central part of the sub-basin. The upper catchment border area and the north-eastern stripes consist of very deep tertiary volcanic aquifers (Kebede, 2013). The major features in the study area (Figure 3) are alluvial and lacustrine sediments, afar series, and the Hamanlei Formation which cover 45%, 24%, and 12 % of the study area. Basalt flows, spatter cones, and hyaloclastites, and the Alghe group have indispensable coverage in southern and south-eastern strips, each covering 7% of the area.

4.2 Geomorphology

The terrain of the study area is characterized by a huge difference in elevation between 346 and 3,022 m above m.s.l. There are two basic landforms in the study area: undulating ridge land on the upper catchment, and the alluvial plain covering much of the area on the central part. The geomorphological classes of the study area (Figure 3) are valleys, middle slope, plains, hills, and high ridges and mountains. The respective areal coverages are 3.04%, 14.72%, 69.91%, 10.02% and 2.29%. Mountains are sloping surfaces facilitate surface runoff rather than infiltration and are ranked the lowest.

4.3 Rainfall

Rainfall is one of the main parameters that influence the hydrogeological condition of an area. The amount of rainfall has a direct effect on the groundwater zone as the main source of recharge. The rainfall point data for the study area as well as neighboring stations was collected from National Meteorological Agency. The study area experienced on average an annual rainfall of 612 mm. A spatial rainfall map of the study area was prepared using the inverse distance weighting (IDW) for interpolation.

4.4 Slope

The slope of the surface is its degree of inclination and is directly proportional to the surface runoff. The slope is an important topographic parameter that can influence surface water distribution. The higher the slope, the steeper the surface and the higher will be the surface runoff, which decreases the infiltration capacity (Morbidelli, Saltalippi, Flammini, & Govindaraju, 2018). The slope map of the study area was produced from DEM data using ArcGIS. The slope was then reclassified into five subclasses (flat sloping, gentle sloping, strong sloping, moderate steep sloping, and very steep sloping). The mountains in the upper catchment area are very steep sloping and are taken to have a lower capability of groundwater potential.

4.5 Lineaments and lineament density

Lineament is a linear structural feature found on a land surface that infers the characteristics of underline geological features of an area. Lineament can be a structure like a fault, fracture, or joint on the landscape (Caran, Woodruff, & Thompson, 1981). The concept of lineaments was familiarized for the first time by Hobbs (1904). He used the idea of lineament to describe crests of ridges, drainage lines, coastlines, and boundary lines of rock formations. The lineament orientations in the study area follow NE-SW trends (Figure 5). The lineament density (L_d) of an area is defined as the proportion of the total length of the lineament structure to the areal coverage (Figure 6).

4.6 Land use and land cover (LULC)

The cover of the Earth’s surface is one of the main characteristics that can influence water availability in any region. LULC of the surface has a huge influence on hydrological as well as hydrogeological systems. The bare land area is more susceptible to surface runoff than to infiltration (Guzha, Rufino, Okoth, Jacobs, & Nóbrega, 2018; Srivastava, Kumari, & Maza, 2020). To produce and classify the LULC, the study used Sentinel 2 satellite imagery. The LULC of the study area presented in Figure 4 is classified into six categories: agricultural land, settlement, forest land, barren land, shrubland, rock out crop, and grassland.

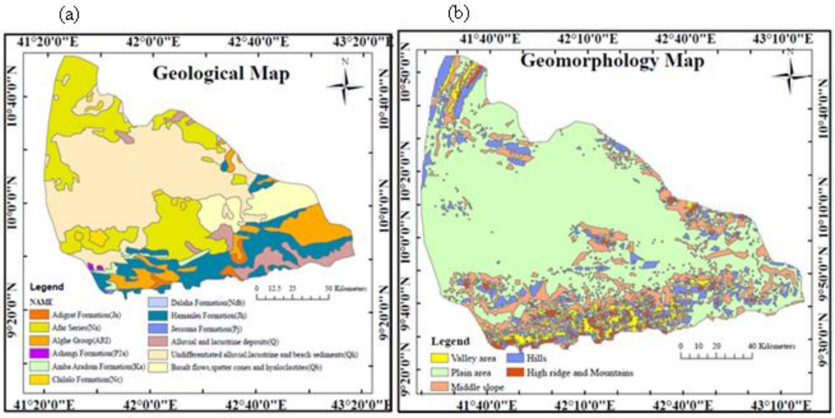

Figure 3. (a) Geological features and, (b) geomorphological classes in the Shinile sub-basin

