

Groundwater Potential Zone Mapping in the Department of Boundiali (Northern Côte d'Ivoire) Using the Analytical Hierarchy Process (AHP) and GIS

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[Doi:10.19044/esj.2026.v22n30p272](https://doi.org/10.19044/esj.2026.v22n30p272)

Submitted: 05 March 2026

Accepted: 06 October 2026

Published: 31 October 2026

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OPEN ACCESS

Cite As:

Deh, S. K., Oulare, S., Kouadio, E. K., Loua, S., Konate, M. F., Yao, M. Y., Kouame, J. K., & Jourda, J. P. R. (2026). *Groundwater Potential Zone Mapping in the Department of Boundiali (Northern Côte d'Ivoire) Using the Analytical Hierarchy Process (AHP) and GIS*. European Scientific Journal, ESJ, 22 (30), 272.

<https://doi.org/10.19044/esj.2026.v22n30p272>

Abstract

This study aims to improve our understanding of groundwater resources in the Boundiali department to meet the ever-growing needs of the population. The main objective of this study is to identify areas with real groundwater potential. The database includes satellite images, borehole data, and hydro-climatic data. Using the hierarchical analytical process method to combine these different types of information made it possible to generate groundwater availability, operability, and accessibility indicators. These indicators were then used as criteria and incorporated using the GIS-based coding aggregation method to develop the groundwater potential map. The

results show that over half (60%) of the territory has good to excellent groundwater availability. The operability and accessibility areas of this resource are estimated at 30% (good) and 53% (excellent), respectively. Analysis of the groundwater potential map derived from these indicators shows that 61% of the study area is suitable for installing high-yield boreholes. This study is a significant step towards solving the drinking water problem in this department, where no advanced hydrogeological studies are available.

Keywords: Accessibility, Availability, Operability, Boundiali, Groundwater Potential

Introduction

Water is an essential resource for human and environmental needs. Thus, ensuring access to water resources and managing these resources are subjects of international debate because their availability is limited in certain regions, with the aim of guaranteeing access by 2030 (WHO & UNICEF, 2017). However, water resources are increasingly being affected by climate change and global population growth. In developing countries, groundwater is the preferred source of drinking water for populations because it is relatively high quality and inexpensive. However, groundwater exploitation is often characterized by low-yield boreholes, particularly in hard rock areas. Hard rock aquifer systems have very complex structures (Vouillamoz, 2002; Dewandel et al., 2011; Lachassagne et al., 2011, 2014; Alle et al., 2018).

In Côte d'Ivoire, 97.5% of the territory is underlain by hard rock, which contains most of the country's groundwater resources. The Boundiali department is entirely located in hard rock areas where access to water resources has been a major issue for several decades. Over 45% of boreholes in these areas have very low yields. These low-yield boreholes are due to a lack of thorough hydrogeological studies and the use of traditional methods, such as the geomorphological method, which have proven ineffective in selecting borehole locations. Several boreholes have dried up after being commissioned (Pinatibi et al., 2015). Identifying large quantities of exploitable water in crystalline hard rock requires a better understanding of the hydrogeology of this complex environment.

Methods of prospecting for groundwater resources in hard rock have evolved considerably, with many based on common electromagnetic (EM) and/or direct current (DC) resistivity techniques (Perdomo et al., 2014; Vouillamoz et al., 2015). While these methods can identify zones that are potentially favourable for well sites based on the structure and geometry of aquifers, their application on a regional scale is limited. They are generally implemented on a local scale as they are costly and time-consuming (Vouillamoz, 2002; Shishaye & Abdi, 2016; Alle et al., 2018). Most studies

of regional groundwater resources use large-scale indicators such as geomorphology, drainage density, lineament density, slope, geology, land use/land cover, soil, rainfall, and elevation (Singh et al., 2018; Kaur et al., 2020; Anteneh et al., 2022).

Over the last few decades, the development of geospatial techniques has made most of these parameters accessible at little or no cost. Remote sensing (RS) and geographic information systems (GIS) are powerful tools that can be used to collect, store and manage most groundwater indicators in a simplified manner. The use of integrated RS and GIS approaches for groundwater prospection is widely accepted (Aluko & Igwe, 2017; Panahi et al., 2017; Savita et al., 2018; Singh et al., 2018; Chaudhary & Kumar, 2018; Aggarwal et al., 2019; Anteneh et al., 2022; Boubacar et al., 2022; Zewdie & Yeshanew, 2023). The number of parameters used to define the occurrence, geological formation and hydrological properties of groundwater depends on the study area. In the integrated approach, these parameters are assigned suitable weights and ranks based on various methods, which are then summed to identify potential zones. The weights and ranks assigned to the parameters were determined using knowledge-based ranking and multi-criteria decision-making analysis (Singh et al., 2017; Savita et al., 2018; Arulbalaji et al., 2019; Zewdie & Yeshanew, 2023). Several studies have been carried out around the world in this context, using GIS coupled with the Analytical Hierarchy Process (AHP). As this study takes various influencing parameters into account, a combined technical and expert approach is better for determining weights than assigning a random percentage. The AHP has proven to be an effective decision-making tool for problems involving multiple criteria (Saaty, 1980, 2008). Due to its ability to rapidly produce comprehensive, cost-effective, repeatable, and feasible spatial and temporal data over a wide area, the AHP method has become invaluable for providing vital information regarding the various variables controlling the presence of groundwater (Aggarwal et al., 2019; Gupta et al., 2018; Arulbalaji et al., 2019; Yabre et al., 2023; Zewdie & Yeshanew, 2023). The AHP method structures decision-making elements hierarchically and calculates normalized weights for each element to produce results with a high degree of confidence and certainty. The AHP method is a popular and effective approach used by researchers such as Patra et al. (2018), Bera et al. (2020), Yabre et al. (2023), Anteneh et al. (2022) and Zewdie et al. (2024). It could therefore be applied to regions with few or no hydrogeological studies to provide preliminary information on groundwater availability. This study aims to use a combination of remote sensing (RS), the analytical hierarchy process (AHP) and geographic information systems (GIS) to identify areas with high groundwater potential suitable for productive borehole installation in the Boundiali department. This will help to ensure a reliable supply of drinking water for the local population. Compared with

other regions of the country, very few hydrogeological studies have been carried out in this department (Jourda et al., 2006; Youan Ta et al., 2011; Koffi et al., 2016; Yao et al., 2022; Kouassi et al., 2019).

Material and Methods

Study area

The study area is the Boundiali department, which is a part of the Bagoue region in the north of Côte d'Ivoire. Located between 730,000 m and 850,000 m West longitudes and 1,000,000 m and 1,120,000 m north latitudes, it covers an area of 4,302 km². Its population is estimated at 198,541 inhabitants. It is bordered to the north by the Kouto department, to the south by the Dianra and Kani departments, to the east by the Korhogo department, and to the west by the Seguela and Madinani departments (Figure 1).

The study area is entirely located in the savannah. In the mountainous western part of the department and the shale zone, there is a relatively wooded and shrubby savannah with open forests in places. The climate is Sudanese, with a tropical transitional pattern marked by an alternation of two seasons, a dry season and a rainy season.

In terms of hydrography, the study area is well supplied with water and drained by the Bandama and Bagoue rivers. These rivers are a source of drinking water for rural populations. The Bagoue River, a tributary of the Niger River, flows from south to north. The Bandama River flows from north to south. There are two hydrological periods: a three-month flood period from July to September, which is most intense in August, and a low-water period from November to April, which is marked by water shortages. Most of the water bodies in this area dry up during the dry season. The study area is characterized by sandstones, metasediments and massive granites, with a hard-rock aquifer system (Figure 2).

