

Application of a Multi-Criteria Approach for the Assessment of Groundwater Potential in the Basement Zone: A Case of Tamou (South West Niger)

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Abstract

The commune of Tamou, located in the Department of Say in Niger, occupies the southwestern part of the Liptako crystallophyllian basement domain. In this area, the problem of the drinking water supply of the populations is acute, because of the low flow rates of the drillings capturing the crystallophyllian formations and the Voltaian sandstones, the failure rates of the drillings are very high there. Therefore, the main objective of this study is to improve the knowledge of the areas potentially favorable for the implantation of drillings likely to give more satisfactory flow rates. The methodological approach, based on the collection of data (Landsat 7 ETM+ satellite imagery, borehole data, geological and topographical maps) and their processing by a combination of remote sensing and GIS tools and a field check, allowed the elaboration of maps of availability, accessibility and exploitability of the groundwater resources in the study area. The maps developed were analyzed with a Spatial Reference Hydrogeological Information System following the technique of aggregation by weighting to generate the map of productive drilling sites. The results show that the area is moderately rich in groundwater (58%) and that only 31% of the potential is exploitable. The groundwater potential map shows that 46% of the study area is suitable for drilling.

Keywords

Multi-Criteria Analysis, Remote Sensing, GIS, Discontinuous Aquifers, Tamou, Niger

1. Introduction

In Niger, recurrent droughts since the 1970s have pushed the populations of the northern part of Tillabéry (Ouallam Department) to move to the south of the region in search of better living conditions.

The commune of Tamou, the study area, was one of the areas where these populations settled. It is an outcrop area of the Niger Liptako with a Sahelo-Sudanese climate, where the potential for water resources is very limited. The exploitable water tables are random and their capacity is low, making access to drinking water for populations and their livestock difficult.

Consequently, several investigation methods have been used to find sites that are favorable for drilling for water (geophysics, fracturing, drilling techniques). Nevertheless, the rate of dry boreholes capturing the crystallophyllian formations of the Liptako and the sandstones Voltaian remains high, more than 23%, and several boreholes considered positive have flow rates of less than 1 m³/hour according to an analysis of 200 borehole data sheets collected for the study area.

This situation of the critical shortage of drinking water has negative impacts on the living conditions of rural populations. The latter is forced to rely on surface water during the winter months (ponds, rivers, koris, etc.) and on groundwater through wells, which are exposed to the risk of pollution [1]. Also, these alluvial aquifers of limited extension are strongly dependent on rainfall patterns [2].

These constraints, likely to increase due to the persistent impacts of climate change and demographic pressure, require a more in-depth study of groundwater resources in general and in the basement zone in particular. The main objective of this study is to improve the conditions for drilling water with higher flow rates (reducing the high rates of negative drilling). Specifically, this study aims to: 1) analyze satellite images and physiographic and hydroclimatic data, hydrogeological characteristics of aquifers and borehole data of the study area; 2) develop maps of Drainage Density (DD), Fracture Density (FD), Alteration Thickness (AT), Static Level (SL), etc.; and 3) apply multi-criteria techniques.

This paper is structured into three parts including generalities, materials and methods, and results and discussion respectively.

2. Presentation of the Study Area

2.1. Geographic Location

The rural commune of Tamou, the area of this study, is located in the Department of Say, Tillabery Region. It lies between 12°40' and 13° North latitude and between 1°50' and 2°50' East longitude (**Figure 1**) in the southwestern part of Niger. It covers an area of 5230 km² with an estimated population of about 104,070 inhabitants in 2016, with an annual growth rate of 3.9%, and a density of 38 inhabitants/km² [3].

The climate is Sahelo-Sudanese, characterized by an average annual rainfall of about 698 mm, observed at the Tamou rainfall station (1981-2016), with average annual temperatures around 29.2°C [4].

