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Mapping of Groundwater Potential by Multicriteria Analysis: Case of the Departments of Yamoussoukro and Toumodi (Central Cote d'Ivoire)

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Abstract

This study focuses on the problem of access to drinking water in the fractured areas of the departments of Yamoussoukro and Toumodi. The problem has become more acute since most of the boreholes drilled have failed. The main objective of this study is to map the areas that are favorable for the installation of large boreholes in the departments of Yamoussoukro and Toumodi in order to increase the population's drinking water needs. Hydroclimatic and cartographic data, technical surveys of boreholes and satellite images were used to conduct this study. The AHP multi-criteria analysis method was adopted. It consists in aggregating the criteria by weighting and allowed to combine these different data to generate maps of groundwater availability, accessibility and exploitability indicators. These different indicators were then considered as criteria and combined using the full aggregation technique to produce the water potential map. These results show that the study area has significant groundwater reserves with nearly 63% of these areas being favorable for the establishment of large flow boreholes. This study provides some answers to the question of groundwater resources and could be used as a decision support tool in the execution of groundwater collection works in the departments of Yamoussoukro and Toumodi in order to avoid the high percentage of drilling failures encountered in past projects.

Keywords

Drilling, Fissured Aquifer, Groundwater, GIS, Cote d'Ivoire

1. Introduction

Groundwater is an important natural resource for domestic, agricultural and industrial use [1]. Indeed, having water in quantity and quality at hand is, along with food, one of the most urgent human needs on earth [2]. In 2010, the human right to safe drinking water and sanitation was explicitly recognized by the United Nations General Assembly [3]. Throughout the world, the issue of access to safe drinking water remains a concern for authorities. Indeed, 30% of the world's population lacks access to domestic drinking water services [4]. In developing countries, accessibility to drinking water is one of the major objectives of development projects. In Côte d'Ivoire, many efforts have been made since 1973 to provide urban, peri-urban and rural centers with quality water. Unfortunately, difficulties remain because drinking water is not yet accessible to all [5]. Indeed, the problem of supplying drinking water to populations is quite recurrent and clearly perceptible in several regions [6]. Thus, accessibility to safe drinking water is one of the major goals of development projects around the world. In developing countries, groundwater is a resource of the first choice for drinking water supply for populations because it has a relatively good quality and low cost [7]. On the other hand, surface water has a questionable physicochemical and bacteriological quality and requires often very expensive treatments. For this reason, the supply of drinking water is oriented towards the search for deep groundwater whose quality generally meets the WHO guidelines [8]. However, access to this precious resource is becoming very difficult precisely in the basement regions where the captured groundwater comes from fissures [9]. In these departments, the drinking water supply of rural populations is mainly provided by groundwater contained in the crystalline and crystallophyll aquifers. Moreover, 65% of the boreholes drilled in this region have failed [10]. This high percentage of failure is alarming and raises a lot of interest, especially scientifically, questioning the level of knowledge on the functioning of fractured aquifers. Moreover, with the increasing demand for water in the political capital (Yamoussoukro), the rate of satisfaction of the drinking water needs of this region could be significantly impacted. It is therefore necessary to have a better knowledge of groundwater reserves in order to orient hydrogeological prospecting campaigns [11]. Consequently, the mapping of favorable areas for the implementation of large flow boreholes in this region appears necessary to reduce this failure rate and contribute to the strengthening of the production capacity of drinking water. It is in this context that the present study was initiated. Its objective is to improve the knowledge necessary for the implementation of large boreholes in this central part of Cote d'Ivoire.

2. Material and Methods

2.1. Study Area

The departments of Yamoussoukro and Toumodi are located in central Côte d'Ivoire. They are located between longitudes 4˚40' and 5˚33' West and between latitudes 6˚15' and 7˚6' North and cover an area of 4789.4 km² (**Figure 1**).

The climate of the basin is of the transitional equatorial type, characterized by a rainy season from March to October and a dry season from November to February, with little temperature variation. These regions benefit from a hydrographic network essentially composed of the Marahoué and N'zi rivers. The relief of the departments of Yamoussoukro and Toumodi is, on the whole, a type of relief of plains and plateaus. Several levels of stepped plateaus can be distinguished, between 200 and 500 meters, separated from each other by a low slope (10 to 30 meters) [12]. The vegetation of the departments of Yamoussoukro and Toumodi belongs to the Guinean domain and is dominated by pre-forest savannah dotted more or less densely with small trees and interspersed with groves and forest islands. Forest galleries occupy the lowlands along the watercourses. On drained sandy soils, stands of roast and palm trees appear in tall grass meadows [12] [13]. Geologically, the study area belongs to the Precambrian basement granite-gneiss peneplain. The main geological formations consist of magmatic rocks and metamorphic rocks [14] [15] [16] (**Figure 2**). Metamorphic rocks are of sedimentary (sandstone, con-glomerates), volcanic (lava, acidic or basic, predominant) and volcano-sedimentary (boulders, tuff, breccia) origin. The magmatic rocks are constituted by recent granitoids, granites and migmatites. These geological formations are covered by essentially ferralitic and brown soils

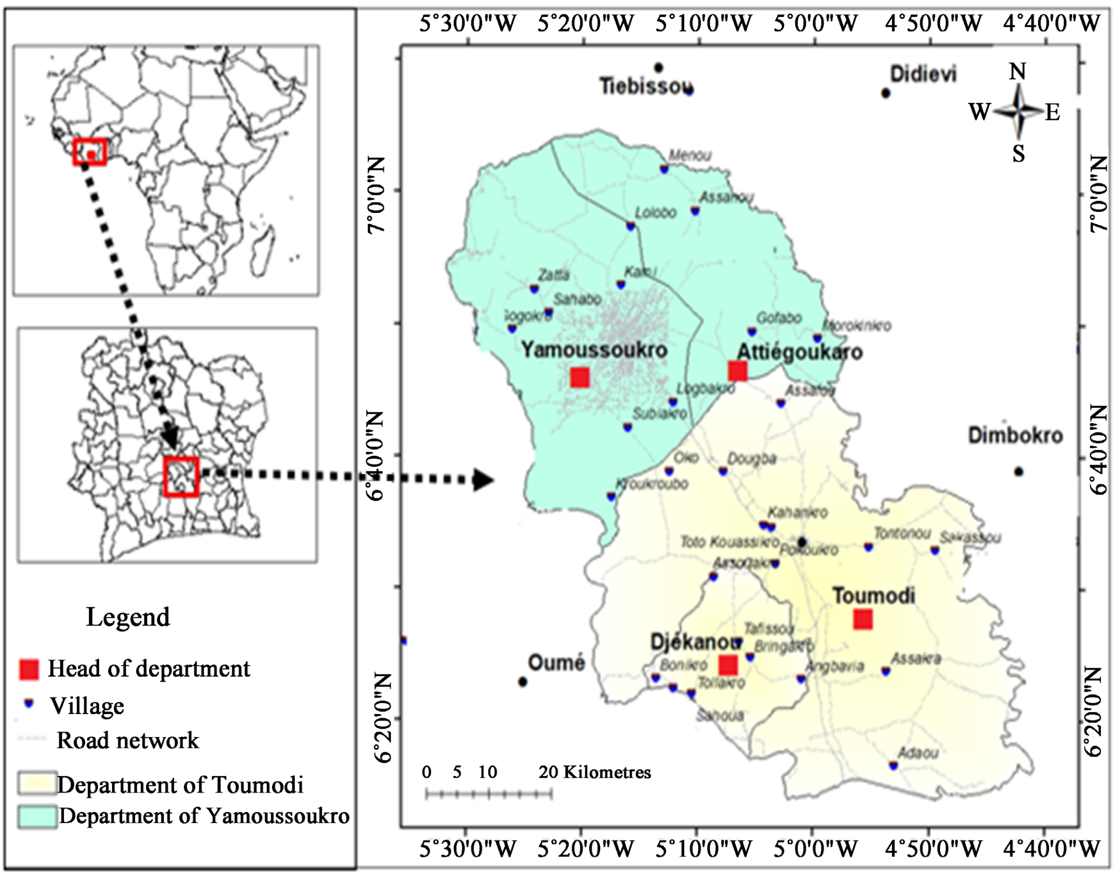


Figure 1. Location of the study area.

