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ORIGINAL ARTICLE

Groundwater potential mapping of the central region using integrated geological and geophysical methods

Haoulata Touré[1] · Cyril D. Boateng[2,6] · Solomon S. R. Gidigasu[1] · David D. Wemegah[2] · Vera Mensah[1] · Jeffrey N. A. Aryee[3] · Marian A. Osei[3,4,5] · Benjamin Boadi[1] · Collins Okrah[7]

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Abstract
Surface waters across Ghana are deteriorating due mainly to poor farming practices, illegal mining activities and also climate change. In the Central region this has led to a rise in the dependence on groundwater as potable water supply. However, the Central Region is known to be characterized by high unsuccessful rates of borehole drilling for groundwater, which usually results in waste of time and resources. The need to delineate groundwater potential areas in the region has long been felt. This study sought to map and delineate the groundwater potential zones of the Central Region by integrating input variables such as lineaments map deduced from magnetic survey data, digital elevation model, geology, soil type, land use/land cover, drainage density, slope and flow accumulation maps using Fuzzy Logic in a GIS software. The final groundwater potential map of the area was validated using borehole yield data and the reliability testing executed using the area under curve operation technique. Results of the study revealed that the region is characterized by very low to high groundwater potential zones. High groundwater potential zones cover the least of about 1083.7 km^2, representing 11.17% and moderate groundwater potential zones cover about 1978 km^2 constituting 20.4%. About 3461.16 km^2 of the region representing 35.68% and 3176.88 km^2 (32.74%) were found to have low and very low groundwater potential respectively. The final output revealed that the high potential areas are mainly located in the central part of the region which is mainly occupied by fractured granitoids. The low groundwater potential areas are mostly encountered in the southeastern but are found also in the northern and central part of the region and fall mainly on non-porous metavolcanics rocks. It is anticipated that the groundwater prospectivity map could be used as a valuable source for sustainable water resource management and development in the Central Region and also serve as guide for drilling campaigns in the region.

Keywords Groundwater potential · GIS · Fuzzy logic · Central region · Ghana

Introduction

Groundwater serves as the principal potable water source for most African countries (MacDonald et al. 2012). According to estimates, around half of world's population depends on groundwater for domestic and industrial purposes. In Ghana, around 49% of the population of 33.79 million people living in rural zones heavily depend on groundwater for their daily needs and agriculture (Asare et al. 2016). The demand and dependence on groundwater are anticipated to increase significantly within the next few years due to the increase in global population (rate of 80 million per year) and urbanization (Vörösmarty et al. 2000). This increase in demand will likely lead to the over-exploitation of available groundwater resources. Compounding this issue is climate change and variability, which are causing precipitation patterns to become more erratic. This situation poses a significant challenge, particularly for underdeveloped and developing countries around the world, especially in Africa, where there is low water security. Low water security can contribute to food insecurity as agriculture heavily relies on water availability and also significantly affects sustainable growth and development in Africa. This is exacerbated by unreliable clean surface water supplies due to increasing

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frequency of severe weather conditions and droughts (Oluwasanya et al. 2022) as well as the pollution of water bodies by anthropogenic activities. Some of these activities that contaminate surface water bodies include the use of harmful chemicals for fishing, farming near water bodies, illegal mining and others, thereby making them unsafe for drinking (Okrah et al. 2012).

In the coastal zones of Ghana, particularly the Central and Western regions, as well as the southern Volta, most irrigation systems rely on groundwater from shallow aquifer systems (Asare et al. 2016), which are replenished by sufficient rainfall, although this rainfall is distributed inconsistently throughout the year (Ewusi and Kuma 2011). This represents the case in the Central Region, where groundwater is the most preferred source of water. Moreover, the erratic rainfall patterns resulting from climate change and variability in recent times have been complicating situation in the region. The rainfall variability, unpredictable precipitation trends, reduction in rainfall, is leading to periods of drought, significantly affecting the recharge rates of aquifers and the availability of groundwater for both domestic and irrigation purposes. As a result, understanding and effectively managing groundwater resources has become increasingly critical to ensure agricultural sustainability and food security in the region. This highlights the urgent need for research focused on innovative exploration and management strategies for groundwater resources in the face of these climatic challenges.

Groundwater identification can be a challenging task due to its hidden nature. Methods like geophysical surveys have been effective in reducing the uncertainty in exploring for groundwater by investigating the physical properties of the Earth. For instance, Yehualaw et al. (2023) combined Vertical Electrical Sounding (VES) and magnetic prospecting techniques to obtain information on subsurface distribution and extent of the aquifer zones. Araffa et al. (2015) opted for the combination of 3D magnetic, 2D resistivity and gravity data interpretation to delineate the groundwater potential. These methods offer valuable insights into the subsurface by providing information on the geological formations and their characteristics but they do not directly detect groundwater and come with several limitations (Díaz-Alcaide and Martínez-Santos 2019). They can be costly and require significant time investment, especially when surveying extensive and geologically complex areas.

In recent years, various artificial intelligence (AI)-based time series analysis modeling techniques have been used to integrate wide range of parameters that influenced groundwater occurrence to aid in its potential mapping. Techniques such as artificial neural networks (ANNs), genetic algorithms (GA), neuro-fuzzy (NF), and fuzzy logic (FL) methods have demonstrated efficiency in several studies (Amponsah et al. 2022a; Echogdali et al. 2022; Gaffoor et al. 2022; Kalu et al. 2022; Owolabi et al. 2020; Tao et al. 2022). AI algorithms have notably excelled in groundwater mapping globally over the last decade (Tao et al. 2022). As said by Mitchell (1997) “The impact of AI is certain to grow over the coming years, as more and more data come online, we develop more effective algorithms and underlying theories for machine learning (ML), the futility of hand-coding increasingly complex systems becomes clear, and human organizations themselves learn the value of capturing and using historical data”. Their ability to incorporate multiple environmental parameters, including geology, soil type, slope, land use land cover (LULC), and precipitation, reduces the uncertainty associated with relying on one single parameter. It enables the coverage of more extensive areas compared to point-based techniques, consequently providing a broader and more reliable understanding of groundwater potential across an area.(Gómez-Escalonilla et al., 2022).

This multi parameters approach has successfully been utilized to map the groundwater potential in some areas in Ghana (Amponsah et al. 2022b; Osiakwan et al. 2022; Siabi et al. 2022). Unfortunately, there is no detailed groundwater potential map of the Central Region of Ghana. Without accurate information about the distribution and availability of groundwater resources, decision-makers face difficulties in planning and implementing sustainable water supply projects. This knowledge gap hampers efforts to meet the increasing water demand and ensure the region’s water security. Access to clean and reliable groundwater is crucial for several sectors such as farming, industry, and domestic use and there is a need for comprehensive groundwater potential mapping in the region to delineate areas with high potential for groundwater resources (Osiakwan et al. 2022).

In this study, we introduce a novel integration of magnetic lineament analysis within a fuzzy GIS-based modeling framework, tailored for the geologically complex Central Region of Ghana, which is predominantly underlain by crystalline granitoid formations. This combination enhances subsurface structural interpretation especially in regions where conventional groundwater indicators may be limited due to the hard rock setting. These basement rocks exhibit limited primary porosity, making secondary structures such as weathered zones and fractures critical for groundwater accumulation. While similar integrated approaches have been applied elsewhere, this study represents one of the first comprehensive and validated groundwater potential (GWP) map of the Central Region using this integrated geophysical-AI approach. This contribution not only addresses a critical knowledge gap but also provides a replicable workflow for similar terrains across Ghana and other parts of Sub-Saharan Africa.

In this project, AI-based algorithms are employed to precisely map the groundwater potential of the Central Region. Thematic layers were developed from various variables affecting groundwater occurrence. These layers were processed and integrated in the Fuzzy Logic algorithm to generate the groundwater potential map of the study area, which was finally validated using boreholes data. This mapping project gives valuable information for sustainable water resource management and development. The following sections cover the study area description followed by the methodology, the results section.

Study area

Located in the southwest of Ghana, the Central Region (Fig. 1) lies within longitudes 2.15888° W and 0.4805 W, and latitudes 5.11455° N and 6.3052° N. Itis bounded to the North-East by the Eastern Region, to the North by the Ashanti Region, the Greater Accra Region to the South-East and the West by the Western Region. Its boundary to the South is the Gulf of Guinea. The temperature in the region is relatively high and ranges between 24 °C in August and 34 °C in March to April. The area falls within the semi-equatorial region with two main raining seasons. The major season runs from May and July, with the highest amount of rain in June and the minor season from September to the end of November. The second rainy season occurs from September to October (Ewusi and Kuma 2011). The annual rainfall is in the range of 800 mm to 1,600 mm. The region has a relative humidity of between 50% and 85%.

Five main rivers drain the region namely the Ochi, Amisa, Kakum in the southern part, and Offin, with the Pra in the north. In the coastal plains, sandy beaches and lagoons are observable, while further inland, the topography becomes more undulating and densely forested, with portions of the region encompassing the verdant rainforests of the Central Forest Reserve (Manu et al. 2019).

The geology of the Central Region of Ghana is depicted in Fig. 2. The region is underlain by rocks of the Birimian Supergroup with granitoids intrusions, the Tarkwaian group, the Togo Structural Unit, and the Coastal sedimentary basin consisting of the Sekondian and Amisian formations.