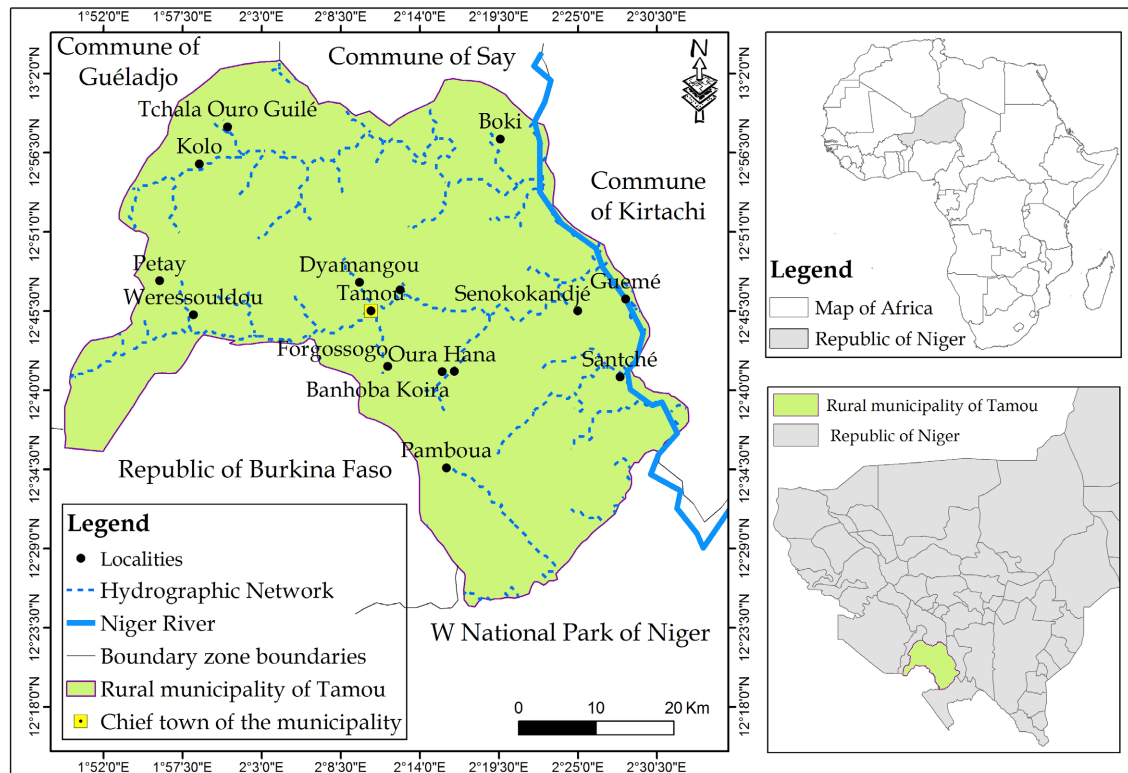


Figure 1. Geographic location of the study area.

The relief of the area is little marked, slightly undulating with altitudes between 170 m and 260 m [5]. The vegetation is presented in the form of a mosaic of facies, and is of the tiger bush type on the cuirassed plateau, while it is organized more as an agroforestry park largely dominated by Combretaceae on the glacis [6]. The study area is on the right bank, drained by three major tributaries of the Niger River: the Goroubi, the Diamangou and the Tapoa. Thus, the Niger River is the only permanent watercourse of the hydrographic network, and crosses the study area over a distance of about 55 km [5].

2.2. Geological and Hydrogeological Context

The geological context of the study area is dominated by three major lithological units (Figure 2) which are:

- Paleoproterozoic or Birimian age formations, 2300 to 2000 Ma [7]; these are greenstone belts (meta-volcano-sedimentary, shales, conglomerates, and greenstones (amphibolites, metagabbros, meta-microgabbros, etc....) and granitoid plutons (quartz or amphibole diorites, syenogranites, manzogranites, grano-diorites);
- The Voltaian formations, essentially constituted by sandstones, quartzic, conglomerates with coarse grains (pebbles and gravels) of size varying from approximately 2 to 8 cm, with sandstone matrix;
- The sedimentary cover grouping the formations of the terminal continental (CT3) and the quaternary deposits.