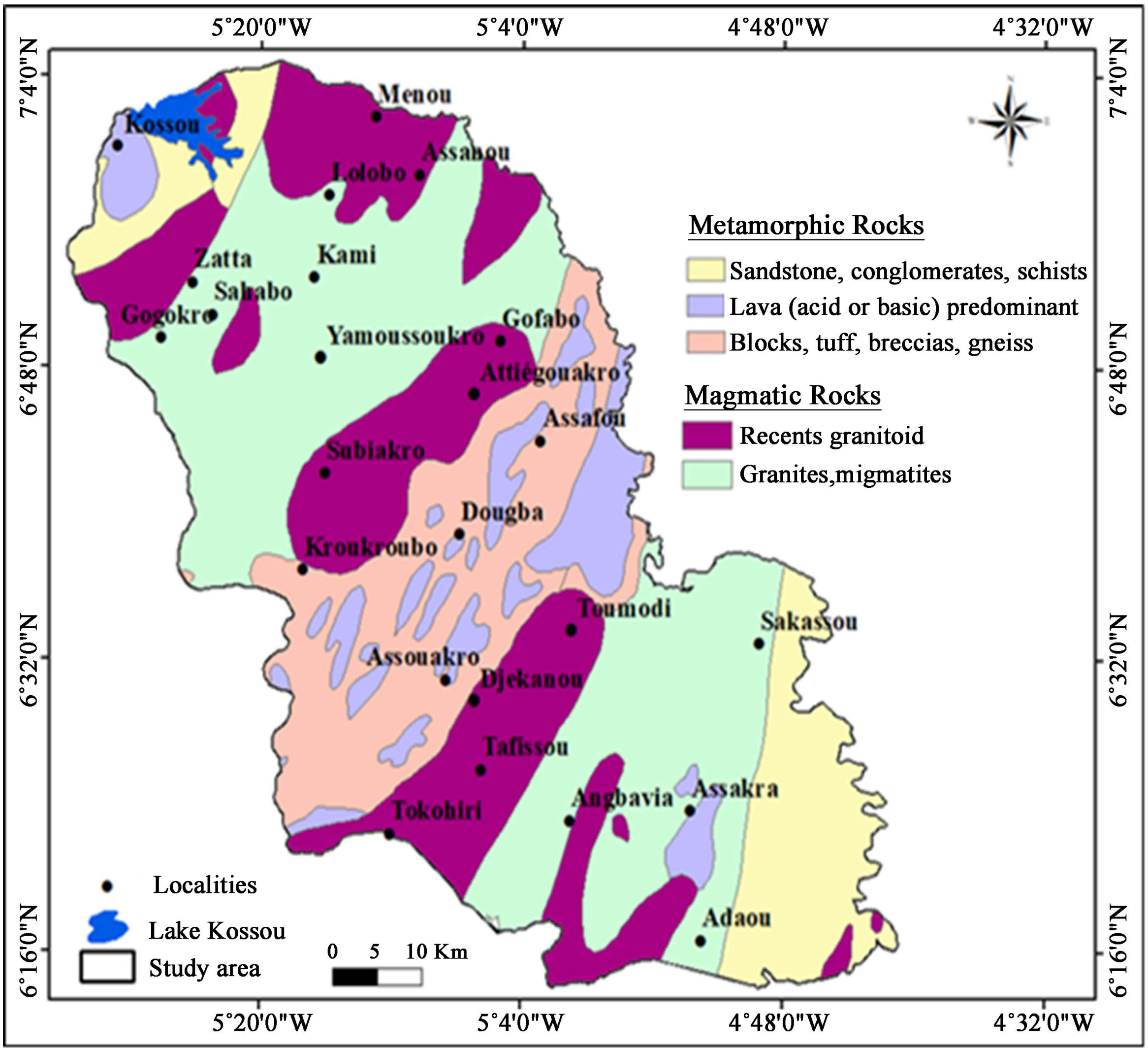


Figure 2. Geological map of the study area.

(ferrisols). Hydrogeologically, the study area has water reserves developing in aquifers, the extent of which depends on the level of weathering and fracturing of the bedrock [7]. Thus, there are two types of aquifers: weathering aquifers (superficial) and fractured aquifers (deeper). These are composite aquifers operating interdependently of each other.

2.2. Materials

In the framework of this work, several types of data were used. These are technical data from 100 boreholes collected at the Regional Directorate of Hydraulics of Yamoussoukro, geological and topographical maps of the square degrees of Yamoussoukro and Toumodi at a scale of 1:200,000 produced by the Directorate of Geology and by the Centre for Cartography and Remote Sensing of Côte d'Ivoire (CCT). Climatic data (rainfall and temperature for the period 1974-2019) were used to estimate infiltration. The satellite images used are Landsat 8 Oli images for the mapping of the lineament network. This is the 197-55 scene acquired on

12/02/2019 with 30 m resolution and available from http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp.

The SRTM terrain elevation model images with 30 m resolution were used for mapping the slope gradient, the hydrographic network and to determine the drainage density. They are available at https://earthexplorer.usgs.gov.

The processing of these data required the use of Envi 4.7 software for the satellite images, Linwin 2.1 for the statistical analysis of the fractures and ArcGIS 10.4.1 for the processing of the fracture network and for the realization of thematic maps.

2.3. Methods

Thematic mapping of groundwater potential areas requires the design and implementation of a hydrogeological database of the study area. The approach followed for the development of the groundwater potential map is inspired by [7] [11] [17] [18] and is based on 1) Identification of criteria; 2) classification, standardization and weighting of criteria for the development of indicators; 3) aggregations following the multi-criteria approach (**Figure 3**).

2.3.1. Identification of Criteria Approach

The hierarchical structure used in this study has three levels. Level 1 is represented by the development of the groundwater potential map. Level 2 refers to the design of three indicators that were used to develop the groundwater potential map. These are groundwater with reference to the work of [7] [17]-[24], a number of criteria are identified, selected, and evaluated to achieve the stated objective. The parameters or criteria used for the delineation of potential groundwater areas are composed of aquifer characteristics, borehole characteristics, physiographic and hydro-climatological data. The groundwater resource in a hydrogeological survey must be available, accessible and exploitable. The parameters related to groundwater potentiality are therefore grouped into three quantitative indicators which are: availability, accessibility and exploitability [9].

Indicator of availability. The availability indicator translates the notion of the existence of an aquifer and constitutes the first condition to know, before any other activity. It results from the combination of parameters such as slope, drainage density, fracture density, alterite thickness and infiltration.

Infiltration is the most important parameter for groundwater availability. In this study infiltration (*Inf*) is calculated according to Equation (1) [7]:

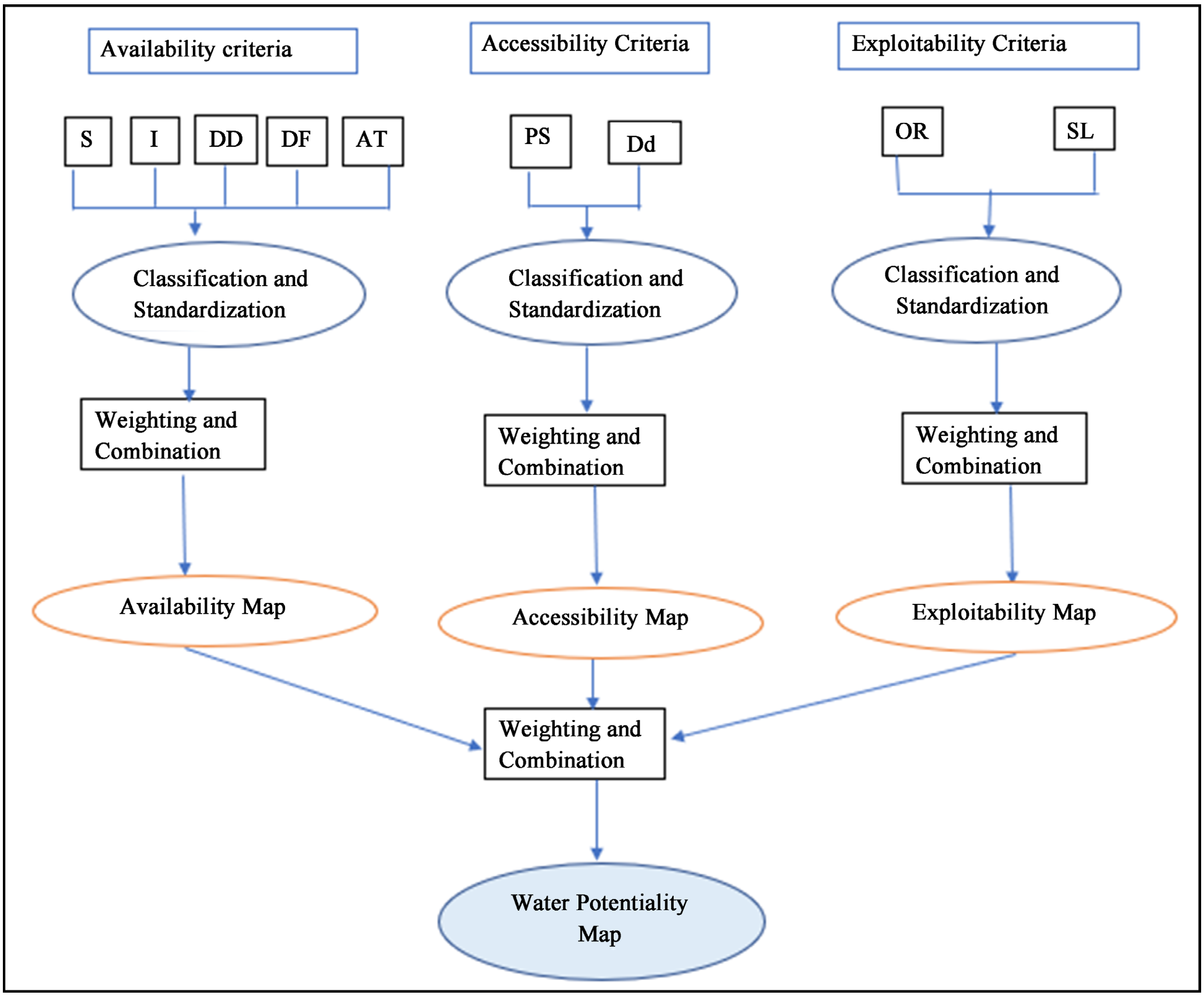
$$Inf = P - (ETR + Lr) \tag{1}$$

where

Inf is infiltration (mm); *P* is precipitation (mm);

ETR is actual evapotranspiration estimated from [25] water balance flow chart; and *Lr* is runoff from the basin (mm).

Indicator of accessibility. Groundwater reserves are only truly usable when certain parameters are combined to make access possible. The most important of



S: Slope; I: Infiltration; DD: Drainage Density; DF: Density of Fracture; AT: Alteration Thickness; PS: Probability of Succes; Dd: Drilling depth; OF: Operating Flow rate; SL: Static Level.

Figure 3. Synthesis of the methodology conceived in this study.

these are the total depth (Pt) of the works and the success index (Is). The success index gives the probability of success of a well and is calculated by the following formula (Equation (2)):

$$a = b/10 \times 100 \quad (2)$$

where a is the success index (%); and b is the operating rate ($m^3 \cdot h^{-1}$).

Indicator of exploitability. The water resource is exploitable only if the exploitation rate is significant (at least 1 $m^3 \cdot h^{-1}$). The exploitation rate itself is conditioned by the quantity of water in the groundwater reserve and the speed of renewal of this reserve in case of high demand [18]. This indicator is produced through the combination of the operating rate and piezometric level criteria.

2.3.2. Classification and Standardization of Criteria

The number of classes was reduced to 5 as defined by [17] [18] [26] [27], for better interpolation. These are the very low, low, medium, high and very high classes. In addition, the different classes of each criterion are standardized according to their influence on the theme. A rating scale ranging from 1 to 10 was used. A rating of 10 is assigned to the class of the criterion qualified as "very weak" or "very strong" depending on whether it contributes to the excellent achievement of the indicator considered. Following the same logic, intermediate values are assigned to the intermediate classes according to a linear distribution. Table 1 and Table 2 illustrate the classification, evaluation and standardization of decision criteria.

2.3.3. Criteria Weighting

The decision criteria are weighted using the linear combination method based

Table 1. Classification and standardization of availability criteria [7] [18].

Indicator	Criteria	Criteria Qualifiers	Classes	Notes
Groundwater availability	Slope (%)	Very low	0 - 1	9
		Low	1 - 2	7
		Medium	2 - 3	5
		High	3 - 4	3
		Very strong	>4	1
	Infiltration (mm)	Very low	<25	1
		Low	25 - 40	3
		Medium	40 - 70	5
		High	70 - 100	7
		Very strong	>100	9
	Drainage density (km/km^2)	Very low	<5	9
		Low	5 - 10	7
		Medium	10 - 15	5
		High	15 - 20	3
		Very strong	>20	1
	Fracture density (km/km^2)	Very low	<5	1
		Low	5 - 10	3
		Medium	10 - 15	5
		High	15 - 20	7
		Very strong	>20	9
	Alteration thickness (m)	Very low	<10	1
		Low	10 - 20	3
		Medium	20 - 30	5
		High	30 - 40	7
		Very strong	>40	9

Table 2. Classification and standardization of accessibility and exploitability criteria [7] [18].

Indicator	Criteria	Criteria Qualifiers	Classes	Notes
Groundwater exploitability	Static level (m)	Very low	<5	10
		Low	5 - 15	8
		Medium	15 - 25	6
		High	25 - 40	3
		Very strong	>40	1
	Operating flow rate (m^3/h)	Very low	<1	1
		Low	1 - 3	3
		Medium	3 - 5	5
		High	5 - 8	8
		Very strong	>8	9
Groundwater Accessibility	Probability of success (%)	Very low	<20	1
		Low	20 - 40	3
		Medium	40 - 60	5
		High	60 - 80	8
		Very strong	>80	10
	Drilling depth (m)	Very low	<25	9
		Low	25 - 52	8
		Medium	52 - 70	7
		High	70 - 85	5
		Very strong	>85	1

on the pairwise comparison technique according to the Hierarchical Analysis Process (HAP) of [28] used by [18] [29]. It produces standardized weights that sum to 1 (**Table 3**).

The weight reflects the relative importance of each criterion in the formation of the indicator.

Based on the matrix generated by the pairwise comparison on the scale proposed by [30], the eigenvector and the weighting coefficient of each criterion are then calculated according to Equations (3) and (4):

$$Vp_j = \sqrt[n]{\prod_{i=1}^{n} g_i} \quad (3)$$

with: Vp_j the eigenvector; n the number of criteria and g_i the score of criterion i obtained in the pairwise comparison matrix.

The weighting coefficient (Cp) of each criterion is obtained by the ratio of its eigenvector and the sum of all the eigenvectors of the other criteria involved in the achievement of a given indicator, from the following Equation (4):

$$Cp_j = \frac{Vp_j}{\sum_{i=1}^{n} Vp_j} \quad (4)$$

with: Cp_j is the weighting coefficient of criterion *i*; and Vp_j is the eigenvector of criterion *i*.

For this study, the pairwise comparison matrices and criteria weights for each indicator and for the three indicators are presented in Table 4.

2.3.4. Aggregation of Factors

The classified and standardized criteria were combined by the full weighting

Table 3. Verbal and numerical expression of the relative importance of a pair of criteria [19].

Expression of one criterion in relation to another	Note
Same importance	1
Moderately important	3
Highly important	5
Very important	7
Extremely important	9
Moderately less important	1/3
Less important	1/5
Strongly less important	1/7
Extremely less important	1/9

Table 4. (a) Indicator availability; (b) Accessibility indicator; (c) Exploitability indicator.