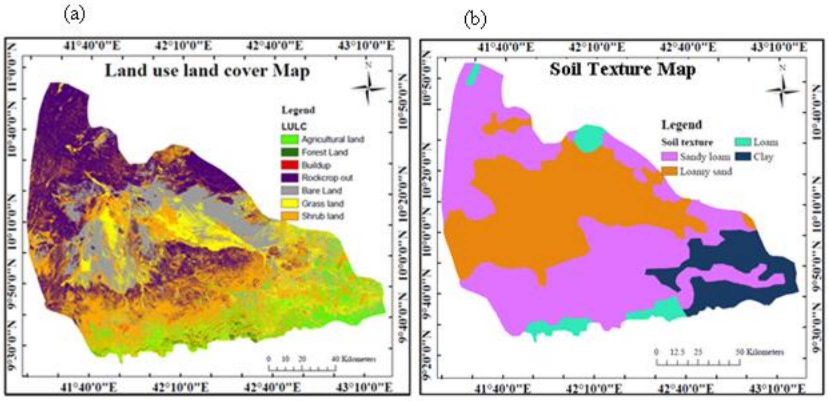

Figure 4. (a) LULC classification, and (b) soil texture classes in the study area

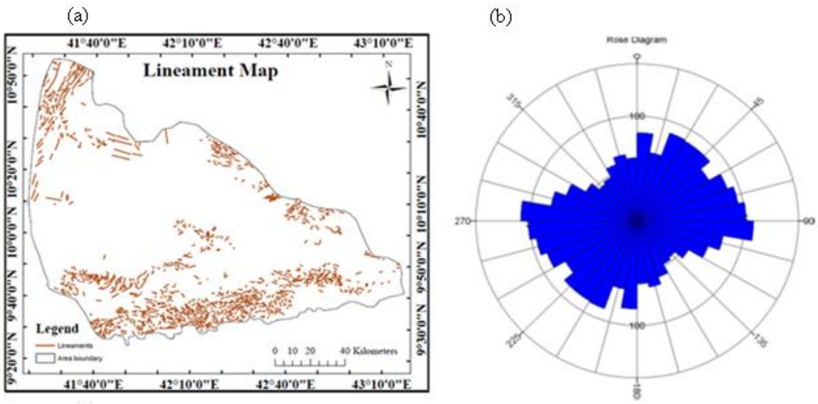

Figure 5. (a) Lineaments distribution in Shinile sub-basin, and (b) rose diagram showing lineament orientation

4.7 Drainage density

The drainage density is defined as the closeness of a channel in any particular catchment. The drainage density of a particular area depends on the hydroclimatic and surface characteristics. (Das, Gupta, & Ghosh, 2017; Krause, Jacobs, & Bronstert, 2007). Drainage density is inversely proportional to the groundwater potential of the zone. The drainage density of a catchment is defined as the ratio of the total length of the stream to the area of the catchment. The map of the study in (km/km^2) units was classified into five categories, from very low to very high (Figure 6).

4.8 Soil

Soil hydraulic properties have a huge role on subsurface percolation and on water-holding capacity of the soil. These characteristics of soil determine the groundwater movement and infiltration capacity (Berhanu *et al.*, 2013). Fine textured soil has a lower infiltration capacity that minimizes the groundwater recharge (Das *et al.*, 2017; Ma W, Zhang, Zhen, & Zhang, 2016). The soil in the study area (Figure 4) is composed of clay, loam, loamy sand, and sandy loam textures.

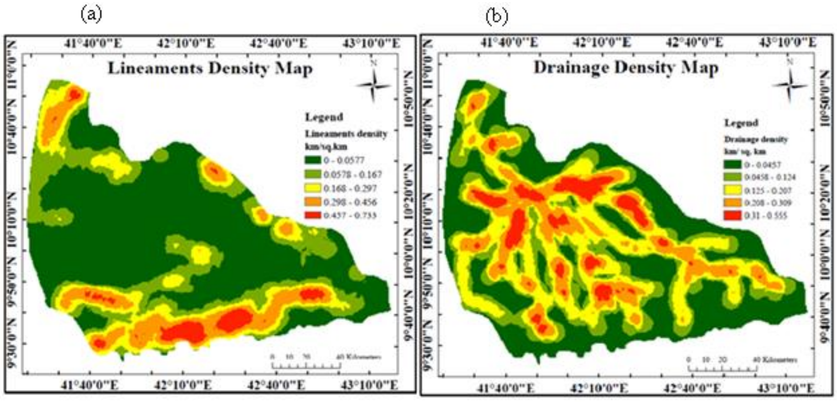

Figure 6. (a) Lineament density map, and (b) drainage density map

4.9 Topographic wetness index

The topographic wetness index (TWI) is also used to describe the effects of topography on pondage and runoff occurrence (Bera, Mukhopadhyay, & Barua, 2020; Pham, Jaafari, Prakash, Singh, Quoc & Bui, 2019). TWI was used for moisture distribution with elevation data of the study area. The topographic wetness has a direct relationship to recharge. The higher the TWI, the higher the water accumulation, and the higher will be the recharge, giving higher groundwater potential for the zone, and vice versa (Wilson & Gallant, 2000). The TWI is defined as:

$$TWI = \ln\left(\frac{A_s}{tan\beta}\right) \quad (3)$$

where *As* = upslope contributing area, β = topographic gradient (slope) in degrees

