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Assessing groundwater potentials of Kaduna state, Northwestern Nigeria, using Geographic Information System (GIS) and Remote Sensing (RS) techniques

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Abstract

The subhumid and subarid terrains of Kaduna State are areas of acute water scarcity which require urgent intervention. This study combined geographic information system (GIS) and remote sensing (RS) techniques for delineating groundwater potential zones across the state to establish an alternative water source for domestic and commercial applications. Ten groundwater control factors were synergized for this study using the analytical hierarchy process (AHP) method with a consistency ratio of 0.4. The factors were slope, elevation, drainage density, fault density, distance to faults, geology, soil, land usage pattern, rainfall, and normalized difference vegetation index (NDVI). The groundwater potential zones map generated was categorized into five groups: very low, low, moderate, high, and very high. Very high and high groundwater potential zones (GWPZ) jointly account for about 41.25% of the total area of Kaduna State. In comparison, very low and low GWPZ jointly accounts for 37.58% of the total area, which suggests that most parts of the state have moderate to good groundwater potential. This presence of favorable groundwater control factors makes western Kaduna more prospective than the eastern part of the state. Assessment of the GWPZ map using borehole yield data collected across the state gave an area under curve (AUC) value of 0.77, indicating good prediction accuracy. The methods adopted in this study can also be applied to groundwater exploration studies in various parts of Nigeria, especially the northern states where water scarcity is rampant.

Keywords GIS · RS · AHP · Kaduna State · ROC · Groundwater potential zones

Introduction

The indispensability of water as a natural resource makes it a distinguished sacred ingredient needed for human survival. This has been the case ever since the inception of the earliest human community development; water is a vital source of life nutrients for day-to-day living. Although this resource is well distributed in nature, its proportion and standard vary from place to place. While 70% of the earth is covered in water, only 2.5% of this water exists as freshwater (IAEA 2011). Of the 2.5%, 70% are trapped in ice caps and glacial, making only 30% available for domestic usage (Baker et al. 2016; Das and Pal 2019). The diminishing accessibility of water for human use is fast becoming a global menace; several places worldwide have reported water scarcity (Mallick et al. 2019; Allafta et al. 2021). This scarcity can be attributed to spontaneous population growth, urbanization, basin development, and climate-related hazards (Saranya and Saravanan 2020). The scarcity of surface water has made groundwater an alternative water source for human usage.

Groundwater, by definition, represents water domiciled in saturated zones within the earth's subsurface. It accumulates in the subsurface by filling pore spaces in mineral grains and rock fractures. Groundwater forms during the infiltration of rain or snowmelt through soils and into the underlying rocks (Nampak et al. 2014). Groundwater is now widely relied upon for domestic and commercial applications such as drinking, agricultural, and industrial activities globally due to its accessibility during dry seasons and

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less susceptibility to pollution (Nsiah et al. 2018; Mallick et al. 2019). Approximately 2.5 billion people worldwide rely on groundwater resources as the only means to tend to their daily water demands (UNESCO 2015).

The northern Nigeria terrain lies within subhumid, sub-arid, and arid climatic zones. Rainfall values mostly fall within the 300 to 700 mm range and rarely exceed 1000 mm annually (NiMet 2021). This is a major contributing factor to water scarcity and drought, which are common in this region. Agricultural activities and many other commercial businesses are constrained because surface water and precipitation are rare and erratically distributed. Groundwater offers a reliable alternative water source in this terrain; however, the lack of proper delineation of groundwater availability factors has made many boreholes sinking campaigns less productive. For a proper sustainable groundwater management plan in this area, there is an urgent need for consummate predictive groundwater modeling, which relies on a classical understanding of geological and hydrogeological processes (Adelana et al. 2008).

The spontaneous population increase in Kaduna State, North-Central Nigeria, commands increased pressure on the water supply in every part of the state. Water providers in the state have not been able to compare with the increasing population with adequate water supply. Major sectors within the state, such as agriculture, health, education, and environmental sanitation agencies, rely heavily on a steady water supply for their diurnal undertakings. The lack of sufficient water supply in the state has led to poor hygiene, lower productivity across the key sectors, over-reliance on water from unsafe sources, increased infant mortality, high absenteeism at the workplace and schools, and the break out of diseases (Bature et al. 2021).

Further, yearly water shortages are being reported in Kaduna State; households in this state often report problems such as inconsistency in water supply from state government sources, farness of water supply sources to populated communities, and insufficient water supply from government sources. Water is mostly supplied to people in the area via channels such as boreholes, hand-dug wells, water vendors, Kaduna State Water Board (KSWB), and streams (Bature et al. 2021). Water from these sources is mainly exiguous and cannot satisfy the state's high population density.

The Guardian newspaper reported a continuous dependency on water from unhygienic sources for the fulfillment of daily domestic necessities as a result of the unavailability of potable water across the state. Some community inhabitants also reported contamination of water from pipe-borne sources due to the presence of heavy dirt. Some of the most affected areas within the state include Ungwan Boro, Ungwan Rimi, Sabon Tasha, Kawo, Television garage, Kakuri, Romi, Narayi, and Hayan Banki areas of Kaduna State. Dry taps have also been reported in some areas across the state (Akhaine 2018).

Groundwater accumulation in an area is guided by several hydro-geological factors, which include topography, lithology, the severity of weathering activities, geological structures, the presence of fractures and secondary porosity, drainage systems, slope, land use/land cover, geomorphology, atmospheric conditions, and rainfall (Kumar and Pandey 2016; Nsiah et al. 2018). Groundwater occurrence within the basement complex terrain of Nigeria is generally low; where it exists, it is steered by geological, structural, and climatic factors (Idris-Nda et al. 2015). This makes groundwater exploration within the basement complex terrain of Nigeria a problematic task. Past publications relied heavily on geophysical surveys to delineate groundwater availability in the Nigerian basement complex terrain (Ako and Olorunfemi 1989; Olayinka and Olorunfemi 1992; Bayewu et al. 2012). The electrical resistivity method is the most popular geophysical method for groundwater exploration (Oladunjoye et al. 2019; Aromoye et al. 2019; Raji and Abdulkadir 2020), it can reveal possible secondary porosity zones within fractured rocks, and this appears in the form of low resistivity values sandwiched between high resistivity zones (Olasehinde et al. 2015; Aromoye et al. 2019; Warsi et al. 2019). However, electrical resistivity and other conventional methods require ground-based activities to delineate groundwater potential zones properly; these activities are often tedious, time-consuming, and costly (Nampak et al. 2014; Mukherjee and Singh 2020).

The recent emergence of geospatial technology has proven an influential innovation in delineating groundwater potential zones. This tool offers rapid, cheap, and efficient groundwater potential zone mapping without territorial constraints (Magesh et al. 2012; Naghibi et al. 2017). Remote sensing (RS) and geographic information systems (GIS) jointly constitute a potent set of tools applicable during the acquisition, management, and storage of spatial data (Saranya and Saravanan 2020). GIS and RS techniques are now being applied globally to solve groundwater problems; several publications have demonstrated the use of geospatial technology in groundwater potential assessment using probabilistic models such as weights-of-evidence (WE) (Corsini et al. 2009; Lee et al. 2012), frequency ratio (FR) (Abrams et al. 2018), fuzzy logic (Ghayoumian et al. 2007; Aouragh et al. 2017), and analytical hierarchy process (AHP) (Kumar and Pandey 2016; Alimi et al. 2022). The analytical hierarchy process (AHP) method is a widely adopted multi-criteria decision making (MCDM) model for groundwater potential zone mapping (Kumar and Pandey 2016; Akbari et al. 2021; Namous et al. 2021). Several researchers have applied artificial intelligence to predict groundwater potential zones globally; such works include Al-Abadi et al. (2016), Chen et al. (2019), Sameen et al. (2019), and Namous et al. (2021).

RS and GIS have also been successfully applied to groundwater exploration projects in several places across the country

(Fashae et al. 2014; Akinwumiju et al. 2016; Ogungbade et al. 2021). There exist publications on the groundwater potential appraisal of the present area of study; most of the researchers applied electrical geophysical method for groundwater potential assessment in some parts of the area, while few have used other methods such as RS and GIS techniques (Aboh 2009; Olaniyan and Olabode 2012; Eduvie and Olaniyan 2013; Hassan et al. 2016; Badamasi et al. 2016; Ebenezer and Martins 2017; Omeiza and Dary 2018; Kure et al. 2019; Alaminiokuma and Chaanda 2020). Groundwater potentials of Kaduna State have not been previously investigated holistically, and the spatial variations of groundwater controlling factors within the state are unknown. The present study aims to investigate the groundwater potentials of Kaduna State as a whole using integrated GIS-RS techniques and hydrological datasets. Hydrological data are helpful predictors in site selection for borehole drilling during groundwater exploitation exercises. Applying such data in combination with GIS and RS analysis will ensure accuracy in predicting groundwater potential zones. The findings of this study will provide an overview of the groundwater potential pattern in the state and form a valuable guide to policymakers in the area of groundwater sustainability planning to mitigate the effect of water scarcity in subhumid and subarid parts of Kaduna State. Recent studies on groundwater potentials mapping have adopted machine learning/artificial intelligence tools for groundwater potential zones prediction (Panahi et al. 2020; Pham et al. 2021; Hasanuzzaman et al. 2022); this is especially possible in areas where hydrogeologic factors governing the occurrence of groundwater have already been established. However, in the present study area, there is an inadequacy of reports on the groundwater potential in the area. The findings of this study would be a foundation upon which other potential groundwater studies can rely, most especially in the usage of advanced groundwater predictive methodologies.