The Birimian Supergroup which are of Paleoproterozoic age and are composed of metasedimentary rocks that are intruded by biotite rich basin type granitoids and metavolcanic rocks, which are also intruded by Belt type granitoids of Proterozoic age. The metasedimentary unit primarily which occupies anticlinal zones, consists of metamorphosed and folded schist, argillites and phyllite with interbedded metagreywacke (Osiakwan et al. 2022). The metavolcanic unit which also occurs in synclinal troughs is characterized by meta-tuff, meta-agglomerate and fine/coarse amphibolites (which are generally referred to as greenstones) are intruded by hornblende rich belt type granitoids. The degree of metamorphism varies from a low-grade green-schist facies to a high-grade granulite facies. There are widespread faults and joints. The granitoids generally 'Basin type granitoids' consist at times of well foliated often migmatic, high potassium content rocks and manifest as granodiorites, muscovite–biotite granite, porphyroblastic biotite gneiss, aplites, and pegmatites (Ewusi and Kuma 2011).

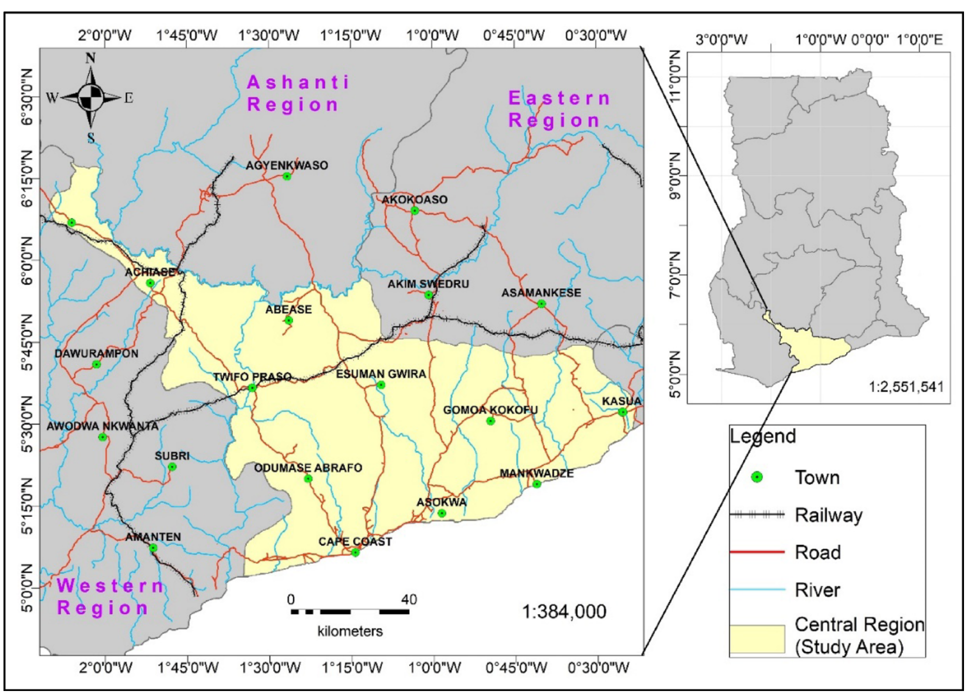

Fig. 1 Location of the central region in Ghana

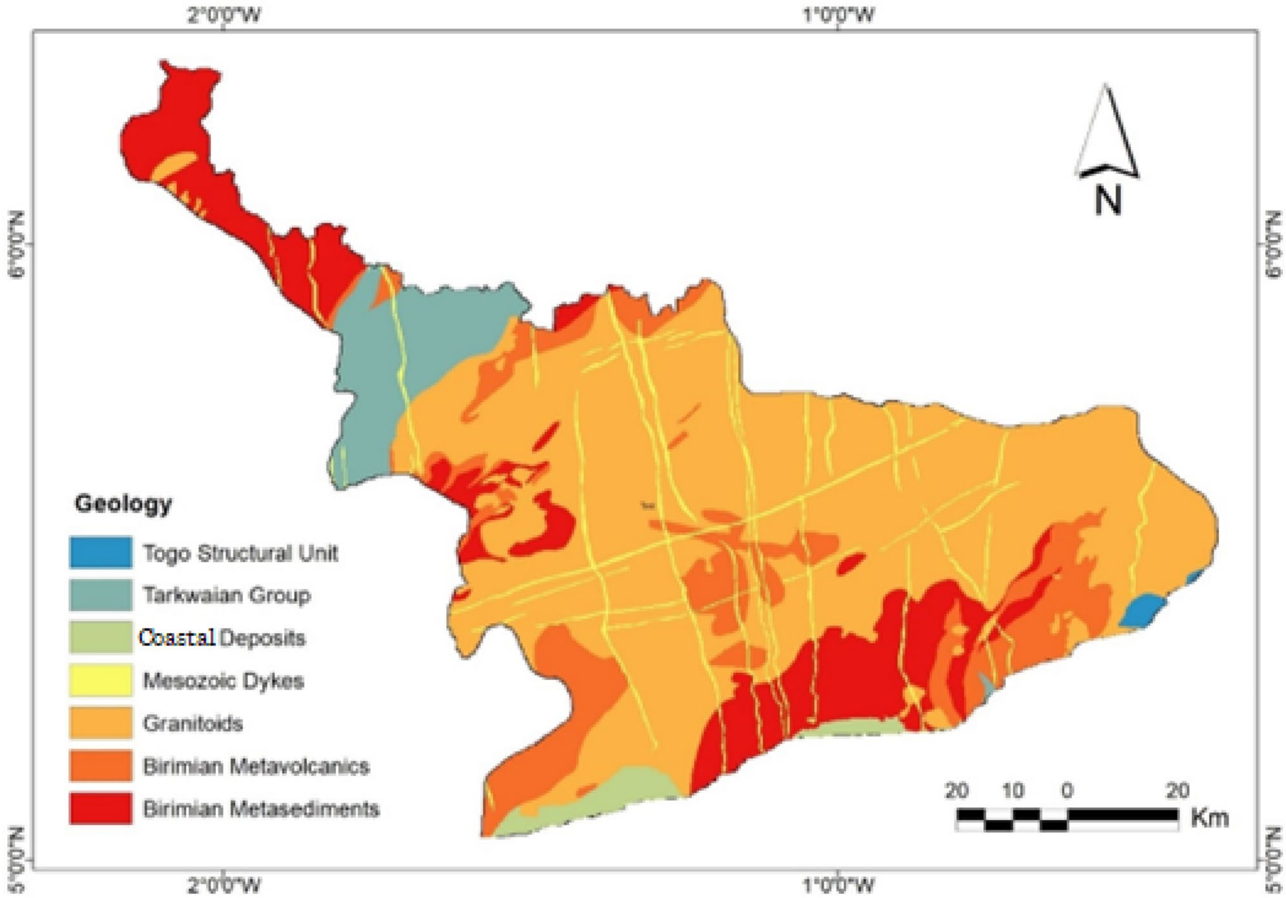

Fig. 2 Geology of the Central region

The Tarkwaian group (paleo-protozoic in age) which rests uncomformably on the Birimian greenstone belt, is made up of four stratigraphic units. They are the Kawere group, Tarkwa phyllite Banket series and Huni sandstones. The Tarkwaian group generally trends Northeast-Southwest and are folded together with the underlying rock. The Huni sandstone is the topmost and youngest rock unit of the Tarkwaian group and consist of sandstone with interbedded quartzites and phyllites, intruded by minor dolerite sills. The second stratigraphic unit is the Tarkwa phyllite which consists of mainly spotted phyllite with and without chloritoid rock. The Banket series is the third stratigraphic unit of the Tarkwaian group and are composed of 3–4 reefs that contain detrital gold mineralization (Eisenlohr and Hirdes 1992). Kawere group is the basal and oldest unit of the Tarkwaian super group, mostly made up of elongated pebbles derived from the greenstone materials and siliceous pebbles. They are composed of sandstones, grit and polymictic poorly-sorted conglomerates (Perrouty et al. 2012; Strogen 1988).

The Togo Structural unit is of the late Proterozoic age. It consists of siliciclastic sediments that have been subjected to a low- to- intermediate grade type of metamorphism. The rocks form a prominent northeast-southwest trending mountain range known as the Akwapim-Togo range. The Togo structural unit is characterized by structures such as foliation, folds, faults, and joints caused by the Pan African Orogeny (Ahmed et al. 1977). The Togo Structural has been subdivided into three main units which reflect their lithological properties. These units are: Phyllite/Phyllonite Unit; Quartz-Schist Unit; and a Quartzite Unit. The Phyllite/Phyllonite Unit consists mainly of phyllite and Phyllonite, which are often talcy. Phyllonites make up a large part of this unit and together with phyllitic rocks are of mylonitic character and belong to the group of rocks called fault rocks. The Quartz-Schist unit encompasses mainly sericitic quartz-schist and chlorite-schist and contains layers of quartzite, phyllite or chlorite schist. The sequence is well-bedded and strongly jointed (Ahmed et al. 1977). Quartzite unit comprises mainly quartzite and the amount of quartz-schist and phyllite is very variable. In some places, quartzite possesses aspects of vaguely banded chert. Quartzite may occur as massive layers of up to 2 m width, flaggy or it may be laminated and with increasing lamination that may grade into Phyllonite (Muff and Efa 2006). Three types of quartzite are recognized namely: Metaquartzite, Micaceous quartzite and Cherty quartzite.

The Sekondian Group is Late Ordovician to Early Cretaceous in age and they rest unconformably on granitic rocks of the Paleoproterozoic Birimian Supergroup. They are composed of sandstone and shale dominated succession but also include coarse breccias and conglomerates. The rocks are extensively faulted and virtually unmetamorphosed. The stratigraphic units of the Sekondian Group consist of a predominantly fine-grained basal unit, Ajua Shale, overlain by six predominantly arenaceous lithologic units: Elmina Sandstone, Takoradi Sandstone, Takoradi Shale, Effia Nkwanta Beds, Sekondi Sandstone, and Essikado Sandstone, in decreasing order of age.