(a)

	Pente	Infiltration	DD	DF	EA	Vp	Cp
Slope	1	1/2	5	3	5	1.72	0.26
Infiltration	2	1	7	5	5	3.23	0.49
Drainage Density (DD)	1/5	1/7	1	1/2	1	0.36	0.05
Fracture Density (DF)	1/3	1/5	2	1	5	0.92	0.14
Alterite thickness (EA)	1/5	1/5	1	1/5	1	0.38	0.06

(b)

	Probability of success	Drilling depth	Vp	Cp
Probability of success	1	1/3	0.58	0.25
Drilling depth	3	1	1.7	0.75

(c)

	Operating flow rate	Static level	Vp	Cp
Operating flow rate	1	3	1.7	0.75
Static level	1 /3	1	0.58	0.25

aggregation method also used by [21] [26] [27] [31] [32] [33].

This method consists of multiplying each factor or indicator by its respective weighting coefficient and then summing these results to produce a fitness index according to the following formula (Equation (5)).

$$S = \sum_{i=1}^{n} W_i X_i \tag{5}$$

where

S is the final score; W_i is the weight of criterion i; and X_i is the standardized value of criterion i.

This approach was used individually for the three decision indicators, accessibility, operability and availability. The weights for these indicators were determined (**Table 5**).

The realization of the thematic map "groundwater potentiality" consists in transferring in space, the different values resulting from the summation of the standardized and weighted values of each indicator intervening in the elaboration of the aforementioned map. A reclassification of the factors will lead to thematic maps with four classes: Bad class; mediocre class; good class and excellent class. The number of classes is set at four for better readability and interpretation of the resulting map [7].

2.3.5. Method of Validation of Thematic Maps: Uncertainty Analysis

The thematic maps produced were validated by calculating uncertainty [7] [9] [29] [34]. Indeed, the method of validation of the thematic maps used in previous studies [17] [18] [21] [31] has shown shortcomings in that it is virtually impossible to find a sensitivity class that reflects 100% of the reality in the field because, next to a borehole with a large flow rate, it is possible to have another borehole with a low flow rate, or even none. Thus, the calculation of the uncertainties on the averages of the various parameters of the main indicators is given by Equation (6):

$$\Delta\bar{X} = \frac{\sigma}{\sqrt{m}} \tag{6}$$

where

$\Delta\bar{X}$: uncertainty about the mean of the data series;

σ: standard deviation of the data series;

m: 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

Table 5. Pairwise comparison matrix determining indicator weights.

	Availability	Accessibility	Exploitability	Vp	Cp
Availability	1	5	3	2.46	0.64
Accessibility	1/5	1	1/3	0.40	0.10
Exploitability	1/3	3	1	1	0.26

calculating the expanded uncertainty. The factor K allows the definition of an interval of sufficient range with the aim of having in the results high confidence. The expression of this factor is (Equation (7)):

$$K = \frac{\left|E - \overline{X}\right|}{\sigma} \quad (7)$$

where

K is the expansion factor; and E is the extreme value of the statistical series which can be the maximum or minimum of the series.

The confidence levels (LC) of the different 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 confidence of 99%.

3. Results and Discussion

3.1. Results

3.1.1. Groundwater Availability Map

The groundwater availability map of the departments of Yamoussoukro and Toumodi is characterized by four classes (Figure 4). The analysis and interpretation

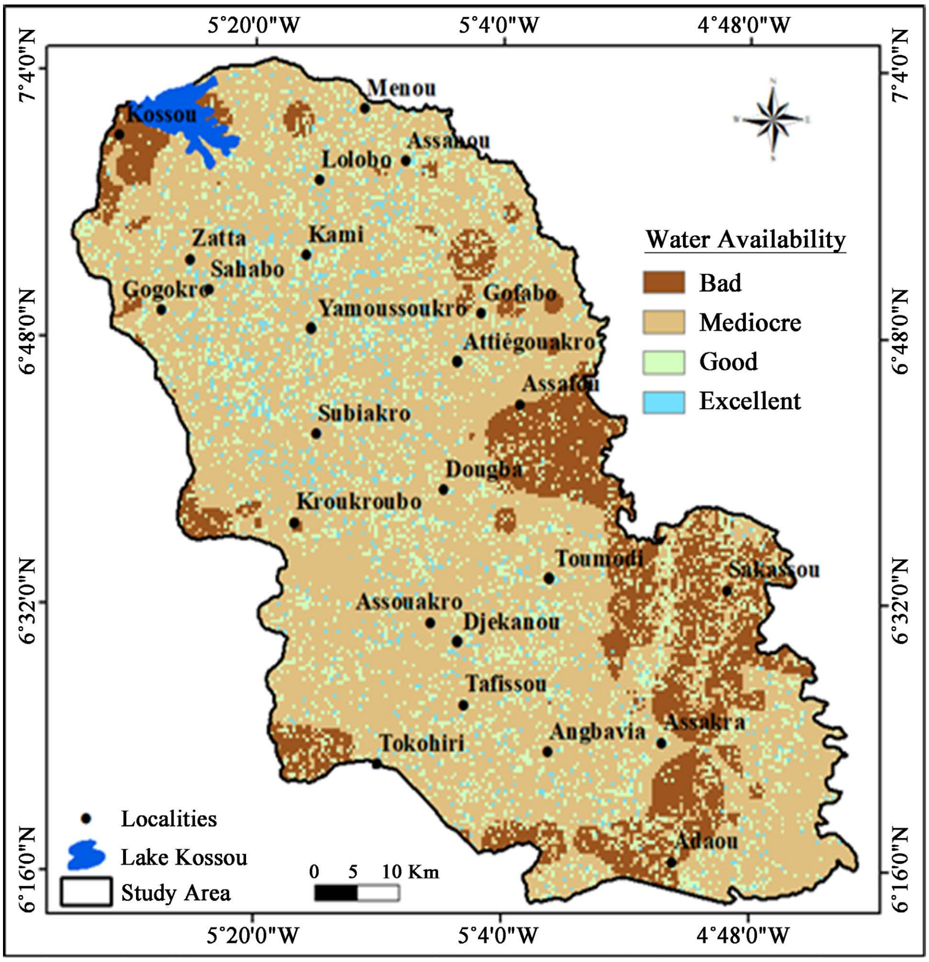


Figure 4. Groundwater availability map.

of these classes indicate that:

- Areas with bad availability represent 14.7% of the study area. These areas are found mainly in the east, south, west and northwest of the study area;
- The mediocre availability class represents 67% of the study area. This class is the most represented and is almost present on the whole study area;
- The good and excellent availability zones occupy respectively 14.7% and 3.6% of the study area. These areas are scattered throughout the study area.

3.1.2. Groundwater Accessibility Map

The accessibility map of groundwater resources in the departments of Yamoussoukro and Toumodi is characterized by four classes (Figure 5):

- The class with bad accessibility occupies 6.6% of the study area. This class appears in the form of pockets, precisely in the localities of Lolobo, Tafissou, Tokohiri, in the southern part of Sahabo, west of Assouakro, north of Sakassou and Dougba, and in part of the center of the study area;