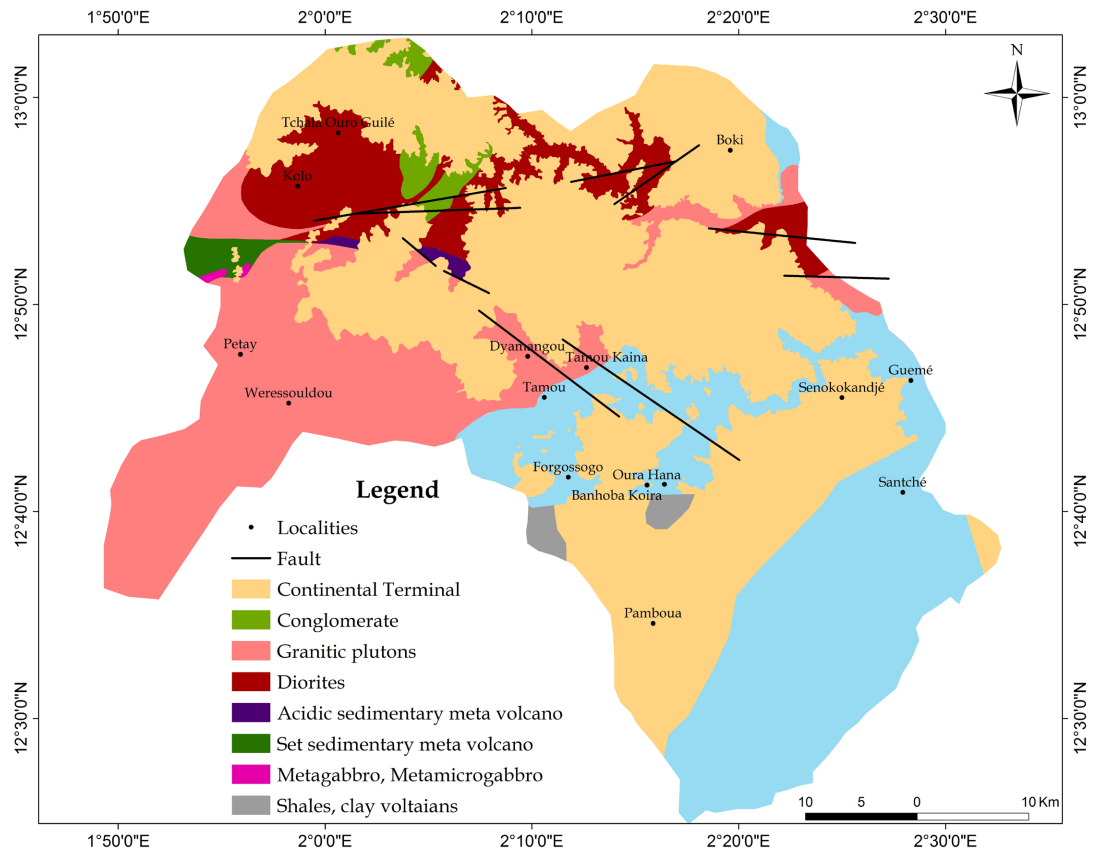


Figure 2. Geological map of the study area.

Groundwater resources are contained in two types of aquifers:

- Continuous aquifers, but of limited extension and localized only in areas of depression. These are the sedimentary formations (CT3, alluvium and colluvium);
- Discontinuous aquifers encountered in fractured horizons of the Paleoproterozoic and Neoproterozoic formations.

This study focuses on discontinuous aquifers which are the most sought after because of their water quality and the high rate of dry drilling.

3. Material and Methods

3.1. Data

The main data used in this study are:

- An extract of the GeoCover Circa 2000 mosaics (N30-10 and N30-15) from the October 2000 Landsat 7 ETM+ satellite image downloaded from <http://earthexplorer.usgs.gov/>;
- Four 30 m resolution SRTM DTM data clippings downloaded from <https://www.earthdata.nasa.gov/>;
- Cartographic backgrounds (geological map of Liptako (1/200,000), printed in 1988 at IGN of Paris under the control of BRGM, provided by the Ministry of Mines of Niger, topographic map of Kirtachi at a scale of 1/200,000, obtained

from the Ministry of Hydraulics and Sanitation of Niger);

- The fracturing and induced permeability maps used in this study are those of [5];
- The data sheets of 199 hydraulic boreholes, acquired from the Ministry of Hydraulics and Sanitation of Niger and its partners;
- Hydroclimatic data, provided by the National Meteorological Directorate of Niger.

The tools used are: Envi 4.4 for processing satellite images and ArcGIS10.2.2 for producing thematic maps.

3.2. Methods

The elaboration of the mapping of groundwater potentialities includes four important steps: 1) identification and elaboration of decision criteria; 2) classification and standardization of these criteria in order to elaborate indicators; 3) weighting of criteria and their combinations according to the multi-criteria approach; 4) validation of the thematic maps through uncertainty analysis.

In fact, the parameters related to groundwater potentiality are grouped into three quantitative indicators: availability, accessibility and exploitability [8] [9] [10].

3.2.1. Identification and Development of Decision Criteria

The work of several authors [2] [8] [10]-[21] was evaluated and synthesized to define the criteria selected for this study. The choice of these criteria refers to the different indicators: availability, accessibility and usability.

