



Investigation of groundwater resources in highland Ethiopia using a geospatial technology

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Abstract

Because of the rapid growth of human population combined with a decline in quality and quantity of surface water, the demand for groundwater has been rapidly increasing in Ethiopia. It is also highly anticipated that climate change-induced variations in hydrometeorological parameters will make groundwater more indispensable and scarce resource in Ethiopia at some point. It is, therefore, essential to well understand the characteristics and potential areas of groundwater for proper management and use. In this study, an attempt has been made to identify groundwater potential zones in the Rib watershed, north-western highland Ethiopia. The thematic layers of the main factors that control the occurrence and movement of groundwater in hard rock regions were ranked, weighted and aggregated in a linear combination equation in ArcGIS Raster Calculator to generate the groundwater potential zone map. The generated map was then classified into five categories which represent very poor to very good groundwater potential zones. It was found that the downstream areas comprising gentle slope, alluvial deposits, and floodplains have very good groundwater potential zone which cover approximately 294 km² (14.87% of the watershed). The upstream areas in the eastern and south-eastern parts of the watershed fall into low (either poor or very poor) groundwater potential zone due to high runoff and low infiltration. The generated groundwater potential zone map was finally validated using borehole points, which showed a good correlation. The results of this study will be helpful for better planning and management of local groundwater resources.

Keywords Geospatial techniques · Groundwater potential map · AHP · Thematic maps

Introduction

Groundwater, or subsurface water, is one of the most precious and limited natural resources of the earth (Nag and Ghosh 2013; Jasrotia et al. 2016; Ghosh et al. 2016). Globally, the demand for groundwater has been drastically increasing due to immense demands for domestic, agricultural, industrial, economic, and ecological requirements (Jasrotia et al. 2013; Kirubakaran et al. 2016; Hussein et al. 2016; Preeja et al. 2011). Climate change and

its extreme impacts on the availability and quality of surface water have also remarkably increased the demand for groundwater (Ibrahim-Bathis and Ahmed 2016; Kirubakaran et al. 2016). The inherent qualities of groundwater such as purity, uniform availability, and nutrient content also make groundwater more preferable over the surface water and lead to excessive extraction (Zektser and Everett 2000; Zekcer 2004).

In many developing nations including Ethiopia, groundwater is being increasingly recognized as an invaluable but untapped resource for major social and economic developments (Gumma and Pavelic 2013; Foster and Chilton 2003). Very little is currently known about the physical extent, accessibility, and development potential of the aquifer system in most African countries (Gumma and Pavelic 2013; Hussein et al. 2016). Ethiopia is commonly described as “the water tower of Africa” (Birkett et al. 1999), because of the huge water resource potential which is estimated to be 122 billion m³ (Awulachew 2007; Gebreyohannes et al. 2013). Out of the country’s

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total water potential, 54.4 billion cubic meters is surface water (Gebreyohannes et al. 2013) and 40 billion cubic meters is subsurface water (Berhanu et al. 2014).

Currently, groundwater in Ethiopia is contributing little to the country's agricultural development despite its huge availability (Worqlul et al. 2017; Hagos and Mamo 2014). In most parts of the country, particularly in north-western highlands, there is little spatially explicit information about the benefits of groundwater for irrigation and other non-domestic water uses and the techniques of utilization (Worqlul et al. 2017). As a result, agriculture in highland Ethiopia has remained rainfed (Awulachew 2007). There are several and complex factors which are limiting the efficient and effective use of groundwater in Ethiopia. The absence of reliable hydrological data, insufficient knowledge of aquifer structure and properties, and limited technology are among the major ones (Worqlul et al. 2017; MacDonald et al. 2012; Hagos and Mamo 2014). Therefore, it is essential to well understand the nature of aquifers and look into cost-effective and user-friendly tools and method for proper delineation, utilization, and management of groundwater resources.

Several conventional approaches such as field-based hydrogeological survey, geophysical resistivity survey, exploratory drilling, photogeological techniques, and stratigraphic analysis have been employed for centuries to determine the location and thickness of aquifers and delineate groundwater potential areas (Gumma and Pavelic 2013; Jha et al. 2010; Pinto et al. 2015). However, in recent years, the revolution of computer and the advent of geospatial technologies such as remote sensing (RS) and geographic information system (GIS) have made it easier to delineate the groundwater potential areas in rapid and cost-effective ways (Jasrotia et al. 2016; Dinesan et al. 2015). With their advantages of spatial, temporal, and spectral availability and manipulation of earth surface and subsurface data covering vast, inaccessible, and non-uniform terrain features, geospatial technologies have opened a new era in accessing, monitoring and conserving groundwater resources (Ibrahim-Bathis and Ahmed 2016).

RS basically serves as the source of quick and useful baseline information about the factors controlling the occurrence and movement of groundwater, whereas GIS enables the integration and management of multi-thematic layers (Huang et al. 2013; Preeja et al. 2011; Yeh et al. 2009; Jasrotia et al. 2016; Nag and Ghosh 2013). In addition to geoprocessing, maps calculus can also easily be done in GIS (Baalousha et al. 2018). The present study emphasizes the identification and mapping of groundwater prospect zones in the Rib watershed, north-western Ethiopia, by integrating the thematic maps rainfall and various terrain features in a spatial domain of ArcGIS.

Materials and methods

Description of the study area

The Rib watershed is located in north-western highland Ethiopia. It encompasses an area of approximately 1975 km² and located between 11°40'N–12°20'N and 37°30'E–38°20'E (Fig. 1) with elevation ranging from 1758 to 4104 m above sea level. It is located in an area where water is a critical resource for agriculture and domestic uses. The upper part of the watershed is dominated by dissected mountainous landscapes and most of the downstream areas are relatively flat or gently undulating. The Rib watershed is characterized by diverse climatic conditions with high spatial and temporal variations due to varied topography. The mean annual rainfall across the watershed is estimated to be 1503 mm. The annual average temperature of the watershed is approximately 17 °C. Most parts of the watershed experience marked differences in rainfall between dry and wet seasons. The wet periods usually occur during March–May (short or *Belg* rain) and June–September (main or *Kiremt* rain). The dry period typically occurs between October and February. The *Kiremt* rain is the main source of water for agriculture in the watershed.