Study area

Kaduna State falls within the northwestern geopolitical zone of Nigeria. The state has a population of 6,113,503 (Population council 2007) and occupies a landmass of ~ 46,053 km^2, making it the fourth largest state in Nigeria and the third most populous state in the country. Kaduna State is bordered in the north by Zamfara, Katsina, and Kano states, in the east by Plateau and Bauchi states, in the south by Nasarawa and the federal capital territory, and in the west solely by Niger state (Fig. 1). Major cities within the state are Kaduna, Zaria, Birnin Gwari, and Kafanchan. Kaduna State falls within the subhumid and subarid climatic zones characterized by sparse shrubs and large isolated trees. Its mean annual rainfall ranges from 300 to 1100 mm with an average temperature of 34 °C. The state is pervaded by two prominent seasons, dry and rainy seasons. The dry season transpires from April to October, while December to January is characterized by appalling harmattan. The elevation range in the state is between 200 m in the western and 1300 m in the eastern
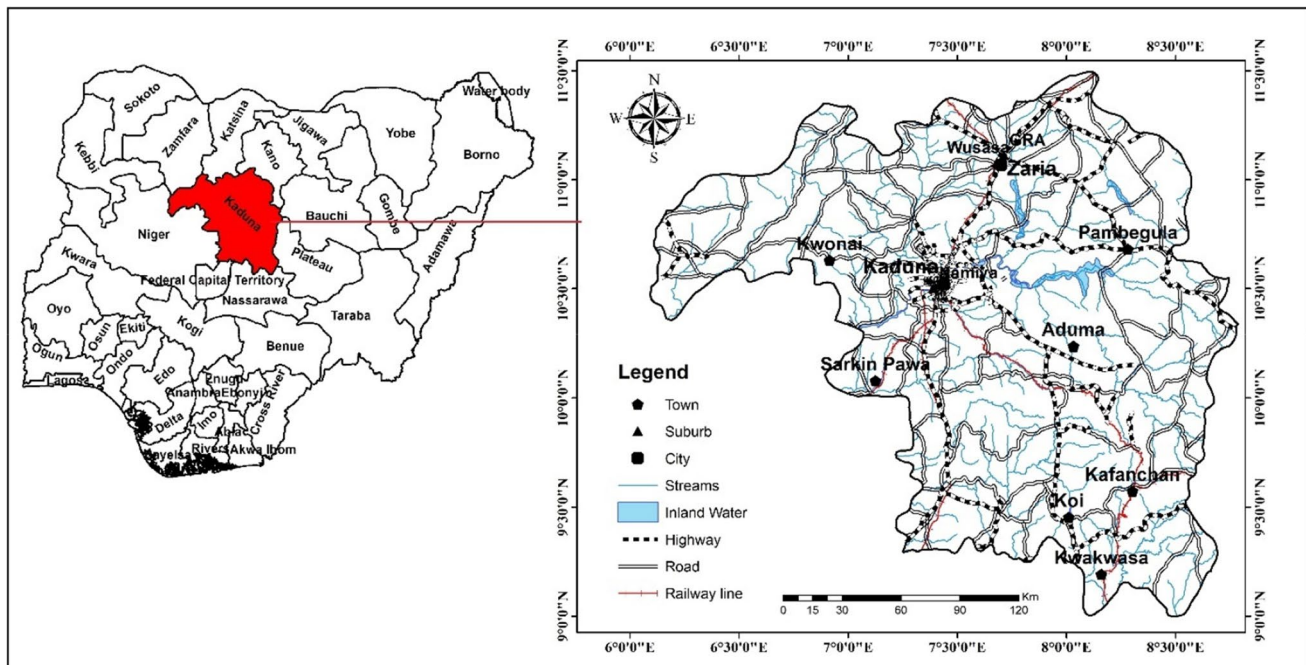

Fig. 1 The location map of Kaduna

parts of the state (Badamasi et al. 2016; Alaminiokuma and Chaanda 2020).

Geologically, Kaduna State lies in the north-central basement complex terrain of Nigeria. Rock groups in this area are dominantly Precambrian metavolcanic and metasedimentary rocks with subordinate Pan-African granitoids and Tertiary to Quaternary volcanic rocks (McCurry 1976; Ogezi 1988). These rocks are highly impervious and poor aquifers unless where fractured or deeply weathered. Groundwater occurrence and movement in this terrain rely on secondary porosity produced by weathered residual overburdened soils and fractures in bedrocks.

The presence of groundwater in Kaduna State was reported in three geological settings: weathered/fractured basement complex, Newer Basalt, and river alluvium (Eduvie and Olaniyan 2013; Alaminiokuma and Chaanda 2020). The weathered sandy sequences comprise coarse-grained sands that exist below clayey laterite. They are often composed of sand or gravel from weathering effects on crystalline rocks. Their thickness rarely exceeds 6 m and forms a good prospect for groundwater accumulation. Most hand-dug wells in the state derive water from this layer (Jones 1985). The Newer Basalts are mostly seen in Kafanchan and Manchok areas close to the eastern margin of the state, where it borders the Jos Plateau. The basalts are believed to be an extension of the Newer Basalts in the Jos Plateau. They occur as lava flows and cones typified by steep-sided central craters higher above their environment (MacLeod et al. 1971; Egboka 1988). They often extend over alluvial deposits. The aquifer prospect of the Newer Basalts is promising; a borehole yield of 370 to 500 m³/day and l2.6 m³/h has been reported within them (Eduvie and Olaniyan 2013). Two highly productive natural springs with a flow of about 11,000 m³/day during the dry season also exist in the Newer Basalts around Kajim and Kajoro area of the state (Umar and Yusuf 2015; Bagu et al. 2019).

Materials and methods

Materials

Data acquired for the integrated groundwater potential zones mapping of Kaduna State include Landsat 8 Operational Land Imager (OLI) satellite image and Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM), which were both acquired from (https://earthexplorer.usgs.gov). Also, Kaduna State's conventional structural and geological maps were sourced from the Nigerian Geological Survey Agency (NGSA). The soil distribution map was acquired from the Food and Agriculture Organization of the United Nations (FAO). Rainfall data of Kaduna State for the year 2021 was sourced from Nigerian Meteorological Agency (NiMet), while the various hydrological data employed for validation in this study were obtained from private water companies within the state. ArcGIS and ENVI software were used for data processing and analysis. Table 1 shows a list of the data employed in this study and their metadata.

Method

The steps and procedures adopted in this study are shown in Fig. 2. Conventional maps were scanned and digitized using GIS software to produce the maps of soil, geology, and structures. Eight SRTM DEM datasets covering the entire Kaduna State were merged and clipped to extract the exact location of the state. They were eventually processed to produce Kaduna State's drainage density, slope, and elevation maps. Eight Landsat 8 OLI/TIRS datasets were also merged and clipped to the exact location of the state. They were employed to produce land use/land cover (LULC) and normalized difference vegetation index (NDVI) maps of Kaduna State. Maximum likelihood supervised method was used for the LULC classifications, while bands 4 and 5 were used for the production of NDVI map. The structural map was used in fault distance and fault density maps production. Rainfall data were kriged to produce the rainfall map. The ten maps were further converted into thematic layers, rasterized, and classified. These layers represent groundwater contributing factors. Each thematic layer has at least five classes; only geology and soil layers have more, indicating that the connections between the classes are far more diverse. The connections among these ten factors were accomplished using AHP (Saaty 1980, 1990). AHP is a conceptualized method that uses a pairwise comparison matrix based on the knowledge and perception of experts to obtain precedence weights. The pairwise comparison is calculated on the principle of

