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

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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 study's primary goal is to identify areas with the potential for high-rate borehole installation. 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 indicators of groundwater availability, accessibility and exploitability. These indicators were then used as criteria and integrated using the coding aggregation method to produce the groundwater potential map. The results show that over half (60%) of the territory has good or excellent groundwater availability. The exploitability and accessibility of this resource are estimated to be 30% and 53% good and excellent, respectively. Analysis of the groundwater potential map derived from these indicators shows that 61% of the study area is suitable for installing high-rate 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, Boundiali, Exploitability, Groundwater potentiality

Introduction

Water is an essential resource for human and environmental needs. Thus, ensuring access to water resources and sanitation, and managing these resources, are subjects of international debate, 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 often poses problems, particularly in hard rock areas. The aquifer systems in these areas have very complex structures, the configuration of which is linked to the lithological environment (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 problem for several decades. Over 45% of boreholes in these areas have very low discharge rates. These low discharge rates 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 siting 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, and 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 region. 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 normalised 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 Boundiali department is part of the Bagoue region in the north of Côte d'Ivoire. Located between longitude 6° and 7° west and latitude 9° and 10° north, it covers an area of 4,302 km². Its population is estimated at 198,541. 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 (see Figure 1).

The department of Boundiali 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 Boundiali department 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, is the main river running through the region. In the Kouto department, the river drains a 4,740 km² basin. In the study area, the Bandama River flows from north to south and the Bagoue River flows from south to north. 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.

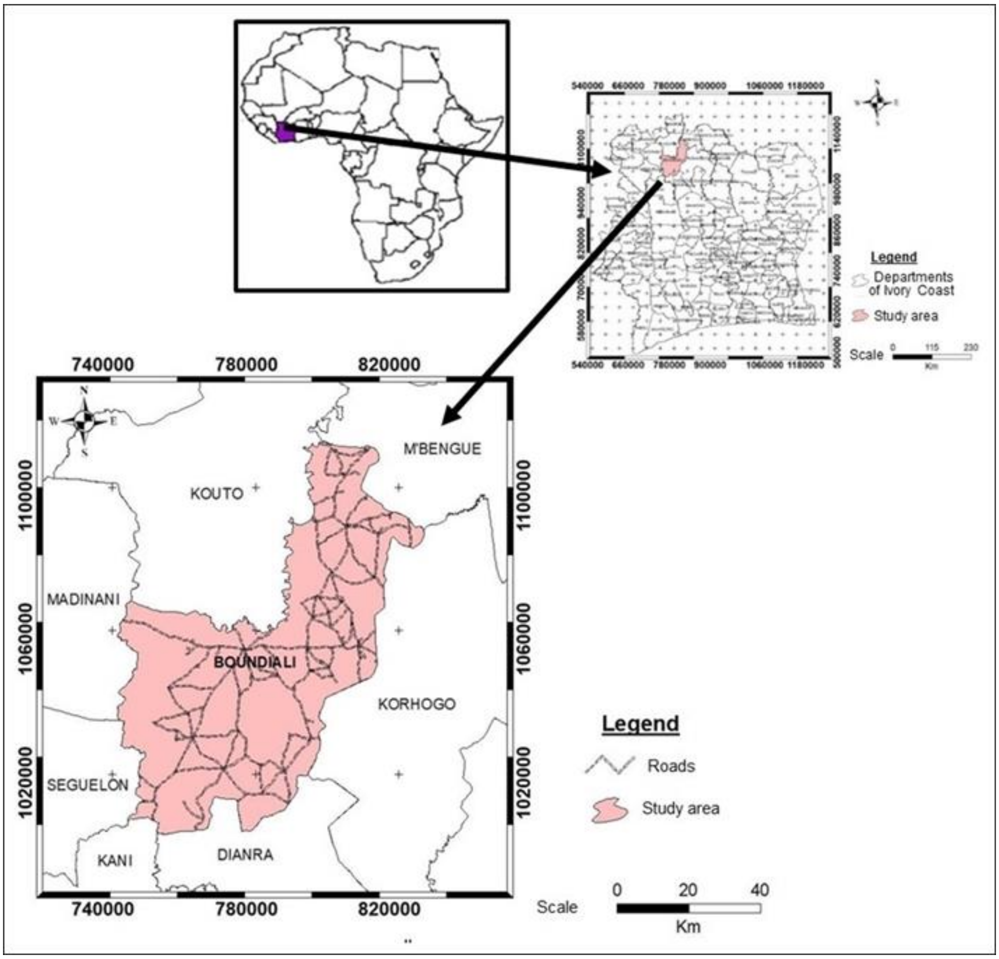

Figure 1: Geographical location of the study area

Data and materials

The data collected for this study includes 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.umiacs.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. These were downloaded from the USGS website at http://srtm.usgs.gov/.
- Borehole data were provided by the Direction Régionale de l'Hydraulique in Boundiali. This data contains information on the depth to the groundwater level, discharge rate, 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 net 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.