The Amissian formation is composed of rocks deposited during the Late Jurassic to Early Cretaceous periods, characterized by interbedded soft, pebbly grits, conglomerates, micaceous sandstone, and shales.

Methodology

Groundwater availability is influenced by the interaction of multiple factors (Echogdali et al. 2022; Park et al. 2014). Some of these factors have been identified (Touré et al. 2024) and include variations in lithology, slope, topographical features, soil type, drainage density, structural characteristics, the composition of the underlying bedrock, vegetation type, and land use patterns (Muthamilsevan et al. 2022). The workflow involves gathering the dataset, generating attributes to reflect the factors that affect groundwater, and merging the different attributes through the fuzzy overlay method.

A magnetic survey data analyzing approach, successfully used in various studies ((Boadi et al. 2022; Forson et al. 2021; Muthamilsevan et al. 2022; Wemegah et al. 2015) was employed in this study to extract the lineaments of the study area. Several filters were applied to the data to enhance it. They were Reduction to the Pole (RTP), First Vertical Derivative (1VD), Analytical Signal, and Tilt derivative. The extracted lineaments were then associated with other geological data, which were chosen after reviewing the different variables that can affect groundwater, are integrated and processed using this combined geospatial approach. The data selected for this study comprises the fault density and the fault buffer of the region, the geology, soil type, digital elevation model (DEM), land use/land cover (LULC), drainage density, flow accumulation, and slope. Figure 3 shows the mapping approach and techniques employed in this study.

The magnetic data, soil type, land use/land cover and geology maps of the study area were acquired from the

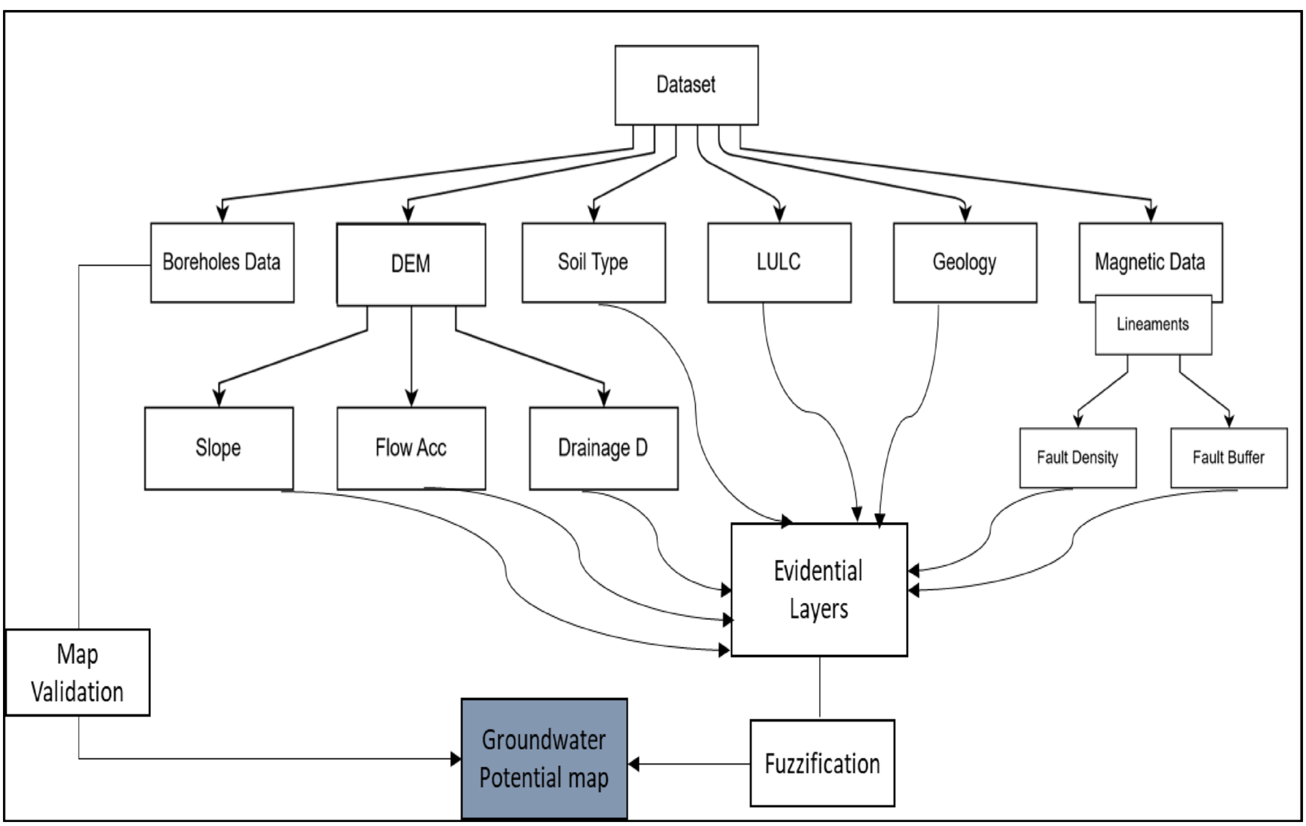

Fig. 3 Study workflow

Ghana Geological Survey Authority. The magnetic data was acquired as part of a high-resolution airborne geophysical surveys of southwestern Ghana conducted by Aerodat Inc. from 1997 to 1998. A Piper Chieftan (C-FESC), a Cessna Titan 404 (C-FYAU) and a Scintrex Cesium SC-2 were the equipment used to collect the geophysical data. The Shuttle Radar Topography Mission (SRTM) was downloaded from the United States Geological Survey (USGS) Earth Explorer in a GeoTIFF format with the images in geographic coordinate system. The downloaded SRTM DEM data was re-projected to the Universal Transverse Mercator (UTM) to match the study area's extent. After obtaining the raster format for all the layers, they were classified utilizing the Jenks natural classification technique. This classification is done considering the water-retention capacity of each of the attributes within the layers. The values are from 1 to 9, with high ones indicating a higher likelihood of groundwater presence.

In the next step of the analysis, the Fuzzy Membership function in ArcGIS was applied to standardize the thematic layers for groundwater potential mapping. Although the overall objective was to delineate areas of high groundwater potential, each thematic layer contributes differently depending on its characteristics. Therefore, either the Fuzzylarge or Fuzzysmall function type was used to assign fuzzy membership values to the attribute classes on a continuous scale ranging from 0 (very low potential) to 1 (very high potential). The Fuzzylarge function was applied to parameters where higher values indicate greater groundwater potential, such as fault density, Geology, flow accumulation, soil type and LULC. Conversely, the Fuzzysmall function was used for parameters where lower values correspond to higher groundwater potential, including slope, DEM, and drainage density. Each thematic layer consisted of at least seven attribute classes, and the fuzzy membership scores were assigned based on relevant literature to reflect the relative influence of each factor on groundwater recharge and storage potential. This standardization ensured that all layers were comparable on a uniform scale before integration.

The fault density and fault buffer datasets resulting from the lineaments data were merged using the Fuzzy AND function. This function was used to create a unified dataset that captured both aspects of fault information. This merging process allowed the combination of the relevant attributes without overwriting the lineaments, ensuring the preservation of the original data.

Further analysis consisted of using overlay techniques to rank and evaluate suitable zones for groundwater potential. By overlaying all the layers utilizing Fuzzy Overlay in GIS, the final integrated output was obtained, which represents the groundwater potential areas in our research area. The final input layers considered were the fuzzified evidential layers, including DEM, slope, drainage density, geology, land use/land cover, the merged lineament density and lineament buffer, flow accumulation. The fuzzy gamma function, which allows for inputs with uncertainty by using fuzzy numbers, was then utilized to overlay the merged lineaments map and all the thematic layers providing the final output. The final map was classified into four classes: high, moderate, low and very low.

Magnetic data processing

The study area's residual magnetic intensity map was enhanced using several data filtering and processing techniques, including reduction to the pole (RTP), Analytic Signal, 1st Vertical Derivative (1VD), and Tilt Derivative. In this study, a RTP filter was applied on the magnetic data gathered at low geomagnetic latitudes (Residual Magnetic Intensity) to position the magnetic anomaly symmetrically over the magnetic source (Roest and Pilkington 1993; Debeglia and Corpel 1997). The Analytical signal filter was applied because it acts as a type of RTP filter that aids in positioning the magnetic anomaly above the source body. 1VD filter was applied to improve the data's surface details. The tilt derivative filter was used on the RTP data to create the slope derivative grid.

The RMI enhanced, was then processed in the Center for Exploration Targeting (CET) grid analysis to extract the lineaments. The Geosoft Oasis Montaj program's CET analysis, along with its texture analysis tool, were utilized. The final process consisted of the extraction of the lineaments.