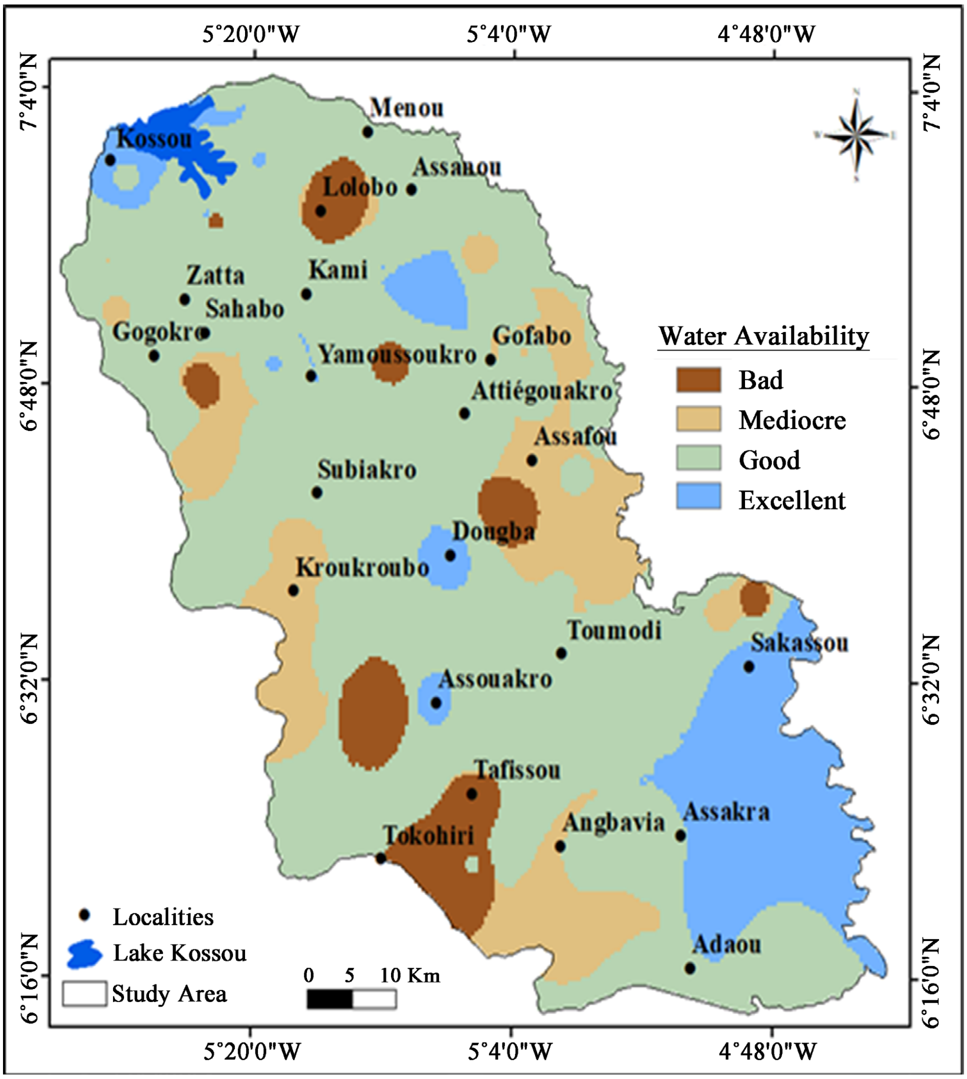


Figure 5. Map of groundwater accessibility.

- Areas with mediocre accessibility represent 13.6% of the study area and are located in the western, southern and eastern parts of the study area;
- The good accessibility class occupies 66% of the study area. It covers most of the area and is almost present in the entire study area;
- The class with excellent accessibility of groundwater resources covers 13.8% of the study area. This class is mainly located in the localities of Kossou, Dougba, and Assouakro, to the west of Kami and in the south-eastern part of the study area.

3.1.3. Map of Groundwater Exploitability

The groundwater resources exploitability map for the departments of Yamoussoukro and Toumodi shows four exploitability classes (Figure 6) which are distributed as follows:

- The bad exploitability class occupies 0.5% of the study area. This class is located in the localities of Lolobo, Gofabo, south of Sahabo, and east of Dougba;

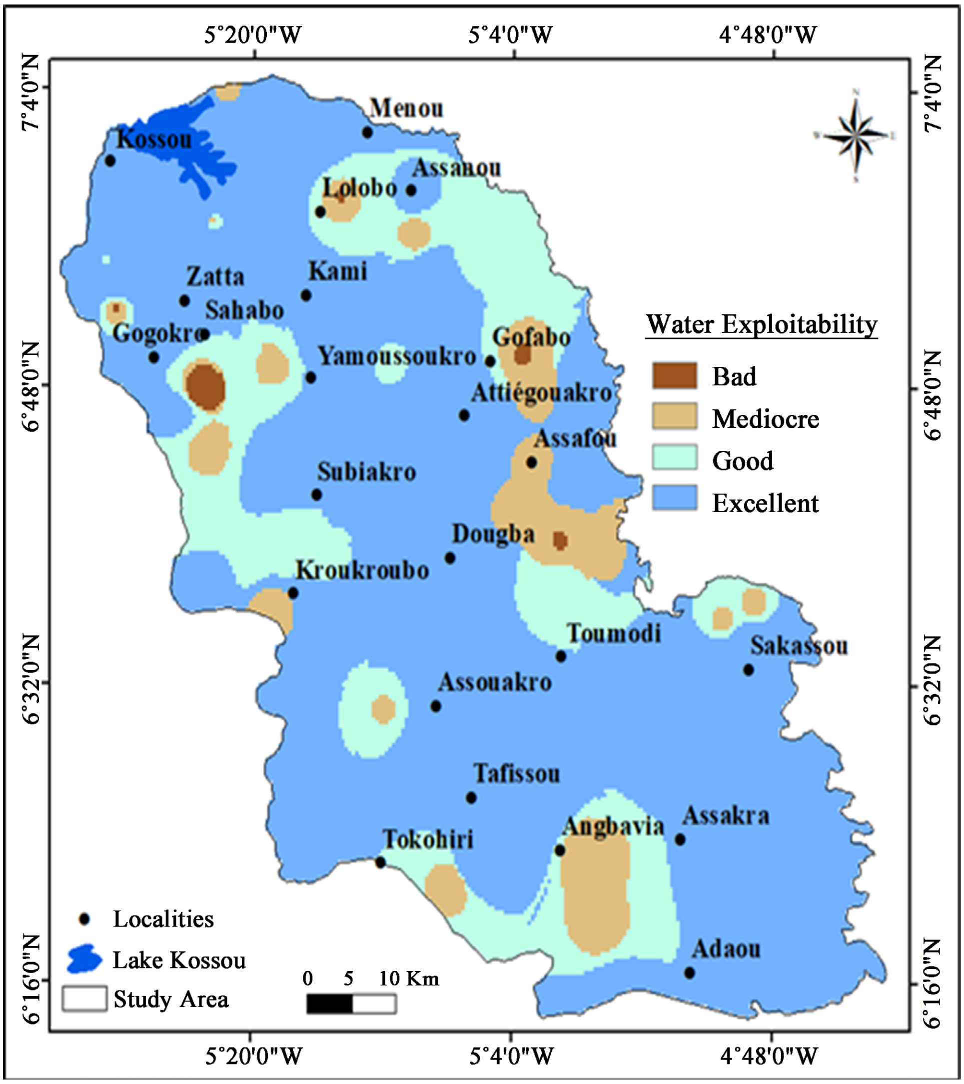


Figure 6. Map of groundwater exploitability.

- The class with mediocre exploitability represents 7.8% of the study area. This class is found mainly in the southern, eastern and western parts of the study area;
- The good exploitability class occupies 18.7% of the study area and is found mainly in the southern, western, eastern and northeastern sectors of the study area;
- The excellent exploitability class is the most representative of the study area with an estimated 73% of the area occupied. This class is almost present throughout the study area.