Table 1 Data types and their properties

| S/n	Data	Sources	Scale/resolution
1	SRTM DEM	https://earthexplorer.usgs.gov	30 m
2	Landsat 8 OLI/TIRS	https://earthexplorer.usgs.gov	30 m
3	Structural map	Nigerian Geological Survey Agency (NGSA)	1:800,000
4	Geological map	Nigerian Geological Survey Agency (NGSA)	1:800,000
5	Soil map	Food and Agriculture Organization of the United Nation (FAO)	1:1,000,000
6	Rainfall	Nigerian Meteorological Agency (NiMet)	
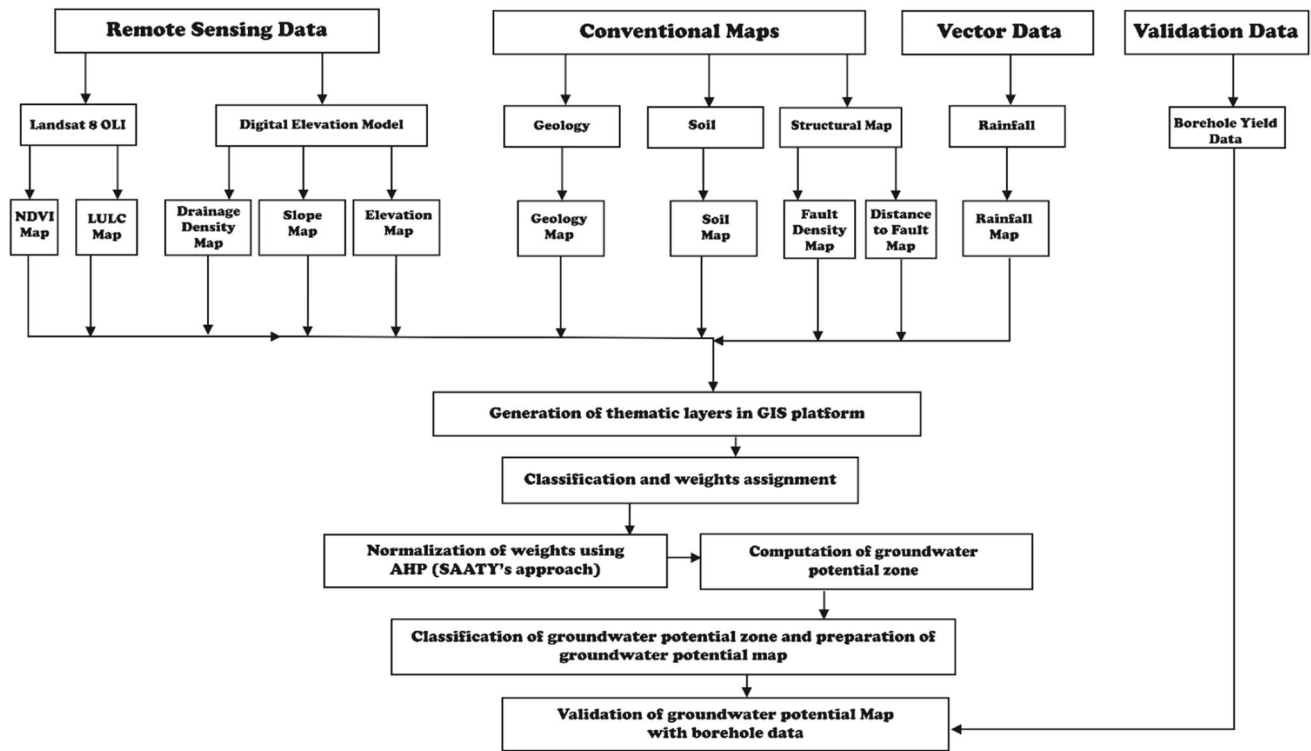
Fig. 2 The flowchart of groundwater potential zones delineation procedures

weightage, and it varies on a scale of 1 to 9, whereby 1 indicates equal importance and 9 indicates extreme importance (Saaty 1990). Table 2 shows the pairwise comparison matrix for the ten layers, it was further normalized, and the consistency ratio (CR) values were obtained as follows:

$$CI = \frac{\lambda_{\max} - k}{k - 1} \qquad (1)$$

$$CR = \frac{CI}{RI} \qquad (2)$$

CI represents the consistency index, *k* is the number of comparisons, $\lambda_{\max}$ is the principal eigenvalue, and *RI* represents the random index. To ascertain the consistency of the order of comparison, CR must be < 0.1 for a consistent order of comparison. At the same time, a CR value > 0.1 indicates an inconsistent order of comparison, which will need to be adjusted (Rajasekhar et al. 2019). The calculated CR value for the present study is 0.04, which attests to the consistency of the comparison order used in the study. Table 3 displays the weight allocation and characteristics of the layers. The weighted overlay method was adopted in producing the groundwater potential zones map of Kaduna State by the

Table 2 Pairwise comparison table

Factors	Geol	DF	FD	RF	Soil	NDVI	Elev	Slope	LULC	DD	Criteria weight	Weighted sum
Geol	1.00	2.00	2.00	3.00	5.00	5.00	3.00	3.00	5.00	6.00	0.239733	2.562376
DF	0.50	1.00	2.00	2.00	4.00	3.00	3.00	5.00	4.00	6.00	0.193871	2.080569
FD	0.50	0.50	1.00	2.00	3.00	3.00	2.00	2.00	4.00	4.00	0.135448	1.452759
RF	0.33	0.50	0.50	1.00	3.00	1.00	2.00	2.00	3.00	4.00	0.101866	1.088167
Soil	0.20	0.25	0.33	0.33	1.00	2.00	0.33	0.50	1.00	3.00	0.04928	0.520917
NDVI	0.20	0.33	0.33	1.00	0.50	1.00	0.33	0.50	3.00	3.00	0.057459	0.603141
Elev	0.33	0.33	0.50	0.50	3.00	3.00	1.00	1.00	3.00	3.00	0.087344	0.937626
Slope	0.33	0.20	0.50	0.50	2.00	2.00	1.00	1.00	2.00	2.00	0.069062	0.7391
LULC	0.20	0.25	0.25	0.33	1.00	0.33	0.33	0.50	1.00	3.00	0.040128	0.413864
DD	0.17	0.17	0.25	0.25	0.33	0.33	0.33	0.50	0.33	1.00	0.025808	0.270006

merger of all the prepared layers; this was done using the formula below:

$$Groundwater\ Potential\ Zones\ (GPZ) = \sum_{i,j=1}^{8} WiXj \qquad (3)$$

Wi represents % weight for each thematic map, and *Xj* represents reclassified map.

Validation was done using borehole data acquired across the state.

Results

The geology of an area is a crucial factor that controls groundwater occurrence in the area. This significantly controls infiltration and rate of flow of groundwater because of variability in the porosity and permeability of subsurface aquifers (Naghibi et al. 2017). Therefore, geology was assigned the highest weight of all the ten layers. Precambrian, Pan-African, and Tertiary to Quaternary-aged rocks underlie the study area (Fig. 3a). The Precambrian rocks in the study area are migmatites, gneisses, amphibolites, and schists, while the Pan-African rocks in the area are the granitoids, and Tertiary to Quaternary volcanic rock is the Newer Basalt. The highest ranks were assigned to the quartzite and Newer Basalt; quartzites are highly fractured metamorphic rocks and permit the easy flow of water through their fractures, thereby influencing groundwater recharge and accumulation. Also, Newer Basalt contains pores that permit water flow, thereby increasing groundwater recharge and storage. Amphibolites were assigned the lowest rank based on their massive nature; they are impervious, with little or no secondary structures that influence groundwater occurrence compared to the rest of the rocks in the area.

Rainfall controls the groundwater recharge rate. The quantity of rainfall received across Kaduna State varies; therefore, the level of groundwater recharge in the state is non-homogeneous. A high quantity of rainfall signifies a high groundwater recharge rate and vice versa (Murmu et al. 2019). Rainfall values within Kaduna State (Fig. 3b) ranged from 700 to 1161 mm, representing a subhumid and subarid climate pattern. The western part of the state received high rainfall, while the eastern received low rainfall, especially the northeastern part. Regions with high rainfall values were assigned higher ranks, while regions with low values were assigned lower ones.

A fault is a type of lineament seen in rocks. It serves as secondary porosity and a conduit through which groundwater can recharge. The presence of fault with other favorable factors indicates the likelihood of groundwater's existence. Faults are deformations produced by tectonism and weathering. The fault density map of Kaduna State (Fig. 4a) shows the areas of high and low concentrations of faults within the

state. Faults are highly concentrated within the western part of the state, while the eastern part has fewer fault concentrations. Hence, higher ranks were assigned to areas with high fault density, and lower ranks were assigned to areas with low fault density. Distance to faults is another crucial factor contributing to groundwater recharge and accumulation. The closer an area is to faults, the higher its chances to host groundwater and vice versa, as these faults represent openings through which water gets into the subsurface. Areas closer to the fault location were assigned higher ranks, while areas farther from faults were assigned lower ranks (Fig. 4b).

The slope shows the small- and large-scale relief that critically impacts aquifer recharge (Gupta and Srivastava 2010; Allafta et al. 2021). It displays the level of steepness or inclination of a surface and can be quantified in degrees (0–90). Slope gradient guides water percolation into subsurface formations, hence its significance in groundwater potential mapping. A high slope gradient terrain means high runoff, while a low slope gradient means low runoff, which is suitable for groundwater recharge and accumulation. Slope values in the state ranged from 0 to 69.57 degrees (Fig. 5a). Higher weights were assigned to areas of low slope gradient, while lower weights were assigned to areas of high slope gradient. Elevation has a similar influence as a slope; it shows patterns of undulations of the ground surface. High elevation leads to high runoff, hindering groundwater recharge, while low elevation permits low runoff, influencing groundwater recharge and accumulation. Elevation values in Kaduna State ranged from 218 to 1354 m (Fig. 5b). The eastern part of the state constitutes the highlands, while the western part of the state forms the lowland.

Soils form at the uppermost layer of the earth and serve as the channel through which water infiltrates the earth. The extent of infiltration is determined by the soil's porosity, permeability, and water retention properties (Gupta et al. 2018; Ogungbade et al. 2021). The various soil types present in Kaduna State (Fig. 6a) were ranked according to their characterized influence on groundwater recharge (FAO 2005). Arenosols and leptosols were ranked highest due to their high permeability, while regosols were ranked lowest. Essential parameters for groundwater recharge and accumulation, such as permeability, soil moisture, and infiltration rate, largely depend on land usage patterns. Built-up areas have a negative influence on the rate of infiltration as a result of reduced permeable surfaces. Contrarily, vegetated lands permit water infiltration as vegetative cover can hold water and facilitate percolation (Allafta et al. 2021). The land usage pattern of Kaduna State (Fig. 6b) shows five classes: built-up, vegetated land, barren land, rock body, and water body. Higher weights were assigned to vegetated land, while low weights were assigned to built-up.