Data used and methodology

To demarcate the groundwater prospect zones of the watershed, different thematic maps such as geomorphology, geology, lineament density, rainfall, drainage density, soil, slope, and land use were prepared from remotely sensed and conventional data. The flowchart of the methodology is shown in Fig. 2. ERDAS Imagine 2014 and ArcGIS 10.3 were utilized to process satellite image, digitize conventional maps, and overlay thematic layers. Individual features of each thematic layer were labeled separately and unique attributes have been assigned. Finally, to develop the groundwater potential zone map, thematic layers were classified into very good, good, moderate, poor, and very poor based on their suitability for groundwater occurrence.

Geomorphology

Geomorphology of the area is one of the most vital features in the delineation and evaluation of groundwater resources. Ethiopia is characterized by a wide variety of landforms generated by complex processes acting on the rocks with different characteristics (Billi 2015). The geomorphology map of the study area (Fig. 3a) consisting of five geomorphic units, namely, alkali basalts (Quaternary), alluvial plain, floodplain, Miocene shield volcano

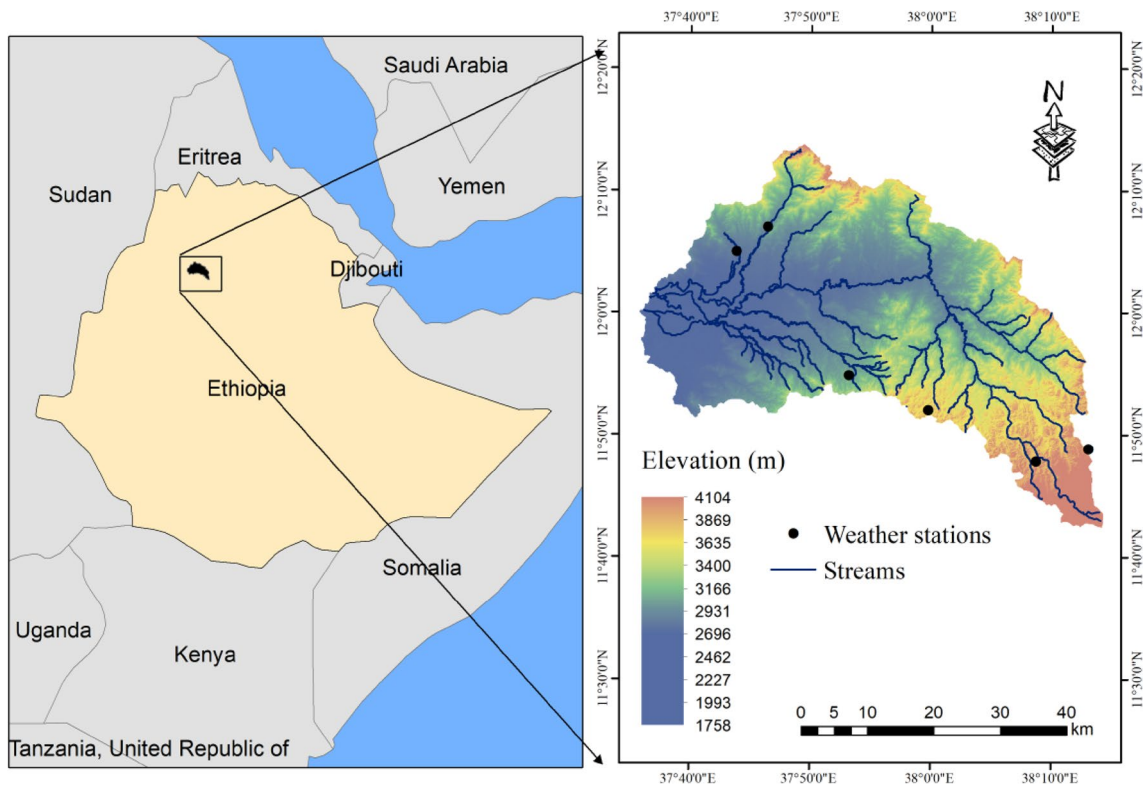
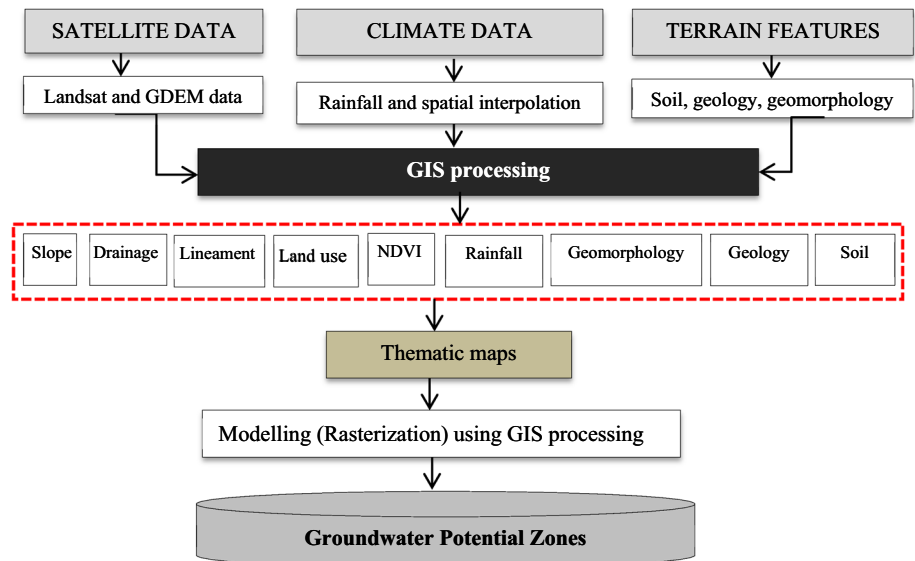