3.1.4. Map of Potential Groundwater Sites

Analysis of the map of areas favorable for the installation of large-scale drilling (Figure 7) shows that the departments of Yamoussoukro and Toumodi are rich in groundwater reserves. Indeed, this analysis describes the zones that are favorable for the installation of large-scale drilling through four classes:

- The class of bad potentiality occupies a small portion of the study area with

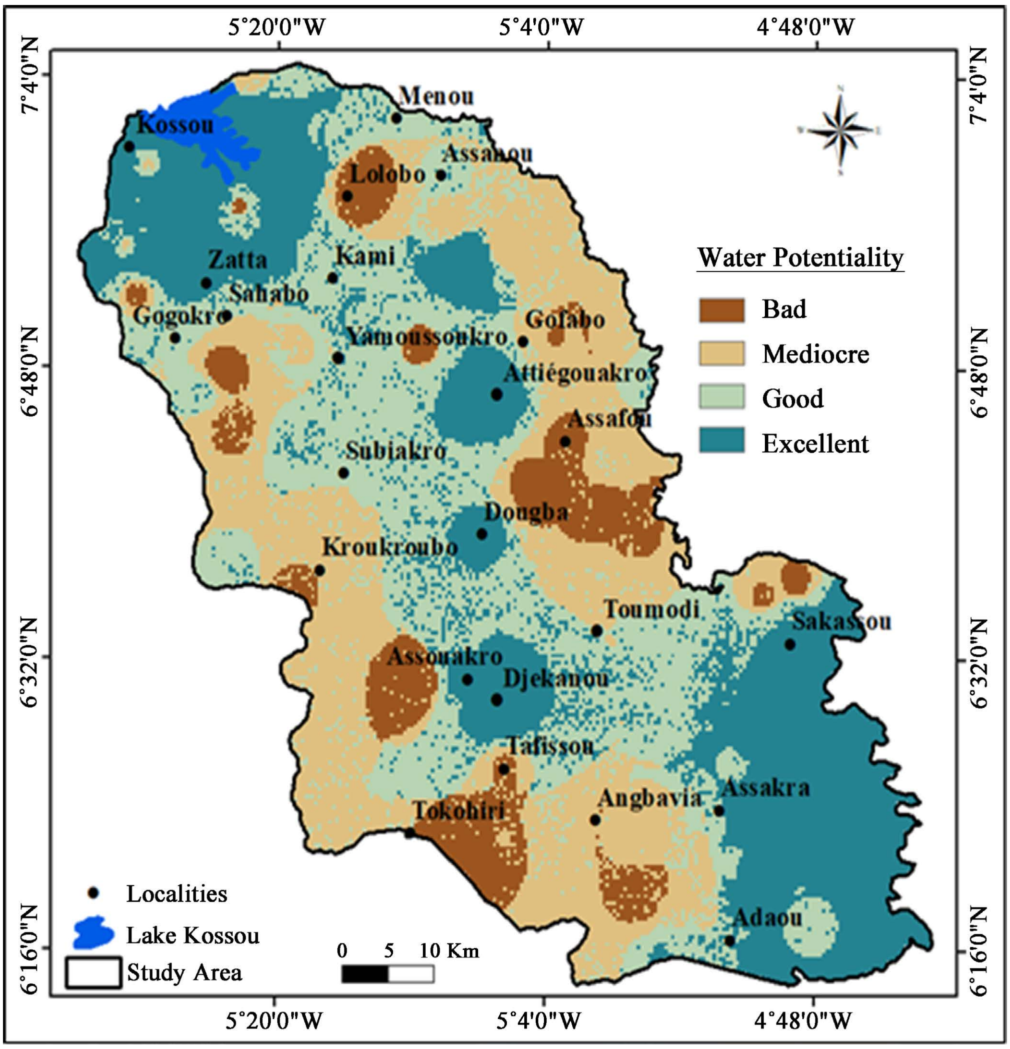


Figure 7. Map of potentiality groundwater sites.

8.9% of occupation. It is mostly in the form of pockets in the southern, eastern, western and northern parts of the study area;

- The class of mediocre potentiality represents 27.6% of the study area. This class extends from the western zone to the southwestern zone, and the northeastern zone to the eastern part of the study area;
- The good potential class occupies 31.4% of the study area. This class is present mainly in the center and extends to the northern and southern parts of the study area;
- The class with excellent potential dominates the study area with a proportion of 32.1%. It is found in the northwest and southeast parts of the study area. This zone is also found in the form of pockets and scattered in the central part of the study area.

3.1.5. Validation of Thematic Maps

Validation of the thematic maps was performed by statistical analysis of the error or uncertainty associated with each map unit (Table 6).

The groundwater availability map has a margin of error of ±0.003 with a confidence level of 99%. This means that the groundwater availability map reflects the realities of the field.

The accessibility map has a margin of error of ±0.004 with a 99% confidence level. This means that the water accessibility map reflects the realities of the field.

The exploitability map has a margin of error of ±0.004 with a confidence level of 99%. These values imply the reliability of the thematic groundwater exploitability map.

The map of potential groundwater sites was also validated. The error calculation yielded an uncertainty of ±0.005, a significantly low value at the 95% confidence level.

These low values of uncertainty obtained for the three indicators attest to the reliability of the groundwater potential map of the departments of Yamoussoukro and Toumodi.

3.2. Discussion

Multi-criteria analysis (MCA) is a technique for clarifying and understanding a decision problem and solving it [35] (Lehoux and Vallée, 2004). MCA can also be defined as a decision support tool developed to solve complex multi-criteria problems that include qualitative and/or quantitative aspects in a decision-making

Table 6. Statistical summary of indicator evaluation criteria.

Parameters	Min	Max	Mean	Standard deviation	Uncertainty	K	LC (%)
Availability	4	7.9	5.1	0.7	±0.003	3	99
Accessibility	1	8	5.5	1.4	±0.004	3	99
Exploitability	1	8.7	6.7	1.5	±0.004	3	99
Potentiality	7.3	23.8	17.3	2.6	±0.005	2	95

process [36] [37] (Mendoza *et al.*, 2000; Conchita, 2011). Thus, the GIS method associated with MCA has been successfully applied in several regions of Côte d'Ivoire. In the departments of Yamoussoukro and Toumodi, it has led to the creation of a potentiality map based on maps of availability, accessibility and exploitability of groundwater resources. The analysis of this groundwater potential map shows that, despite high infiltration, nearly 80% of the department's surface area is characterized by areas of bad and mediocre availability. These results could be due to very steep slopes associated with high drainage densities, which accelerate water flow and thus slow down infiltration into the aquifer [38]. These areas are not conducive to the formation of large underground reservoirs. Nevertheless, a borehole located at the rights or intersection of open mega-fractures can provide exceptional flow rates, even though it is in a bad or mediocre availability zone. We also note the presence of good and excellent availability classes that represent nearly 20% of these departments. These classes are due to areas of low slopes with a high density of fracturing that would result in good infiltration of water in the aquifer [7] [9] [29] [34] [39]. This good infiltration results above all from the abundance of rainfall, which is the primary source of aquifer recharge. Indeed, in humid tropical areas such as Côte d'Ivoire, aquifers are essentially fed by rainfall via surface infiltration [40]. In the department of Oumé, east-Central Côte la d'Ivoire, [33] showed that 50% of the area is characterized by bad to mediocre class availability. The areas with excellent and good accessibility cover 13.8% and 66% of the study area respectively. These areas would be favored by the total depth of the boreholes, most of which are shallower with good flow rates. The bad and mediocre accessibility classes occupy respectively 6.6% and 13.6% of the study area. These results obtained are close to those obtained by [41] in the Lobo watershed (central-western Côte d'Ivoire) with 69.7% of the excellent accessibility class; 21.5% of the good class and 8.4% of the mediocre and bad accessibility classes. Exploitability is dominated by 73% of the excellent class and 18.7% of the good class. This dominance is favored by the predominantly granitoid formations that are present over almost the entire study area. This good exploitability of the granitoid waters could also be related to the high density of fracturing, which represents nearly 50% of the study area. Indeed, according to [42] granites and shales are the lithological formations that are generally very productive. Areas with bad potential represent 8.9% of the study area. These areas are characterized by poor to excellent availability, with bad to mediocre accessibility and exploitability. These areas are difficult to access, with low exploitation rates. They are not suitable for drilling because they belong to the unsuitable zone and are therefore strongly discouraged. The zones with mediocre potentiality occupy 27.6% of the study area. They are characterized by bad to excellent availability, mediocre to good accessibility and mediocre to excellent exploitability in places. These areas belong to a high potential zone because of their flow. They can be recommended for the implementation of boreholes within the framework of village hydraulics and improved village hydraulics. Areas with good potential occupy 31.4% of the study area. They are characterized by bad to excellent availability, good accessibility, and excellent exploitability. These zones belong to the suitable class and are recommended for the installation of boreholes in the context of improved village hydraulics and the search for areas with large flows. Zones with excellent potential dominate the department with a proportion of 32.1%. This class is characterized by bad to excellent availability, good to excellent accessibility and excellent exploitability. These areas belong to the suitable class and are strongly recommended for the establishment of large flow boreholes. The departments of Yamoussoukro and Toumodi have significant groundwater reserves, with more than 90% of the zones favorable to the installation of boreholes in the context of village water supply and improved village water supply. Nearly 63% of these areas are favorable for the installation of large flow boreholes. These areas are the most sought-after for the supply of drinking water to large urban centers such as the city of Yamoussoukro. These results are similar to those obtained by [33] in the department of Oumé (east-central Côte d'Ivoire) with 4.83% of the class with bad potential, 36% of the class with mediocre potential, and 58.25% of the classes with good and excellent potential. The validation of the thematic maps produced in this study by calculating the uncertainties is justified by the fact that the method of evaluation by trend curves proposed by [21] has shown its limitations. Indeed, it is practically impossible to find a sensitivity class that reflects 100% the reality of the field, in the sense that next to a borehole with a large flow, it is possible to have another borehole with a small flow, or even none. To overcome these shortcomings, some authors [7] [9] [11] [29] [34] [43] recommend the use of sensitivity tests and calculation of uncertainties to rank the various parameters used in order of importance in the development of water potentiality maps. The very low uncertainties calculated in this study support the reliability of the data used. Thus, this thematic map of potential groundwater sites in the departments of Yamoussoukro and Toumodi can be used as a guide to making the right decision when looking for areas for the establishment of large boreholes. It should be noted that the use of GIS through the interpolation method used for the realization of the different maps, can often present limitations in the choice of the number of classes to interpret.

