ORIGINAL ARTICLE

Fuzzy logic techniques and GIS-based delineation of groundwater potential zones: a case study of Anger river basin, Ethiopia

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Abstract

As the demand for drinking water worldwide increases for human consumption, agriculture and industrial uses, the need to assess the potential of groundwater and aquifer productivity also increases. Access to water supply in Ethiopia is among the lowest in the world. In some regions of Ethiopia, people make three–five round trips to get dirty water from the river per day. Each roundtrip takes 2–3 h and water is carried in around "50-lb jerrycans" according to an article by Tina Rosenberg for National Geographic. Therefore, delineation of groundwater potential in Ethiopia is a need of an hour. The objective of this study is to develop a spatial model using a fuzzy logic approach integrated with geographic information system (GIS) domain to demarcate the groundwater potential zones (GPZ) of Anger river basin Ethiopia. Nine thematic layers such as geology, slope gradient, drainage density, Roughness, profile curvature, plan curvature, wetness index, soil texture, soil type, and land use were prepared, analyzed and studied for GPZ delineation. The groundwater potential zone map thus obtained was categorized into five classes: very good, good, moderate, low and very low. The study reveals that about 28.44% of the Anger river basin is covered under very good GPZ. Very poor, poor, moderate and good GPZ are observed in 8.06%, 15.47%, 21.36%, and 26.67%, respectively. The area under very poor and poor potential zones is recorded only in very limited areas in the basin. This study proved the efficiency of the fuzzy logic approach coupled with GIS an efficient model for demarcation of GPZ and can be applied at a continental scale.

Keywords Fuzzy logic · GIS · Anger river basin · GPZ

Introduction

There would be serious crises of freshwater in the world by 2025 (Danilenko et al. 2010). Among the various water resources, groundwater is one of the most important freshwater resources located in the underground geological formations (Fitts 2002). Both natural and anthropogenic factors determine the spatial distribution and presence of groundwater (Banks et al. 2002; Greenbaum 1992; Lee et al. 2012; Oh et al. 2011). In developing countries like Ethiopia, the population explosion and socio-economic factors lead to an increase in the demand for freshwater. Ethiopia is called the water tower of East Africa. However, due to

significantly large temporal and spatial variations in rainfall in East Africa, especially in Ethiopia due to complex aquifers, water is often not available when necessary (Seleshi et al. 2007; Semu 2012).

Geospatial tools have opened new windows in water resources studies. Remote sensing provides multi-temporal, multi-spectral and multi-sensor data of the earth's surface (Chowdhury et al. 2003). Geospatial technology helps in the assessment and monitoring of groundwater resources spatially as well as temporally. Many studies have used geospatial tools to study the groundwater potential of their region of interest (Elbeih 2015; Hussein et al. 2016; Kumar et al. 2014; Magesh et al. 2012). Geospatial technology has been used for the possible demarcation of GPZ in hard rock terrain of southern India by superimposing spatial data (such as geomorphology, geology, land use/land cover, lineament, relief, and drainage) in the GIS domain (Dar et al. 2010). Groundwater prospects evaluation in Kancheepuram district of Tamil Nadu, South India, has been done based on hydrogeomorphological mapping using remote sensing and

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GIS (Dar et al. 2010). GIS-based groundwater targeting in the Tigray region, Ethiopia is also documented (Tesfa et al. 2018). There are very few regional studies regarding the utilization of geospatial technology for the demarcation of groundwater potential in Ethiopia (Tesfa et al. 2018). In the present study, an attempt has been made to delineate the groundwater potential zones in the Anger river basin, Ethiopia using Fuzzy logic membership coupled with GIS tools.

Location of study area

The present study was conducted in the Anger river basin, one of the sub-basins of the Blue Nile basin, Ethiopia. Its X and Y geographic coordinates are 174,463.7–293,630.6 m E and 1,000,213.1–1,109,939.4 m N (Fig. 1), respectively. Anger River, being a tributary of Blue Nile River, drains some parts of the Benshangul Gumuz and Oromia Regions. It has a catchment area of about 7901.5 square kilometers in size. There are 18 zones situated in the Anger River basin with a total population of 1,136,584.

Spatial occurrence and distribution of groundwater in any terrain are dependent on the geological settings (Yeh et al. 2016).

The study area is dominated by Undifferentiated Lower Complex covering 51.96% (area 4105.58 km^2) followed by Adigrate Sandstone, Wollaga Basalts, Infra-Adigrate Classics, Basalts related to Volcanic centers, Posttectonic granites and Syntectonic granites with their areal extents of 18.42% (1455.68 km^2), 25.58% (2021.38 km^2), 2.27%

(179.27 km^2), 0.17% (13.58 km^2), 1.38% (108.80 km^2) and 0.22% (17.29 km^2), respectively (Fig. 5a). Infiltration is particularly good in areas covered by thick Alluvial and Coalluvial sediments. Groundwater potential of the Anger River basin follows the following order based on transmission, yield and hydraulic conductivity: Adigrate Sandstone > Wollaga Basalts > Infra-Adigrate Classics > Syntectonic granites > Posttectonic granites Basalts related to Volcanic centers > Undifferentiated Lower Complex.