The availability indicator provides information on the existence of a groundwater aquifer [11] [21]. Indeed, in the crystalline and crystalline basement zone, several criteria condition the existence of the availability of groundwater resources, nevertheless, six criteria have been selected in this study because of their importance. These are: effective infiltration (mm), slope (%), drainage density (Km/Km²), fracture density (Km/Km²), induced permeability (m/s) and alteration thickness (m).

The accessibility indicator identifies areas where groundwater is accessible. According to these authors [11] [12] [18] [21] [22] [23], it is obtained by combining the depth of the structures (m) and the success index. These two criteria are considered as economic and social factors, because they promote or not the access to the resource [14].

The exploitability indicator conditions the presence or absence of drilling in a given area, because as soon as it has been proven that the resource is not exploitable, there is no need to drill [16]. It combines criteria such as: the exploitation rate (m³/h) and the piezometric level (m).

3.2.2. Classification and Standardization of Criteria

This classification took into account previous works [8] [11] [13] carried out in similar areas and also on the one proposed by the CIEH (Comité Interafricain

des Etudes Hydrauliques) for criteria such as flow rate and alteration thickness. The number of classes is 3 in this study, for a simple and better interpretation. These are the classes: weak, medium and strong.

The phase of standardization allowed normalizing the criteria that were measured at different scales and in different units. In fact, a common interval of 1 to 10 is maintained, according to which the most favorable class is rated 10, while the most unfavorable is rated 1.

3.2.3. Weighting and Aggregation of Criteria

Weighting is used to assign weights to each criterion. Thus, according to [16], the value of the weights is relative to the importance of the criterion in the accomplishment of the phenomenon that the indicator reflects. The weighting is based on mathematical calculations while giving weighting coefficients and standardized, between 0 and 1 [11] to the criteria of a factor, and whose sum is equal to 1. Within the framework of this study, the method of weighting chosen is that of comparisons by pair through the process of hierarchical analysis (Analytical Hierarchy Process). This method was developed by the mathematician [24]. Indeed, several authors [8] [11] [13] [14] [16] [17] [21] [25] have used this method successfully in the pedestal zone, contrary to the weighting technique based on the arbitrary choice of weights [13] [16].

The matrix in **Table 1** shows the pairwise comparison proposed by [24]. It allows calculating the eigenvector values V_p , which will facilitate the determination of the weighting coefficients C_p . The procedure is described as follows:

- The comparison judgment matrix: The generation of the comparison matrix is based on the pairwise comparison method of [24]. A matrix is obtained (**Table 2**), as a result of the judgment made by comparing the criteria two by two, while transcribing the values of the evaluations in **Table 3** in each corresponding column;
- To configure a reciprocal rectangle matrix formed by the evaluations of the ratios of weights ($K \times K$), K being the number of elements compared; we obtain in this way: $a = a_{ij}$ with $a_{jj} = 1$ and $a_{ji} = 1/a_{ij}$ (inverse value), where a is the value of each factor; and i and j constitute the rows and columns, respectively [26].

Calculation of the eigenvector V_p and weight of the criteria, the values of the eigenvectors were obtained by calculating their geometric mean per line, according to Equation (1):

$$V_p = \sqrt[n]{\prod_i^n g_i} \quad (1)$$

V_p : eigenvector; n : number of criteria; g_i : score of criterion i .

The weighting coefficient for each criterion is obtained by dividing each eigenvector by the total sum of them. The values of the eigenvectors and the weighting coefficients are recorded in **Table 3**.

Table 1. Comparison scale.

| Digital Scale or Intensity | Verbal Scale or Definition | Commentary |
|----------------------------|---|---|
| 1 | Equal importance of both elements: equally important | Both elements compete in the same way with the objective |
| 3 | One item is slightly more important than the other: Slightly more important | Experience and personal judgment slightly favor one element over the other |
| 5 | One element is more important than the other: highly important | Experience and personal judgment really favor one element over the other |
| 7 | One element is much more important than the other: very strongly important | One element is largely dominant, and this dominance is demonstrated in practice |
| 9 | One element is absolutely important than the other: very strongly important | The dominance of one element over another is demonstrated and absolute |
| 1,1, 2, 4, 6 | Intermediate value between two judgments | Used to refine one's judgment |
| Reciprocity | If element i is assigned one of the previous numbers when compared to element j , then j will have the inverse value when compared to i | |

Source: Comparison scale from [24], modified.