Fig. 1 Map of the study area

Fig. 2 Flowchart for methodology



(alkali basalts, tuffs, and agglomerates), and alkali basalt with tuffs and rare rhyolites (oligo-Pliocene) was prepared from the geomorphology map of Lake Tana Basin, Ethiopia (Ludwin et al. 2013). Alluvial plain and floodplain are composed of unconsolidated sedimentary deposits and comprise sands and silts with minor interactions with clay (Mandal et al. 2016). These landforms act as good aquifers

and have more impact on the occurrence of groundwater (Soumen 2014; Hussein et al. 2016). Due to their excellent quality of storing water (Deolankar 1980), alkali basalts also make good aquifers for groundwater recharge (Shelton 1981). Therefore, alluvial plain, floodplain, and alkali basalts were assigned with high groundwater suitability score.

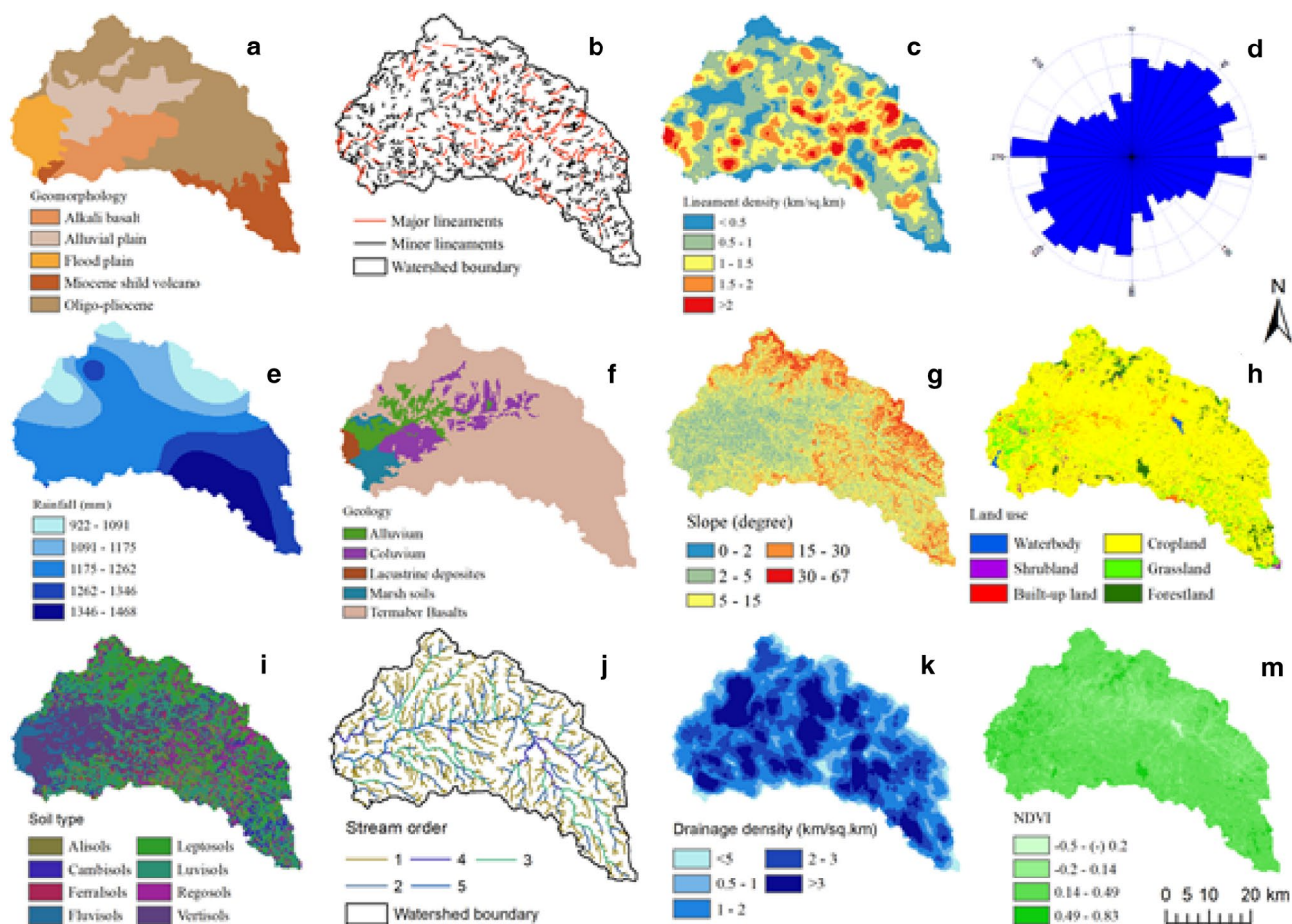


Fig. 3 Thematic maps used for delineation of groundwater potential zones: **a** geomorphology, **b** major and minor lineaments, **c** lineament density, **d** rose diagram, **e**) rainfall, **f** geology, **g** slope, **h** land use, **i** soil types, **j** stream order, **k** drainage density, **m** NDVI

Lineament density

Lineaments are linear or curvilinear structures (Kirubakaran et al. 2016) representing the fractured zones such as fault and dike on the geological arrangement of an area and considered as a secondary aquifer in hard rock regions (Nag and Ray 2015; Selvam et al. 2015; Mogaji et al. 2016). In the hydrological system of a watershed, lineaments are considered as excellent indicators of groundwater prospect areas as they determine the relationship between infiltrations and recharge rates (Nag and Ray 2015). Several techniques including PCI Geomatica and ENVI have been developed to extract and delineate lineament features of a given watershed (Mahmoud and Alazba 2016). The lineaments of the study area (Fig. 3b) were extracted from Landsat 8 images through the integrated use of PCI Geomatica 2017 and ENVI 5.1 software.