Methodology

Model description

Fuzzy logic and fuzzy sets have been used in a wide range of environmental problems, such as suitability for arable land (Nisar et al. 2000), prediction and modeling of soil erosion (Mitra et al. 1998), time series models of air pollution (Nunnari et al. 1998), evaluation of spatial and temporal change of salinity (Metternicht 2001), modeling distribution spatial and density of vegetation species (Kampichler et al. 2000), mineral exploration and spatial prediction of the danger of landslides (Gorsevski et al. 2003). Among the various site selection models, fuzzy logic has been chosen in this study. The fuzzy logic methodology has been employed to evaluate the interrelationship of topographic features defining the groundwater prospectus. Determinant thematic layers of Anger River basin, such as slope gradient, drainage density, roughness, curvature, wetness index, soil texture, and land use were analyzed and assigned fuzzy membership values according to their influence on groundwater. Each thematic map was reclassified and assigned fuzzy logic membership values and presented in the figures. Its values range from 0 (unlikely or unsuitable for groundwater potential) to 1 (most likely or suitable to groundwater potential) (Assimakopoulos et al. 2003). Therefore, the higher the fuzzy membership value, the more suitable the site and vice versa. All the "fuzzified" layers were allowed to overlay using the "fuzzy overlay" tool in the GIS domain to help better in site selection for groundwater potential zones. Fuzzy product, fuzzy sum, and fuzzy gamma operators have been used for factor themes integration (Fig. 2). The output of the fuzzy logic overlay was further reclassified into five classes, viz., very good, good, moderate, poor and very poor groundwater potential zones.

Description of input parameters

Slope gradient

The information on the nature of the geologic and geodynamic processes operating at a regional scale can be inferred
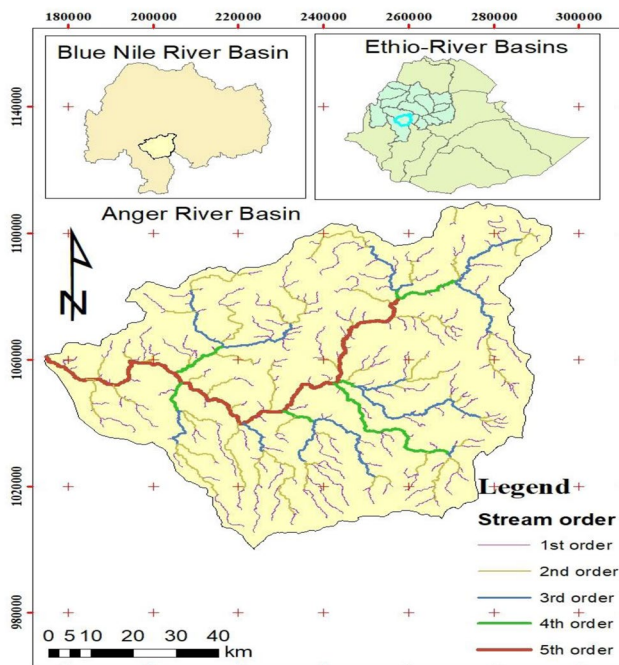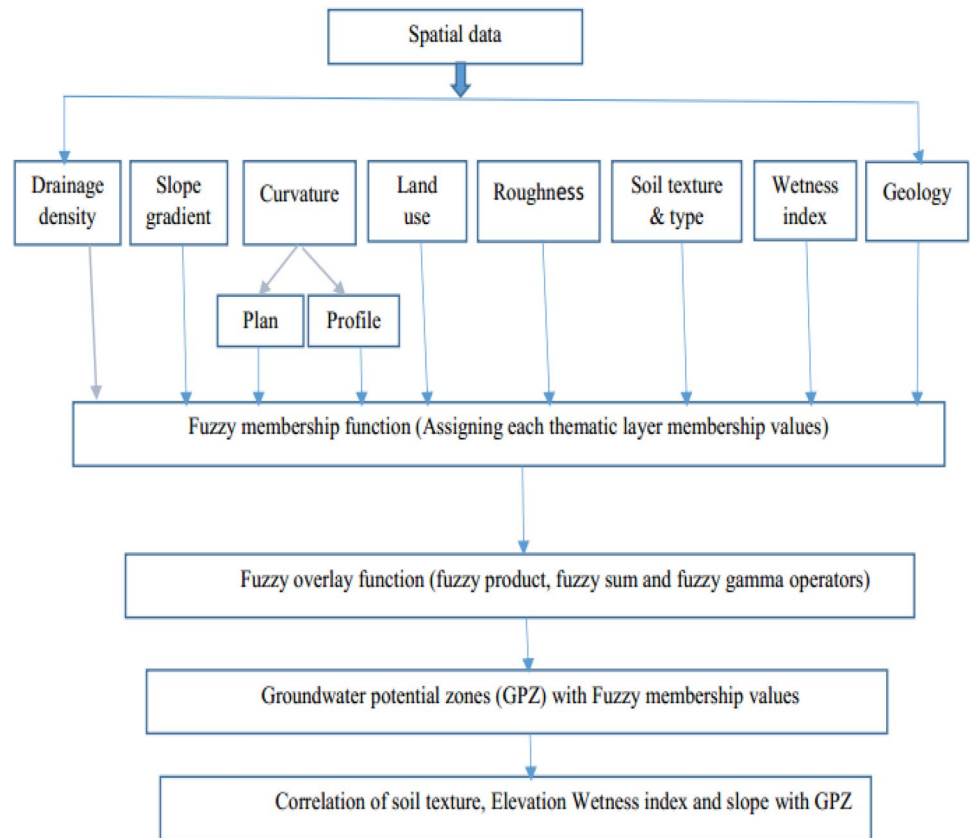

Fig. 1 Location and stream order map of Anger river basin, Ethiopia

Fig. 2 Methodology employed

from the slope gradient. The slope gradient influences the rate of infiltration and surface runoff (Singh et al. 2013). The slope gradient of the Anger River basin has been calculated using the spatial analyst tools in the GIS environment. DEM of Anger River basin (resolution 20 m * 20 m) was used as an input for calculating the slope gradient.