A close relationship exists between groundwater occurrence and the normalized difference vegetation index (NDVI); healthy vegetation signatures indicate the presence of groundwater

Table 3 Arrangement and weight assessment for groundwater potential zone mapping

| Parameters	Realm of effect	Influence level	Ranks	Weights
Geology	Quartzite, Newer Basalt	Very high	9	24
	Schists	High	7	
	Migmatitic gneiss, migmatite, granite gneiss	Moderate	5	
	Granitoids	Low	3	
	Amphibolites	Very low	1	
Distance to fault (DF) in km	0–2	Very high	9	19
	2–4	High	7	
	4–6	Moderate	5	
	6–8	Low	3	
	8–10	Very low	1	
Fault density (FD) in km/km^2	0.26–0.14	Very high	9	14
	0.14–0.09	High	7	
	0.09–0.05	Moderate	5	
	0.05–0.01	Low	3	
	0.01–0.0	Very low	1	
Rainfall (RF) in mm	1161–1054	Very high	9	10
	1054–986	High	7	
	986–914	Moderate	5	
	914–833	Low	3	
	833–741	Very low	1	
Soil	Arenosols, leptosols	Very high	9	5
	Cambisols, Fluvisols	High	7	
	Lixisols	Moderate	5	
	Luvisols, Acrisols	Low	3	
	Regosols	Very low	1	
Normalized difference vegetation index (NDVI)	0.04 to − 0.02	Very high	9	6
	− 0.02 to − 0.03	High	7	
	− 0.03 to − 0.05	Moderate	5	
	− 0.05 to − 0.06	Low	3	
	− 0.06 to − 0.17	Very low	1	
Elevation (Elev.) in m	218–503	Very high	9	9
	503–605	High	7	
	605–703	Moderate	5	
	703–859	Low	3	
	859–1354	Very low	1	
Slope in degrees	0–3.29	Very high	9	7
	3.29–6.58	High	7	
	6.58–11.52	Moderate	5	
	11.52–20.57	Low	3	
	20.57–69.97	Very low	1	
Land use/land cover (LULC)	Vegetation	Very high	9	4
	Water body	High	7	
	Barren land	Moderate	5	
	Rock body	Low	3	
	Built-up	Very low	1	
Drainage density (DD) in km/km^2	0.16–11.02	Very high	9	3
	11.02–15.99	High	7	
	15.99–20.95	Moderate	5	
	20.95–26.38	Low	3	
	26.38–39.73	Very low	1	
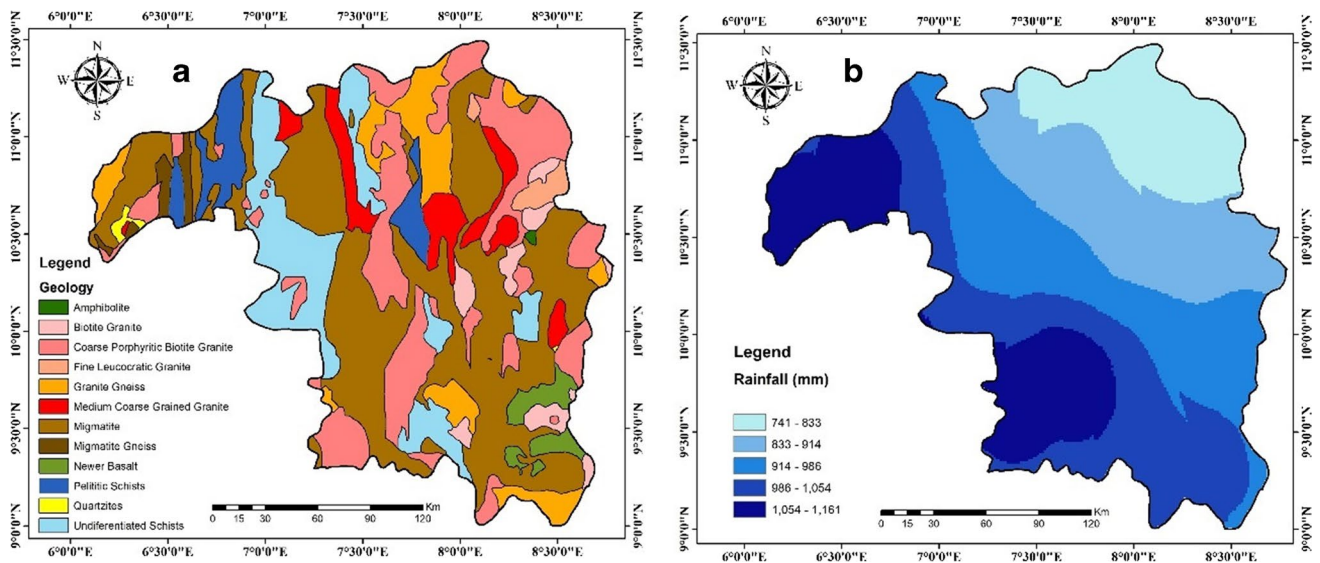
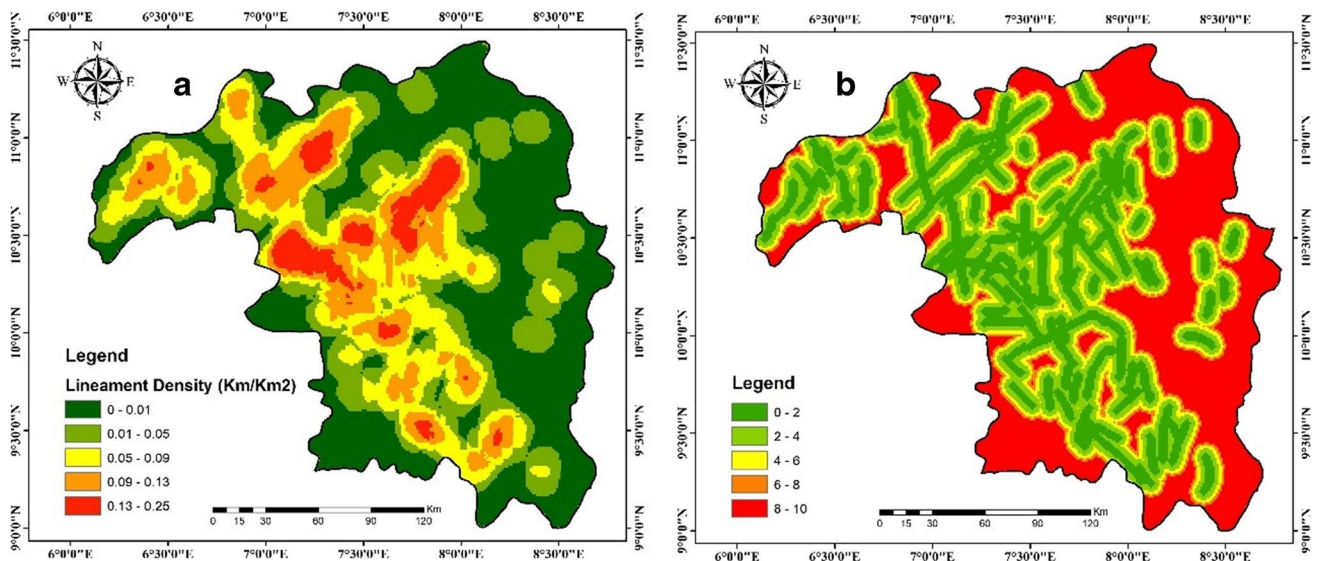**Fig. 3** **a** Geological map of Kaduna State. **b** Rainfall map of Kaduna State

Fig. 4 **a** Fault density map of Kaduna State. **b** Fault distance map of Kaduna State

availability, while lack of vegetation signature indicates the possible absence of groundwater (Putra and Masduqi 2018). NDVI values of Kaduna State were calculated using bands 4 and 5 of Landsat 8 data. The NDVI value ranges from -1 to $+1$, which is a function of the area's flora cover. Equation (4) below was used to compute the NDVI values of Kaduna State:

$$NDVI = \frac{(NIR - R)}{(NIR + R)} \tag{4}$$

NIR represents near infrared red band (band 5 in Landsat 8), while *R* represents red band (band 4 in Landsat 8).