Evidential layers

Groundwater availability is influenced by the interaction of multiple factors (Echogdali et al. 2022; Park et al. 2014). These factors include variations in lithology, slope, topographical features, soil type, drainage density, structural characteristics, the composition of the underlying bedrock, vegetation type, and land use patterns (Muthamilsevan et al. 2022). Lithology directly influences the porosity and permeability of subsurface formations. For instance, sedimentary rocks like sandstone and limestone tend to allow better groundwater storage compared to impervious formations such as shale or unfractured crystalline rocks. A study in Ethiopia showed that lithological units with higher permeability received the highest suitability ranking in potential assessments (Bulbula and Serur 2024). Slope affects runoff dynamics and infiltration rates—gentle slopes promote longer residence time for rainfall to percolate, while steep slopes enhance runoff and reduce recharge. Studies confirm gentle terrain ($<5°$) as most favorable for infiltration, whereas steep areas significantly limit groundwater occurrence. Topography also influences subsurface flow directions and contributes to the understanding of recharge and discharge zones (Hussein et al. 2017). When it comes to consolidated rocks, they generally do not have primary porosity. Secondary porosity such as weathering and fractures, which constitute structural characteristics, allows the water to infiltrate into ground thereby recharging the groundwater system (Rajaveni et al. 2017). Soil texture and structure influence the balance between runoff and infiltration. Coarse-textured soils enable faster percolation, unlike clay-rich soils that resist infiltration and increase surface runoff. These properties also affect groundwater vulnerability, with finer soils posing greater contamination risk during infiltration events. Drainage density is a measure of the total channel length per unit area, and is inversely proportional to groundwater recharge potential. Regions with low drainage density often reflect higher infiltration rates, as less water is lost directly as runoff. In contrast, high drainage density areas drain quickly and reduce recharge opportunities, limiting groundwater storage potential (Njumbe et al. 2023). Vegetation cover significantly affects infiltration and evapotranspiration. Dense herbaceous or forested areas typically reduce runoff and support infiltration, whereas built-up or barren surfaces reduce infiltration capacity. Forest zones may decrease recharge due to transpiration but generally offer protection against soil erosion and compaction (Mostafa et al. 2025).

Geology

Geology plays a crucial role when it comes to infiltration of surface water into an aquifer. This happens through pores in the rock, hence, controlled by the permeability and porosity, which can differ among various geological formations (Ponnusamy et al. 2022). Figure 4a show the geological map of the Central region. From the map the granitoids which are generally impermeable occupy about 5570 km^2 (57%) the largest part of the study area. This result implies that 57% of the area is impermeable (if no consideration is given to any other parameters). The Metavolcanics and the Mesozoic dykes which covered 1731 km^2 (17.8%) and 35,28 km^2 (0.36%) of the study area respectively and are also considered to be impermeable hence are classified as being very poor for accumulation of groundwater. This is attributed to the absence of primary porosity; consequently, low rating is assigned. The sedimentary and metamorphic rock groups

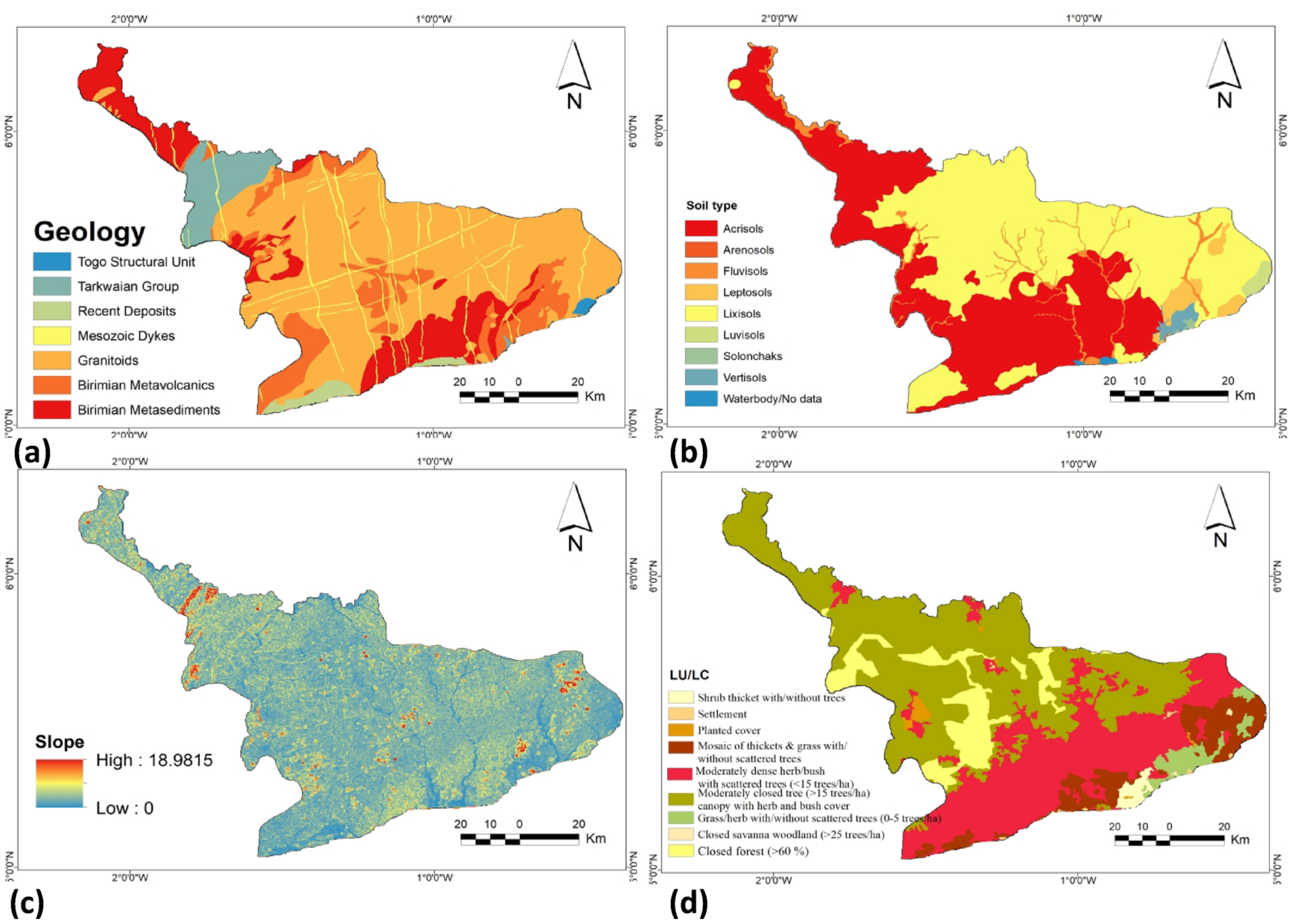

Fig. 4 **a** Geology map of the study area **b** Soil type map of the study area **c** Slope map of the study area **d** LULC map of the study area

sandstones, phyllites and slates which occupies about 6.75% of the study area (0.36 km^2) were assigned moderate to high Fuzzy Membership (FM) values. The highest values in the study area are attributed to two main geological formations. First, the recent deposits, which cover 2% of the area (approximately 195.6 km^2), consist of a series of interbedded materials including conglomerates, micaceous sandstones, arkose, and clay. Second, the Birimian metasediments which occupy a much larger area of 1527.76 km^2, representing about 15.72% of the total study area. The Tarkwaian Group is characterized as having a shallow water continental origin, which is derived from the Birimian and the associated granites (Osiakwan et al. 2022). This group is composed entirely of conglomerates.

Soil type

Soil type is an important factor that also plays a crucial function groundwater infiltration (Githinji et al. 2022). The nature of the soil covering the ground plays a crucial role in determining how quickly rainwater can seep into the ground, which in turn greatly contributes to groundwater recharge. Certain soil types such as Fluvisols, Luvisols facilitate water percolation, while others, for instance Vertisols or Acrisols, act as a barrier (Danso and Ma 2023).The different soils distribution is presented in Fig. 4b. They include Acrisols, Arenosols, Fluvisols, leptosols, Lixisols, Luvisols, solonchaks and Vertisols. A big part of the area (approximatively 49%) is covered with leptosols soil type (4782.68 km^2). This soil type falls on the high elevation region of the study area, overlying the granitoids. Acrisols and Vertisols form the second major soil cover of the area (4169.06 km^2), accounting for about 43% of the area. These soil types are assigned moderate to low FM values due to moderate capacity to allow for water infiltration. The solonchaks (14.6 km^2 corresponding 0.15%) are areas of least interest in terms of their capability to bear groundwater hence were assigned the lowest FM values, which rank from 0.0003 with a maximum value of 0.9497 for the highest. The highest FM value of 0.9497 was assigned to Lixisols covering 72.6 km^2 (0.74%), Luvisols covering 87.16 km^2 (1%) and Fluvisols covering 231.04 km^2 (2.37%). These soil types have high capacity to absorb surface water hence increasing infiltration. Aeronosols soil type also found in a small part of the area (360.04 km^2) and was moderate FM value.

Slope

Increase in slope result in high runoff and this affect water absorption by lowering the infiltration in those areas (Amponsah et al. 2022b). Figure 4c shows the slope map of the study area calculated in degrees, which ranges from 0° to 18.98°. The high surface gradient (slope) zones, varying from 3.38° to 18.98°, occupy more than 600 km^2 representing approximately 7 to 8% of the study area. 50% of the study area had slope gradient ranging from 1.34° to 3.38° and covers 4889.56 km^2. Low surface gradient (slope) zones vary from 0° to 1.34° and occupy 4107.08 km^2, which is 42%. The FM has values ranking from 0.0003 for steep areas to 0.9497 for gentle slopes areas. These areas represent the best areas in term of water infiltritation because they allow for low run-off. The steep areas (3.38° to 18.98°), representing the least part of the study area, indicate low groundwater prospectivity due to high runoff of surface water in those areas hence are assigned low FM of 0.0003. Majority of the area, in terms of slope gradient, is considered to be gentle, consequently the area will have moderate runoff leading to moderate infiltration. This situation provides conditions for moderate groundwater prospectivity. The flat areas in our study area are of interest because they are favorable to water infiltration into the subsurface and can therefore, indicate high groundwater potential.