Drainage density

Groundwater availability and contamination are inferred by the drainage density (Ganapuram et al. 2009). The Lithology determines the drainage network and influences the infiltration rate. Drainage density is the ratio of the total length of all the channels in a basin to the total area of the basin (Yeh et al. 2016). Drainage density is a reverse function of permeability. The drainage theme of the Anger river basin has been generated from DEM using the following steps in the GIS environment:

1. Filling of sinks of DEM of Anger River basin;
2. Generation of flow direction raster using filled-in DEM as an input;
3. Computing flow accumulation raster using flow direction raster as an input;
4. Generation of Streams/drainage raster using flow accumulation raster as an input.

Drainage density was calculated mathematically in the ArcGIS environment (Eq. 1).

$$\text{Drainage density} = \frac{L_{\text{total}}}{A_{\text{total}}}, \tag{1}$$

where L_{total} is the total length of the basin, A_{total} is the total area of the basin.

Roughness

Groundwater availability was affected by topographic roughness, which expresses the amount of difference in elevation between adjacent cells (Riley 1999). The roughness of the study area was generated by the following procedures in the ArcGIS environment.

1. Input the filled DEM for calculating maximum statistics in Neighborhood
2. The output neighborhood types were a rectangle
3. Statistics type was maximum/minimum/mean
4. Ignore no data in the calculation

To calculate the roughness by raster calculator in ArcGIS environment mathematically (Eq. 2),

$$\text{Roughness} = \frac{\text{Focal mean} - \text{Focal minimum}}{\text{Focal maximum} - \text{Focal minimum}}. \quad (2)$$

Curvature

This parameter indicates the shape and curvature of the slope. The curvature value can be used to find the pattern of soil erosion, as well as the distribution of water on the ground. The curvature of the profile affects the acceleration and deceleration of the flow and, therefore, influences erosion and deposition. The curvature of the flat shape influences the convergence and divergence of the flow. The curvature of any terrain can be concave upwards or convex upwards (Nair et al. 2017). The curvature of the profile and the curvature of the flatness of the Anger river basin have been calculated using DEM as an entry in the GIS domain. The curvature of the profile highlights the concavity and convexity in the direction of the maximum gradient.

Topographic wetness index

Topographic wetness index (TWI) computes the topographic control on the hydrological process (Mokarram et al. 2015). The TWI of the Anger River basin has been calculated using the following syntax in the GIS domain:

1. Generating flow direction and flow accumulation from filled DEM of Anger River basin
2. Calculate slope in degree from filled DEM
3. Calculate Tan slope from: con ('slope' > 0, Tan (slope), 0.001) by map algebra
4. Calculate flow accumulation scaled from (Flow accumulation + 1)*cell size
5. Topographic wetness index = *Ln (flow accumulation scaled)/ (Tan slope)*

Soil texture and soil types

The soil textural class and soil types are very important in the determination of groundwater potential areas. Infiltration rate and groundwater recharge are dependent on the type of soil (Ibrahim et al. 2017). These parameters were extracted from the map of the Blue Nile basin in which the study area was found and then converted from vector to raster format for further analysis in the ArcGIS environment.

Land use land cover changes

Land use gives information about soil moisture, surface water, groundwater, infiltration, in addition to providing an indication about groundwater prospectus (Yeh et al. 2016; Ibrahim-Bathis and Ahmed 2016). The land use/land cover

map of the study area was prepared based on the satellite image downloaded from https://earthexplorer.usgs.gov. Supervised classification of land use/land cover was performed using the ERDAS Imagine 2016 software. Depending on the specific types of land cover, the types of land cover in the study area were classified into six types of land cover (Fig. 6b).

Results

Slope gradient vs. groundwater potential

Based on the aforementioned methodology, the slope gradient of the Anger River basin ranges from 0 to 73 degrees. The output slope gradient raster is shown in Fig. 3a. Larger slopes do not have sufficient residence time to infiltrate and recharge the saturated zone (De Reu 2013).

Drainage density vs. groundwater potential

As indicated in the above-mentioned procedure for generating drainage density, the output drainage raster of the Anger River basin is shown in (Fig. 3b). The drainage density raster has been computed from drainage raster using a Line density tool in the GIS environment. The output drainage density of the Anger River basin ranges from 0 to 13.78 km/km^2 (Fig. 3c). Areas with the least drainage density value reflect very good groundwater potential; while, the highest-drainage density value areas are unfavorable for the tapping of groundwater.

Roughness vs. groundwater potential

The undulating topography is characteristic of a mountainous region where erosion and erosion processes continuously modify the landscape of a rough surface on a flat smooth surface at the end. Based on the mathematical roughness calculation (Eq. 2), Fig. 3d illustrates the roughness map of the Anger river basin and the values vary from 0.11 to 0.89. The values were reclassified into five categories, namely: 0.11–0.29, 0.3–0.41, 0.42–0.52, 0.53–0.63 and 0.64–0.89. High weights are assigned for low roughness values and vice versa.