NVDI values in Kaduna State ranged between -0.17 and 0.04 (Fig. 7a). Negative NDVI values indicate a lack of vegetation, while positive NDVI values depict the presence of vegetation. Therefore, higher ranks were assigned to areas with positive NDVI values, while negative NDVI values were ranked lowly. Drainage density is a function of the proximity of stream channels; it quantifies the overall expanse of each stream order section per unit area, making it an indirect consequence of permeability. Low permeability causes low infiltration; therefore, areas with high drainage density contribute less to groundwater recharge and accumulation, while areas with low drainage density strongly influence groundwater recharge and accumulation.
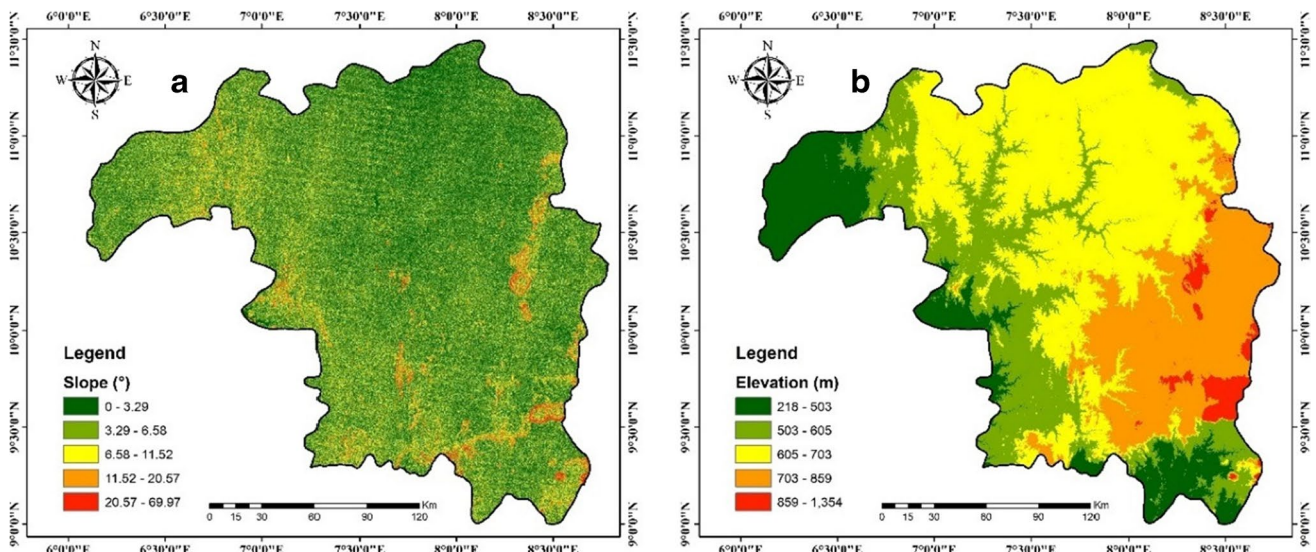
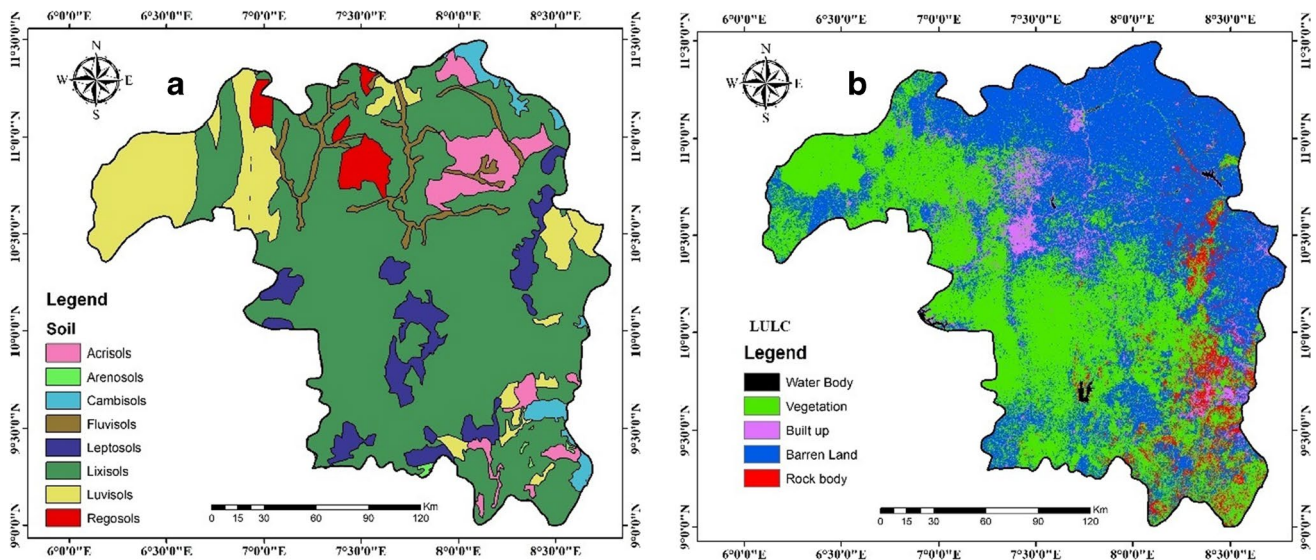**Fig. 5** **a** Slope map of Kaduna State. **b** Elevation map of Kaduna State

Fig. 6 **a** Soil map of Kaduna State. **b** Land use/land cover map of Kaduna State

Consequently, the drainage density (Fig. 7b) values have been ranked according to their influence. Groundwater occurrence is inversely connected to the drainage density due to its connectivity with permeability and surface runoffs (Magesh et al. 2012).

Groundwater potential zones mapping

The groundwater potential zones (GWPZ) map of Kaduna State was produced by merging all the thematic layers generated (geology, soil, elevation, slope, faults density, fault distance, drainage density, rainfall, and NDVI and land use/land cover) using weighted overlay in ArcGIS. The output GWPZ

was categorized into five: very high, high, moderate, low, and very low (Fig. 8). The areal coverage of each class is shown in Table 4. From Fig. 8, the very low groundwater potential zone covers 18.55% of the total area of study, low groundwater potential occupies 19.03%, moderate GWPZ accounts for about 21.17%, high GWPZ occupies 25.23%, and very high GWPZ covers 16.02% of the total area of study. Very high and high GWPZ jointly covers 41.25% of the area, while very low and low GWPZ covers 37.58% of the total study area. This suggests that most parts of Kaduna state have good groundwater potential. High and very high GWPZ mostly dominates the western part of Kaduna State, while low and very low GWPZ are mostly seen in the eastern part of the state.
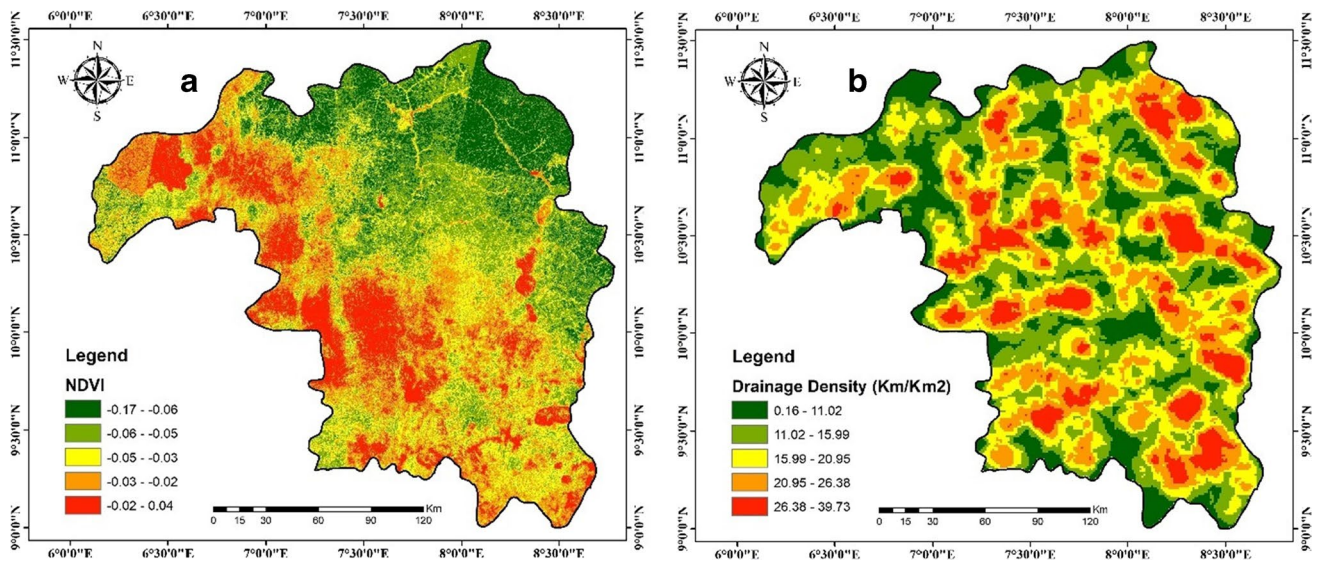
Fig. 7 **a** NDVI map of Kaduna State. **b** Drainage density map of Kaduna State

Further, the areas within high and very high GWPZ receives high rainfall across the year, which is crucial for groundwater recharge; elevation and slope values are also low in these areas, which slows runoff, thereby giving surface water enough time to infiltrate the soils. These regions are also closer to faults and have high fault density which is required for water infiltration into subsurface formations. Favorable rock and soil types are also present in these areas. Also, NDVI and land usage maps show that these terrains are well vegetated. In contrast, areas with very low and low