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 potential groundwater zones are aquifer characteristics, such as fracturation, weathering thickness and discharge rates, as well as physiographic parameters, such as slope and drainage network. 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, exploitability, and availability (Doumbouya 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, drainage density, lineament density, weathering thickness and potential recharge (Doumbouya et al., 2012; Cocker et al., 2020).
- Slope 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 in ArcMap was used to produce the slope map from SRTM images (Figure 2).
- Drainage density 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-density drainage 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 digitised from SRTM images in ArcMap. This represents the total length of drains per unit area, expressed as (1) m/km² (Figure 3).

$$d = \frac{\sum Li}{A} \tag{1}$$

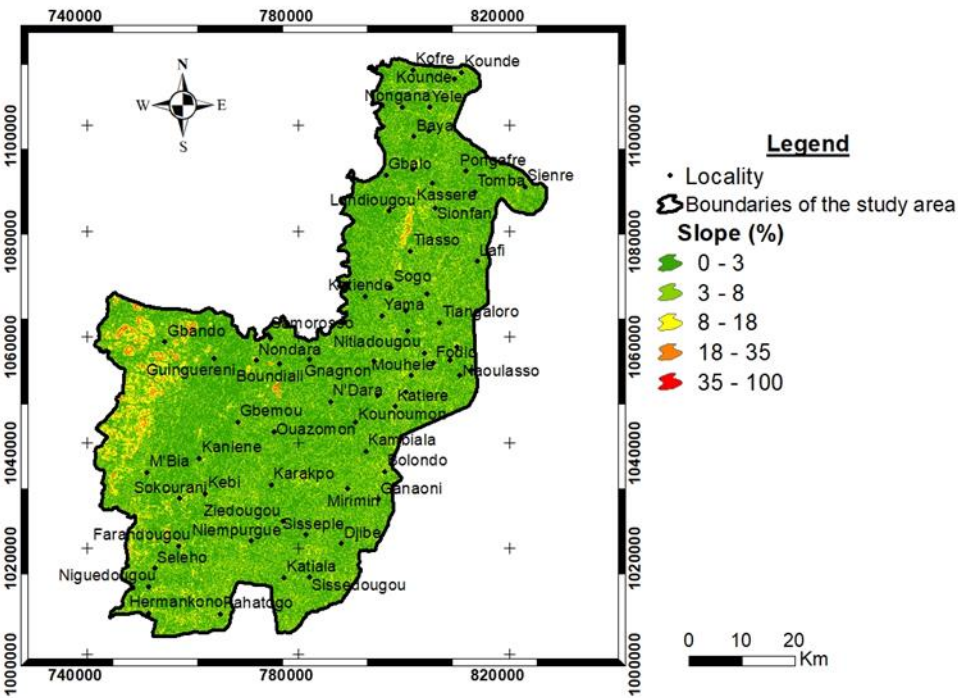

Figure 2: Slope map

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 to studies of groundwater potential in hard rock areas (Pinto et al., 2017). In this study, lineament density was digitised using the "Line Density" tool in ArcMap, in the same way as drainage density (Figure 4).

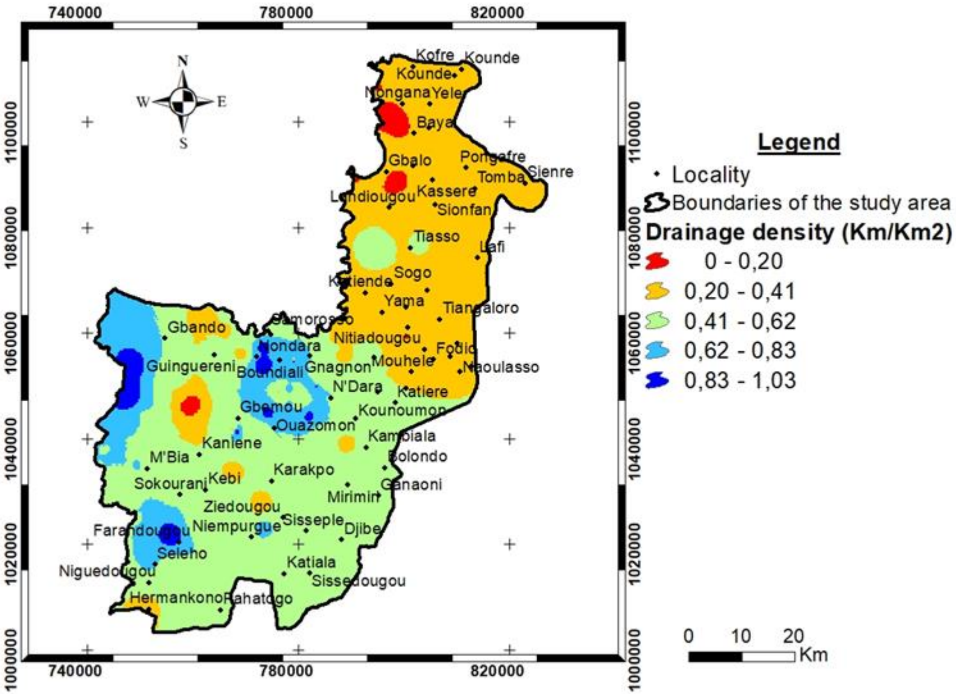

Figure 3: Drainage density map

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 (see Figure 5). The stratiform fractured layer refers to a weathered layer that has fractured. These two weathered units (the saprolitic layer and the stratiform fractured layer) form an integrated aquifer system (Lachassagne et al., 2011; 2014). Several studies confirm that drilling success rates (e.g. 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 from borehole data (Figure 6).