Curvature vs. groundwater potential

The output indicates that the positive values of profile curvature reflect the concavity (hence, the acceleration of the flow) of the surface and the negative values reflect the convexity (deceleration of flow) of the surface; while, the planform curvature highlights the concavity and convexity perpendicular to the slope gradient, in which the positive

Fig. 3 **a** Slope gradient (in degrees), **b** drainage, **c** drainage density (in km/km^2) and **d** roughness in the Anger river basin
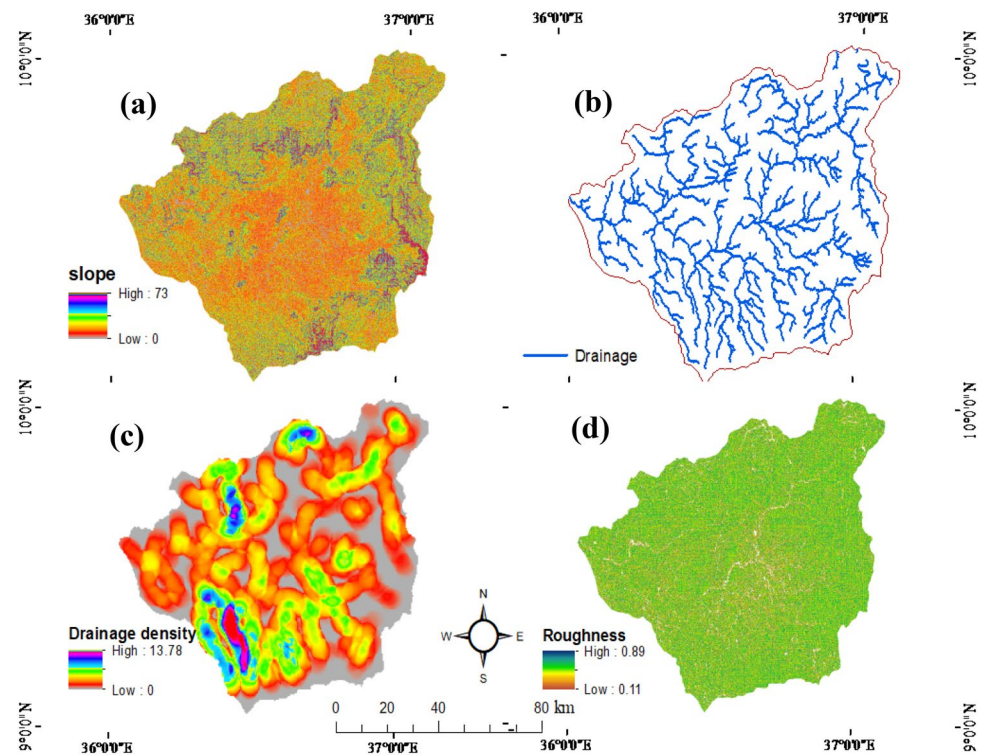
values and negative values reflect the convexity (divergence of flow) and concavity (convergence of flow) of the surface, respectively. The zero values in both the profile and planform curvature reflect that the terrain is flat. The output raster of Profile and planform curvature raster of Anger River basin are depicted in Figs. 4a and b, respectively.

Topographic wetness index vs. groundwater potential

TWI is a measure of wetland potential. Areas with the high positive TWI value reflect its wetland potential. Areas with the low positive TWI value reflect its erosion potential.
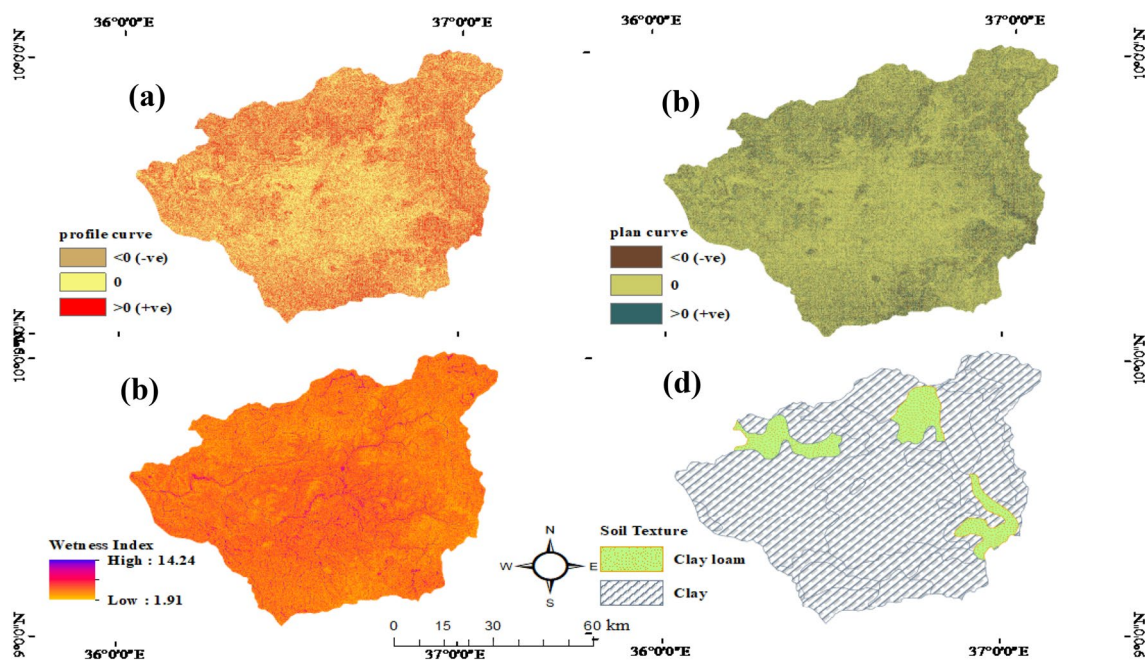

Fig. 4 **a** Profile curve, **b** plan curve, **c** wetness index, **d** soil texture of the Anger river basin

The high TWI values have been observed at low elevation areas in the Anger River basin. The high weights have been assigned for high TWI and vice versa. The output raster of TWI is shown in Fig. 4c.