Fig. 8 The groundwater potential zones map of Kaduna State
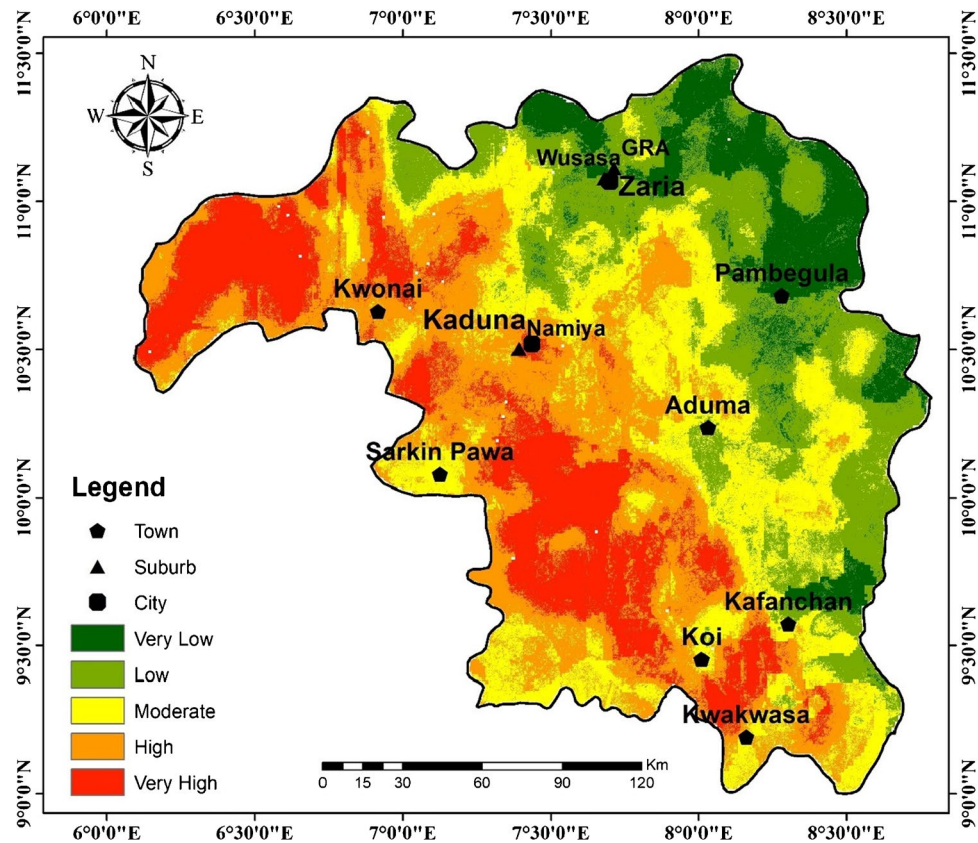
groundwater potentials have properties dissimilar to those of very high and high GWP terrains. They have high elevation and slope values, low fault density values, distal from faults, high drainage density, negative NDVI values, receive little rainfall annually, and less favorable geology and soils. Kaduna City, the capital of Kaduna State, falls into the high and very high groundwater potential regions. At the same time, Zaria, a major city within Kaduna State, falls within the low groundwater potential terrains.

Validation of GWPZ using well data

To authenticate the precision of the output groundwater potential map of Kaduna State, borehole yield data was employed. These data were secured from various borehole drilling activities across Kaduna State. The locations of the sixty boreholes used in this study are shown in Fig. 9. The groundwater potential zones map of Kaduna State was reclassified into three (low, moderate, and high); the borehole yield data was also categorized into three, where values less than 1 l/sec represent low yield, 1–2.99 l/sec represent moderate yield, and 3 l/sec represent high yield. These classes were plotted on Kaduna State's reclassified groundwater potential zones map. From Fig. 9, it can be observed that most of the low borehole yield values are plotted in the low groundwater potential zones of the map. The same can be said for the moderate and high borehole yield values, which are plotted within the map's moderate and high groundwater potential zones. To further establish the accuracy of the assessments, the receiver operating characteristics (ROC) curve was employed (Fig. 10) by contrasting the borehole yield data with the reclassified groundwater potential zones map of Kaduna State. This curve displays the relationship between true-positive and false-positive values for several cutoff points of a variable; each point on the curve indicates the sensitivity pair relative to a threshold (Rajasekhar et al. 2019). The area under the curve (AUC) measures the outstanding efficiency of a parameter among two indicative categories. AUC value ranging between 0.5 and 0.6 indicates poor prediction accuracy, while 0.9 to 1 represents perfect prediction accuracy. AUC values between

0.6 to 0.7, 0.7 to 0.8, and 0.8 to 0.9 indicate average, good, and very good accuracy predictions, respectively (Andualem and Demeke 2019; Das and Pal 2019). The AUC value for this study is 0.77, which indicates good prediction accuracy.

Discussions

The results of Kaduna State's groundwater potential zones mapping suggest that geology, rainfall, lineaments, and distance to lineaments are crucial to groundwater occurrence. The presence of favorable rock types alone does not determine high groundwater potential. The occurrence of faults within the basement rocks provides the openings through which groundwater aquifers are recharged. It can be observed that within the western portion of the study area, numerous basement rocks are highly deformed, most especially within the schists and quartzites. There is a high lineament concentration in these zones, making groundwater accumulation and aquifer recharge possible. In contrast, the eastern portion of the study area has a lower lineament density. Also, the eastern portion of the Kaduna does not show the presence of highly porous and permeable younger granitoids that dominates the western part.

Further, the rainfall pattern in the eastern part of the study area is sparse, infrequent, and low compared to the western part. This can explain why there is higher groundwater potential in the western part of Kaduna than in the eastern part. The elevation is a natural index of water control; surface water flows from high-elevation areas to lower elevations; this makes aquifer recharge and groundwater accumulation possible within the low-elevation terrains. Consequently, the western part of the study area has a lower elevation than the eastern part. Land usage and soil types appear to have little effect on groundwater potential patterns in Kaduna State. The dominant soil types appear to underlain both the western and eastern parts of the area of study, which indicates that the controls of groundwater accumulation and aquifer recharge depend on more profound tectonic influence. Also, similar land use land cover types can be observed in both the western and eastern parts of the study area; this does not affect the groundwater potential of the area. NDVI values within the western part of Kaduna showed a positive vegetation index, while negative vegetation indices are observable in the eastern parts. Positive vegetation indices are typical of healthy plant communities and forests, which are only seen in areas where water is present in the form of rivers, lakes, or streams. Negative vegetation indices are dominant in the eastern part of Kaduna unsurprisingly; as this area also receives little rainfall throughout the year, it is impossible for sufficient groundwater accumulation and aquifer recharge in this area, which also affects plant community growth.

Table 4 The groundwater potential zones of Kaduna state with areal extents

Groundwater potential	Potential index	Area (km^2)	Area (%)
Very low	5	8542.4	18.55
Low	4	8758.92	19.03
Moderate	3	9748.47	21.17
High	2	11,617.65	25.23
Very high	1	7377.98	16.02

Fig. 9 The groundwater potential zones map with observation well locations
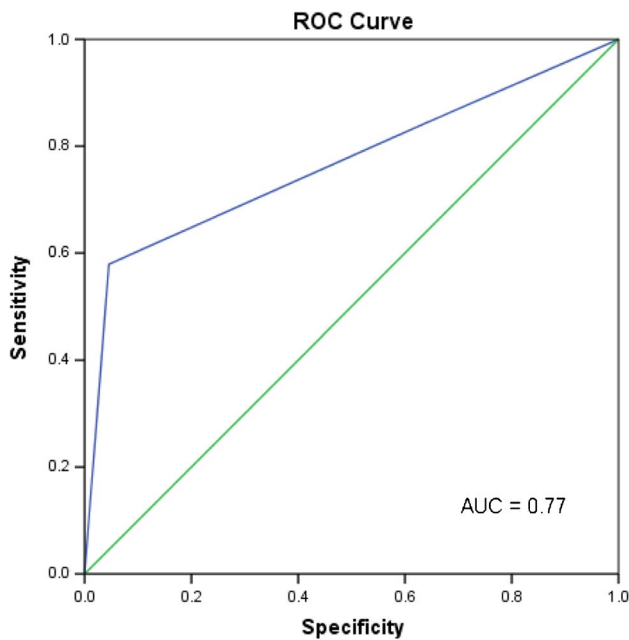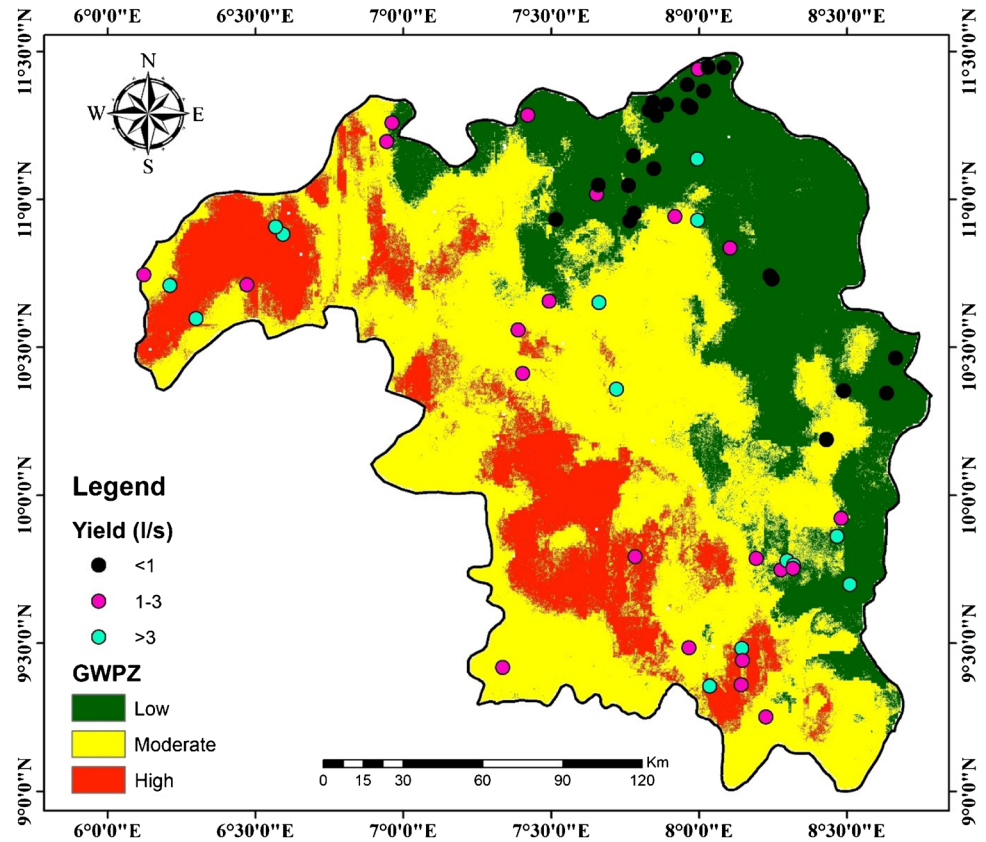
Fig. 10 The ROC of groundwater potential zones accuracy assessment