Land use/Landcover

The integration of LULC is employed in studies mapping groundwater potential and is crucial factor responsible for groundwater storage and recharge. It refers to two distinct concepts: land cover, which encompasses the different varieties of land for instance vegetation, geology, water bodies, forests, etc., and land use, which refers to how the land is utilized for activities like agriculture and human-induced actions.(Chaudhry et al. 2021; Gómez-Escalonilla et al. 2022; Osiakwan et al. 2022). An irrigated agricultural ecosystem, for instance, is likely to facilitate moderate to high degree of groundwater recharge compared to natural rangeland ecosystems with less or no recharge (Osiakwan et al. 2022). Figure 4d shows the LULC map of the study area. Among the different types of LULC in the region, moderately closed trees, a canopy with herb and bush cover dominates, covering 46.40% of the study area (4509.44 km^2). They also constitute the most favorable LULC type for high groundwater potential in the area. Consequently, they are assigned the highest FM value of 0.9214. They are followed by shrub thickets with or without trees covering 104.76 km^2 which is 1.07% of the study area, followed by closed forest, planted cover, mosaic of thickets and grass with/without scattered trees. These LULC types together constitute 18% of the area, and covers 1749.6 km^2. They have moderate FM values as well as the closed savanna which is barely found in the study area (6.28 km^2) and the moderately dense herbs/bush with scattered trees found in the center to the south of the study region and covers 3074.28 km^2 (i.e. 31.63%). The lowest FM values were attributed respectively to grass/

herb with or without trees (2.6%) and the settlement areas which are concluded to be the most improbable zones to find groundwater. They cover 18.32 km^2 which represents 0.19% of the study region.

Digital elevation model

The region has ground elevation values ranging from −2 m to 380 m (Fig. 5a). Areas with ground surface situated at lower elevated areas range from −2 m to 89 m above the mean sea level (MSL), accounting for 39.5% of the study area. These represent the areas with high potential due to high groundwater holding times that enhance the opportunity for higher recharge of groundwater and was assigned a high FM value. These zones are encountered in the eastern part of the study region. Groundwater flows from high contours to lower elevations due to change in gradient promoting higher runoff of rainfall water. The high elevations are mainly found in the center and northern part of the study region varying from 380 m to 133 m above MSL and account for 26.8% of the area (2639.24 km^2). The remaining 33.26% is considered to be moderately elevated areas (133 to 89 m) covering around 3281.12 km^2. In this study the DEM map is mainly utilized to generate the drainage density, the flow accumulation and the slope maps as they highly affect water infiltration.

Drainage density

Drainage density is another crucial factor when investigating groundwater potential (Echogdali et al. 2022). It has an inverse relationship with infiltration. When the drainage density is high, it means there are more streams and rivers in the area. This leads to increased runoff, which affects the water infiltration into the subsurface (Rajaveni et al. 2017). The drainage density of the study region ranges from 0 to 1.099 km^{-1}. Based on the classified map (Fig. 5b), a large portion of the area falls in the range of 0 to 0.2150 of drainage density values, accounting for more than 5900 km^2 of the study area, which represents approximately 60%. Also, values ranging from 0.2950 to 1.0800 occupy a smaller part of the study region covering 2578 km^2 (26%) of the study area. The moderate drainage values occupying 16% of the study area (1382.52 km^2) range from 0.2150 to 0.2950. High drainage density usually indicates low potential of groundwater. The drainage density classes were scored based on that. High scores were given for low drainage density areas (values above 0.3750) as these areas will be our areas of interest (high groundwater potential areas) and low scores for high drainage density areas corresponding to high runoff thus low infiltration areas. The FM values observed within the study area rank from 0.0003 for the high drainage areas and 0.9497 for low drainage density areas.

Flow accumulation

Flow accumulation led to the improvement of the groundwater recharge process. The more the water is accumulated the more the chances for infiltration are high (Echogdali et al. 2022). Figure 5c illustrates the flow accumulation pattern of the study region. Areas likely to accumulate the maximum of water, covers about 7086 km^2 which represents 72% of the study region. The remaining part of the study area is divided as follows: moderate flow accumulation area covers 624.2 km^2, which is 6.32% of the study area, followed by low flow accumulation area (2153.4 km^2, which is 21.8% of the study area.).

Lineaments density

The geology of the Central region is mostly made up of granitoids, which are known to be impermeable, but permeability and secondary porosity could occur, through processes like fracturing and weathering. The groundwater potential in that case rely on the rate of weathering and fracturing and also the recharge potential of the groundwater resources (Ewusi and Kuma 2011; Okrah et al. 2012). This involves understanding and analyzing the lineaments potential of the area. Lineaments can be defined as geological structures or features such as faults, fractures and joints that are represented as like-line or curvilinear weaknesses on the Earth's surface. They indicate areas where the bedrock has experienced faulting and fracturing, which in turn contribute to the development of permeability and secondary porosity. These characteristics are significant as they enhance the productivity of wells and the movement of groundwater within the subsurface (Osiakwan et al. 2022). Similarly strong relation exists between high lineament density and the presence of a well-developed infiltration zone, which promotes the movement of groundwater (Echogdali et al. 2022). High lineament density areas are considered to have high potential for groundwater occurrence, in that they provide the most probable zones for infiltration of water. In the study area, about 2131 km^2 which represents 12.32% have high lineament density and are found along the Mesozoic dykes, in the Birimian metavolcanics and the Tarkwaian (Fig. 5d). The rest of the study area varies from moderate, covering 2840 km^2 (28.79%), to low lineament density values 5808 km^2 (58.89%). The values, after conversion to FM, rank from 0.0003 for the areas of least interest (low lineament density areas) to 0.9497 for the areas considered to have high groundwater potential (high lineament density areas).

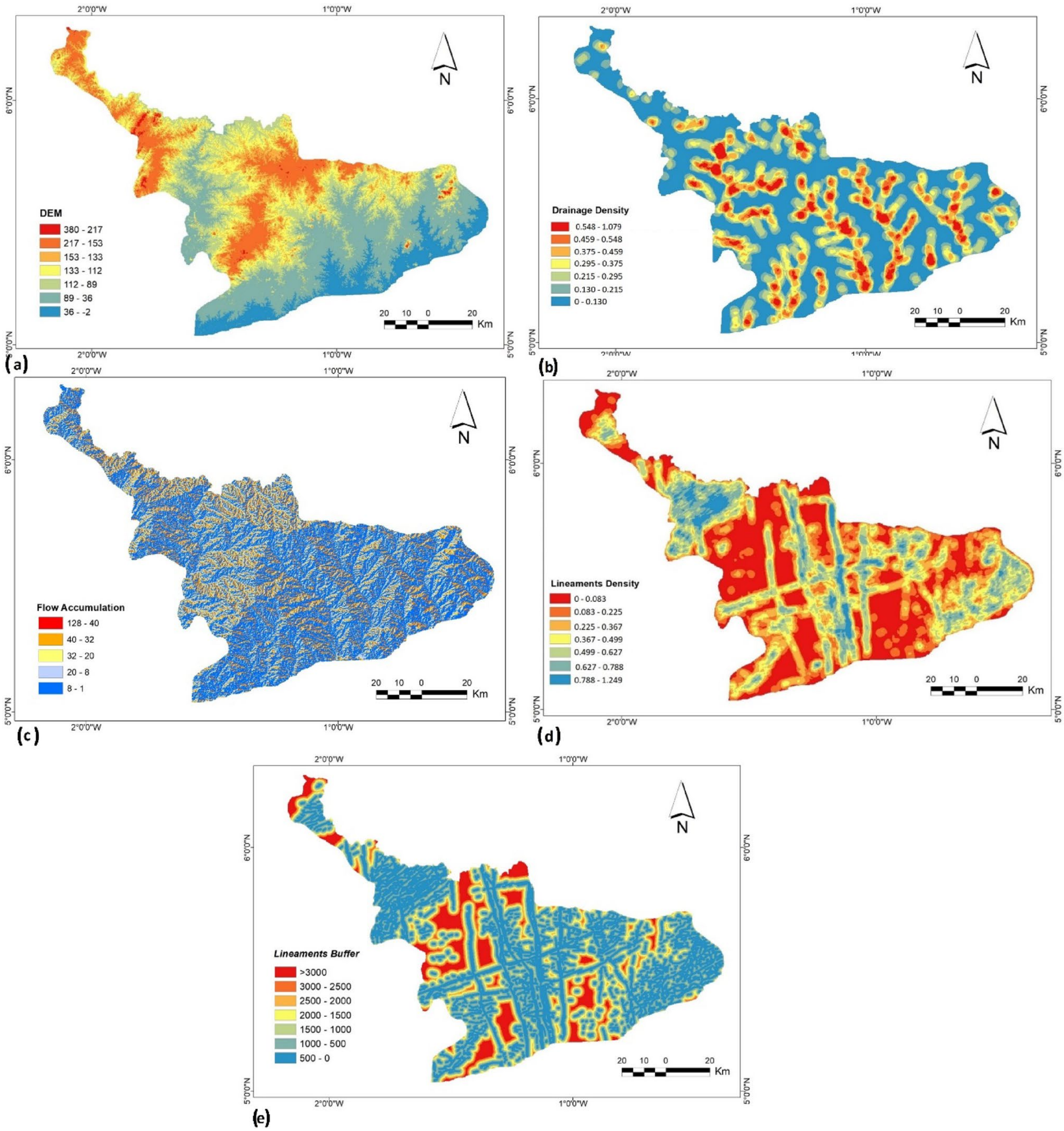

Fig. 5 **a** DEM map of the study area **b** Drainage Density map of the study area **c** Flow accumulation **d** Lineaments Density map of the study area **e** Lineaments Buffer map of the study area

Lineament buffer

Distances to lineaments is also very important as it affects water infiltration because faults facilitate water penetration in the subsurface. The proximity to lineaments goes from 0 to >3000 m as shown in Fig. 5e. A vast part of the study region (7428 km^2) ranged from 0 to 1500 m away from the lineaments. Due to their proximity to the lineaments, these proximal areas represent areas of interest. They are followed by 1500–2000 m (778 km^2), 2000–3000 m (895 km^2) and >3000 m (763 km^2). The FM map spatial distribution values range from 0.0060 to 0.9210 in the zone. Areas closer (0–1500 m) to the lineaments are consequently those with the higher FM values allocated as recharge is possibly high more than the areas located at long distance from lineaments (1500–3000 m away).