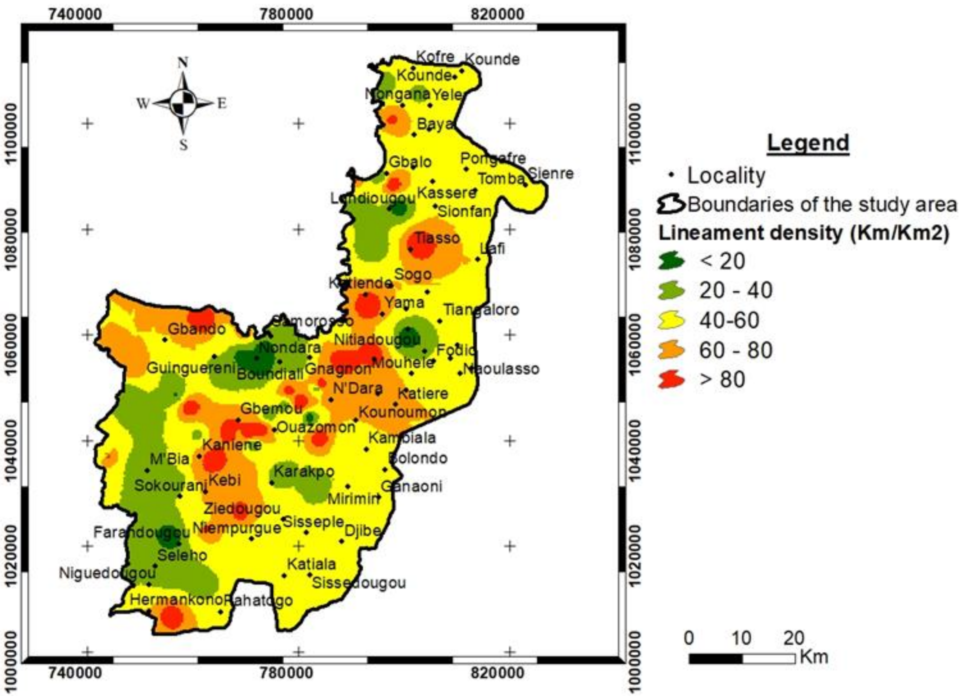

Figure 4: Lineament density map

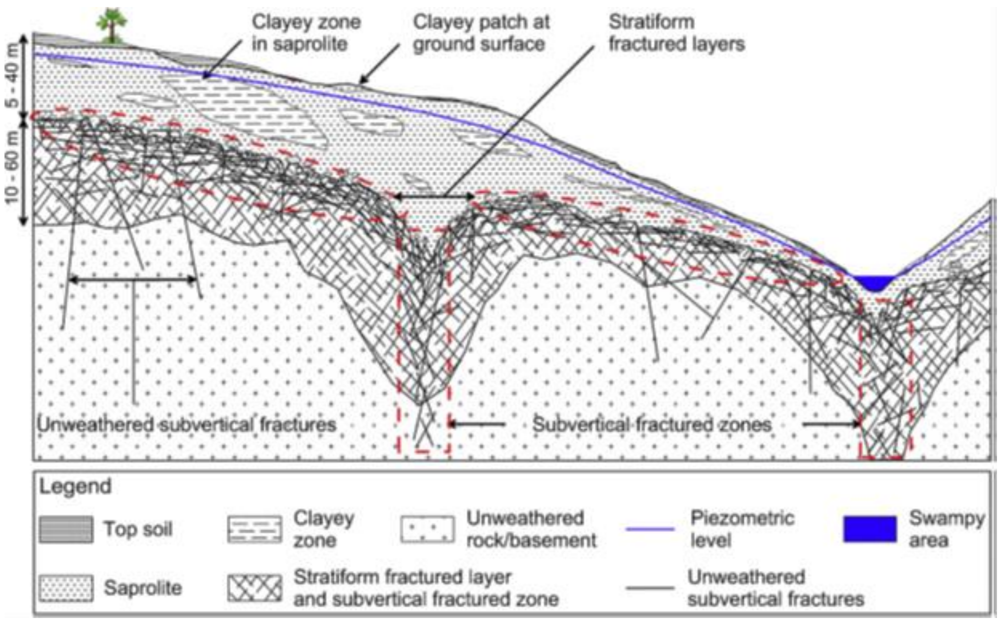

Figure 5: Hydrogeological conceptual model of weathered hard rock (adapted from Dewandel et al., 2011 *in* Alle et al., 2018

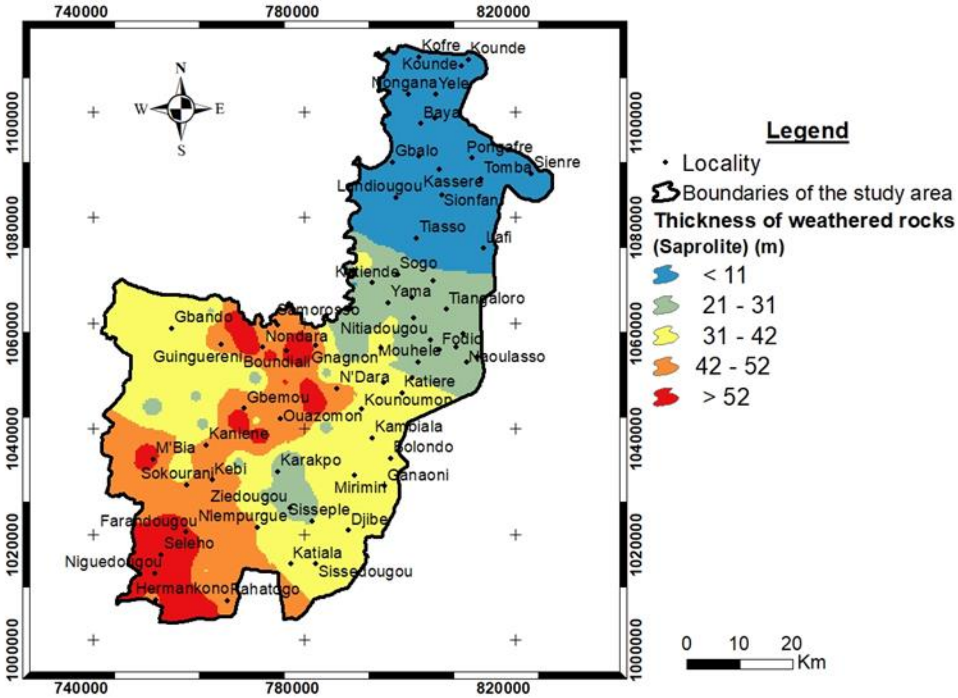

Figure 6: Thickness of weathered rocks

Net 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). In this study, the water balance method was used to produce the net potential recharge map (Figure 7).