The density algorithm function in ArcGIS spatial analyst tool was used to generate a lineament density map (Fig. 3c). The values of lineament density range from 0 to 3.39 km/

km² and were categorized into five classes: low (<0.5 km/km²), moderate (0.5–1.0 km/km²), high (1.0–1.5 km/km²), very high (1.5–2 km/km²), and extremely high (>2 km/km²). Since lineament density has a direct relation with infiltrations and recharge rates, a high score was assigned to high lineament density and vice versa. The orientation of lineaments is analyzed using a rose diagram which displays the frequency of lineaments on orientation bin, 360° circle with a 15° interval. The rose diagram orientation in this study shows that open fractures are concentrated in the NE–SW direction and a minor orientation is apparent in E–W direction (Fig. 3d).

Rainfall

Rainfall is one of the most important factors which highly influence the recharge rate of aquifers (Karami et al. 2016). The water that could be percolating into the groundwater system is largely a function of the amount of rainfall (Mogaji et al. 2016). This is due to the fact that rainfall is the main

source of the natural hydrologic cycle which largely controls groundwater prospects (Hussein et al. 2016). In this study, the daily precipitation records (1986–2016), which later converted into annual rainfall, were obtained from 12 stations located within and around the Rib watershed. The Inverse Distance Weighting (IDW) interpolation method in ArcGIS 10.3 was employed to prepare the rainfall map of the studied watershed. The annual rainfall of the watershed ranges from 922 to 1468 mm and classified into five rainfall zones (Fig. 3e). Areas with a high amount of rainfall were classified as very good groundwater prospect sites due to the direct influence of rainfall in the amount of water available for infiltration into the subsurface.

Geology

Geology or lithology plays a great role in governing groundwater recharges (Deepa et al. 2016). This is due to the fact that porous rocks contribute to higher groundwater storage and the opposite is true for impermeable rocks. The geology of Ethiopia comprises a mixture of ancient crystalline basement rocks, volcanic rocks associated with the East African Rift system, and sediment of various ages (Smedley 2001). About two-thirds of the Rib watershed is covered with Termaber basalts (Fig. 3f). The Tarmaber basalt is thick and consists of basaltic rocks interlocked with tuffs, scoriaceous lava, and paleosols (Engidasew and Barbieri 2014). Alluvial sediments composed of coarse-grained materials are found in the downstream parts of the watershed. Termaber basalts fall under very good suitability rank because of their good capacity to infiltration, whereas lacustrine deposits (predominantly covered with clays, or unconsolidated sediments) were grouped under very poor category due to the limited capacity of water storage.

Slope gradient

The slope is another crucial factor which significantly controls the occurrence and movement of groundwater. Steeper slopes cause less recharge because of rapid runoff. The slope is inversely proportional to recharge of terrain surface, i.e., if the slope value fluctuates, the recharge potential also significantly fluctuates (Kirubakaran et al. 2016). The slope map of the study area (Fig. 3g) was prepared from ASTER GDEM (30-m resolution) using Spatial Analyst Tools in ArcGIS 10.3 software. The slope of the study area ranges from 0° to 67° and classified into five categories: level to nearly level sloping (0–2), gentle sloping (2–5), moderate sloping (5–15), steep sloping (15–30), and very steep sloping (> 30°). A slope of less than 2° is considered as relatively flat, which is usually a very good subsurface recharge zone because of low runoff. On the contrary, the area with a

slope greater than 30° is considered as a very poor recharge zone due to rapid runoff.

Land use

Land use gives necessary information on infiltration, soil moisture, and surface water (Ibrahim-Bathis and Ahmed 2016), and highly determines the occurrence and development of groundwater (Pinto et al. 2015). Cultivated and vegetation areas reduce surface flow while barren and settlement areas increase runoff (Muralitharan and Palanivel 2015). The land use map of the study area (Fig. 3h) was prepared using Landsat 8 OLI image of 2017 and grouped into cropland, forestland, shrubland, grassland, waterbody, and built-up land. The scoring of land use classes was decided based on the character of each land use feature to infiltrate water into the ground and hold water on the subsurface aquifer.

Soil

Soil determines the rate of groundwater recharge potential by using the characteristic nature of transmissivity and water-bearing capacity (Kirubakaran et al. 2016). Soil significantly affects the movement of surface water into the aquifer system and it is directly related to rates of infiltration, percolation, and permeability (Pothiraj and Rajagopalan 2013). The soil map of the study area (Fig. 3i) was extracted from the Soil Map of Ethiopia (FAO/UNESCO). The main soil types of the study area include Vertisols, Alisols, Regosols, Leptosols, Ferralsols, Fluvisols, Luvisols, and Cambisols. The groundwater suitability ranks were assigned to each soil type based on their multiple characteristics as suggested by Gumma and Pavelic (2013), FAO (2006), and Pothiraj and Rajagopalan (2013).

Drainage density

Drainage density indicates the closeness of the spaces between stream channels (Singh et al. 2013). It is the inverse function of permeability which plays a vital role in the runoff distribution and level of infiltration (Ibrahim-Bathis and Ahmed 2016). Low drainage density is related to higher recharge and higher groundwater prospect zone. Drainage density provides a quantitative measure of the average length of stream channels per unit area (km/km²) and can be calculated using Eq. 1 (Deepa et al. 2016):

$$D_d = \sum_{i=1}^{i=n} \frac{D_i}{A} \quad (1)$$

where D_d is the drainage density, A is the area under consideration, D_i is the drainage length, and i indicates the number of stream channels.