4. Conclusion

At the end of this study, it should be noted that the application of the multi-criteria analysis method leads to the conclusion that the departments of Yamoussoukro and Toumodi have significant groundwater reserves. The study of groundwater potentiality indicates that about 63% of this region has good and excellent potentiality. These areas include the northern, central and southern parts of the study area. As far as accessibility is concerned, the study area is dominated by good and excellent accessibility (79.8%) of its water resources. The map of the exploitable resources reveals that 91.7% of the resources available in the Oumé region are potentially exploitable. These resources are located over almost the entire study area. In fact, more than 90% of these areas are favorable to the implementation of drilling in the context of village hydraulics and improved village hydraulics and nearly 63% of these areas are favorable to the implementation of large flow boreholes, necessary for the supply of large urban centers. Consequently, the results could considerably reduce the failure rate in the future implementation of groundwater catchment structures in these departments.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Faye, C., Solly, B., Dièye, S. and Fall, A. (2021) Evaluation des zones potentielles d'eaux souterraines avec l'utilisation des SIG et de la télédétection Cas du sous-bassin de la Sandougou (bassin de la Gambie). *African Journal on Land Policy and Geospatial Sciences*, **4**, 53-75.

[2] Akokponhoué, Y.N., Yalo, N., Akokponhoué, H.B., Youan Ta, M. and Agbahoungba, G. (2019) Apport de la télédétection et de la géophysique dans la cartographie des fractures hydrauliquement actives en zone de socle au Centre-Ouest du Benin. *European Scientific Journal*, **15**, 426-447. https://doi.org/10.19044/esj.2019.v15n27p426

[3] Robert, B., Alves, D., Latorre, C., Macleod, N., Payen, G., Roaf, V. and Rouse, M. (2018) Manuel des Droits de l'Homme à l'Eau Potable et à l'Assainissement à l'intention des Praticiens. IWA (International Water Association) Publishing, Alliance House, 12 Cax-ton Street London, Londre (Royaume-Uni), 124 p.

[4] OMS & UNICEF (2017) Progrès en matière d'eau, d'assainissement et d'hygiène: mise à jour 2017 et évaluation des Objectifs de Développement Durable. Rapport du Joint Monitoring Program, New York (Etats-Unis), 116 p.

[5] Kouadio, E.K., Savané, I., Lasm, T. and Biémi, J. (2008) Hydrogeology Prospecting in Crystalline and Metamorphic Area by Spatial Analysis of Productivity Potential. *European Journal of Scientific Research*, **22**, 373-390.

[6] Joseph, K., Pétanhangui, A.Y. and Yussef N.K. (2018) L'eau est une préoccupation majeure en Côte d'Ivoire. Dépêche, Abidjan (Côte d'Ivoire), 8 p.

[7] Yao, A.B., Goula, B.T.A., Kane, A., Mangoua, M.J. and Kouassi, K.A. (2016) Cartographie du potentiel en eau souterraine du bassin versant de la Lobo (Centre-ouest, Côte d'Ivoire). Approche par analyse multicritère. *Hydrological Sciences Journal*, **61**, 856-867. https://doi.org/10.1080/02626667.2014.932360

[8] Biémi, J. (1992) Contribution à l'étude géologique, hydrogéologique et par télédétection des bassins versants subsahariens du socle précambrien d'Afrique de l'Ouest:

Hydrostructurale, Hydrodynamique, Hydrochimie et Isotopie des aquifères discontinus de sillons et aires granitiques de la haute Marahoué (Côte d'Ivoire). Thèse de Doctorat d'Etat, Université de Cocody, Abidjan, 479 p.

[9] Kouassi, W.F., Kouassi, K.A., Mangoua, M.J., Kamenan, Y.M. and Kouadio, Z.A. (2019) Evaluation des potentialités en eau souterraine de la portion Ivoirienne du bassin versant du Niger. *International Journal of Innovation and Applied Studies*, **25**, 774-784.

[10] Soro, G., Soro, N., Ahoussi, K.E., Lasm T., Kouamé, F.K., Soro, T.D. and Biémi, J. (2010) Evaluation des propriétés hydrauliques des aquifères fracturés des formations cristallines et métamorphique dans la région des Lacs (Centre de la Côte d'Ivoire). *Estudios Geológicos*, **66**, 227-242. https://doi.org/10.3989/egeol.40123.093

[11] Cocker, F., Vodounou, J.B. and Yabi, J. (2020) Cartographie du potentiel en eau souterraine de la basse vallée de l'Ouémé, sud-Bénin (Afrique de l'Ouest). *La Houille Blanche*, **106**, 74-85. https://doi.org/10.1051/lhb/2020018

[12] PRICI (2016) Projet de Renaissance des Infrastructures de Côte d'Ivoire. Rapport final du cadre de gestion environnementale et sociale, Côte d'Ivoire, 203 p.

[13] Stary, B. (1985) Du village à la capitale: L'émergence de Yamoussoukro à travers la presse et le discours officiel ivoirien, mémoire de maitrise de géographie, Paris, 288 p.

[14] Yacé, I. (1976) Le volcanisme éburnéen dans les parties centrales et méridionales de la chaîne précambrienne de Fétékro en Côte d'Ivoire. Thèse de Doctorat, Université de Cocody, d'Abidjan, 373 p.

[15] Soro, G. (2010) Evaluation quantitative et qualitative des ressources en eaux souterraines dans la region des lacs (centre de la côte d'ivoire): hydrogeologie et hydrochimie des aquifères discontinus du district de Yamoussoukro et du departement de Tiebissou. Thèse de doctorat, Université Félix Houphouët Boigny (Côte d'Ivoire), 254 p.

[16] N'guessan, K.A., Kouassi, A.M., Gnaboa, R., Traoré, K.S. and Houenou, P.V. (2014) Analyse de phénomènes hydrologiques dans un bassin versant urbanisé: Cas de la ville de Yamoussoukro (Centre de la Côte d'Ivoire). *Larhyss Journal*, **17**, 135-154.

[17] Jourda, J.P., Djagoua, É.V., Saley, M.B., Kouame, K.J., Biémi, J. and Razack, M. (2006) Utilisation des données ETMþ de Landsat et d'un SIG pour l'évaluation du potentiel en eau souterraine dans le milieu fissuré précambrien de la région de Korhogo (nord de la Côte d'Ivoire): Approche par analyse multicritère et test de validation. *Rev Teledetect*, **5**, 339-357.