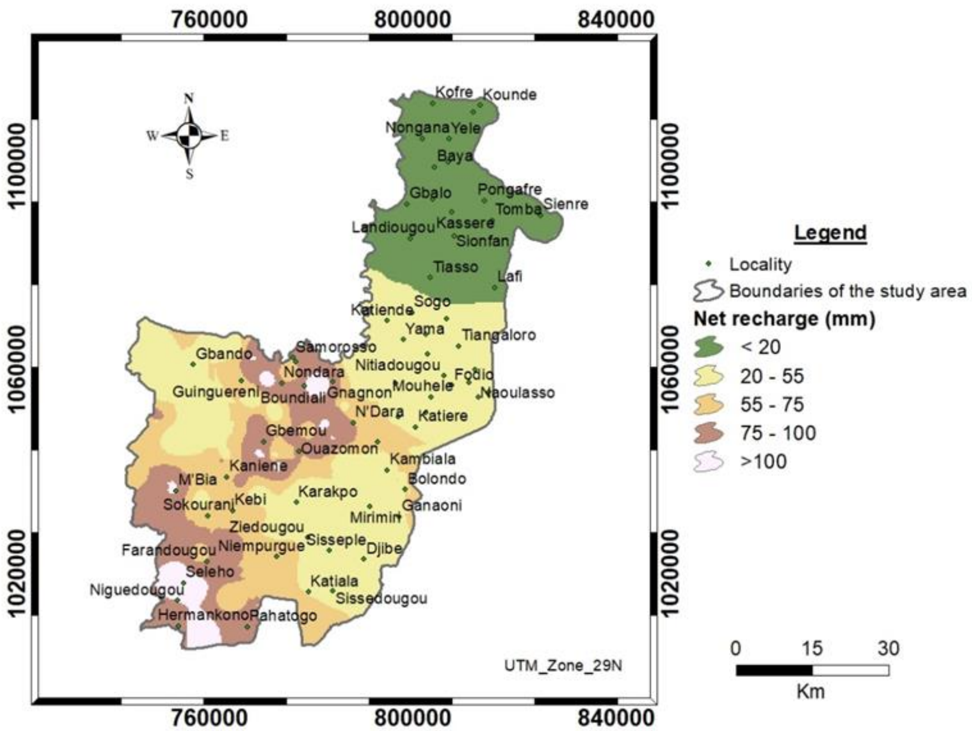

Figure 7: Net potential recharge map

Exploitability indicator

This indicator represents the productivity of boreholes. It is calculated by combining the rate of each borehole and the depth to the groundwater level.

- Discharge rate is an important parameter for a borehole. It depends on the amount of water in the aquifer and how quickly the aquifer can be replenished in times of high demand. This parameter is used to calculate borehole yield in hydrogeological studies. In the study area, a discharge rate map was produced by interpolating the discharge rates of the boreholes using IDW techniques in ArcGIS (Figure 8).
- The depth of the 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. 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 9).