Data and materials

The data collected for this study include the following:

- Landsat 8 and SRTM (Shuttle Radar Topographic Mission) images. Landsat 8 images were used to map lineaments. Scenes 198-53 and 198 were acquired on 3 March 2019 and 15 March 2019, respectively, and are available at <http://glcfapp.umi.acs.umd.edu:8080/esdi/index.jsp>. The Landsat 8 scenes used are composed of 11 bands, with spatial resolutions ranging from 15 m to 100 m;
- SRTM images with a resolution of 30 m were used to map the slope of land surface. These were downloaded from the USGS website at <http://srtm.usgs.gov/>.
- Borehole data were provided by the «Direction Régionale de l'Hydraulique de Boundiali». These data contain information on the depth to

the groundwater level, borehole yields, borehole depth, and weathering thickness (saprolite). A total of 196 boreholes were used;

- Climatic data containing rainfall and temperature measurements were also used. These data come from the Boundiali rainfall station for the period 1988 to 2018. They were used to calculate groundwater potential recharge.

The hardware used to process this dataset mainly consists of computer tools. Envi 5.1 software was used to pre-process and process Landsat 8 images, while ArcGIS 10.5 was used for mapping parameters and implementing the GIS.

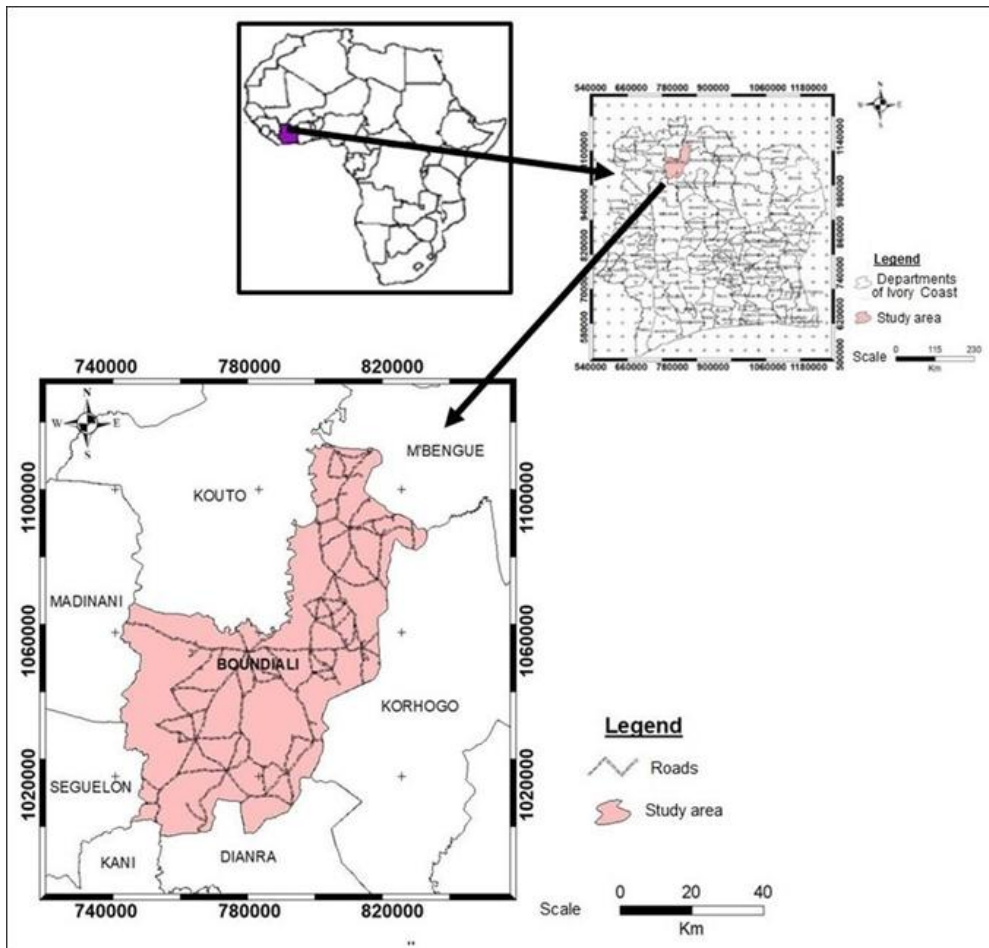


Figure 1: Geographical location of the study area

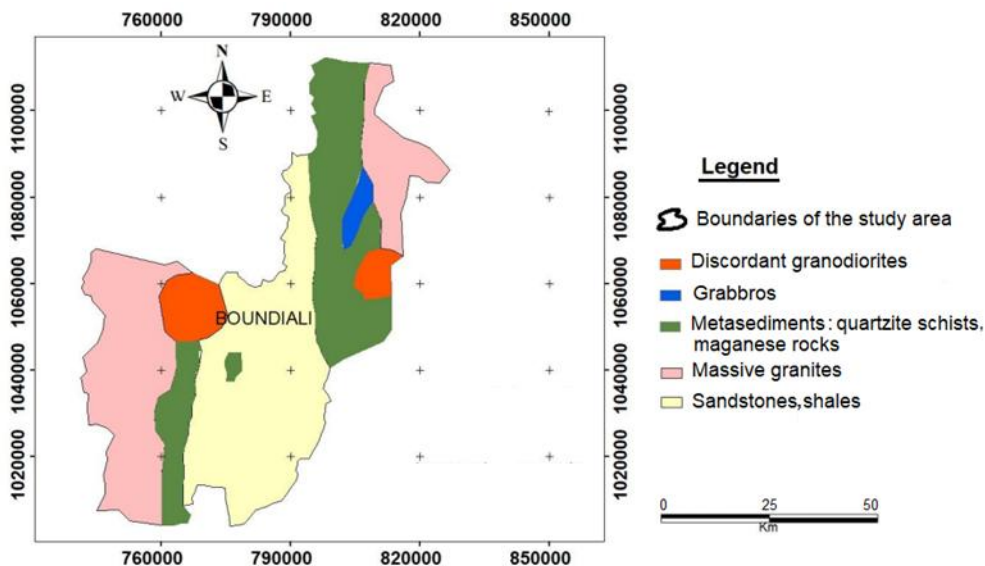


Figure 2: Geological map of the study area

Methodology

The approach used to produce the groundwater potential map is a classic multi-criteria analysis method (Gupta et al., 2018; Arulbalaji et al., 2019; Bera et al., 2020; Zewdie et al., 2024). It includes the following steps: (i) identification of criteria; (ii) classification and standardisation of criteria; and (iii) weighting and aggregation of criteria.

Criteria identification

The parameters used to identify groundwater potential zones are aquifer characteristics, such as fractures, weathering thickness, borehole yields, and well depth, as well as physiographic parameters, such as slope of land surface and drainage network of surface water. Aquifer characteristics are provided by borehole data and other external factors, while physiographic parameters are derived from satellite images. All parameters are grouped into three quantitative indicators according to their role, accessibility, operability, and availability (Doubouya et al., 2012; Yao et al., 2016; Cocker et al., 2020).

Availability indicator

The availability indicator reflects the existence of an aquifer, which is the first thing to establish before carrying out any other activities. It is determined by parameters such as slope of land surface, drainage density of surface water, lineament density, weathering thickness, and groundwater potential recharge (Doubouya et al., 2012; Cocker et al., 2020) :

- The slope of the land surface is an important factor in controlling groundwater accumulation in the aquifer. A steep slope results in high runoff and significantly reduces the potential for groundwater recharge. Conversely, a lower slope allows water to flow slowly and infiltrate the soil, significantly increasing groundwater accumulation. In ArcGIS software, the 'Slope' tool was used to produce the slope of land surface map from SRTM images (Figure 3);

- The drainage density of surface water is a factor linked to soil permeability. Permeability is an important hydrogeological parameter that provides information on infiltration rates. Several studies have shown that a dense drainage network indicates impermeable soil, resulting in lower infiltration rates. Conversely, a low drainage density network indicates highly permeable soil, as most surface water infiltrates rapidly into the subsurface (Rajaveni et al., 2017; Gupta et al., 2018). The drainage network of the study area was digitized from SRTM images in ArcGIS. It represents the total length of drains per unit area, expressed as (1) (Figure 4) :

$$d = \frac{\sum Li}{A} \quad (1)$$

Where Dd is the drainage density (km/km²); Li is the length of drain per unit of area (Km), A is the unit of area (km²);