[18] Youan Ta, M., Lasm, T., Jourda, J.P., Saley, B.M., Adja, M.G., Kouamé, K. and Biémi, J. (2011) Cartographie des eaux souterraines en milieu fissuré par analyse multicritère: Cas de Bondoukou (Côte-d'Ivoire). *Revue Internationale de Géomatique*, **21**, 43-71. https://doi.org/10.3166/rig.21.43-71

[19] El Morjani, Z. (2002) Conception d'un système d'information à référence spatiale pour la gestion environnementale; application à la sélection de sites potentiels de stockage de déchets ménagers et industriels en région semi-aride (Souss, Maroc). Thèse de Doctorat, Université de Genève, Genève, 300 p.

[20] Hentati, I., Zairi, M. and Dhia, H.B. (2005) Utilisation des SIG pour l'évaluation de la vulnéra-bilité environnementale des aquifères phréatiques: Cas de la nappe de Sfax-Agareb (Sud-Est tunisien). In: Communication SIG 2005, Environnement/Eau, Is-sy-les-Moulineaux, France.

[21] Jourda, J.P. (2005) Méthodologie d'application des techniques de télédétection et des systèmes d'information géographique à l'étude des aquifères fissurés d'Afrique

de l'Ouest. Concept de l'hydrotechnique spatiale: Cas des zones tests de la Côte d'Ivoire. Thèse de Doctorat d'Etat, Université de Cocody, Abidjan, 430 p.

[22] Kouame, K.J. (2007) Contribution à la gestion intégrée des ressources en eaux (GIRE) du district d'Abidjan (Sud de la Côte d'Ivoire): Outils d'aide à la décision pour la prévention et la protection des eaux souterraines contre la pollution. Thèse de Doctorat, Université de Cocody, Abidjan, 194 p.

[23] Dibi, B. (2008) Cartographie des sites potentiels d'implantation des points d'eau dans le département d'Aboisso (Sud-est de la Côte d'Ivoire): Apport du SIG et de l'analyse multicritère. Thèse unique de Doctorat, Université de Cocody, Abidjan, 164 p.

[24] Youan Ta, M. (2008) Contribution de la télédétection et des systèmes d'informations géographiques à la prospection hydrogéologique du socle précambrien d'Afrique de l'ouest: Cas de la région de Bondoukou (Nord-est de la Côte d'Ivoire). Thèse Unique de Doctorat, Université de Cocody, Abidjan, 237 p.

[25] Thornthwaite, C.W. (1954) An Approach toward a Rational Classification of Climate. *Transaction American Geophysics Union*, **27**, 55-99.

[26] Saley, M.B. (2003) Système d'informations à référence spatiale, discontinuités pseu-do-images et cartographies thématiques des ressources en eau de la région semi-montagneuse de Man (Ouest de la Côte d'Ivoire). Thèse de Doctorat, Université de Cocody, Abidjan, 209 p.

[27] Savané, I. (1997) Contribution à l'étude géologique et hydrogéologique des aquifères discontinus du socle cristallin d'Odienné (Nord-ouest de la Côte d'Ivoire): Apport de la télédétection et d'un système d'information hydrogéologique à référence spatiale. Thèse de Doctorat d'Etat, Université de Cocody, Abidjan, 398 p.

[28] Saaty, T.L. (1977) A Scaling Method for Priorities in Hierarchical Structures. *Journal of Mathematical Psychology*, **15**, 234-281. https://doi.org/10.1016/0022-2496(77)90033-5

[29] Doumouya, I., Brou, D., Kouassi, I.K., Saley, M.B., Jourda, J.P., Savané, I. and Biémi, J. (2012) Modelling of Favourable Zone for the Establishment of Water Points by Geographical Information System (GIS) Multicriteria Analysis (MCA) in the Aboisso Area (South-East of Côte d'Ivoire). *Environmental Earth Sciences*, **67**, 1763-1780. https://doi.org/10.1007/s12665-012-1622-2

[30] Saaty, T.L. (2008) Decision Making with the Analytic Hierarchy Process. *International Journal of Services Sciences*, **1**, 83-98. https://doi.org/10.1504/IJSSCI.2008.017590

[31] Koudou, A, Kouame, K.F., Youan Ta, M., Saley, M.B., Jourda, J.P. and Biemi, J. (2010) Contribution des données ETMþ de Landsat, de l'analyse Multicritère et d'un SIG à l'identification de secteurs à potentialité aquifère en zone de socle du bassin versant du N'Zi (Côte d'Iv-oire). *Photo Interpretation European Journal of Applied Remote Sensing*, **46**, 98-115.

[32] Koudou, A. (2013) Conception d'outils d'aide à la décision pour la gestion intégrée des ressources en eau dans un contexte de variabilité climatique: application à la sélection des zones à potentialité aquifère et moins vulnérables à la pollution du bassin versant du N'zi. Thèse Unique de Doctorat, Université Félix Houphouët Boigny de Cocody, Abidjan, 225 p.

[33] Youan Ta, M., Yao, K.A.F., Baka, D., De Lasme, Z.O., Lasm, T., Adja, M.G., Kouakou, S., Onetie, Z.O., Jourda, J.P. and Biémi, J. (2015) Cartographie des zones potentielles à l'implantation des forages a gros débits en milieu fissure par analyse multicritère: cas du département d'Oumé (Centre-ouest de la Cote d'Ivoire). *Lar-*

hyss Journal, **23**, 155-181.

[34] Mangoua, M.J. (2013) Evaluation des potentialités et de la vulnérabilité des ressources en eau souterraine des aquifères fissurés du bassin versant de la Baya (Est de la Côte d'Ivoire). Thèse Unique de Doctorat, Université d'Abobo-Adjamé, Abidjan, 171 p.

[35] Lehoux, N. and Vallee, P. (2004). Analyse multicritère, introduction: Quel modèle choisir ?. Ecole Polytechnique de Montréal. 38 p.

[36] Mendoza, G.A., Macoun, P., Prabhu, R., Sukadri, D., Purnomo, H. and Hartanto, H. (2000) Application de l'analyse multicritère à l'évaluation des critères et indicateurs. Cirad, Cifor, 84 p.

[37] Conchita, G., K,. M., G. (2011). SIG et analyse multicritère pour l'aide à la décision en agriculture urbaine dans les pays en développement, cas de Ouagadougou au Burkina Faso. Thèse de doctorat, Université Paris 8 Vincennes Saint-Denis, 301 p.

[38] Shankar, R.M.N. and Mohan, G. (2006) Assessment of the Groundwater Potential and Quality in the Bhatsa and Kalu River Basins of Thane District, Western Deccan Volcanic Province of India. *Environmental Geology*, **49**, 990-998. https://doi.org/10.1007/s00254-005-0137-5

[39] Mangoua, M.J., Yao, A.B., Douagui, G.A., Kouassi, K.A., Goula, B.T.A. and Biémi, J. (2019) Évaluation des potentialités en eau souterraine des aquifères fissures dans le bassin versant du Bandama (Côte d'Ivoire). *Larhyss Journal*, **37**, 53-74.

[40] Yao, K.T., Fouché-Grobla, O., Oga, M.-S. and Assoma, V. (2012) Extraction de linéaments structuraux à partir d'images satellitaires, et estimation des biais induits, en milieu de socle précambrien métamorphisé. *Revue Télédétection*, **10**, 161-178.

[41] Yao, A.B. (2015) Evaluation des potentialités en eau du bassin versant de la Lobo en vue d'une gestion rationnelle (Centre-ouest de la Côte d'Ivoire). Thèse unique de Doctorat, Université Nangui Abrogoua, Abidjan, 225 p.

[42] N'go, Y.A., Goné, D.L., Savane, I. and Goblé, M.M. (2005) Potentialités en eaux souterraines des aquifères d'Agboville (Sud-ouest de la Côte d'Ivoire): Caractérisation hydro-climatique et physique. *Afrique Science*, **1**, 127-144. https://doi.org/10.4314/afsci.v1i1.35401

[43] Samake, M.B., Laing, Z.T., N'doh, M.W.I., Kasereka, K. and Balogun, W.O. (2011) Groundwater Vulnerability Assessment in Shallow Aquifers in Linfen Basin, Shanxi Province, China Using DRASTIC Model. *Journal of Sustainable Development*, **4**, 53-71. https://doi.org/10.5539/jsd.v4n1p53