Fuzzy logic

Fuzzy logic (FL) offers the advantage of integrating data from various measurement scales, providing researchers with the flexibility to analyze different types of data. Additionally, experts have complete control over the weighing of evidence, allowing them to fine-tune the analysis according to their expertise and knowledge. Moreover, the FL paradigm facilitates the combination of weighted maps, enabling researchers to create more nuanced and comprehensive models. In the context of GIS modeling, implementing FL is relatively straightforward, making it a valuable tool for researchers. Figure 6 illustrates the various steps undertaken in this study, including the crucial fuzzification step. Each step in the figure is designed to build upon the previous one, ensuring a comprehensive approach to the study's methodology.

Fuzzy Logic methods, which are based on fuzzy quantities, have proven effective in groundwater levels forecasting. A study by Nadiri et al. (2019) provided background information on the performance of fuzzy logic models, highlighting their robustness to parameter changes and their ability to handle imprecision and uncertainty. The FL is a form of AI that deals with issues involving vagueness, imprecision, partial truth or uncertainty. It is a well-known tool in the field of soft computing. It helps create algorithms by incorporating structured human knowledge. Instead of strict precision, FL focuses on modeling human interpretation, which is often inexact. It can be used in intelligent systems designing based on human language expressed information (Kambalimath and Deka 2020). The fuzzy approach on the other hands, involves two steps: calculating fuzzy membership (FM) values for each attribute using an appropriate FM function and integrating these Fuzzy-based layers in a GIS software employing a suitable operator (Singha et al. 2021). According to Zadeh (1965), fuzzy set system allows for the representation of the degree of existence of the object within a set on a scale from 0 to 1.

In groundwater potential mapping (GWP), the utilization of remote sensing (RS) and geographic information systems (GIS) has become really popular lately. These tools have gained a lot of attention in research, especially when it comes to analyzing and mapping geographic data (Singha et al. 2021). Fuzzy logic is part of the most popular GIS-based models used in the field of hydrological studies (Tao et al. 2022). Its feasibility for groundwater level prediction has been proven in recent studies (Mallik et al. 2021; Nadiri et al. 2019).

There are 5 distinct combinations of Fuzzy operators available for the fuzzy logic overlay algorithm (Fuzzy OR, Fuzzy Product, Fuzzy AND, Fuzzy Gamma and Fuzzy Sum). The Fuzzy AND operator considers only the smallest value of membership of the pixels, resulting in a conservative outcome. The Fuzzy OR operator takes the highest pixel membership degree across all maps, leading to an optimistic output. The Fuzzy Product operator multiplies the membership degree of a pixel in several maps, reducing the final membership. This operator tends to assign a small

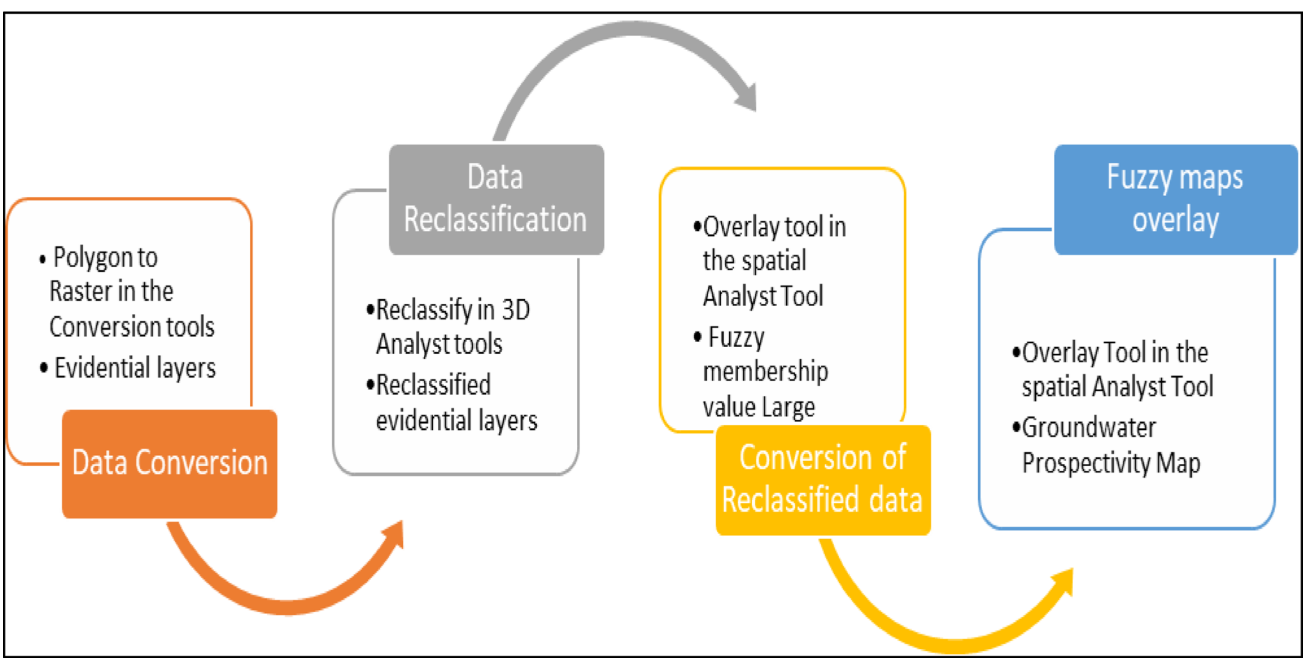

Fig. 6 Data processing steps

weight to each pixel, in the case of multiple input layers, the score can be close to zero. The Fuzzy Sum operator tends to assign a membership value of 1 to pixels in the final map when there are various input layers. It is suitable for modeling and is used when features reinforce each other. The Fuzzy Gamma operator combines the characteristics of the product and sums operators. These operators provide different ways to combine Fuzzy membership values and generate the final map in fuzzy logic-based overlay algorithms (Aretouyap et al. 2022).

For the final integration, Fuzzy Gamma was utilized because it introduces a control parameter (γ), typically ranging between 0 and 1, which allows for an adjustable compromise between these two extremes. In this study, an optimal γ value of 0.9 was selected as it provides a realistic balance between high and low membership values. This approach enhances the accuracy and spatial continuity of the groundwater potential mapping results.

The basic equation used in Fuzzy logic can be expressed in terms of Fuzzy sets. A Fuzzy set A is characterized by a membership function μ_A(x), which defines the degree to which an element x belongs to the set A. The equation can be represented as follows:

μ_A(x) = {0, if x is not a member of A [0, 1], if x is a member of A to a certain degree 1, if x is fully a member of A}.

In addition to this, Fuzzy logic involves operations such as (Zadeh 1965):

$$\text{Fuzzy AND} : m\_A \cap B(x) = \min(m\_A(x), m\_B(x)) \quad (1)$$

$$\text{Fuzzy OR} : m\_A \cup B(x) = \max(m\_A(x), m\_B(x)) \quad (2)$$

$$\text{Fuzzy NOT} : m\_A'(x) = 1 - m\_A(x) \quad (3)$$

Result

Groundwater potential map

The groundwater potential map of the Central Region produced by the integration of nine evidential layers in ArcMap 10.8 is presented in Fig. 7. The map was classified into four classes utilizing the function of natural break Jenks in ArcGIS. Interestingly, the analysis revealed that approximately 11.17% (1083.7 km^2) of the study region falls under areas having high groundwater potential and 20.4% (1978 km^2) falls under region having moderate groundwater potential. Generally, the high groundwater potential zones tend to follow the geological structures located in the central part of the region which is mainly occupied by granitoids. Commonly, granitoids have very low primary porosity hence are not suitable for water infiltration. This study, in addition to rock types take into account the geological structures in the study region and seven other layers. The high prospectivity area was characterized by high lineament density, high proximity to the lineaments and also suitable LULC of mostly moderately closed tree canopy with herb and bush cover type for water infiltration. The least potential areas are mainly located in the south-eastern section of the region found mainly in the central and northern part of the region and fall mainly on metavolcanics rocks. The central region lineament map shows highly fractured aspect of the region. Based on that, the central region can be classified in general as being high in groundwater potential. The result of this study demonstrate that the region is suitable to be classified as a region with high groundwater potential. This shows the importance of incorporating various and accurate layers likely to affect groundwater occurrence in a particular region. The choice of the thematic layers should be based on the geology and hydrogeology parameters of the investigated study area.

Validation

Validation of the final output map is crucial when it comes to mapping groundwater potential. One commonly used approach is to interpolate the boreholes yield onto the groundwater map (Echogdali et al. 2022; Githinji et al. 2022; Osiakwan et al. 2022). This does not only provide insight into the accuracy of the employed method but also helps to identify highly suitable areas based on groundwater presence and yield. In this study, this approach was utilized to validate the obtained groundwater potential map. The obtained map (Fig. 7) was validated using a set of 104 boreholes with yields ranging from 0 (dry) to 100 L/min. About five of the boreholes exhibit high yields (61–100 L/min). An interpolation of the boreholes on the potential map revealed that these five boreholes coincide with the area mapped as high to moderate for groundwater potential zones (Fig. 8). Seven boreholes with yield ranging from 33 to 60 L/min also fell on moderately potential zones. Majority of the boreholes with yield in the range of 32–0 L/min and mainly fell on low to very low potential zones.