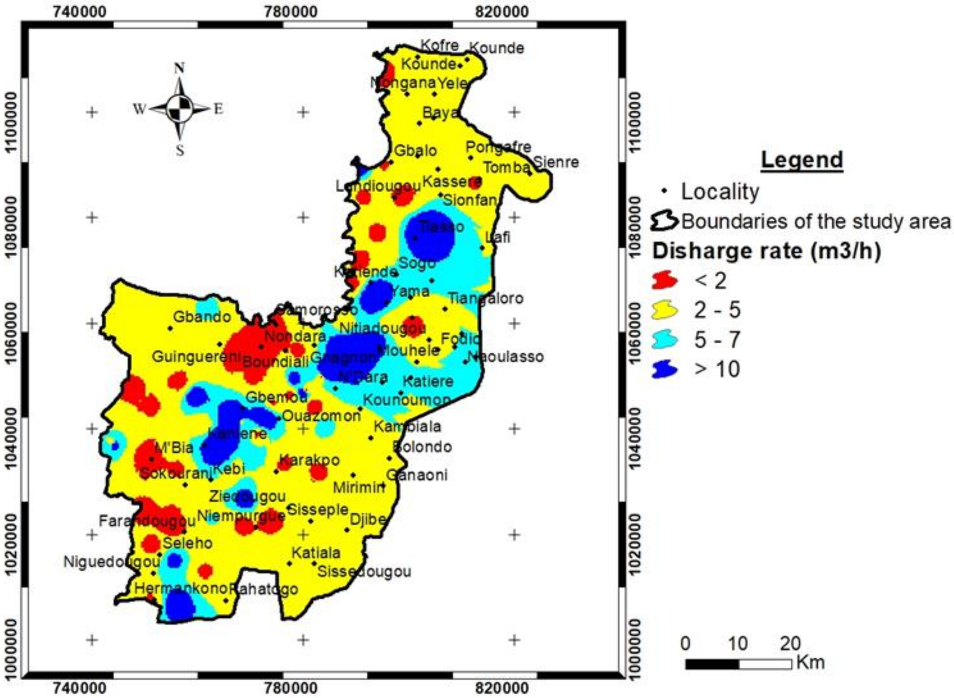

Figure 8: Discharge rate

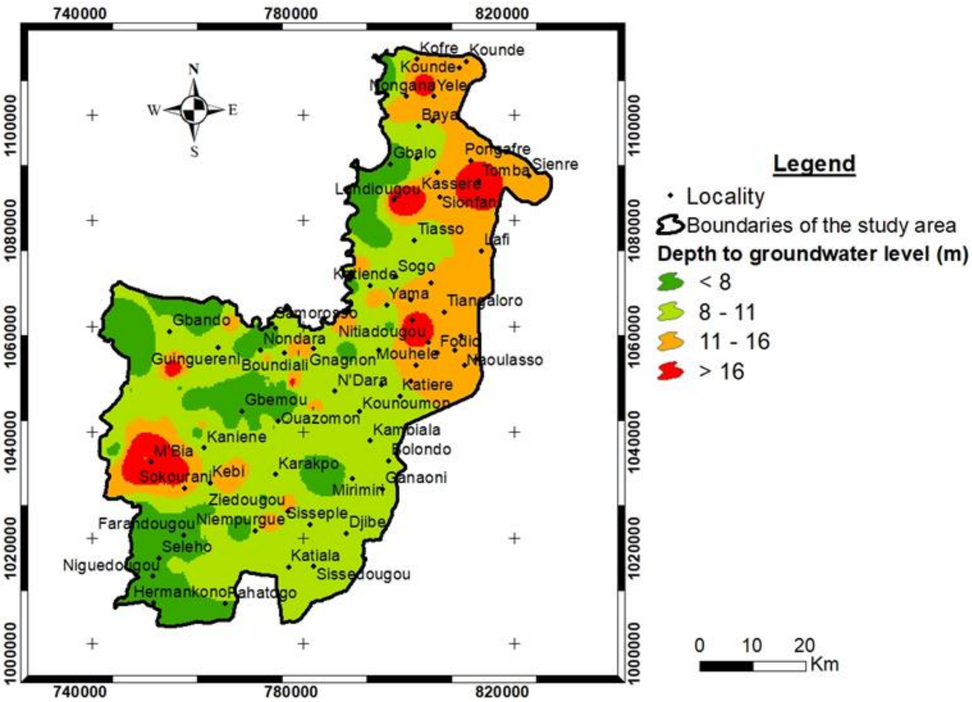

Figure 9: Depth to groundwater level

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 metres. 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. It is calculated using the following formula (Doumbouya et al., 2012):

$$a = \left(\frac{b}{10}\right) \times 100 \tag{2}$$

where a is the success index (%), b is the borehole rate (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 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 standardised 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 is qualified as 'very low' or 'very high', depending on whether it contributes to achieving the indicator excellently. 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 standardisation of the criteria considered in this study.

The AHP aggregation method was used to combine classified and standardised 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
	Net 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
Exploitability of groundwater resource	Discharge rate (m^3/h)	Very low	<2	1
		Low	2 – 3	3
		Medium	3 – 5	5
		High	5 – 7	8
		Very high	> 10	10
	Depth to groundwater level (m)	Very low	< 8.21	10
		Low	8.21-10.53	8
		Medium	10.53-12.75	5
		High	12.75- 16.28	3
		Very High	16.28-27	1
Accessibility of groundwater resource	Total borehole depth (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. The resulting comparison matrix (Table 2) is then used to determine the weight (Wi) of each criterion using eigenvectors (V_p) (3). The weight (Wi) for each criterion is obtained by dividing each eigenvector by the sum of the eigenvectors (4). The sum of the weights of all the criteria in a matrix must equal 1 (see Table 2). Tables 3, 4 and 5 present the eigenvectors (V_p) and weights calculated for the groundwater availability, exploitability and accessibility criteria.

$$Vp = \sqrt[k]{W1 \times \ldots \times Wk} \tag{3}$$

Where Vp is eigenvectors ; k is the number of parameter considered ; Wk is Parameter scores.

$$Wi = \frac{Vp}{Vp1 + \cdots Vpk} \tag{4}$$

Where Wi is Weight, Vp is eigenvector.

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

Availability indicators						**Exploitability indicators**			**Accessibility indicators**		
Criteria	**Slope**	**Ei**	**Dd**	**Ld**	**Wt**	Criteria	**Dr**	**Gl**	Criteria	**Bd**	**Si**
Slope	1	1/3	5	3	5	**Dr**	1	3	**Bd**	1	3
Ei	3	1	7	5	5	**Gl**	1/3	1	**Si**	1/3	1
Dd	1/5	1/7	1	1/3	1						
Ld	1/3	1/5	3	1	5						
Wt	1/5	1/5	1	1/5	1						

Ei= Effective infiltration or potential recharge; Dd= Drainage density; Ld= Lineaments density; Wt= Weathering thickness; Dr= Discharge rate; Gl= Depth to groundwater level; Bd= Borehole depth, Si= success index

Table 3: Eigenvectors and Weight for groundwater availability criteria

Indicators	Criteria	Slope	Ei	Dd	Ld	Wt	Vp	Wi
Availability	**Slope**	1	1/3	5	3	5	$Vp = \sqrt[5]{1 \times 1/3 \times 5 \times 3 \times 5}$ =1.904	0.265
	Ei	3	1	7	5	5	$Vp = \sqrt[5]{3 \times 1 \times 7 \times 5 \times 5}$= 3.5	0.488
	Dd	1/5	1/7	1	1/3	1	$Vp = \sqrt[5]{1/5 \times 1/7 \times 1 \times 1/3 \times 1} = 0.394$	0.055
	Ld	1/3	1/5	3	1	5	$Vp = \sqrt[5]{1/3 \times 1/5 \times 3 \times 1 \times 5}$= 1.00	0.139
	Wt	1/5	1/5	1	1/5	1	$Vp = \sqrt[5]{1/5 \times 1/5 \times 1 \times 1/5 \times 1}$= 0.381	0.053
Sum		4.73	1.87	17	9.53	17	7.18	1

Table 4: Eigenvectors and Weight for groundwater exploitability criteria

Indicator	Criteria	Dr	Gl	Vp	Wi
Exploitability	**Dr**	1	3	$Vp = \sqrt[2]{1 \times 3} = 1.73$	0.75
	Gl	1/3	1	$Vp = \sqrt[2]{1/3 \times 1} = 0.58$	0.25
Sum		1.33	4	2.31	1

Table 5: Eigenvectors and Weight for groundwater accessibility criteria

Indicator	Criteria	d	i	Vp	i
Accessibility	**Bd**			$Vp = \sqrt[2]{1 \times 3}$=1.73	.75
	Si	/3		$Vp = \sqrt[2]{1/3 \times 1 =}\ 0.58$	.25
		.33		2.31	

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:

$$S = \sum_{i=2}^{n} W_i . X_i \tag{5}$$

Where, *S* represents a groundwater indicator, *Wi* is the weight of the criterion, Xi refers to the raster layer of this criterion.