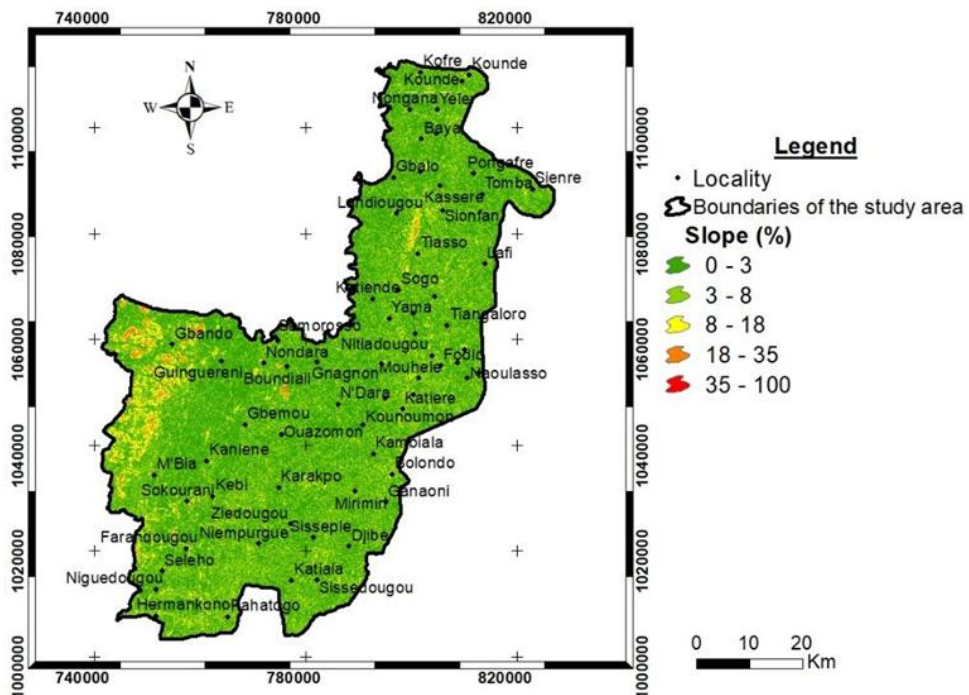


Figure 3: Slope of land surface map

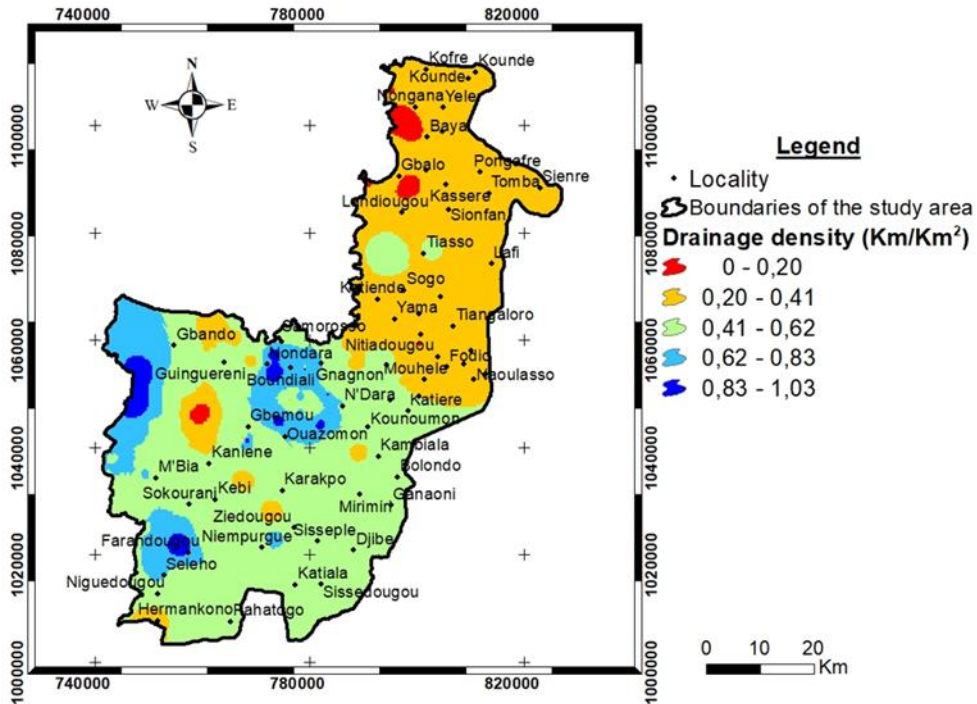


Figure 4: Drainage density of surface water map

- The lineaments are the visible manifestation of underlying lithological structures, such as faults, fractures, and cleavages. They play a key role in the occurrence and circulation of groundwater. The movement of water between the surface and the subsurface is controlled by fractures and faults. Lineaments are essential in groundwater potential studies in hard rock areas (Pinto et al., 2017). In this study, lineament density was digitized using the “Line Density” tool in ArcGIS (Figure 5);

- The thickness of saprolite is a key factor in the study of aquifer productivity in hard rock areas. Saprolite is the top layer of unconsolidated, weathered rock located above the stratiform fractured layer (Figure 6). The stratiform fractured layer refers to a weathered layer that has fractured. These two weathered units form an integrated aquifer system (Lachassagne et al., 2011; 2014). Several studies confirm that drilling success rates (Vouillamoz et al., 2015) and borehole productivity are linked to the thickness of the weathered units. In the study area, a map of saprolite thickness was generated using the IDW interpolation method in ArcGIS based on borehole data (Figure 7);