The drainage lines of the watershed were extracted from ASTER GDEM with the help of Arc Hydro Analysis 10.3 for ArcGIS 10.3 software. As indicated in Fig. 4j, stream branches drain from almost all parts of the watershed to western direction, towards Lake Tana. After extraction of drainage lines, the drainage density map (Fig. 3k) was generated using density algorithm function in ArcGIS 10.3 Spatial Analyst Tool. The drainage density values range from 0 to 10.25 km/km² and were categorized into five classes: low (<0.5 km/km²), moderate (0.5–1.0 km/km²), high (1.0–2.0 km/km²), very high (2.0–3.0 km/km²), and extremely high (>3.0 km/km²). Since drainage density and infiltration are inversely related, high suitability scores were given for low density and vice versa.

Normalized Difference Vegetation Index (NDVI)

The NDVI is often regarded as the best determinant of ground parameters like ground cover, photosynthetic activities of plants, surface water, leaf area index and the amount of biomass (Dhar et al. 2015) and, thus, highly decides surface infiltration and the availability of groundwater. Vegetation cover determines the rate of infiltration and runoff by dissipating the raindrop energy before it reaches the ground (Miyata et al. 2009). The NDVI characterizes the quality and

nature of vegetation based on the reflected energy by plants in the near infrared band. The NDVI map of the present study was prepared using Sentinel-2 satellite image (10-m resolution). The red (band 4) and near-infrared (band 8) were used for NDVI calculation (Eq. 2).

$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}} \quad (2)$$

The values of calculated NDVI range from –0.54 to 0.83 and classified into three categories: no vegetation (–0.54 to 0.1), moderate vegetation (0.1–0.3), and good vegetation (0.3–0.83) as indicated in Fig. 3m. The negative NDVI values represent the water bodies and values between 0 and 0.1 indicate barren lands, rocks, and built-up areas.

Determination of theme weights

Appropriate weights were assigned to all thematic layers and their individual features after understanding their importance in influencing groundwater potential. Scores and weights were assigned to all thematic layers based on their roles in groundwater potential including infiltration, aquifer transmission, and storage. The knowledge of researchers and the available literature (Agarwal and Garg 2016; Preeja et al. 2011; Pinto et al. 2015) were taken into consideration

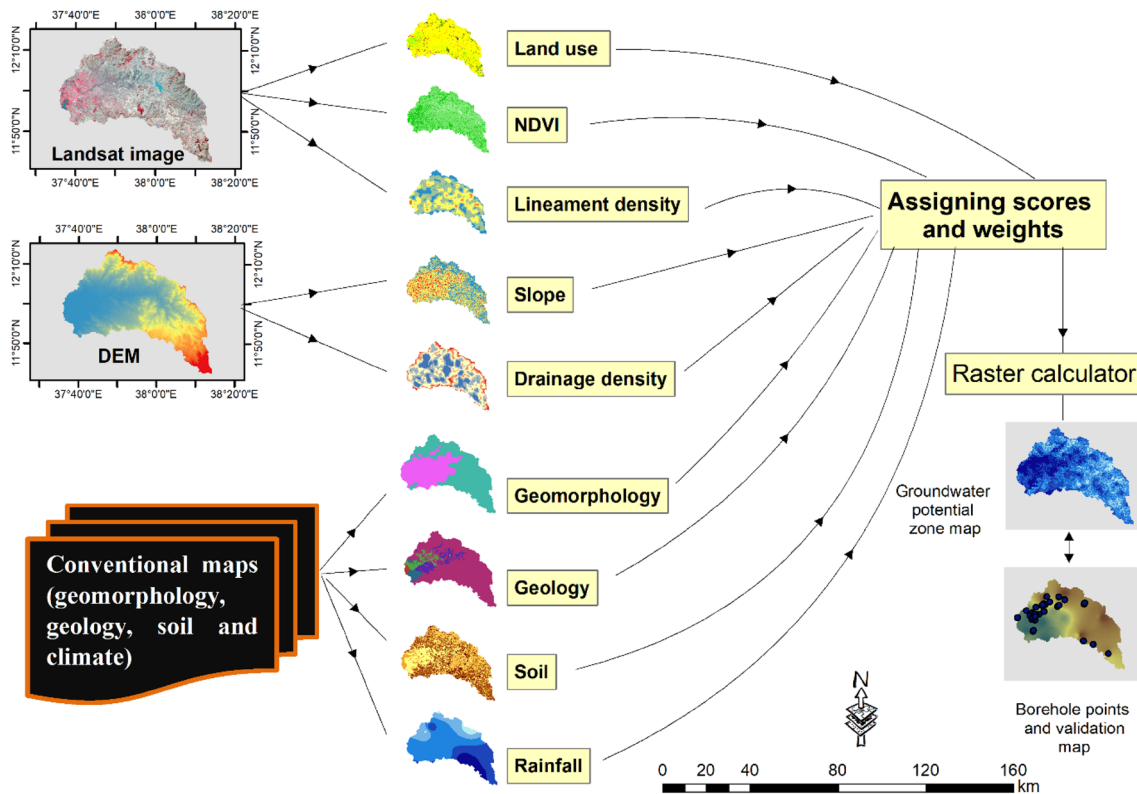


Fig. 4 Integration of thematic layers using ArcGIS software

while scoring the themes and standardizing the weights. The scores and weights assigned to the individual features of the nine themes considered in this study are summarized in Table 1.