Soil texture and soil type vs. groundwater potential

Soil texture of the Anger River basin is dominated by Clay (8710.80 km^2, 55.57%) followed by Clay loam (6288.90 km^2, 40.12%). The soil texture map of the Anger River basin is shown in Fig. 4d. Clay loam has good infiltration capacity than clay. Therefore, the soil texture of clay loam has good groundwater potential as compared with clayey texture. Dystric nitisols soil covers an area of 3750.23 km^2 (47.47%) and dominates the soil type of the Anger river basin (Fig. 5a) followed by Eutric cambisols, Eutric nitisols, Orthic solonchaks, Chromic luvisols, Dystric gleysols, Haplic xerosols, Leptosols, Chromic cambisols, Orthic luvisols, Orthic acrisols, Phaeozems, Gypsic yermosols, Vertic cambisols, Calcic cambisols, Calcic xerosols and Chromic vertisols with their areal extents of 627.65 km^2 (7.95%), 458.44 km^2 (5.80%), 442.96 km^2 (5.61%), 375.78 km^2 (4.76%), 259.42 km^2 (3.28%), 230.58 km^2 (2.92%), 195.54 km^2 (2.48%), 179.27 km^2 (2.27%), 127.78 km^2 (1.62%),

68.92 km^2 (0.87%), 27.10 km^2 (0.34%), 13.75 km^2 (0.17%), 6.00 km^2 (0.08%), 1.55 km^2 (0.02%), 0.77 km^2 (0.01%).

Land use/land cover vs. groundwater potential

Agricultural land with an areal extent of (4649.69 km^2, 58.85%) dominates the land use of the Anger River basin followed by Forestland (2108.24 km^2, 26.68%), Shrubland (1102.57 km^2, 13.95%), Bare lands (32.94 km^2, 0.42%), Buildup's (8.09 km^2, 0.10%), and waterbody (0.05 km^2, 0.001%), (Fig. 5b). Land use class like agriculture land is considered a very good land use for groundwater potential and urban land is considered as unfavorable for groundwater potential (Rajaveni et al. 2017).

Groundwater potential zone

Based on the designed methodology for this study, each thematic layer was converted into a raster file and appropriate fuzzy membership values were given using fuzzy membership function in a GIS environment. The fuzzy membership values for each thematic map are shown in Figs. 6 and 7. The final output of the fuzzy logic overlay shows the locations of the best sites of groundwater potential with combined input fuzzy membership values (Fig. 8). The output of the fuzzy
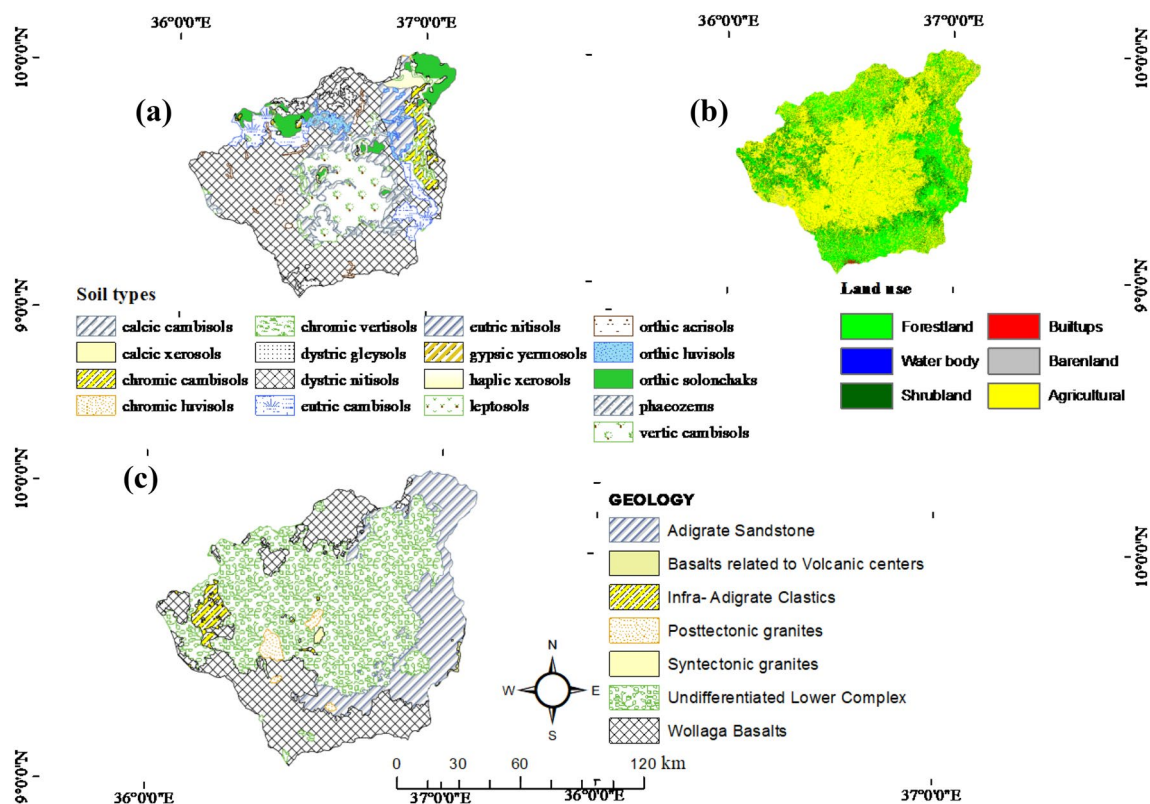