Table 2. Pairwise comparison matrix for the availability, accessibility and exploitability indicator criteria.

| Disponibility Indicator | | | | | | |
|-------------------------|-----|-----|----|-----|-----|----|
| Parameters | P | IE | DD | FD | Pi | AT |
| P | 1 | 1/3 | 5 | 3 | 5 | 5 |
| IE | 3 | 1 | 7 | 5 | 5 | 5 |
| DD | 1/5 | 1/7 | 1 | 1/2 | 1/3 | 1 |
| FD | 1/3 | 1/5 | 2 | 1 | 1 | 3 |
| Pi | 1/5 | 1/5 | 3 | 1 | 1 | 3 |
| AT | 1/5 | 1/5 | 1 | 1/3 | 1/3 | 1 |

| Accessibility Indicator | | |
|-------------------------|-------------|------------------|
| Parameter | Total Depth | Index of Success |
| Total Depth | 1 | 3 |
| Index of Success | 3 | 1 |

| Exploitability Indicator | | |
|--------------------------|---------------------|-------------------|
| Parameter | Operating Flow Rate | Piezometric Level |
| Exploitation Rate | 1 | 3 |
| Piezometric Level | 3 | 1 |

P: Slope; IE: Effective Infiltration; DD: Drainage Density; DF: Fracture Density; Pi: Induced Permeability; AT: Alteration Thickness.

Table 3. Eigenvector values and weighting coefficients.

| Indicators | Criteria | Vp | Cp | Total |
|-----------------------|----------|------|------|----------|
| Disponibility | P | 1.72 | 0.26 | 1 |
| | IE | 2.83 | 0.43 | |
| | DD | 0.30 | 0.05 | |
| | DF | 0.63 | 0.10 | |
| | Pi | 0.64 | 0.11 | |
| | AT | 0.31 | 0.05 | |
| Accessibility | TD | 1.73 | 0.75 | 1 |
| | Is | 0.58 | 0.25 | |
| Exploitability | Qex | 1.73 | 0.75 | 1 |
| | NP | 0.58 | 0.25 | |

TD: Total Depth; Is: Success Index; and Qex: Operating Flow.

Consistency Ratio (CR), the method of Saaty [24] [26] has an advantage of checking the consistency of the judgment made when comparing more than two criteria, through the calculation of the consistency ratio. This check is made on the availability indicator where the compared criteria exceed 2. The coherence ratio is determined by the ratio of the Coherence Index (CI) and the Random Index (RI) proposed by Saaty [26]. Thus, a reasoning is said to be consistent when its consistency ratio is less than or equal to 10%. The values of the random index are given in **Table 4** according to the number of parameters compared.

However, IC is obtained following a methodological approach divided into five steps:

First step is to multiply each column by the corresponding weighting Coefficient (Cp), which gives the matrix of **Table 5**, below:

Second step is to sum the elements of each row of the matrix; the results of this step are given in **Table 6**.

Third step is to divide the totals of each line by the Cp corresponding to it, **Table 7** represents this step.

Fourth step lies in determining a parameter λ_{\max} , which is the average of the results obtained in step 3. The operation is as follows (Equation (2)):

$$\lambda_{\max} = (6.56 + 6.56 + 6.16 + 6.18 + 3.06 + 6.07)/6 = 6.26 \quad (2)$$

Fifth step corresponds to the calculation of the CI while applying the formula in Equation (3):

$$CI = (\lambda_{\max} - \text{number of criteria})/(\text{number of criteria minus one}) \quad (3)$$

$$IC = (6.26 - 6)/(6 - 1)$$

This index will determine the Consistency Ratio (CR) which must be less than or equal to 10% (Equation (4)).

Table 4. Scale of random indices according to the number of elements compared [25].

| | | | | | | | | | | | | | | | |
|-----------|---|---|------|-----|------|------|------|-----|------|------|------|------|------|------|------|
| N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| IA | 0 | 0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.4 | 1.45 | 1.49 | 1.51 | 1.48 | 1.56 | 1.57 | 1.59 |

N: Number of Criteria. In this study, N = 6, then IA = 1.24.