Several studies (Dar et al. 2011; Singh et al. 2013; Preeja et al. 2011) reveal that geomorphology of a given area plays a dominant role in the movement and storage of groundwater. Hence, among the nine thematic layers considered in this study, the highest weight was given to geomorphology. Lineament density, rainfall, and geology were given the next most important weight, respectively. Out of the total weights assigned to each thematic layer, about 79% was allocated for geomorphology, lineament density, rainfall, and geology. The maximum score for geomorphology was 1.55 followed by 1.1, 0.75, and 0.55 score values for lineament density, rainfall, and geology, respectively. Table 2 shows the approach used to determine weights and possible maximum scores for the themes.

GIS-based multi-criteria evaluation techniques based on Saaty's Analytical hierarchy process (AHP) were employed to rank and weight thematic layers. The AHP method breaks down the complex decision problems into a hierarchy based on a pairwise comparison of the importance of different criteria based on the 9-point rating scale (Saaty 2005) (Table 3). The accuracy of the pairwise comparison was checked by computing consistency ratio (CR). The CR shows the degree of consistency achieved when comparing the criteria or the probability that the matrix rating was randomly generated (Mogaji et al. 2016). If the value of CR exceeds 0.1, the judgments are considered as untrustworthy because they are too close for comfort to randomness. The CR can be calculated using Eq. 3.

$$CR = \frac{(\lambda_{\max} - n)/(n - 1)}{RI} \quad (3)$$

where CR is the consistency ratio, λ_{\max} is the average value of consistency vector (the principal eigenvalue) computed by eigenvalue vector technique, n is the number of factors (i.e., nine in this study), and RI is the ration index. The value of RI for different n values is given in Table 4 (Saaty 1980). The CR of 0.03 was obtained, which indicates an acceptable consistency.

Integration of thematic layers

All the thematic maps considered in this study were converted from vector to raster and integrated based on the scores and weights assigned to them using linear combination technique in an ArcGIS software package to delineate groundwater potential zones. The following formula was used to estimate the groundwater potential map (Jasmin and Mallikarjuna 2015; Kumar et al. 2014):

$$GWP = \sum_{i=1}^n W_i \times R_i \quad (4)$$

where GWP is the groundwater potential, i is the thematic map, W is the weight of the thematic map, R is the criterion rank, and n is the number of themes. Figure 4 represents the overall approach followed to integrate thematic layers and produce the groundwater prospect map using ArcGIS.

Results and discussion

Delineating groundwater potential zones

Mapping groundwater prospect zone is essential in areas like the Rib watershed where rainfall is irregular and there is no perennial water reservoir to supply water for agriculture and household use. To fulfill the domestic water supplies and sustain agricultural production through irrigation, the farmers of the study area are forced to drill and construct bore wells. The present study was intended to expose the meaningful information and best sites for exploration of groundwater. The availability and distribution of groundwater are always governed by various hydromorphological settings which influence soil infiltration and aquifer recharge (Hussein et al. 2016). The groundwater potential zone map of the study area (Fig. 5) was generated through the integration of various thematic layers including rainfall and characteristics of terrain features such as geology, geomorphology, and slope. The entire watershed can be classified into very poor, poor, moderate, good, and very good groundwater prospect zones.

Moderate groundwater prospect zone is widely distributed across most parts of the watershed. The total area covered by moderate groundwater prospect zone is 732 km² (37% of the total watershed size). The very good groundwater prospect zone, occupying 14.87% of the watershed, is concentrated in the western and central parts of the watershed due to the distribution of alluvial deposits, floodplains, fluvisols, nearly flat slopes, and agricultural lands with high infiltration ability. This result is in a good agreement with the findings by Mahmoud (2014), Ibrahim-Bathis and Ahmed (2016), and Magesh et al. (2012) who reported high infiltration and aquifer recharge rates in areas with flat slope, deep soil, and alluvial deposits. The river banks, wetlands, and Lake fringes of the Rib watershed also exhibited very good groundwater potential zones. Drainage density and lineament density are other important factors controlling the infiltration ability of the groundwater system (Magesh et al. 2012). High groundwater potential zones in the study area are mainly found along with high lineament density and low drainage density.

Table 1 Summary of scores and weightages assigned to themes influencing groundwater potential

Theme	Domain of effect	Area, km ²	Area, %	Suitability rank	Score	Weightage
Geomorphology	Flood plain	321.62	16.28	Very good	5	0.31
	Alluvial plain	265.27	13.48	Very good	5	
	Alkali basalt	270.39	13.69	Very good	5	
	Oligo-pliocene	183.27	9.28	Good	4	
	Miocene	935.28	47.41	Good	4	
Lineament density (km/km ²)	<0.5	334.75	16.95	Very poor	1	0.22
	0.5–1.0	922.53	46.71	Poor	2	
	1.0–1.5	672.95	34.07	Moderate	3	
	1.5–2.0	43.07	2.18	Good	4	
	>2.0	1.43	0.07	Very good	5	
Rainfall (mm/year)	922–1031	59.27	3	Moderate	3	0.15
	1031–1140	341.31	17.28	Moderate	3	
	1140–1249	921.63	46.67	Good	4	
	1249–1359	467.53	23.67	Good	4	
	1359–1468	185.88	9.41	Very good	5	
Geology	Termaber	1545.25	78.24	Very good	5	0.11
	Alluvium	138.82	7.03	Good	4	
	Coluvium	183	9.27	Moderate	3	
	Marsh soils	81	4.1	Poor	2	
	Lacustrine	26.85	1.36	Very poor	1	
Slope (degree)	Nearly level	37.8	1.91	Very good	5	0.07
	Gentle	179.67	9.1	Good	4	
	Moderate	829.48	42	Moderate	3	
	Steep	547.78	27.74	Poor	2	
	Very steep	380.1	19.25	Very poor	1	
Land use	Cropland	1737.35	87.97	Very good	5	0.05
	Shrubland	24.59	1.25	Good	4	
	Grassland	118.22	5.99	Moderate	3	
	Forestland	67.86	3.44	Very poor	1	
	Waterbody	6.49	0.33	Very poor	1	
	Built-up land	20.57	1.04	Very poor	1	
Soil	Fluvisols	86.14	4.36	Very good	5	0.04
	Regosols	190.63	9.65	Very good	5	
	Cambisols	61.81	3.13	Good	4	
	Luvisols	590.3	29.89	Good	4	
	Ferrasols	42.12	2.13	Good	4	
	Vertisols	450	22.78	Moderate	3	
	Alisols	132.07	6.69	Poor	2	
	Leptosols	421.19	21.33	Very poor	1	
Drainage density (km/km ²)	<0.5	88.34	4.47	Very good	5	0.03
	0.5–1.0	259.46	13.14	Good	4	
	1.0–2.0	705.85	35.74	Moderate	3	
	2.0–3.0	550.56	27.88	Poor	2	
	>3.0	370.95	18.78	Very poor	1	
NDVI	–0.54 to 0.1	83.33	4.22	Very Poor	1	0.02
	0.1–0.3	1411	71.44	Moderate	3	
	0.3–0.83	480.52	24.33	Good	4	