Fig. 5 **a** Soil type, **b** land use and **c** geology of the Anger river basin
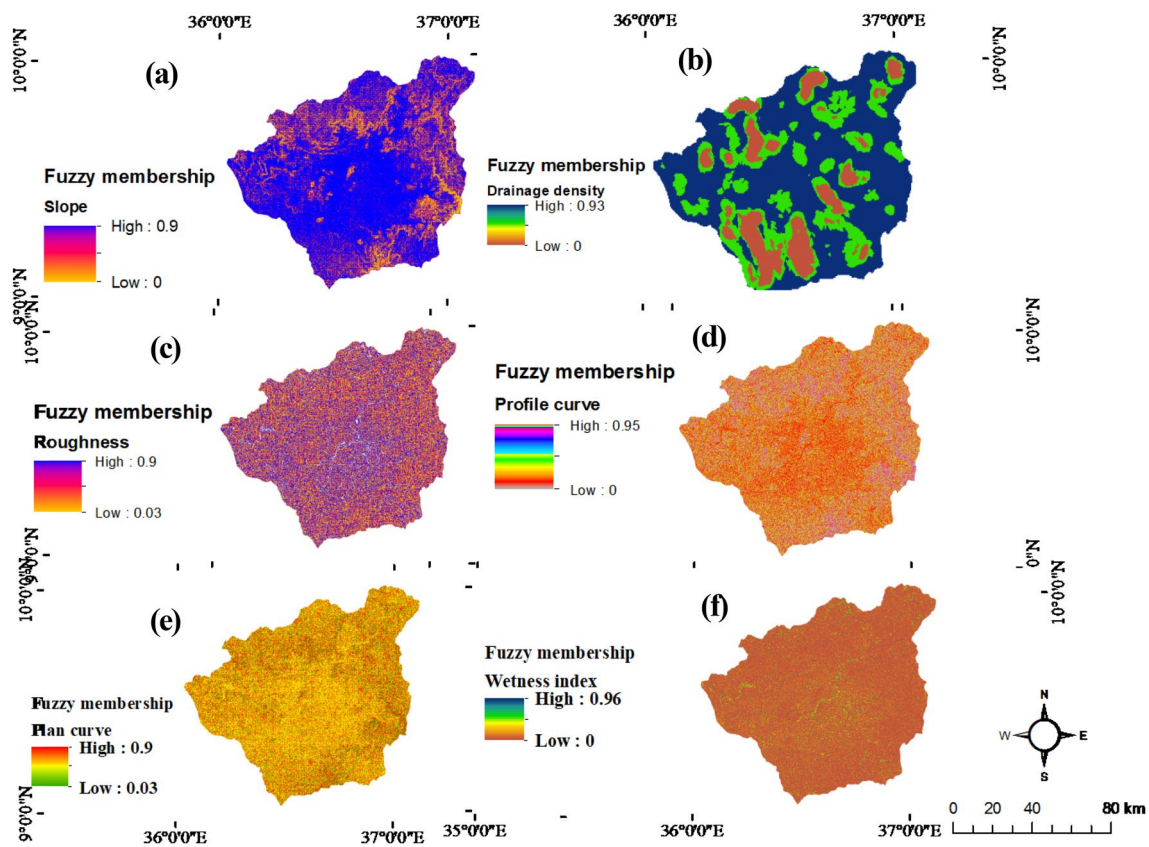
Fig. 6 Fuzzy Membership values for **a** slope, **b** for drainage density, **c** for distance to faults and **d** for profile curvature, **e** plan curvature, **f** topographic wetness index
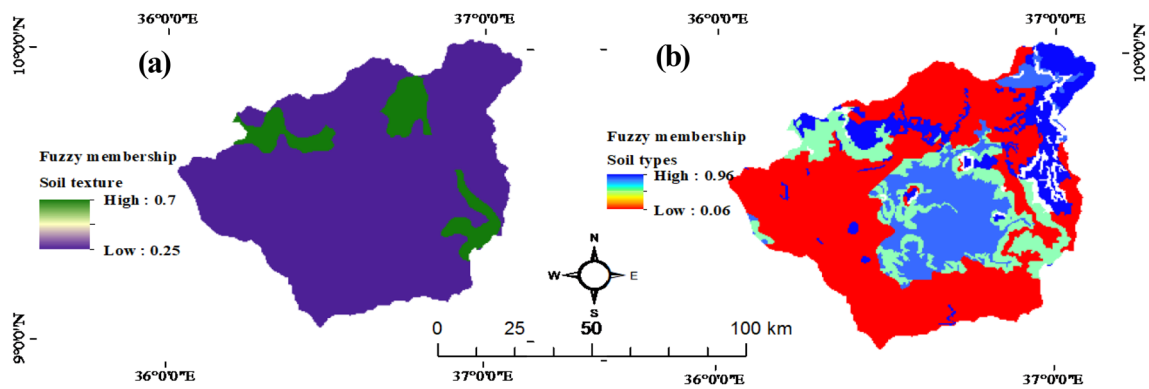

Fig. 7 Fuzzy membership values for **a** soil texture and **b** soil type

logic overlay was further reclassified into five classes, viz., very good, good, moderate, poor and very poor groundwater potential zones. The zonal statistics were used to obtain the areal extent of each of the five fuzzy membership values and are presented in Table 1. The positive correlation between the final map of the groundwater potential zone and the soil texture, elevation contour, wetness index, and slope maps are presented in Figs. 9 and 10).