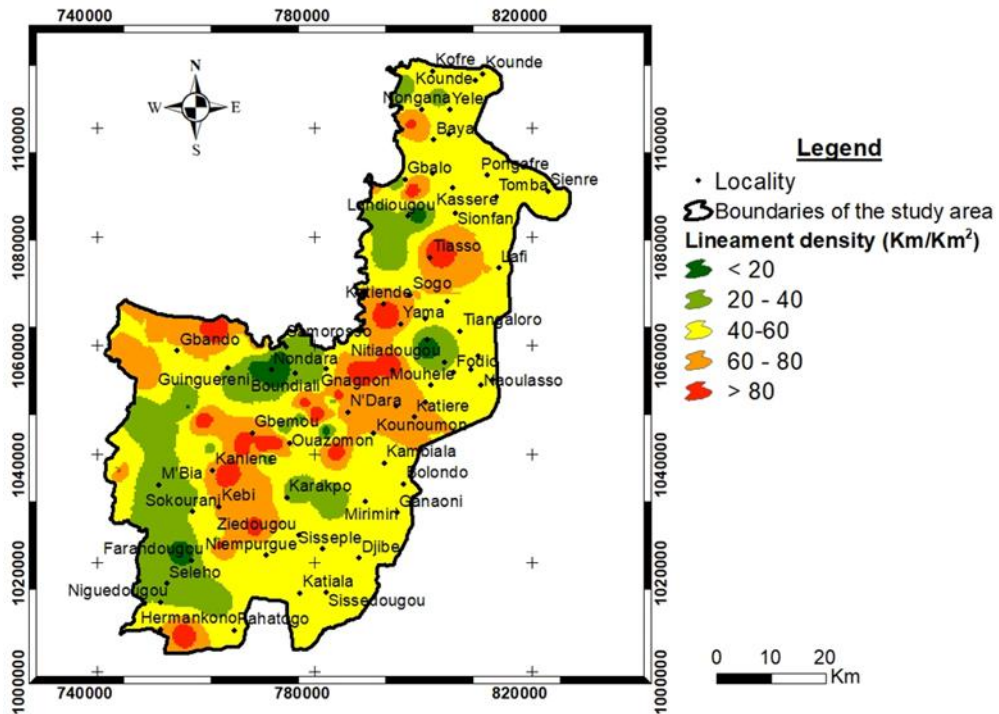


Figure 5: Lineament density map

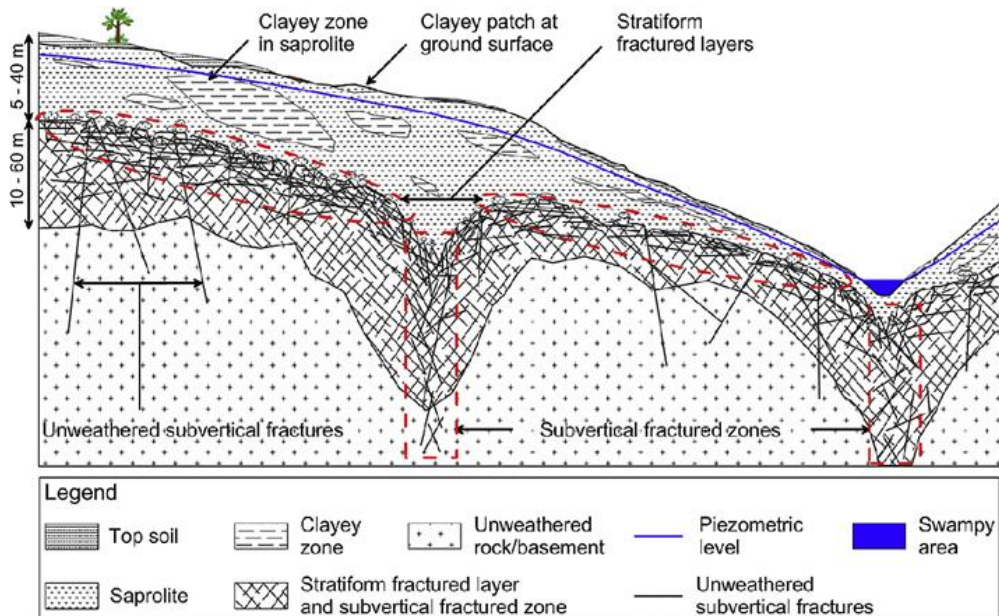


Figure 6: Hydrogeological conceptual model of weathered hard rock
(adapted from Dewandel et al., 2011 in Aller et al., 2018)

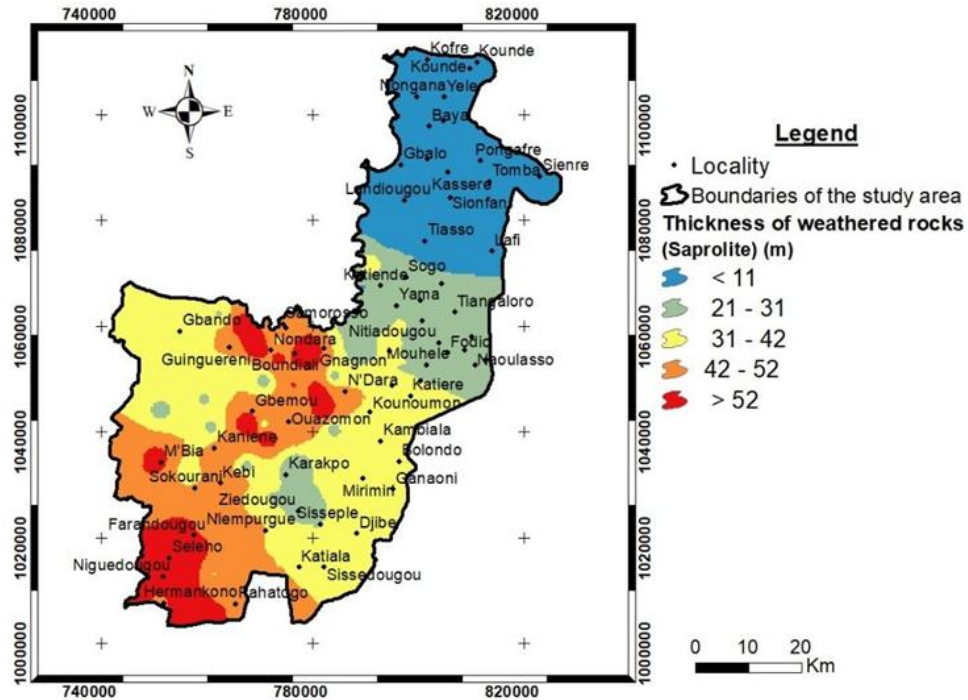


Figure 7: Thickness of weathered rocks map

- The groundwater potential recharge represents the amount of water that infiltrates the ground and reaches the water table. The greater the recharge, the greater the volume of available groundwater. Several methods of assessing recharge are described in the literature. These include the water balance method, the hydraulic method, the isotopic method, and the GIS approach (Deepa et al., 2016; Das and Pal, 2019). The water balance method was used to calculate water infiltration (or groundwater recharge) from the following formula (2):

$$I = P - (ETR + R) \quad (2)$$

Where I is the amount of water infiltration (or groundwater recharge) (mm); P is the total rainfall (mm); ETR is the actual evapotranspiration (mm); R is the amount of runoff water (mm). Rainfall, actual evapotranspiration and, runoff data were provided by the previous studies.

The groundwater recharge values obtained for each point considered in the study area were interpolated using IDW method in ArcGIS to produce a groundwater recharge map (Figure 8).

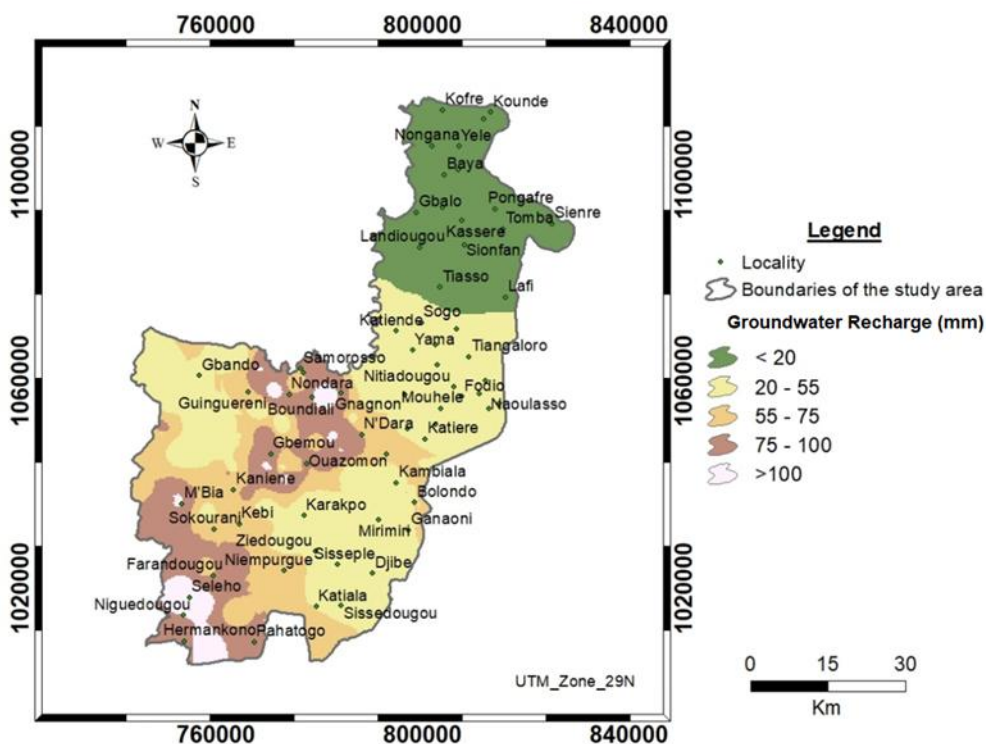


Figure 8: Groundwater potential recharge map

Operability indicator

This indicator represents the productivity of boreholes linked to the flow rate, which depends on the depth. This indicator also represents the exploitation (or operation) of the borehole, characterized by the pumping rate. It is determined by combining the borehole yields and the depths to the groundwater level:

- The borehole yield is an important parameter which depends on the amount of water in the aquifer and how quickly the aquifer can be replenished in times of high demand. In this study, the borehole yield corresponds to the groundwater pumping rate, which was measured upon commissioning of the borehole. The borehole yields map was produced by interpolating the borehole yield values using IDW technique in ArcGIS (Figure 9) ;

- The depth to groundwater level provides information about the conditions of aquifer recharge and the available water volume. In the case of an unconfined aquifer, the depth to the water table is very close to the surface during the rainy season and relatively deep during the dry season. Generally, higher water levels indicate greater groundwater potential. This parameter was acquired based on the year the wells were drilled. The depth to groundwater level map for the study area was produced by interpolating groundwater levels from borehole data using the inverse distance weighting (IDW) technique in ArcGIS (Figure 10).