Table 2 Approach used to determine weighs and possible maximum scores for the nine themes

Theme	Theme weight	Score range	Scores given	Maximum possible score	Maximum possible total pixel score
Geomorphology	0.31	4–5	4, 5	5	$0.31 \times 5 = 1.55$
Lineament density	0.22	1–5	1, 2, 3, 4, 5	5	$0.22 \times 5 = 1.1$
Rainfall	0.15	3–5	3, 4, 5	5	$0.15 \times 5 = 0.75$
Geology	0.11	1–5	1, 2, 3, 4, 5	5	$0.11 \times 5 = 0.55$
Slope	0.07	1–5	1, 2, 3, 4, 5	5	$0.07 \times 5 = 0.4$
Land use	0.05	1–5	1, 3, 4, 5	5	$0.05 \times 5 = 0.25$
Soil	0.04	1–5	1, 2, 3, 4, 5	5	$0.04 \times 5 = 0.2$
Drainage density	0.03	1–5	1, 2, 3, 4, 5	5	$0.03 \times 5 = 0.15$
NDVI	0.02	1–4	1, 3, 4	4	$0.02 \times 4 = 0.08$

Table 3 The relative criterion weights (percent of influence)

	GM	LD	RF	GE	SL	LU	SO	DD	ND	Weight
GM	0.35	0.42	0.40	0.35	0.31	0.27	0.24	0.22	0.20	0.31
LD	0.18	0.21	0.26	0.26	0.25	0.23	0.21	0.19	0.18	0.22
RF	0.12	0.11	0.13	0.17	0.18	0.18	0.17	0.16	0.16	0.15
GE	0.09	0.07	0.07	0.09	0.12	0.14	0.14	0.14	0.13	0.11
SL	0.07	0.05	0.04	0.04	0.06	0.09	0.10	0.11	0.11	0.07
LU	0.06	0.04	0.03	0.03	0.03	0.05	0.07	0.08	0.09	0.05
SO	0.05	0.04	0.03	0.02	0.02	0.02	0.03	0.05	0.07	0.04
DD	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.04	0.03
ND	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

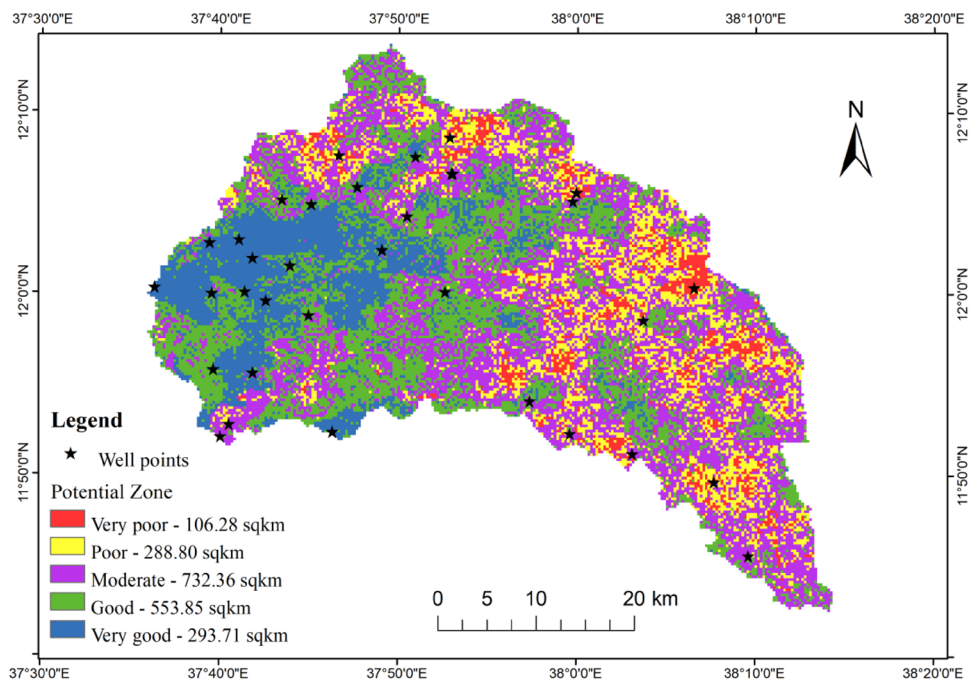
Table 4 Saaty’s ratio index values based on the number of factors under analysis

Number of factors	1	2	3	4	5	6	7	8	9	10	11	12	
RI		0.00	0.00	0.58	0.90	1.01	1.24	1.32	1.41	1.45	1.49	1.51	1.48

The hilly terrains located in northern, eastern and south-eastern parts of the watershed were found to have poor (14.6%) and very poor (5.4%) groundwater prospect zones. The low groundwater availability in these areas is basically attributed to high runoff and low infiltration rates caused by steep slopes. The steep slope facilitates the runoff processes, and gentle slope region permits the rain-water to infiltrate to the soil (Ibrahim-Bathis and Ahmed 2016). It is obvious that forest (vegetation) reduces surface runoff and allows water to penetrate into the ground through tree roots, which finally yield good groundwater potential (Magesh et al. 2012; Ibrahim-Bathis and Ahmed 2016). In this study, however, low suitability scores were assigned to forest areas because the small remnant forests are merely concentrated in hilly and mountainous areas where steep slopes of the terrain with fine drainage density significantly impedes infiltration. Therefore, forest areas in the studied watershed fall under poor groundwater potential zone.