The second step is to combine the groundwater availability, exploitability and accessibility indicator maps using the coding method (Jourda et al., 2006).

Table 6 shows the codes assigned to the different classes determined for each groundwater indicator. Each groundwater indicator is considered as a criterion. Figure 10 summarizes the methodology flowchart.

Table 6: Codes assigned to the groundwater indicators

Indicator	Indicators (or criteria)	Classes	Codes
Groundwater potentiality	Availability	Excellent	400
		Good	300
		Poor	200
		Very poor	100
	Exploitability	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 rates (Arulbalaji et al., 2019; Saranya & Saravanan, 2020; Yabre et al., 2023; Zwedie et al., 2024). In this study, borehole rates 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 potentiality indicators (Doumbouya et al., 2012; Kouassi et al., 2019; Cocker et al., 2020). The calculation is given by (6) :

$$\Delta\bar{X} = \frac{\sigma}{\sqrt{m}} \qquad (6)$$

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

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 level of confidence in the results. The expression of this factor is defined by (7) :

$$K = \frac{|E - \bar{X}|}{\sigma} \qquad (7)$$

Where, K is the expansion factor and E is the extreme value of the data, which can be the maximum or the minimum. 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%.

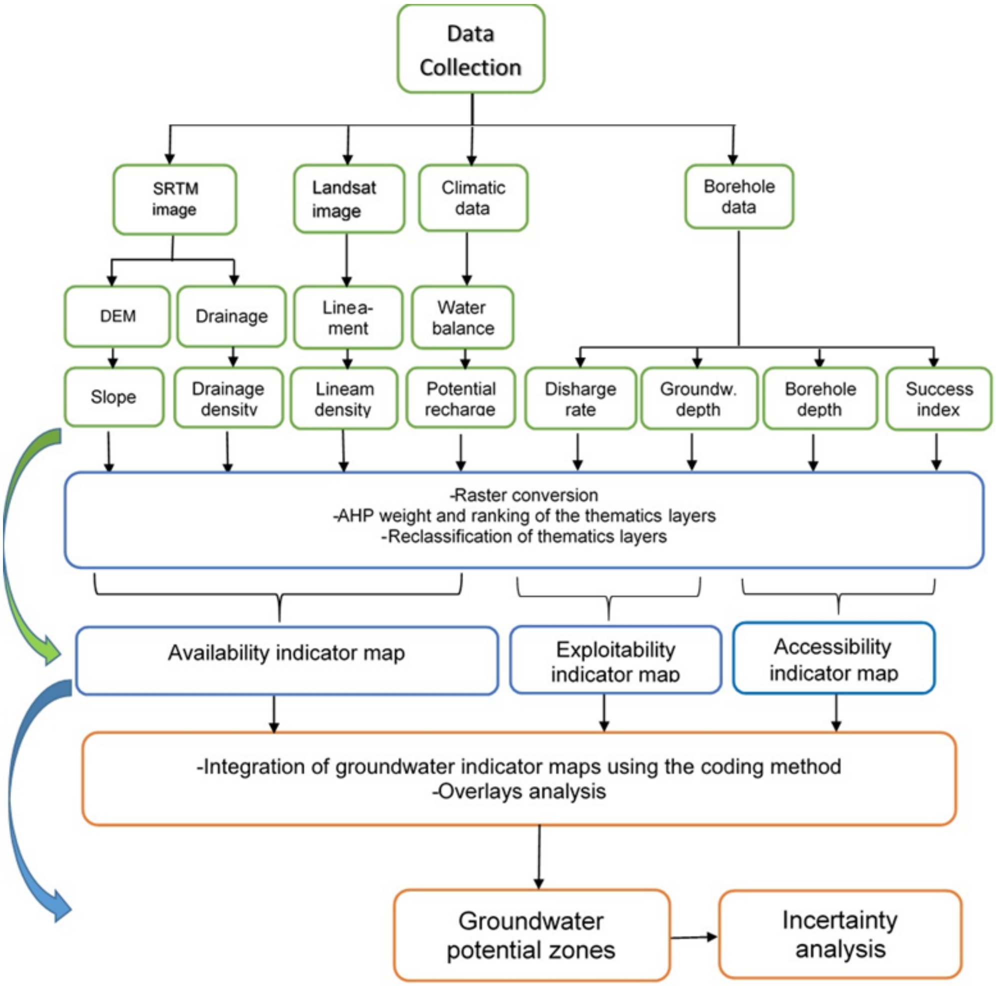

Figure 10: Flowchart of the methodology

Results

Groundwater resource availability map

The groundwater availability map is the most important indicator when selecting areas suitable for drilling boreholes (see Figure 8). The production of this map took into account all potential factors that could indicate the presence of groundwater. Analysis of the map shows that groundwater resources are available in satisfactory quantities in the study area. The good and excellent availability classes occupy 60% of the study area, compared to 40% for the very poor and poor availability classes (see Figure 11).