Discussion

The output of the study indicates that the fuzzy membership values ranging from 0.9 to 1.0, representing very good GPZ, cover 28.44%, (2247.56 km²) of the Anger River basin; whereas, the fuzzy membership values ranging from 0.8 to 0.9 (Good GPZ), 0.7 to 0.8 (Moderate GPZ), 0.6

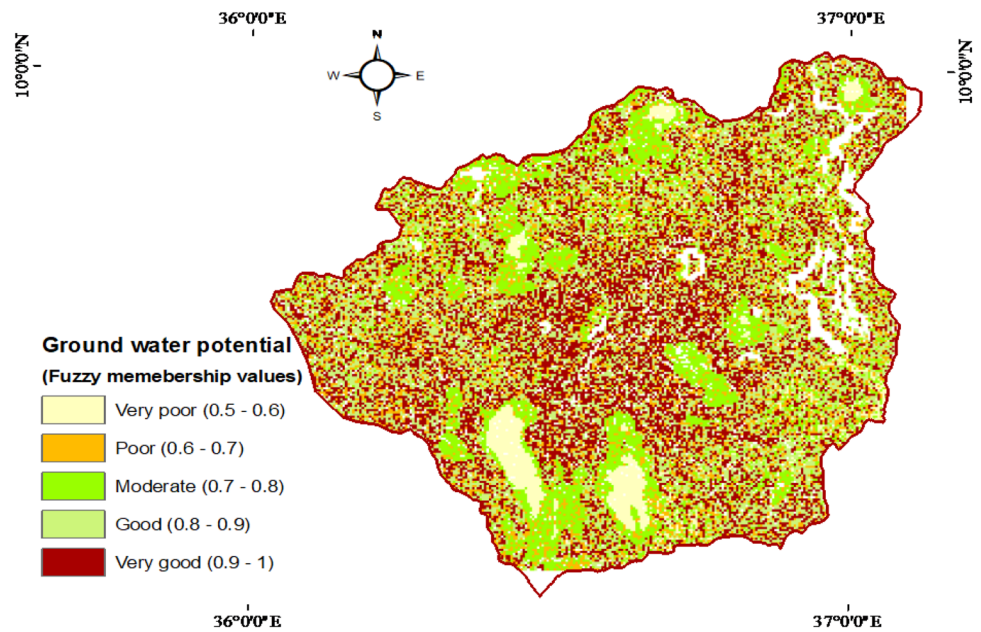**Fig. 8** Groundwater prospectus along with the fuzzy membership values of Anger river basin, Ethiopia

Table 1 GWP, fuzzy membership values, areal extent in the Anger river basin

GPZ	Fuzzy membership value	Area (km^2)	% of the total area
Very poor	0.5–0.6	636.77	8.06
Poor	0.6–0.7	1222.49	15.47
Moderate	0.7–0.8	1687.55	21.36
Good	0.8–0.9	2107.14	26.67
Very good	0.9–1.0	2247.56	28.44

to 0.7 (Poor GPZ) and 0.5 to 0.6 (Very poor GPZ) cover 26.67% (area 2107.14 km^2), 21.36% (area 1687.55 km^2), 15.47% (area 1222.49 km^2) and 8.06% (area 636.77 km^2), respectively. While correlating the final output map of groundwater potential with the soil texture, it was found that the areas covered by clayey soil texture represented very poor to poor groundwater potential in the Anger river basin; while clay loam was found to favor the good to moderate groundwater potential (Fig. 9). In case of correlation between the groundwater potential and elevation contour is concerned, it was found that the low elevation of the Anger river basin favors very good groundwater potential, while high elevation favors the very poor groundwater potential (Fig. 9). Correlation between groundwater potential and TWI indicates that high TWI values are associated with very good groundwater potential; whereas, very poor to poor groundwater potential is associated with low TWI values in the Anger river basin (Fig. 10). Furthermore, the spatial distribution of slope affects the groundwater potential. It has been found that the very good groundwater

potential in the Anger River basin is positively correlated with the presence of flat slope (Fig. 10). It is because of the occurrence of the very high infiltration rate of surface water on a flat slope; whereas, very poor to poor groundwater potential is reflected by the areas covered with a steep slope.