4.10 Topographic roughness index

The topographic roughness index is a morphological parameter that can influence the groundwater potential of an area. Terrain roughness indicates the texture of the surface that can be rough or smooth. A smoother surface with flatter the slope favors water infiltration to the subsurface (Roy, Chakrabortty, Chowdhuri, Malik, Das, & Pal, 2020). Topographic roughness index (TRI) is given by:

$$TRI = \frac{FS_{mean} - FS_{min}}{FS_{max} - FS_{mn}} \quad (4)$$

Here FS_{mean} is the mean focal statistic, FS_{max} is the maximum focal statistic, and FS_{min} is the minimum focal statistic of the surface (Mukherjee & Singh, 2020).

4.11 Groundwater potential zone map

Modeling the groundwater potential with the ten thematic layers involved the integration of these layers into one raster map that shows the groundwater potential zones (Dhar, Sahoo S., & Sahoo M., 2015; Panigrahi, Nayak, & Sharma, 1995). All the thematic layers were converted into raster format for overlay analysis. The weights were given according to the influence of each criterion on groundwater recharge. The ArcGIS weighted overlay analysis results in low, moderate, and high groundwater potential zones. High groundwater potential areas are alluvial and lacustrine sediment areas (Figure 7), clearly assuring that the alluvial plain has very good groundwater potential for development.

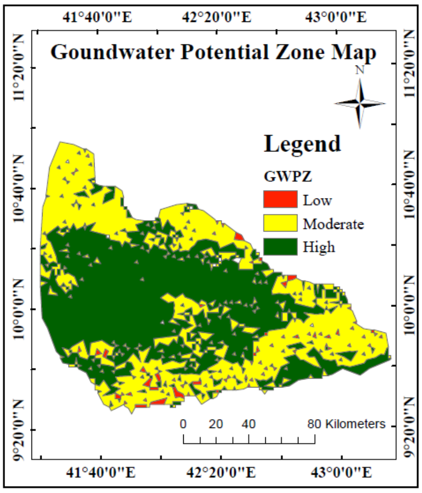

Figure 7. Map of groundwater potential classes

4.12 Validation

Literature showed that one of the methods of validation of groundwater potential zone maps was through borehole and spring data (Andualem & Demeke, 2019; Senapati & Das, 2022). In order to validate the groundwater potential model, the area under the curve (AUC) of the receiver operating characteristic (ROC) was assessed (Figure 8). The predicted value shows a very good potential (94.1%). This gives a clue of the accuracy of GIS and remote sensing methods in groundwater potential zone mapping, in the study area.

5. Conclusions

Studying and developing groundwater resources is crucial for ensuring sufficient food security and sustainable development in arid and semi-arid regions like the Shinile sub-basin. The current study aimed to investigate the

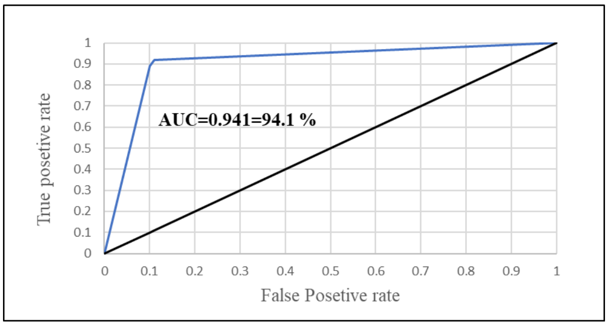

Figure 8. The receiver operating characteristic (ROC)

groundwater potential zones in the Shinile sub-basin using GIS and remote sensing with the AHP technique. Ten elements that significantly relate to the groundwater potential zones were included as criteria. The ultimate groundwater potential area was assigned three levels, for a total area of 19,478.83 sq.km: low (310.04 sq.km), intermediate (8,392.73 sq.km), and high (10,776.06 sq.km). The results indicate that 55.32% of the area is covered by a high groundwater zone. The high groundwater development potential of the alluvial plain is evident in the alluvial and lacustrine sediment deposits. The area under the ROC curve for the model shows very good performance (94.1%). This study demonstrated the zoning for groundwater potential by taking into account a variety of influencing elements, which can increase the accuracy of the investigation. The methodology used in this study could be applied in other locations with similar hydroclimatic conditions. The results could be utilized by planners and policy makers in the region's water resources sector.

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