Borehole yield data from across the state showed a 77% agreement with the groundwater potential zones map of the area. High yields were mainly recorded within the very high and high groundwater potential zone regions. In contrast, extremely low and low yields were recorded amid the moderate to low groundwater potential zones terrain. Previous studies in some parts of Kaduna State by Sani (2008), Musa et al. (2009), Ibe et al. (2012), and Badamasi et al. (2016) have all reported a high groundwater potential within the high lineament density zones in the state. This further corroborates the findings of this research. However, there is an inadequacy of research focusing on the groundwater potentials of the state as a whole. The findings of this research would be a guide for future groundwater studies in the state.

Conclusion

For a comprehensive assessment of groundwater potentials across Kaduna State, Northwestern Nigeria, remote sensing and GIS techniques were integrated using the AHP method. This study considered ten factors, such as elevation, slope, drainage density, fault density, distance to faults, geology, soil, land usage pattern, NDVI, and rainfall, which significantly influence groundwater recharge and accumulation. The factors were weighted and ranked using the AHP

method with an accuracy of 0.4. The generated groundwater potential zones map of Kaduna State was categorized into five groups, very low, low, moderate, high, and very high, occupying 18.55%, 19.03%, 21.17%, 25.23%, and 16.02% of the total area of the study, respectively. Very high and high GWPZ together dominates about 41.25% of the area, while very low and low GWPZ jointly dominate 37.58% of the total area of study, which suggests that most of the state have moderate to good groundwater potentials. However, the western part of the state appears to be more prospective for groundwater than the eastern part. This can be attributed to the presence of favorable groundwater contributing factors in the west than in the east. The authenticity of the groundwater potential zones map of Kaduna State was assessed using borehole data collected from various drilled points across the state. This was computed using the ROC curve, giving an AUC value of 0.77, representing good prediction accuracy. The findings of this study are anticipated to serve as a practical guide for government and policymakers in the state toward water sustainability planning. The methods adopted for this study can also be applied to various other parts of Nigeria, especially the northern states where water scarcity is rampant.

Declarations

Conflict of interest The authors declare that they have no competing interests.

References

Aboh HO (2009) Assessment of the aquifers in some selected villages in Chikun local government area, Kaduna state, Nigeria. Sc World J 4:37–42

Abrams WQ, Ghoneim E, Shew RD, LaMaskin TA, Al-Bloushi K, Hussein S, AbuBakr MM, Almulla E, Al-Awar M, El-Baz FK (2018) Delineation of groundwater potential (GWP) in the northern United Arab Emirates and Oman using geospatial technologies in conjunction with simple additive weight (SAW), analytical hierarchy process (AHP), and probabilistic frequency ratio (PFR) techniques. J Arid Environ 157:77–96

Adelana SMA, Olasehinde PI, Bale RB, Vrbka P, Edet AE, Goni IB (2008) An overview of the geology and hydrogeology of Nigeria: Chapter 11 in Adelana, S. and McDonald, A. (Eds). Applied groundwater studies in Africa: IAH Selected Papers on Hydrogeology 13: 171–198

Akbari M, Meshram SG, Krishna R, Pradhan B, Shadeed S, Khedher KM, Sepehri M, Ildoromi A, Alimerzaei F, Darabi F (2021) Identification of the groundwater potential recharge zones using MCDM models: full consistency method (FUCOM), best worst method (BWM) and analytic hierarchy process (AHP). Water Resour Manag 35:4727–4745

Akhaine S (2018) Residents lament as water scarcity hits Kaduna. The Guardian 19 April 2018. Retrieved from: https://guardian.ng/news/residents-lament-as-water-scarcity-hits-kaduna/

Akinwumiju AS, Olorunfemi MO, Afolabi O (2016) GIS-Based integrated groundwater potential assessment of Osun drainage basin, Southwestern Nigeria. Ife J Sci 18:147–168

Ako BD, Olorunfemi MO (1989) Geoelectric survey for groundwater in the Newer Basalts of Vom, Plateau State. J Min Geo 25:247–250

Al-Abadi AM, Pradhan B, Shahid S (2016) Prediction of groundwater flowing well zone at An-Najif Province, central Iraq using evidential belief functions model and GIS. Environ Monit Assess 188:549

Alaminiokuma GI, Chaanda MS (2020) Groundwater potential of Mando Kaduna, Crystalline Basement Complex, Nigeria. J Earth Sci & Geotec Eng 10:15–26

Alimi SA, Andongma TW, Ogungbade O, Senbore SS, Alepa VC, Akinlabi OJ, Olawale LO, Muhammed QO (2022) Flood vulnerable zones mapping using geospatial techniques: case study of Osogbo Metropolis Nigeria. Egypt J Remote Sens Space Sci 25:841–850

Allafta H, Opp C, Patra S (2021) Identification of groundwater potential zones using remote sensing and GIS techniques: a case study of the Shatt Al-Arab Basin. Remote Sens 13:112

Andualem TG, Demeke GG (2019) Groundwater potential assessment using GIS and remote sensing: a case study of Guna tana landscape, upper Blue Nile Basin. Ethiopia J Hydrol Reg Stud 24:100610

Aouragh MH, Essahlaoui A, El Ouali A, El Hmaidi A, Kamel S (2017) Groundwater potential of Middle Atlas plateaus, Morocco, using fuzzy logic approach, GIS and remote sensing. Geomat Nat Hazards and Risk 8:194–206

Aromoye SA, Alimi SA, Bello OS, Raji WO, Olawale LO, Bonde DS (2019) 2-D Electrical resistivity tomography for groundwater potential in basement terrain of a part of Ilorin Sheet 223 NW Nigeria. Saudi J Eng Technol 4:357–362

Badamasi S, Sawa BA, Garba ML (2016) Groundwater potential zones mapping using remote sensing and geographic information system techniques (GIS) in Zaria, Kaduna State, Nigeria. American Scientific Res J Eng Techn Sci 24:51–62

Bagu ZB, Garba AD, Adewuyi T, Taiwo T (2019) Assessment of water quality of Kajim and Kagoro springs in Kaura local government area, Kaduna state, Nigeria. J Environ Hydrol 27:1–9

Baker B, Aldridge C, Omer A (2016) Water: availability and use. Mississippi State University Extension 3011

Bature AS, Opotu LA, Mounkaila N (2021) Evaluation of water supply and sanitation situation in Kaduna Metropolis in Northern Nigeria. Public Health Res 11:1–14

Bayewu OO, Oloruntola MO, Mosuro GO, Watabuni FG (2012) Groundwater exploration in Ago-Iwoye Area of Southwestern Nigeria, using very low frequency electromagnetic (VLF-EM) and electrical resistivity methods. Int J Appl Sci Eng Res 1:452–462

Chen W, Pradhan B, Li S, Shahabi H, Rizeei HM, Hou E, Wang S (2019) Novel hybrid integration approach of bagging-based fisher's linear discriminant function for groundwater potential analysis. Nat Resourc Res 28:1239–1258

Corsini A, Cervi F, Ronchetti F (2009) Weight of evidence and artificial neural networks for potential groundwater spring mapping: an application to the Mt. Modino area (Northern Apennines, Italy). Geomorphology 111:79–87

Das B, Pal SC (2019) Combination of GIS and fuzzy-AHP for delineating groundwater recharge potential zones in the critical Goghat-II block of West Bengal, India. HydroResearch 2:21–30

Ebenezer OK, Martins E (2017) Geoelectrical evaluation of the variation in the spatial distribution of aquifers in the basement complex – a case study of Laduga Community, Kaduna State, North Central, Nigeria. IOSR J Appl Geophy 5:35–44

Eduvie MO, Olaniyan IO (2013) Groundwater quality appraisal in southern parts of Kaduna State, Nigeria. Am J Environ Engineer 3:77–83

Egboka BCE (1988) The hydrogeological provinces of Nigeria. Water Quality Bull 13:117–125

FAO (Food and Agricultural Organization) (2005) AQUASTAT-FAO's information system on water and agriculture in Nigeria, Water Report no.29. Food and Agricultural Organization, Rome.