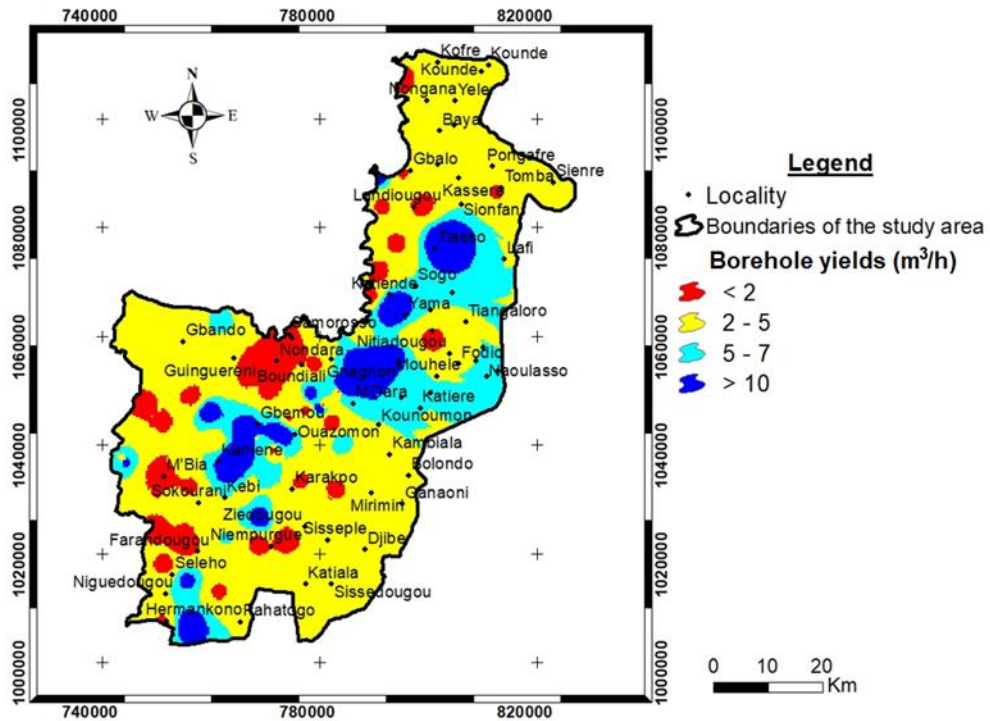


Figure 9: Borehole yields map

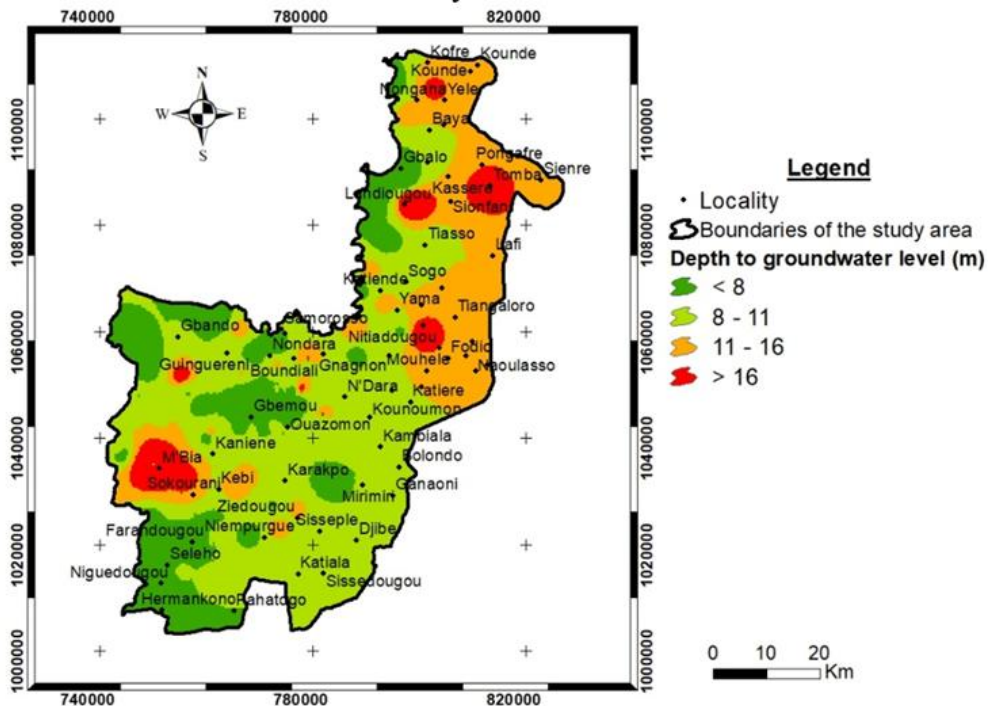


Figure 10: Depth to groundwater level map

Accessibility indicator

Accessibility is the indicator that determines access to groundwater resources. These conditions are therefore considered economic and social factors because they determine access to the resource (Doumbouya et al., 2012). The main factors contributing to the accessibility indicator are total well depth and the success index:

- The total depth of the borehole provides information about the cost, which depends on the number of meters. The deeper the borehole, the higher the cost. Due to the high cost of drilling, access to groundwater can be limited in regions where the water table is deep. Furthermore, some studies suggest that the productivity of boreholes in hard rock areas diminishes beyond a certain depth (Neves & Morales, 2007). This parameter is included in groundwater potential studies by several authors (Yao et al., 2016; Oussou et al., 2019; Cocker et al., 2020). The map showing the total depth of boreholes in the study area was created using borehole data;

- The success index indicates the likelihood of a productive borehole. The success index of a borehole is 100% when the borehole yield is 10 m³/h. It is calculated using the following empirical formula (3) (Doumbouya et al., 2012):

$$a = \left(\frac{b}{10} \right) \times 100 \quad (3)$$

Where a is the success index (%); b is the borehole yield (m³/h).

Classification and standardization of criteria

The choice of classes was based on the variance of the criteria. The number of classes was limited to four or five to allow for better interpolation (Youan Ta et al., 2011; Oussou et al., 2019; Yabre et al., 2023). These classes are: 'very low', 'low', 'medium', 'high', and 'very high'. Additionally, as the criteria are measured on different scales using different units, they must be standardized to enable a more accurate multi-criteria analysis. A rating scale ranging from 1 to 10 was used. A score of 10 is attributed to the class of criterion that contributes to achieving positive responses. Conversely, a score of 1 is assigned to the class of criterion qualified as "very low" or "very high", depending on whether it contributes to the excellent achievement of the considered indicator. Following the same logic, intermediate values are assigned to intermediate classes according to a linear distribution. Table 1 illustrates the classification and standardization of the criteria considered in this study. The AHP aggregation method was used to combine classified and standardized criteria.