The general agreement between high-yielding boreholes with high potential values in the map imply reliability of the methodology used in this study. The receiver operating characteristics (ROC) was employed to assess the precision of the produced map. It is effective for arranging classifiers and displaying their effectiveness. Furthermore, it aids in evaluating and comparing algorithms by determining the area under curve value (AUC) (Githinji et al. 2022). In this particular study this was assessed and the ROC/AUC operation revealed the satisfactory result of 61% of the final

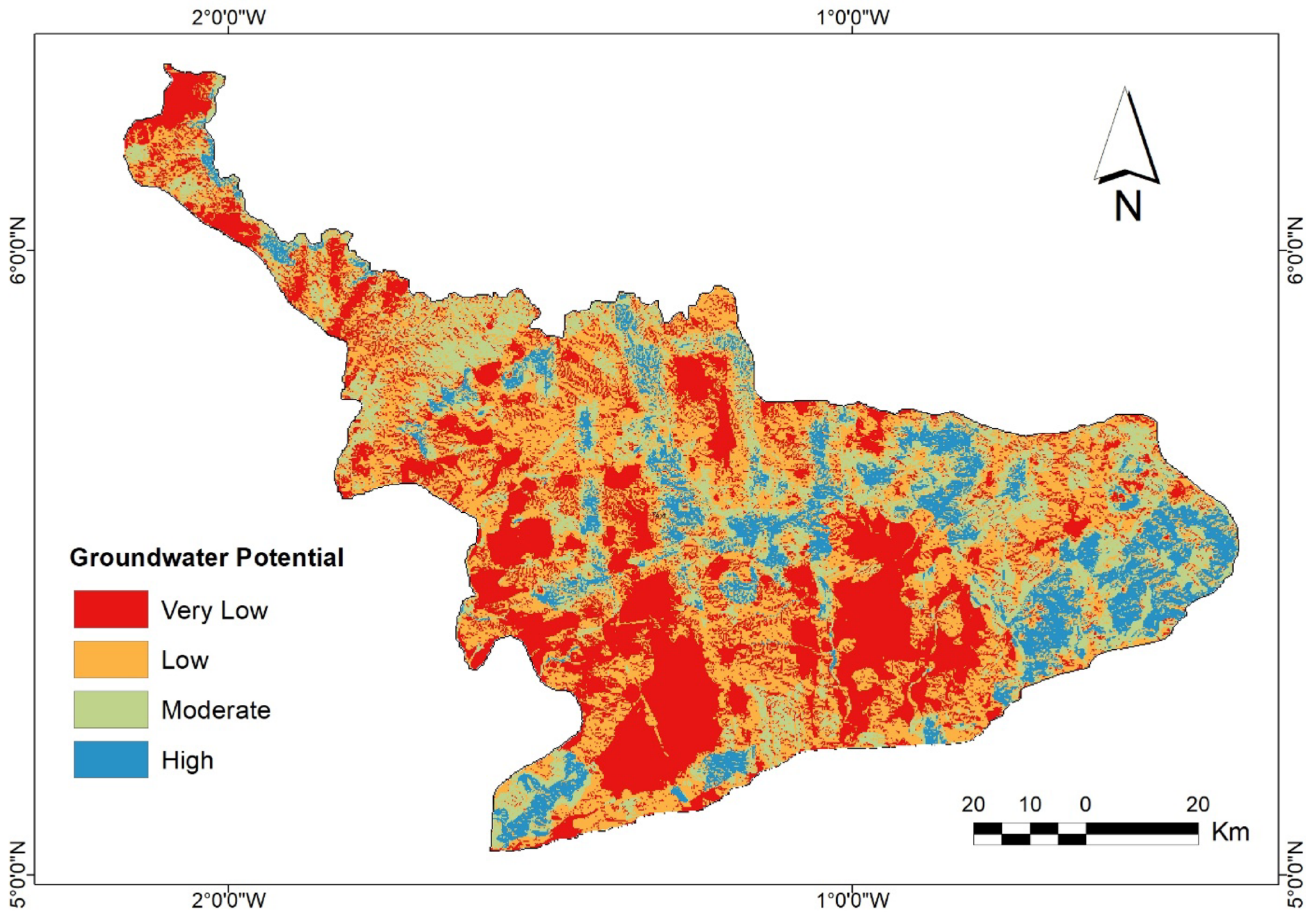

Fig. 7 Groundwater potential map

output (Fig. 9). This suggests that the model is effective as it performs above the non-effective threshold of 50%.

Discussion

In this research, the integration of nine (9) evidential layers obtained from Remote Sensing and magnetic datasets using Fuzzy logic has shown efficiency compared to techniques involving measurements taking over very large areas such as done by Ewusi and Kuma (2011) in the Central region. Groundwater occurrence is controlled by the interaction of various factors. These factors are mainly related to structural, geological, geomorphological, hydrological and hydrogeological conditions of an area (Echogdali et al. 2022). In the Central region the main factor controlling the occurrence of groundwater is found to be the lineaments due to the absence of primary porosity (Asare et al. 2021) of the main rocks in the area. Literature revealed of studies that attempt to map groundwater in the Central region neglected this important factor (Gumma and Pavelic 2013; Osiakwan et al. 2022). This study provides a new framework integrating this variable with other relevant ones including geology, soil type, DEM, land use land cover, drainage density, flow accumulation, and slope to accurately map the groundwater potential of the study area. Another particularity of this study is the dissociation of geology as input variables from lineaments. The geology of an area is a very important component when it comes to the occurrence of groundwater. This study used the geology factor to generally investigate the area for suitable geological formations where infiltration can occur while lineaments factor was utilized as an independent factor for details about secondary porosity, dissociating the two different variables.

In this study it is proven that the integration of different factors such as geology, soil type, DEM, land use land cover, drainage density, flow accumulation, and slope is crucial for delineating groundwater zones because the occurrence of groundwater is a result of the interaction of different factors. Based on the scores assigned to the attributes of each of the variables, the best groundwater retention areas were selected and integrated in the GIS software using the Fuzzy Logic algorithm. This also shows that for accurate results,

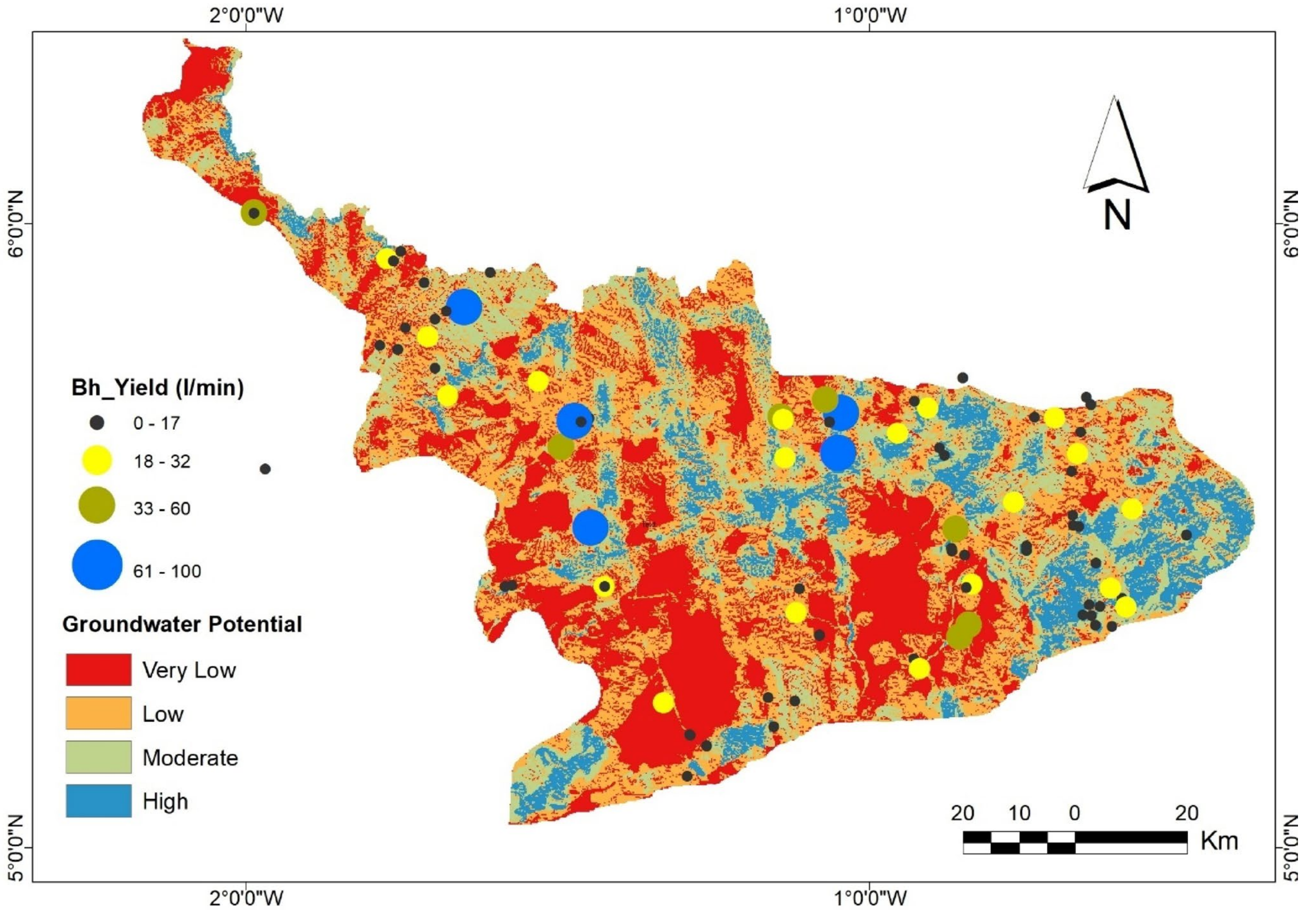

Fig. 8 GWP and Boreholes map

integration of the maximum factors possible each being important, is crucial for accuracy of the results.