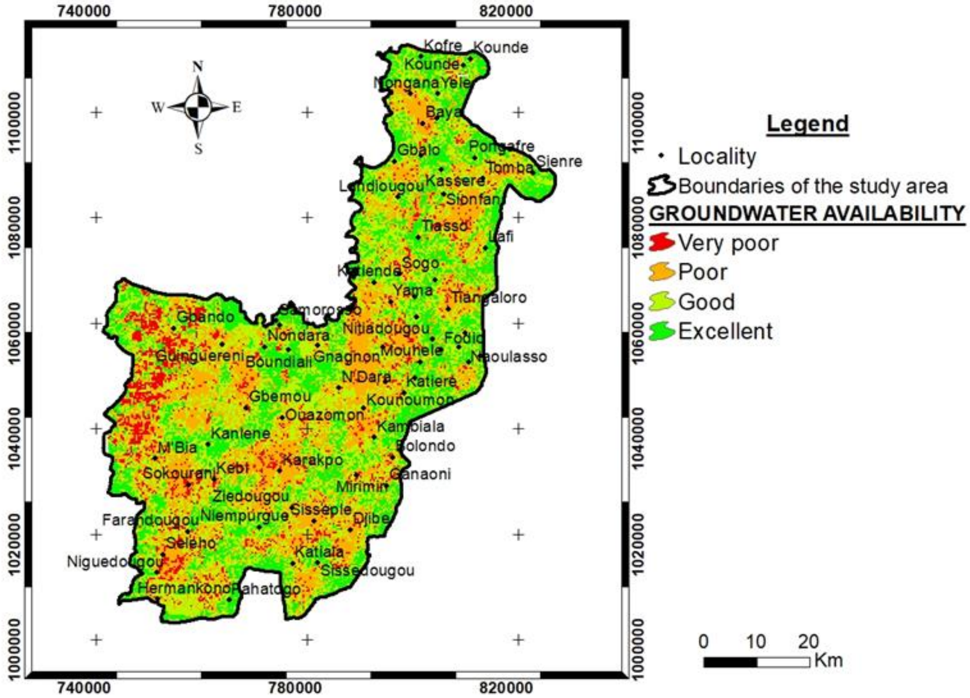

Figure 11: Groundwater resource availability map

Groundwater resource exploitability map

Figure 12 depicts the groundwater exploitability map, marked by very poor and poor exploitability classes covering 70% of the study area. The good exploitability class covers only 18% of the department. Lastly, the excellent exploitability class is found in small plots scattered from the north to the center of the department.

Groundwater resource accessibility map

Overall, groundwater accessibility is good, with the excellent and good accessibility classes covering 53% of the department compared to 47% for the poor and very poor classes (see Figure 13). The areas with the best access to groundwater are generally located in the south-west of the department. The northern part of the department is dominated by the 'very low' accessibility class (29%). Finally, the poor accessibility class (18%) is concentrated in the north and south of the department.