Table 1: Classification and standardization of criteria

Indicators	Criteria	Classes	Criteria qualification	Scores
Availability of groundwater resource	Drainage density (Km/km ²)	Very low	0 – 0.20	10
		Low	0.20 – 0.41	8
		Medium	0.41 – 0.62	5
		High	0.62 – 0.83	3
		Very high	0.83 – 1.03	1
	Lineaments density (Km/Km ²)	Very low	< 20	1
		Low	20-40	3
		Medium	40-60	5
		High	60-80	8
		Very high	>80	10
	Weathering thickness (m)	Very low	< 10.68	1
		Low	21.16 – 31.64	3
		Medium	31.64 – 42.12	5
		High	42.12 -52	8
		Very high	> 52	10
	Groundwater recharge (mm)	Very low	< 20	1
		Low	20 – 55	3
		Medium	55 – 75	5
		High	75 – 100	8
		Very high	> 100	10
	Slope (%)	Very low	0 – 3.10	10
		Low	3.10 – 8.28	8
		Medium	8,28 - 17,59	5
		High	17.59 – 34.67	3
		Very high	34.67 – 100	1
Operability of groundwater resource	Borehole yields (m ³ /h)	Low	<2	1
		Medium	3 – 5	5
		High	5 – 7	8
		Very high	> 10	10
	Depth to groundwater level (m)	Low	< 8	10
		Medium	8-11	8
		High	11-16	5
		Very high	> 16	1
Accessibility of groundwater resource	Total depth of borehole (m)	Very low	10-24	10
		Low	24-38	8
		Medium	38-52	5
		High	52-66	3
		Very high	>80	1
	Probability of success (%)	Very low	5.0 – 24	1
		Low	24- 43	3
		Medium	43 – 62	5
		High	62 – 80	8
		Very high	80 – 100	10

Weighting and aggregation of criteria

Criteria weighting involves assigning a weight to each criterion contributing to the calculation of a groundwater indicator. The weight value indicates the criterion's relative importance in realising the phenomenon reflected by the groundwater indicator. In this study, the weighting of the criteria was calculated using Saaty's (1980) AHP pairwise comparison method. This method involves comparing each criterion with every other criterion according to their relative importance on a scale of 1 to 9. In this study, the calculated consistency ratios of the various matrices are less than 10%, demonstrating the reliability of the judgements (Table 2). The resulting comparison matrix is then used to determine the weight (W_i) of each criterion using eigenvectors (V_p) from formula (4). The weight (W_i) for each criterion is obtained by dividing each eigenvector by the sum of the eigenvectors from formula (5). The sum of the weights of all the criteria in a matrix must be equal to 1, as illustrated in Tables 3, 4, and 5, which present the eigenvectors (V_p) and weights calculated for the groundwater availability, operability and, accessibility criteria.

$$V_p = \sqrt[k]{W_1 \times \dots \times W_k} \quad (4)$$

Where V_p is the eigenvector; k is the number of parameters considered; W_k is the parameter score.

$$W_i = \frac{V_p}{V_{p1} + \dots + V_{pk}} \quad (5)$$

Where W_i is the weight; V_p is the eigenvector.

The process of integrating all the criteria is carried out in two steps: First, availability, operability, and accessibility indicator maps are generated based on the weighted criteria obtained using the AHP method. These maps are produced using the following equation (6):

$$S = \sum_{i=2}^n W_i \cdot X_i \quad (6)$$

Where S represents a groundwater indicator; W_i is the weight of the criterion; X_i refers to the raster layer of this criterion.

Table 2: Comparison matrix of groundwater availability, operability, and accessibility criteria

Availability Indicators						Operability indicators			Accessibility indicators		
Criteria	Slope	Gr	Dd	Ld	Wt	Criteria	Dr	Gl	Criteria	Bd	Si
Slope	1	1/3	5	3	5	Dr	1	3	Bd	1	3
Gr	3	1	7	5	5						
Dd	1/5	1/7	1	1/3	1						
Ld	1/3	1/5	3	1	5	Gl	1/3	1	Si	1/3	1
Wt	1/5	1/5	1	1/5	1						

Gr= groundwater recharge; Dd= Drainage density; Ld= Lineament density;
Wt= Weathering thickness; Dr= borehole yield; Gl= Depth to groundwater level;
Bd= Borehole depth, Si= success index.

Table 3: Eigenvectors and Weights for groundwater availability criteria

Indicators	Criteria	Slope	Gr	Dd	Ld	Wt	Vp	Wi
Availability	Slope	1	1/3	5	3	5	$\sqrt[5]{1 \times 1/3 \times 5 \times 3 \times 5} = 1.904$	0.265
	Gr	3	1	7	5	5	$\sqrt[5]{3 \times 1 \times 7 \times 5 \times 5} = 3.5$	0.488
	Dd	1/5	1/7	1	1/3	1	$\sqrt[5]{1/5 \times 1/7 \times 1 \times 1/3 \times 1} = 0.394$	0.055
	Ld	1/3	1/5	3	1	5	$\sqrt[5]{1/3 \times 1/5 \times 3 \times 1 \times 5} = 1.00$	0.139
	Wt	1/5	1/5	1	1/5	1	$\sqrt[5]{1/5 \times 1/5 \times 1 \times 1/5 \times 1} = 0.381$	0.053
Sum							7.18	1

Table 4: Eigenvectors and Weights for groundwater operability criteria

Indicator	Criteria	Dr	Gl	Vp	Wi
Operability	Dr	1	3	$\sqrt[2]{1 \times 3} = 1.73$	0.75
	Gl	1/3	1	$\sqrt[2]{1/3 \times 1} = 0.58$	0.25
Sum				2.31	1

Table 5: Eigenvectors and Weights for groundwater accessibility criteria

Indicator	Criteria	Bd	Si	Vp	Wi
Accessibility	Bd	1	3	$\sqrt[2]{1 \times 3} = 1.73$	0.75
	Si	1/3	1	$\sqrt[2]{1/3 \times 1} = 0.58$	0.25
Sum				2.31	1

The second step is to combine the groundwater availability, operability, and accessibility indicator maps using the complete aggregation approach by coding as suggested by Jourda et al. (2006). The coding system adopted prioritizes the groundwater availability indicator over the groundwater operability and accessibility indicators, and the operability indicator over the accessibility indicator. Four classes (excellent, good, poor, and very poor) were defined for each indicator groundwater map using the

GIS. The values of 400, 300, 200, and 100 were assigned to the classes of the availability indicator map, respectively. The values of 40, 30, 20, and 10 were assigned to those of the operability indicator map and, 4, 3, 2, and 1 to those of the accessibility indicator map, respectively. The groundwater availability, operability, and accessibility indicator maps were considered as criteria. These thematic maps were combined into a single layer using GIS to produce the groundwater potential map of the study area. Table 6 shows the codes assigned to the different classes for each groundwater criterion.

Table 6 : Codes assigned to the groundwater indicators

Indicator	Criteria	Classes	Codes
Groundwater potential	Availability	Excellent	400
		Good	300
		Poor	200
		Very poor	100
	Operability	Excellent	40
		Good	30
		Poor	20
		Very poor	10
	Accessibility	Excellent	4
		Good	3
		Poor	2
		Very Poor	1

Validation of groundwater potentiality map

Several methods for validating groundwater potential maps are described in the literature. The most popular method is cross-validation using borehole yields (Arulbalaji et al., 2019; Saranya & Saravanan, 2020; Yabre et al., 2023; Zwedie et al., 2024). In this study, borehole yields were used to identify groundwater (Kouassi et al., 2019; Cocker et al., 2020). The approach adopted to validate the groundwater potential map is based on assessing the uncertainty of the data used to produce the results. Uncertainty analysis validation consists of calculating the uncertainty in the averages of the different parameters of the main groundwater potential indicators (Doubouya et al., 2012; Kouassi et al., 2019; Cocker et al., 2020). The calculation is given by (7) :

$$\Delta \underline{X} = \frac{\sigma}{\sqrt{m}} \quad (7)$$

Where, $\Delta \underline{X}$ is the uncertainty in the mean of the data; σ is the standard deviation of the data; m is the number of data.

The mean and standard deviation values of each established indicator map are provided in the GIS.

An expansion factor (K) is then calculated to determine the confidence level. The determination of this parameter is based on the statistical principle of calculating expanded uncertainty. This factor (K) is used to define an interval of sufficient range to ensure a high confidence level in the results. The expression of this factor is defined by the formula (8) :

$$K = \frac{|E - \bar{X}|}{\sigma} \quad (8)$$

Where, K is the expansion factor; E is the extreme value of the data, which can be the maximum or the minimum. σ is the standard deviation of the data. The confidence levels of the various parameters were deduced from the different values of K . Thus, $K=1$ for a confidence level of 68%, $K=2$ for a confidence level of 95% and $K=3$ for a confidence level of 99%.

Figure 11 shows the flowchart of the methodology used.