Conclusion

This study applied a fuzzy logic approach based on geospatial technology in the Anger River Basin, Ethiopia, to spatially demarcate areas of groundwater potential. Nine thematic layers were analyzed and prepared in the ArcGIS environment. Each layer was assigned the fuzzy logic membership values and overlaid using the "fuzzy overlay" tool in the GIS domain. The output of this study revealed that 2247.56 km^2 (28.44%) of the Anger River basin fall in the Very good groundwater potential zone; while, very poor, poor, moderate and good groundwater, potential zones cover the areal extents of 636.77 km^2, 1222.49 km^2, 1687.55 km^2, and 2107.14 km^2, respectively. This study shows the large spatial variability of groundwater potential across the Anger river basin due to variability in the geology, soil and land use/land cover in the study area. Furthermore, the most promising potential zone in the area is related to high TWI values at low altitudes; whereas, very poor to poor groundwater potential zones were marked by clayey soil, with low TWI values at high altitudes. This study testifies the efficiency of the fuzzy logic tool in the demarcation of groundwater potential zones and can be successfully used elsewhere with appropriate modifications.
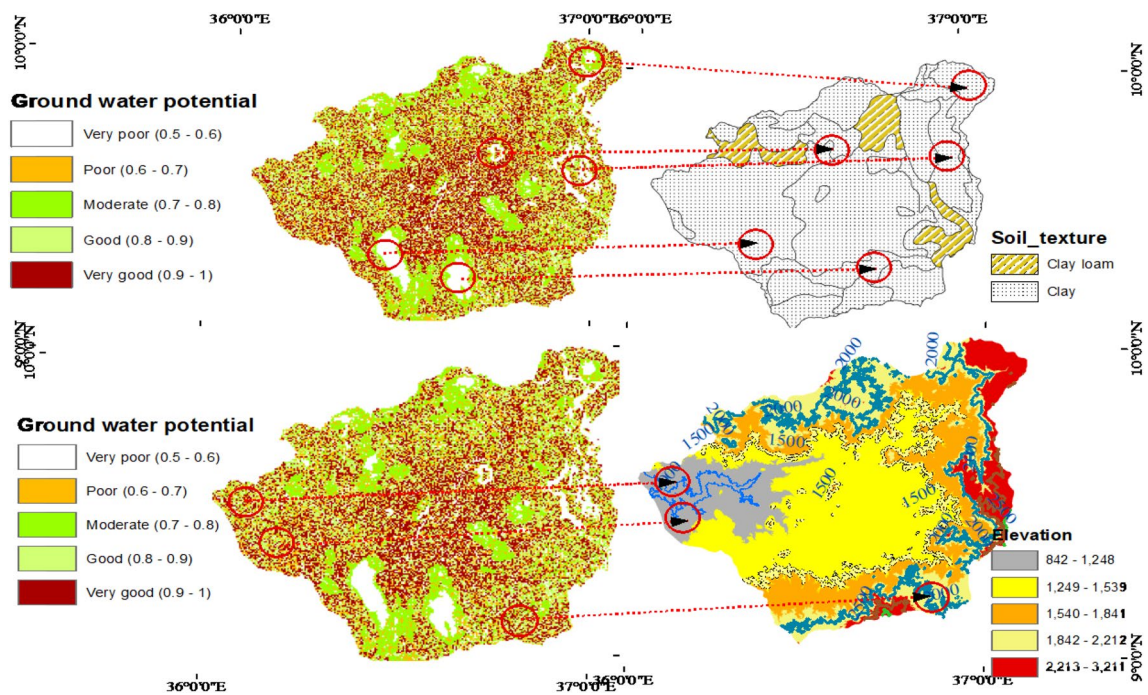
Fig. 9 Very poor and poor groundwater potential is positively correlated with the presence of clayey soil texture as well as excellent groundwater potential is positively correlated with a low elevation in Anger river basin, Ethiopia
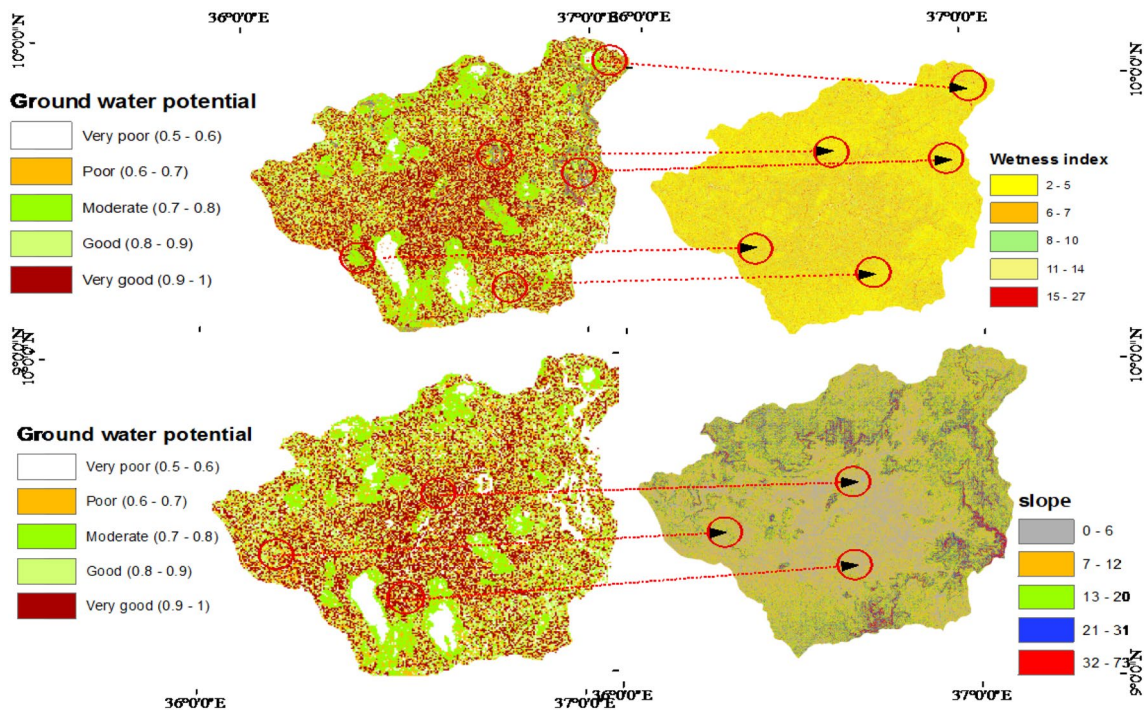

Fig. 10 Excellent groundwater potential is positively correlated with the highest positive wetness index values and flat slope in Anger river basin, Ethiopia

Author contributions AT designed the methodology, intellectualized the study, collected the data, analyzed and interpreted the data and wrote the manuscript. AH, IA and MT reviewed, edited and corrected all errors in the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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