Areas with high rainfall are always expected to have a good groundwater potential due to the direct influence of the precipitation on aquifer recharge (Karami et al. 2016). However, our results reveal that high rainfall receiving areas at the uppermost parts of watershed fall within poor groundwater potential zone, while the downstream areas with low rainfall fall under very good groundwater potential zone. This can be highly attributed to: (1) the movement of sub-surface water from the upstream to the downstream, and (2) the downstream areas facilitate the infiltration of the available precipitation into the groundwater system due to lower drainage and slope. Similar findings are also reported in many researchers conducted in different part of the world. For example, the report by Pinto et al. (2015) indicates that low rainfall receiving areas in Comoro watershed in Timor Leste have a good groundwater potential due to the sub-surface water movement from high rainfall receiving upstream areas. Similarly, the study by Sar et al. (2015) shows poor groundwater availability in high

Fig. 5 Groundwater potential zone map of the study area along with borehole locations



rainfall receiving mountainous areas of Keleghai River Basin in India due to the slope and drainage effects.

Comparison with borehole data

To verify the accuracy of the proposed method, the generated groundwater prospect zone map was checked against borehole (well) points collected from the Agricultural office of Amhara National Regional State. From the total of 36 borehole points collected, 27 were considered for validation, and the remaining were excluded from the test due to insufficiency. The location points or GPS values of the boreholes were overlaid with groundwater potential map to check the correlations. The validation result confirms that the highest groundwater potential zones coincide with areas of higher borehole yield, while the lowest groundwater prospect zones fall within lower borehole yield. The maximum borehole depth was 150 m below ground level (mbgl), which falls under the very poor groundwater potential zone, and the minimum depth was 33 mbgl falling within a very good category. Table 5 shows the different boreholes parameters used for validation. Based on the validation result, it can be inferred that the generated groundwater prospect zones are reliable and representative. The proposed method can be successfully used by hydrologists in groundwater assessment and evaluation studies.

Conclusions

This study is an attempt to the delineation of groundwater potential zones in hard rock aquifers of highland Ethiopia using an integrated approach consisting of RS, GIS, and AHP. Several thematic layer maps which deeply influence the availability and movement of groundwater were considered to demarcate potential zones. The results reveal that out of the total 1975 km² area, around 293.7 km² is identified as a very good groundwater prospect zone, which covers 14.9% of the total watershed. Moderate prospect zone, which covers 732 km² (around 35% of the watershed), is distributed across the whole watershed. The high slope and mountainous terrains located along the northern, eastern and south-eastern parts are identified as poor and very poor groundwater potential zone. The predicted results were validated using the borehole data obtained from the regional water resource development offices.

The study demonstrated the capability of a geospatial approach in delineating groundwater potential zones in areas with non-uniform terrain features. The advantage of this approach over others is the consideration of the spatial and temporal variations and low data required. This

Table 5 Parameters of wells used for validation of generated groundwater prospect zone map

Well ID	Well depth (mbsl)	Yield (L/s)	Well location on the map	Validation remark
WP1	60	1.2	Very poor	Agreed
WP2	46	1.5	Poor	Agreed
WP3	150	1.5	Very poor	Agreed
WP4	53	1.5	Very poor	Partially agreed
WP5	79	2	Poor/very good	Agreed
WP6	58	2.2	Poor	Agreed
WP7	52.5	2.5	Poor	Agreed
WP8	109	2.9	Moderate	Disagreed
WP9	68	3	Moderate	Agreed
WP10	49	3	Moderate/poor	Disagreed
WP11	37	3	Moderate	Agreed
WP12	43	3	Moderate	Agreed
WP13	35	3.5	Good	Disagreed
WP14	37	3.8	Moderate	Agreed
WP15	42	4	Moderate	Agreed
WP16	43	4	Moderate	Agreed
WP17	55	4.5	Good	Agreed
WP18	45	5	Moderate	Partially agreed
WP19	51	5	Good/moderate	Agreed
WP20	40	6	Good	Agreed
WP21	64	6.5	Good	Agreed
WP22	37	8	Very good	Agreed
WP23	48	8	Very good	Agreed
WP24	33	8	Good	Agreed
WP25	53.5	8.2	Very good	Agreed
WP26	51	10	Very good	Disagreed
WP27	44	49	Very good	Agreed

approach is also enabled to access and manipulate data covering vast and inaccessible areas within a short time. Despite numerous benefits, the utilized approach might also have some possible limitation. Since the groundwater potential map is the aggregate output of input thematic layers, the resolution of raster maps can significantly affect the accuracy of the quantitative analysis. This approach also needs a skilled and experienced analyst. Although it is essential to incorporate the subsurface hydrological parameters such as transmissivity, hydraulic conductivity, discharge, drawdown, water table/level data of the different time, and specific capacity in groundwater delineation, such parameters are not always available in most areas including the study area and, thus, could affect the quality of the analysis.

The high potential groundwater potential zones will have a key role in the development of irrigation in the studied watershed. Moreover, our findings will serve as a base for further hydrological investigations in the study area or other places experiencing similar geophysical situations.

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