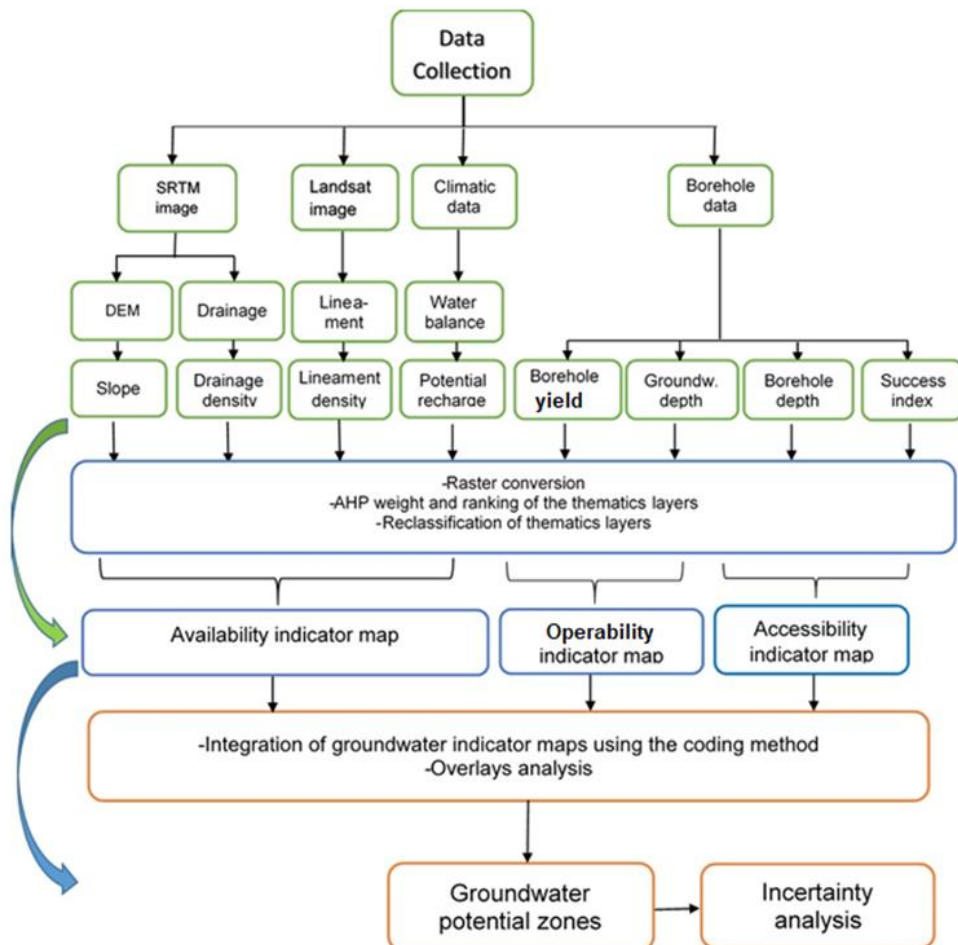


Figure 11: Flowchart of the methodology

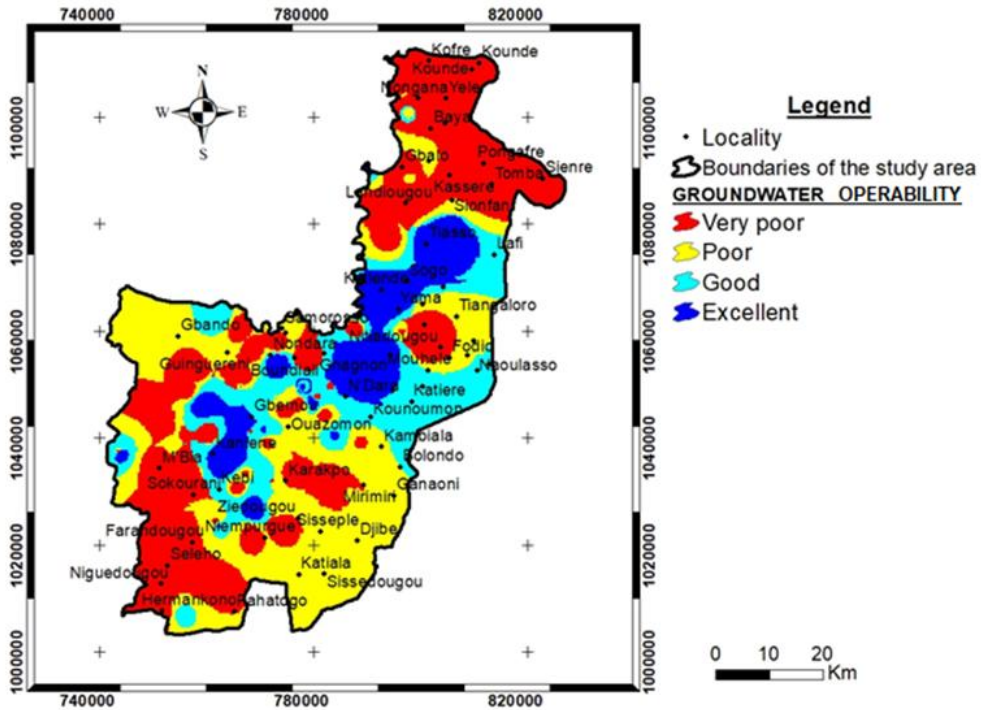


Figure 13: Groundwater resource operability map

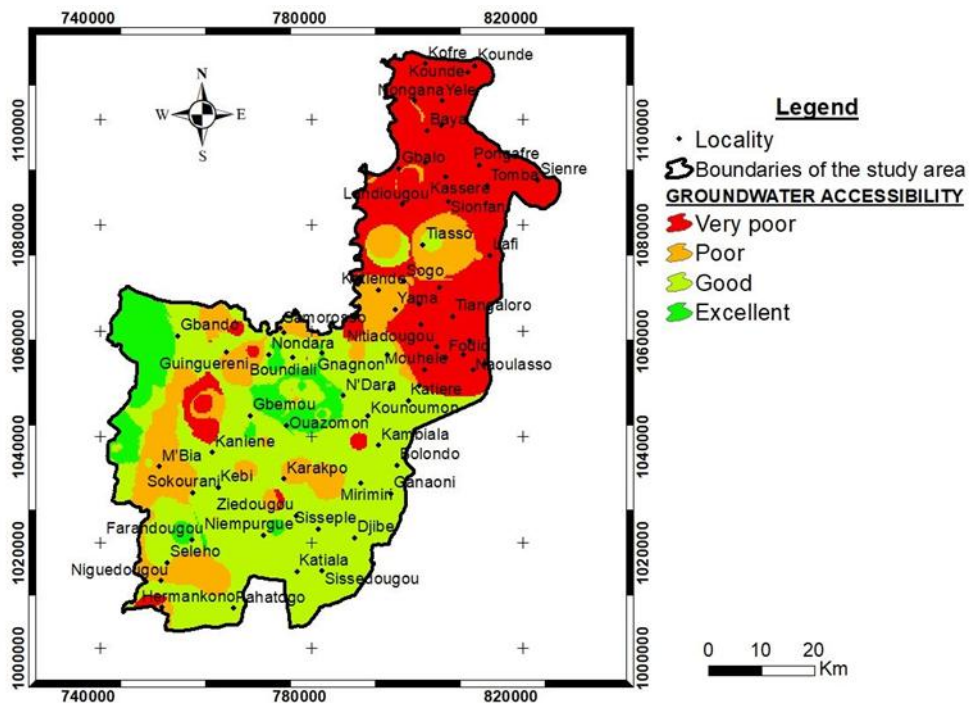


Figure 14: Groundwater resource accessibility map

Groundwater resource potential map

The groundwater potential includes all the above-described indicators, i.e., availability, operability, and accessibility. It can therefore be used to identify areas suitable for drilling boreholes. Analysis of the groundwater potential map in the study area indicates that this department is dominated by the good and excellent potential classes. These classes cover 61% of the study area, compared to 39% for the very poor and poor classes (Figure 15). The excellent potential class (25%) is indeed found almost everywhere in the department, particularly in localities such as Kaniene, Niempurgo, and Sissédougou. The good potential class (36%) has a similar spatial distribution to the excellent class. The towns of Boundiali and Siempurgo, the region's main cities, are included in this class. The poor potential class (8%) is located further southwest in the department. Finally, the very poor class (31%) is found in areas such as Karakpo and Mirimiri.