The performance of the model was evaluated using Receiver Operating Characteristic (ROC) analysis, yielding a moderate AUC value of 0.61. While this does not reflect a highly predictive model, it does indicate reasonable discriminatory power, especially considering the geological complexity of the study area and the limited availability of calibration data.

The resulting groundwater potential map classified the area into high, moderate, low and very low potential zones. Approximately 11.17% of the study area was classified as high potential, 20.4% as moderate, 35.68% as low and 32.74% as very low. The areas with high groundwater prospectivity were predominantly associated with dense lineament networks, close proximity to lineaments, and favorable LULC types particularly moderately closed tree canopies with herbaceous and bush vegetation that support water infiltration. In contrast, the zones with the lowest groundwater potential are primarily situated in the southeastern portion of the region, especially across the central and northern parts, and are largely underlain by metavolcanic rock formations. This spatial distribution highlights the heterogeneity of subsurface conditions across the Central Region.

While the results of this study are promising, certain limitations remain that may affect the accuracy and applicability of the groundwater potential map. One key limitation is the exclusion of temporal climatic factors such as rainfall variability and evapotranspiration, which play a significant role in groundwater recharge and seasonal availability.

Future research should incorporate a more extensive borehole dataset to improve model calibration and validation. Integrating climatic patterns such as seasonal rainfall variability, evapotranspiration, and drought frequency will enhance the temporal sensitivity of the model. Expanding this integrated approach to other regions in Ghana with similar crystalline basement terrain would allow for broader application and comparison, contributing to national-scale groundwater management strategies.

The groundwater recharge potential map produced in this study can serve as resource information database for decision-making processes, water resource managers, and policymakers. Along with other thematic maps such as climate

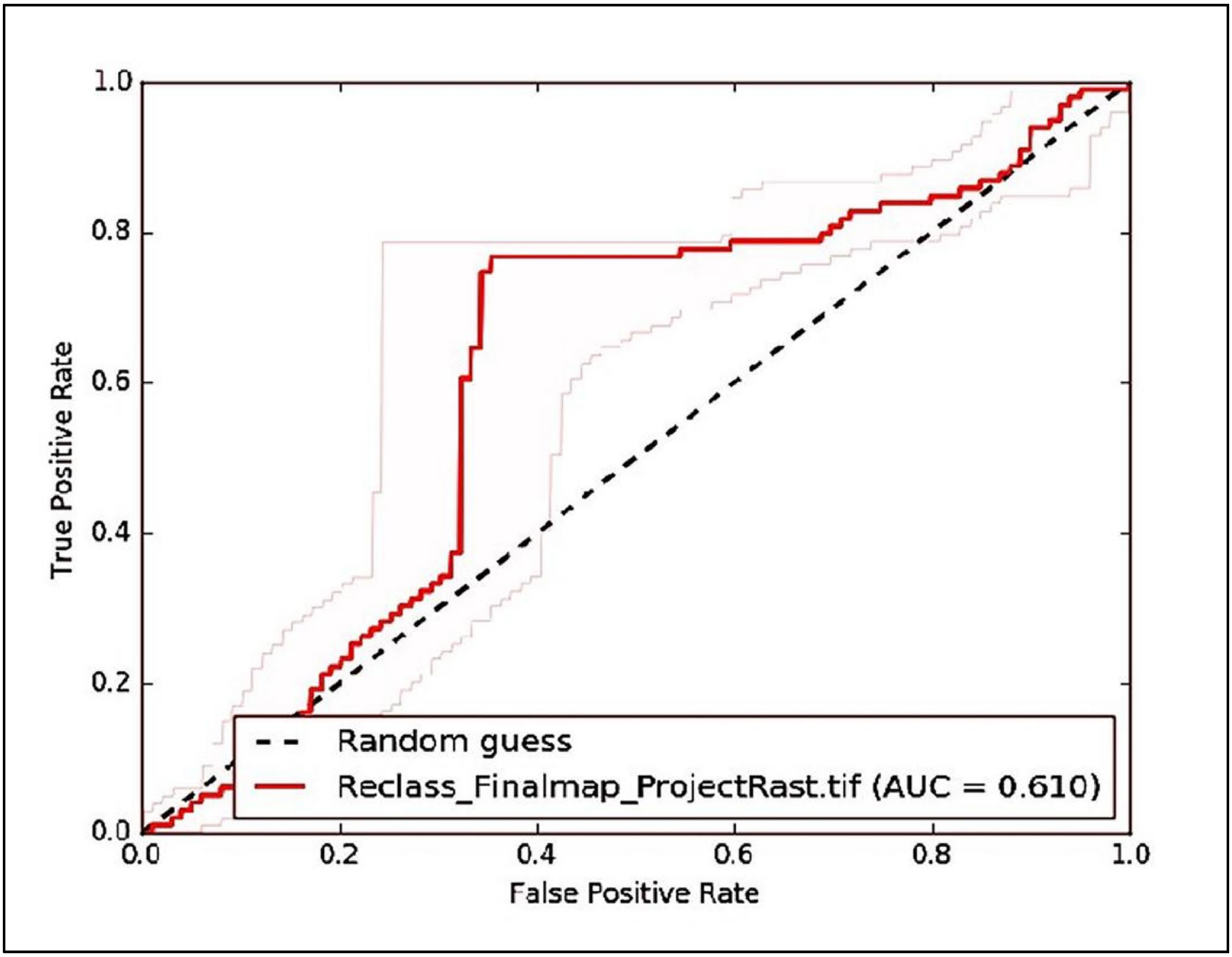

Fig. 9 ROC/AUC curve

related variables and hydrogeological parameters the produced map can be updated for a better accurate outcome.

Conclusion

The main goal of this research was to create a comprehensive map of the groundwater distribution in the Central Region. To achieve this, various evidential layers controlling groundwater occurrences derived from geological, geophysical and Remote Sensing datasets were integrated based on their weighting. The final groundwater potential map was generated classifying the potential into four different classes: high, moderate, low and very low. Interestingly, the analysis revealed that approximately 68.5% of the study region falls under areas having low to very low potential classes. To validate the accuracy of the map, borehole data was used. This comparison helped confirm the reliability of the approach utilized in this project, which is a commonly employed method in similar studies.

This study produced the first detailed groundwater potential map of the Central Region of Ghana using an integrated geospatial data and Fuzzy Logic approach. The results reveal that nearly 70% of the region exhibits low to very low groundwater potential while 30% of the area shows moderate to high groundwater potential, underscoring the challenges of groundwater exploration in hard rock terrains. Validated with moderate accuracy (AUC = 0.61), this map still provides crucial guidance for groundwater exploration and long-term water resource planning.

Overall, this project successfully mapped the potential of groundwater in the Central Region using a combination of geological and geophysical techniques. The resulting map gives valuable information into the availability and classification of groundwater potential in the region, which can greatly be useful in informed decision-making and sustainable water resource management.

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Author contributions Conceptualization of the research was done by authors 1, 2, 3 and 4. Data curation was done by authors 1,2,3 and 4. The formal analysis was done by authors 1, 4 and 8. The investigation was done by 1,2 3 and 4. The methodology was established by authors 1, 2 and 3. The project administration was done by author 2. The resources were provided by author 2. The work was supervised by authors 2, 3, 4, 5 and 6. The validation was done by authors 1, 2, 3, 4, 5, 6, 7, 8 and 9. The Visualization was done by authors 1, 2, 3 and 8. The original draft was written by author 1. The written article was edited by authors 1, 2, 3, 4, 5, 6, 7, 8 and 9.

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Data availability Available on request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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Authors and Affiliations

Haoulata Touré[1] · Cyril D. Boateng[2,6] · Solomon S. R. Gidigasu[1] · David D. Wemegah[2] · Vera Mensah[1] · Jeffrey N. A. Aryee[3] · Marian A. Osei[3,4,5] · Benjamin Boadi[1] · Collins Okrah[7]

✉ Cyril D. Boateng
cyrilboat@knust.edu.gh

Haoulata Touré
haoulatatoure02@gmail.com

Solomon S. R. Gidigasu
ssrgidigasu@yahoo.com

David D. Wemegah
wemega2@yahoo.co.uk

Vera Mensah
vera_mensah17@gmail.com

Jeffrey N. A. Aryee
jeff.jay8845@gmail.com

Marian A. Osei
marianosans92@gmail.com

Benjamin Boadi
kwesiboadi101@yahoo.com

Collins Okrah
collinsokrah@gmail.com

1 Department of Geological Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

2 Department of Physics, College of Science, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

3 Department of Meteorology and Climate Science, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

4 Centre for Ecology and Hydrology, Crowmarsh Gifford, Oxfordshire, UK

5 School of Earth and Environment, University of Leeds, Leeds, UK

6 Caburu Company Ltd, P.O.BOX MD 2046, Madina, Accra, Ghana

7 Water Research InstituteCSIR, Accra, Ghana