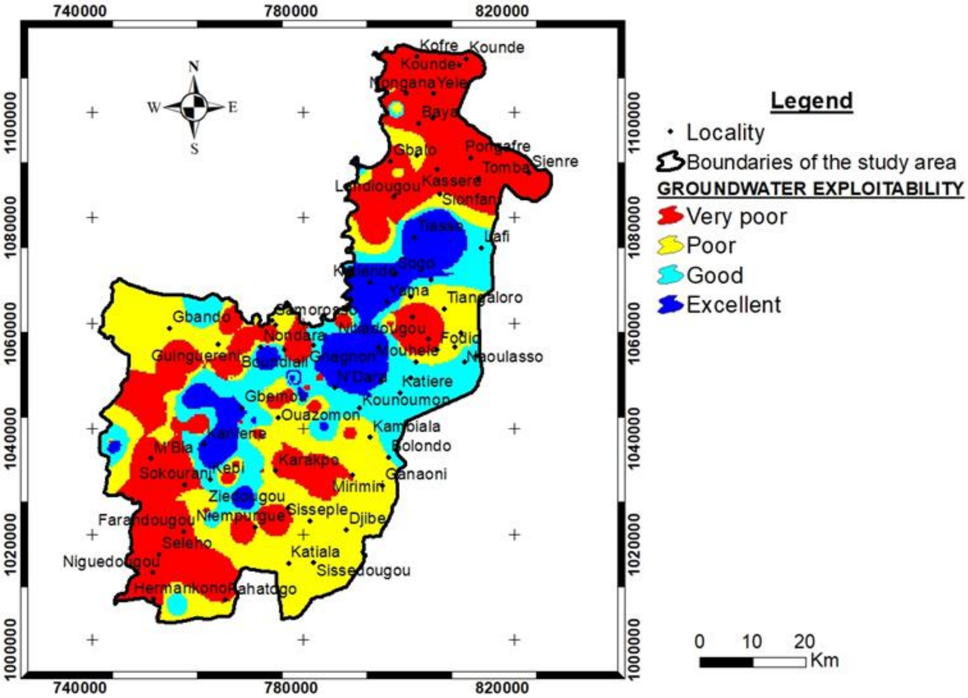

Figure 12: Groundwater resource exploitability map

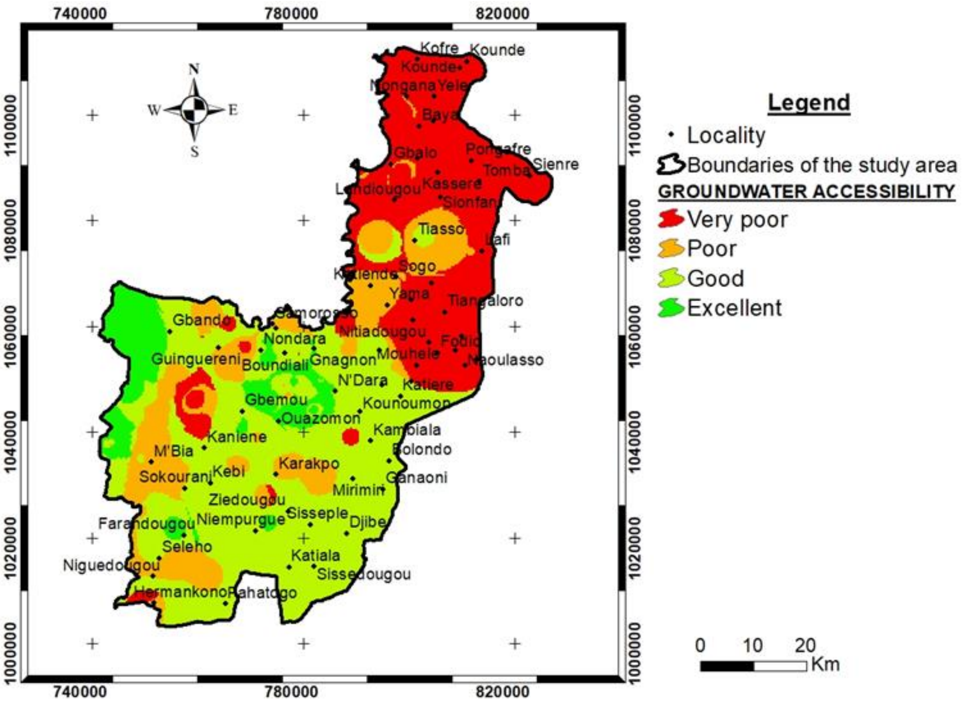

Figure 13: Groundwater resource accessibility map

Groundwater resource potentiality map

The groundwater potential includes all the above-described indicators, i.e. availability, exploitability and accessibility. It can therefore be used to identify areas suitable for drilling boreholes. Analysis of the groundwater potential map for the Boundiali department indicates that the area 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 (see Figure 14). The excellent potential class (25%) is indeed found almost everywhere in the department, particularly in localities such as Kaniene, Niempurgo and Sissedougou. 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-discharge-rate boreholes, thereby improving the local population's access to drinking water.

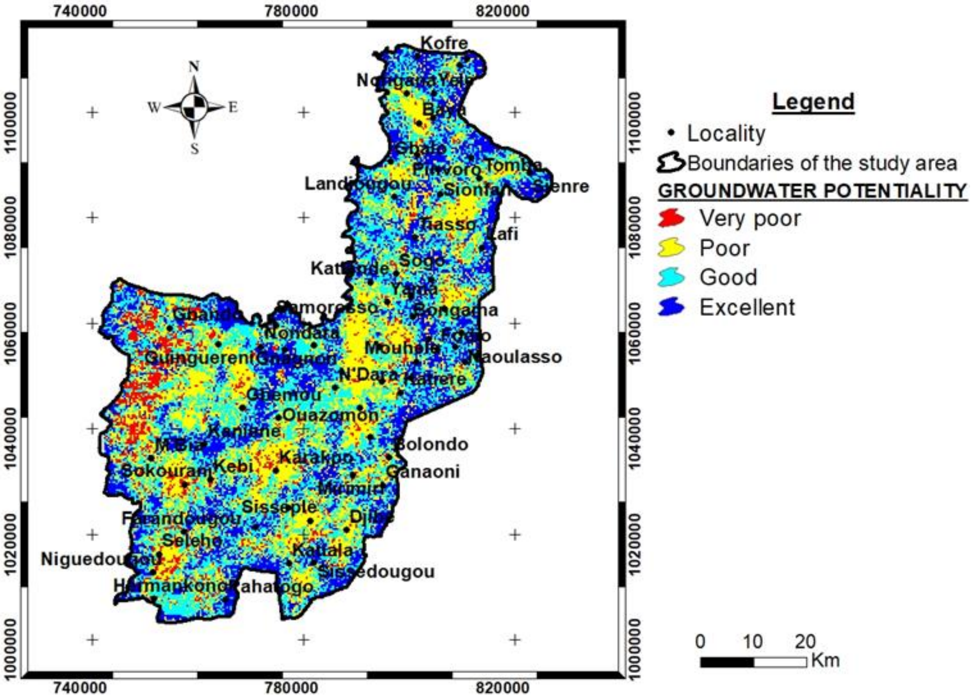

Figure 14: Groundwater resource potentiality map of the study area

Assessment of uncertainties in the groundwater potential map

All the maps of the groundwater indicators (availability, exploitability 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 availability, exploitability and accessibility of groundwater are ±0.004, ±0.008 and ±0.007, respectively, with respective confidence rates of 99%, 68% and 99% (see Table 7). Secondly, the uncertainty of the groundwater resource potential map was assessed. The calculated uncertainty value is ±0.53 at a 95% confidence level.

The low uncertainty values in this study may be due to the reliability of certain data, such as net recharge, discharge rates 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 potentiality assessment parameters

Groundwater indicators	Standard deviations	Averages	Uncertainties	K	Confidence levels
Availability	0.789	4.943	±0.004	3	99%
Exploitability	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 map of potential groundwater zones in the Boundiali department 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 region's groundwater potential. 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 characterised 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, exploitability, and accessibility. The groundwater availability category comprises five parameters: slope, lineament density, drainage density, weathered thickness and potential recharge. Exploitability indicators are represented by borehole rate 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, exploitability and accessibility rather than to all parameters directly (Doumbouya et al., 2012; Yao et al., 2016; Cocker, 2020).

The groundwater potential map, which is based on indicators of availability, exploitability and accessibility, shows that the Boundiali department has good to excellent groundwater potential, representing 61% of the total surface 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 rates (Arulbalaji et al., 2019; Saranya & Saravanan, 2020; Yabre et al., 2023; Zwedie et al., 2024). In this study, borehole rates 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 (Doumbouya et al., 2012; Yao et al., 2016). A detailed study requires an integrated approach combining indirect and direct methods, such as geophysics, discharge rates, continuous groundwater level recording and in situ hydrogeological recording.

Conclusion

The groundwater potential in Boundiali 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 department. 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 potential groundwater zones. Almost 60% of the department has good or excellent groundwater potential. These zones are ideal for installing high-capacity 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.

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