This groundwater potential map could be used by the region's municipalities as a guide to indicate favourable and unfavourable areas for drilling boreholes. Ultimately, this map will facilitate the successful implementation of high-yield boreholes, thereby improving the local population's access to drinking water.

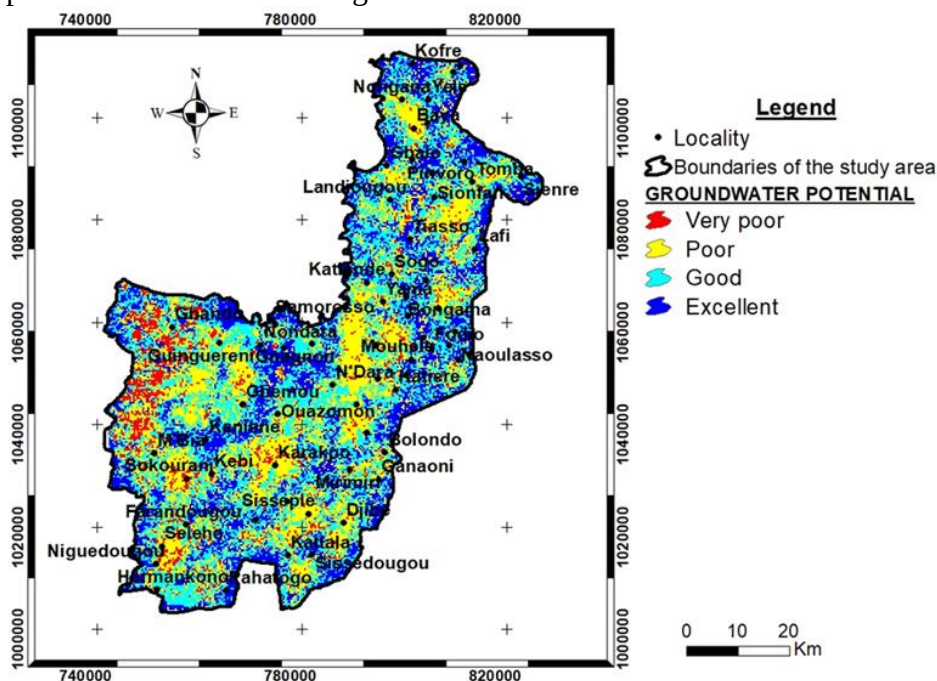


Figure 15: Groundwater resource potential map of the study area

Assessment of uncertainties in the groundwater potential map

All the maps of the groundwater indicators (availability, operability, and accessibility) used to produce the groundwater potential map were first

validated by calculating the uncertainties according to the approach described above. The uncertainties in the groundwater availability, operability, and accessibility maps are ± 0.004 , ± 0.008 and, ± 0.007 , respectively, with 99%, 68%, and 99%, confidence levels, respectively (Table 7). The confidence level obtained for the groundwater operability map is likely related to the data used and their interpolation in the GIS, which did not produce the expected result.

Secondly, the uncertainty of the groundwater potential map was assessed. The calculated uncertainty value is ± 0.53 at a 95% confidence level, which is acceptable.

The low uncertainty values in this study may be due to the reliability of certain data, such as groundwater recharge, borehole yield, and the thickness of weathered rocks, which are difficult parameters to collect. Nevertheless, this assessment of groundwater potential in the study area could provide important preliminary information for future hydrogeological studies aimed at improving the groundwater supply.

Table 7: Statistical values of groundwater indicators and groundwater potential maps

Groundwater indicators	Standard deviations	Averages	Uncertainties	K	Confidence Levels
Availability	0.789	4.943	± 0.004	3	99%
Operability	0.955	1.883	± 0.008	1	68%
Accessibility	1.338	5.247	± 0.007	3	99%
Potentiality	99.424	277.661	± 0.538	2	95%

Discussion

The groundwater potential zones map in the study area was produced using a combination of geographic information systems and multi-criteria analysis based on the AHP method. This approach is well established in hydrogeology due to its cost-effectiveness and efficiency (Gupta et al., 2018; Saranya & Saravanan, 2020; Bera et al., 2020; Yao et al., 2022; Yabre et al., 2023; Zwedie et al., 2024). It provides important preliminary information on the groundwater potential in the study area. However, this approach has some limitations, particularly when it comes to applying multi-criteria analysis using the AHP method. According to Saaty and Vargas (1980), the number of parameters should be limited to seven per level of hierarchy to achieve the best results. This number is rarely adhered to in many studies of groundwater potential in hard rock areas, which are characterized by their complexity. In these areas, the number of parameters used is often close to or greater than ten. Indeed, the number of parameters considered in each study is significant for the region in question (Saranya & Saravanan, 2020; Kaur et al., 2020; Oussou et al., 2019; Yao et al., 2022; Zwedie et al., 2024). This study considers nine parameters. These are the most significant parameters contributing to increased borehole productivity in hard rock areas. The parameters were then grouped into three categories: groundwater availability, operability, and

accessibility. The groundwater availability category comprises five parameters: slope, lineament density, drainage density, weathered thickness, and groundwater recharge. Operability indicators are represented by borehole yield and depth to groundwater (two parameters), while accessibility indicators include total borehole depth and borehole success rate (two parameters). This approach limits the number of parameters at each level of the hierarchy because AHP is applied to groups of parameters representing indicators of groundwater availability, operability, and accessibility rather than to all parameters directly (Doubouya et al., 2012; Yao et al., 2016; Cocker, 2020).

The groundwater potential map, which is based on indicators of availability, operability, and accessibility, shows that the Boundiali department has good to excellent groundwater potential, representing 61% of the study area. These values are comparable to those obtained by Kouassi et al. (2019), Cocker et al. (2020) and Bera et al. (2000), who found good and excellent potential in 59% (Côte d'Ivoire), 66% (Benin) and 49% (India) of their respective territories. However, these values are lower than those calculated by Aluko et al. (2017), Yao et al. (2022), and Yabre et al. (2023), for whom the good and excellent classes represent 36%, 35%, and 34% of the territory, respectively. Additionally, certain hard rock areas may possess significant groundwater potential, with good and excellent classes accounting for 75-80% of the territory (Zwedie et al., 2024; Youan Ta et al., 2024).

The main difficulty in delineating groundwater potential zones is validating the results. This is one of the most important tasks in any scientific analysis (Gupta et al., 2018). Several methods for validating groundwater potential maps are described in the literature. The most popular method is cross-validation using borehole yields (Arulbalaji et al., 2019; Saranya & Saravanan, 2020; Yabre et al., 2023; Zwedie et al., 2024). In this study, borehole yields were used as indicators of groundwater potential. The validation method employed herein is a relatively straightforward statistical approach for evaluating uncertainties in groundwater potential zones (Doubouya et al., 2012; Yao et al., 2016). A detailed study requires an integrated approach combining indirect and direct methods, such as geophysics, borehole yields, continuous groundwater level recording and in situ hydrogeological recording.

Conclusion

The groundwater potential in the study area was assessed using the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS). The results of this study indicate that 60% of the department has good to excellent groundwater availability. Most of these areas are located in the north, centre, and east of the study area. Analysis of the accessibility map

shows that over half of these groundwater resources (53%) are potentially accessible. These are found in the centre-east, south, and west of the department. In terms of exploitable resources, however, the good and excellent classes represent only 30% of the territory. These are mainly located in the centre and east of the department. Combining all these maps has made it possible to delineate groundwater potential zones. Almost 60% of the study area has good or excellent groundwater potential. These zones are ideal for installing high-yield boreholes. These can be found in different parts of the region: the north, centre, east, and south. The groundwater potential map obtained as part of this study provides essential information for selecting borehole locations and can also be used to indicate any hydrogeological prospecting.

Conflict of Interest: The authors reported no conflict of interest.

Data Availability: All data are included in the content of the paper.

Funding Statement: The authors did not obtain any funding for this research.

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