Fashae OA, Tijani MN, Talabi AO, Adedeji OI (2014) Delineation of groundwater potential zones in the crystalline basement terrain of SW-Nigeria: an integrated GIS and remote sensing approach. Appl Water Sci 4:19–38

Ghayoumian J, MohseniSaravi M, Feiznia S, Nouri B, Malekian A (2007) Application of GIS techniques to determine areas most suitable for artificial groundwater recharge in a coastal aquifer in southern Iran. J Asian Earth Sci 30:364–374

Gupta M, Srivastava P (2010) Integrating GIS and remote sensing for identification of groundwater potential zones in the hilly terrain of Pavagarh, Gujarat. India Water Int 35:233–245

Gupta D, Yadav S, Tyagi D, Tomar L (2018) Multi-criteria decision analysis for identifying of groundwater potential sites in Haridwar. Eng J Appl Scope 3:9–15

Hasanuzzaman M, Mandal MH, Hasnine M, Shit PK (2022) Groundwater potential mapping using multi-criteria decision, bivariate statistic and machine learning algorithms: evidence from Chota Nagpur Plateau. India Appl Water Sci 12:58

Hassan H, Waru SM, Bukar GA, Abdullahi KM (2016) Groundwater potentials estimation of a basement terrain using pumping test data for parts of Sanga Local Government Area, Kaduna State, Northwestern Nigeria. Open J Mod Hydrol 6:222–229

IAEA (International Atomic Energy Agency) (2011) Bulletin 53:1

Ibe SO, Egwuonwu GN, Osazuwa IB (2012) Delineation of all-season-recharged groundwater reservoir from Two Valleys, Zaria. Nigeria J Environ Hydrol 20:11

Idris-Nda A, Abubakar SI, Waziri SH, Dadi MI, Jimada AM (2015) Groundwater development in a mixed geological terrain: a case study of Niger State, Central Nigeria. Conference: Water Resources Management VIII

Jones MJ (1985) The weathered zones aquifers of basement complex area of African. Quarterly J Eng Geol 18:35–45

Kumar A, Pandey AC (2016) Geoinformatics based groundwater potential assessment in hard rock terrain of Ranchi urban environment, Jharkhand state (India) using MCDM–AHP techniques. Groundw Sustain Dev 27:41

Kure N, Daniel HI, Afuwai CG, Adoyi EJ, Bello IA (2019) The delineation of groundwater and geotechnical parameters within Marmara Area of Chikun Local Government of Kaduna State, Nigeria. J Nig Soc Phys Sc 1:1–5

Lee S, Kim YS, Oh HJ (2012) Application of a weights-of-evidence method and GIS to regional groundwater productivity potential mapping. J Environ Manage 96:91–105

MacLeod WN, Turner DC, Wright EP (1971) The geology of Jos-Plateau. Geological Survey of Nigeria Bulletin 1

Magesh NS, Chandrasekar N, Soundranayagam JP (2012) Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. Geosci Front 3:189–196

Mallick J, Khan RA, Ahmed M, AlQadhi S, Alsubih M, Falqi II, Hasan MA (2019) Modeling groundwater potential zone in a semi-arid region of Aseer using fuzzy-AHP and geoinformation techniques. Water 11:2656

McCurry P (1976) The geology of the Precambrian to Lower Paleozoic rocks of Northern Nigerian, a review. In: Kogbe CA (ed) Geology of Nigeria. Lagos, Elizabethan Publishing Co, pp 15–39

Mukherjee I, Singh UK (2020) Delineation of groundwater potential zones in a drought-prone semi-arid region of east India using GIS and analytical hierarchical process techniques. CATENA 194:104681

Murmu P, Kumar M, Lal D, Sonker I, Singh SK (2019) Delineation of groundwater potential zones using geospatial techniques and analytical hierarchy process in Dumka district, Jharkhand. India Groundw Sustain Dev 9:100239

Musa IJ, Shehu A, Lukman S (2009) Distribution, methods and supply problems of Tap water in urban Zaria Area, Kaduna State. Elec J Env Agricult Food Chem 8:294–300

Naghibi SA, Moghaddam DD, Kalantar B, Pradhan B, Kisi O (2017) A comparative assessment of GIS-based data mining models and a novel ensemble model in groundwater well potential mapping. J Hydrol 548:471–483

Namous M, Hssaisoune M, Pradhan B, Lee C, Alamri AM, Elaloui A, Edahbi M, Krimissa S, Eloudi H, Ouayah M, Elhimer H, Tagma T (2021) Spatial prediction of groundwater potentiality in large semi-arid and Karstic Mountainous region using machine learning models. Water 13:2273

Nampak H, Pradhan B, Manap MA (2014) Application of GIS based data driven evidential belief function model to predict groundwater potential zonation. J Hydrol 513:283–300

NiMet (Nigerian Meteorological Agency) (2021) Seasonal rainfall prediction. A Publication of the Nigerian Meteorological Agency, Abuja

Nsiah E, Appiah-Adjei EK, Adjei KA (2018) Hydrogeological delineation of groundwater potential zones in the Nabogo basin, Ghana. J Afr Earth Sci 143:1–9

Ogezi AE (1988) Geochemistry and geochronology of basement rocks from North Western Nigeria. Unpublished Ph.D Thesis, University of Leeds

Ogungbade O, Ariyo SO, Alimi SA, Alepa VC, Aromoye SA, Akinlabi OJ (2021) A combined GIS, remote sensing and geophysical methods for groundwater potential assessment of Ilora, Oyo Central. Nigeria Environ Earth Sci 81:74

Oladunjoye MA, Adefehinti A, Ganiyu KA (2019) Geophysical appraisal of groundwater potential in the crystalline rock of Kishi area. Southwestern Nigeria J Afr Earth Sci 151:107–120

Olaniyan IO, Olabode OT (2012) Assessment of the groundwater potential of a typical "Fadama" in Kaduna State, Nigeria. Researcher 4:10–15

Olasehinde PI, Amadi AN, Idris-Nda A, Katu MJ, Unuevho CI, Jimoh MO (2015) Aquifers characterization in Agaie, North-Central Nigeria using electrical resistivity method and borehole lithologs. Am J Environ Prot 3:60–66

Olayinka AI, Olorunfemi MO (1992) Determination of geoelectrical characteristics in Okene area and implication for boreholes siting. J Min Geol 28:403–412

Omeiza AJ, Dary DM (2018) Aquifer vulnerability to surface contamination: a case of the New Millennium City, Kaduna, Kaduna State Nigeria. World J Appl Phys 3:1–12

Panahi M, Sadhasivam N, Pourghasemi HR, Rezaie F, Lee S (2020) Spatial prediction of groundwater potential mapping based on convolutional neural network (CNN) and support vector regression (SVR). J Hydrol 588:125033

Pham B, Jaafari A, Phong T, Mafi-Gholami D, Amiri M, Van Tao N, Duong V, Prakash I (2021) Naïve Bayes ensemble models for groundwater potential mapping. Eco Inform 64:101389

Population Council (2007) Report of Nigeria's National Population Commission on the 2006 Census. Popul Dev Rev 33:206–210

Putra AR, Masduqi A (2018) Delineation of groundwater potential zone on Brantas groundwater basin. IAETSD J Adv Res Appl Sci 5:58–64

Rajasekhar M, Sudarsana Raju G, Sreenivasulu Y, Siddi Raju R (2019) Delineation of groundwater potential zones in semi-arid region of Jilledubanderu river basin, Anantapur District, Andhra Pradesh, India using fuzzy logic, AHP and integrated fuzzy-AHP approaches. HydroResearch 2:97–108

Raji WO, Abdulkadir KA (2020) Geo-resistivity data set for groundwater aquifer exploration in the basement complex terrain of Nigeria, West Africa. Data Br 31

Saaty TL (1990) How to make a decision: the analytic hierarchy process. Eur J Oper Res 48:9–26

Saaty TL (1980) The analytic hierarchy process**.** McGraw-Hill, New York 20–25

Sameen MI, Pradhan B, Lee S (2019) Self-learning random forests model for mapping groundwater yield in data-scarce areas. Nat Resour Res 28:757–775

Sani M (2008) Urban water supply in Nigeria and the prospects for commercialization. Environ Technol Sci J (ETSJ) 3:72–80

Saranya T, Saravanan S (2020) Groundwater potential zone mapping using analytical hierarchy process (AHP) and GIS for Kancheepuram District, Tamilnadu, India. Model Earth Syst Environ 6:1105–1122

Umar S, Yusuf AS (2015) Assessment of well water quality: a case study of Kaduna South Local Government Area, Kaduna State Nigeria. Merit Res J Environ Sci Toxicol 3:39–43

UNESCO (United Nations Educational, Scientific and Cultural Organization) (2015) The United Nations World Water Development Report 2015: Water for a Sustainable World. UNESCO Publishing, Paris

Warsi T, Kumar VS, Dhakate R, Manikyamba C, Rao TV, Rangarajan R (2019) An integrated study of electrical resistivity tomography and infiltration method in deciphering the characteristics and potentiality of unsaturated zone in crystalline rock. HydroResearch 2:109–118