Table 5. First step of the determination of the CI.

| Parameters | P | IE | DD | FD | Pi | AT |
|------------|-------|-------|-------|-------|-------|------|
| P | 0.262 | 0.144 | 0.24 | 0.303 | 0.525 | 0.25 |
| IE | 0.786 | 0.432 | 0.336 | 0.505 | 0.525 | 0.25 |
| DD | 0.052 | 0.062 | 0.048 | 0.051 | 0.035 | 0.05 |
| DF | 0.087 | 0.086 | 0.096 | 0.101 | 0.105 | 0.15 |
| Pi | 0.052 | 0.086 | 0.144 | 0.101 | 0.105 | 0.15 |
| AT | 0.052 | 0.086 | 0.048 | 0.034 | 0.035 | 0.05 |

Table 6. Second step of the CI calculation.

| Parameters | P | IE | DD | FD | Pi | AT | Total |
|------------|-------|-------|-------|-------|-------|------|--------------|
| P | 0.262 | 0.144 | 0.24 | 0.303 | 0.525 | 0.25 | 1.724 |
| IE | 0.786 | 0.432 | 0.336 | 0.505 | 0.525 | 0.25 | 2.834 |
| DD | 0.052 | 0.062 | 0.048 | 0.051 | 0.035 | 0.05 | 0.298 |
| DF | 0.087 | 0.086 | 0.096 | 0.101 | 0.105 | 0.15 | 0.626 |
| Pi | 0.052 | 0.086 | 0.144 | 0.101 | 0.105 | 0.15 | 0.639 |
| AT | 0.052 | 0.086 | 0.048 | 0.034 | 0.035 | 0.05 | 0.305 |

Table 7. Third step of the CI determination.

| Parameters | Cp | Total (T) | T/Cp |
|------------|-------|-----------|------|
| P | 0.263 | 1.724 | 6.56 |
| IE | 0.432 | 2.834 | 6.56 |
| DD | 0.048 | 0.298 | 6.16 |
| DF | 0.101 | 0.626 | 6.18 |
| Pi | 0.105 | 0.639 | 6.06 |
| AT | 0.050 | 0.305 | 6.07 |

$$CR = CI/AI \leftrightarrow CR = 0.052/1.24 \quad (4)$$

Aggregation of the criteria, which is the sum of the standardized and weighted values of each criterion involved in the development of the indicator concerned. This provides a suitability index on a scale of 0 to 10 [12], since the sum of the weighting coefficients generated by Saaty's method is 1. It is expressed by Equation (5):

$$S = \sum_{i=2}^n W_i X_i \quad (5)$$

S : sum; W_i : weight of criterion i ; X_i : standardized value of factor criterion i .

The establishment of the thematic map of a given indicator, will consist of plotting in a geographical space the different values resulting from the sum of the standardized and weighted values of each intervening criterion of said indicator [13] [27].

Validation of multi-criteria maps by uncertainty analysis, this step is based on uncertainty analysis. The method used in this study is based on the work of [10] [15] [21]. The formula in Equation (6) is used to calculate the uncertainties in the averages of the various parameters of the main indicators given:

$$\Delta X = \sigma / \sqrt{m} \quad (6)$$

ΔX : uncertainty in the mean of the data set; σ : standard deviation of the data set; m : number of data.

Thus, an expansion factor (K) is calculated, in order to determine the confidence level. The parameter K is used to define a sufficiently wide confidence interval with the aim of having high confidence in the results [21]. The expression of this factor K is given by Equation (7):

$$K = (E - X) / \sigma \quad (7)$$

K : expansion factor and E : the extreme value of the statistical series (the minimum or maximum of the series).

The confidence levels of the different parameters were deduced from the different values of K . Thus, $K = 1$ for a 68% confidence level; $K = 2$ for a 95% confidence level and $K = 3$ for a 99% confidence level.

4. Results

4.1. Coherence Ratio

The value of the Coherence Ratio found is 4.2%, which is less than 10%, which justifies that the reasoning is said to be very consistent.

4.2. Availability of Groundwater Resources

The thematic availability map (Figure 3) is composed of three qualifying classes, which are distributed as follows:

- The low availability class represents 34%, and is scattered throughout the study area. This class is characterized by a low thickness of red sandy-silty soils with armor, constituting the products of alteration. These parameters are unfavorable to the recharge of a water table, hence the works are less productive;
- The class with average availability occupies 50% of the study area. It is found mainly in the shallows of the major and minor beds of the Goroubi and Diamangou rivers and in the southern part (bed of the Tapoa) of the study area, where there is active vegetation. In addition, this class is also characterized by a relatively flat relief. Consequently, these two geomorphological units are favorable for groundwater recharge;

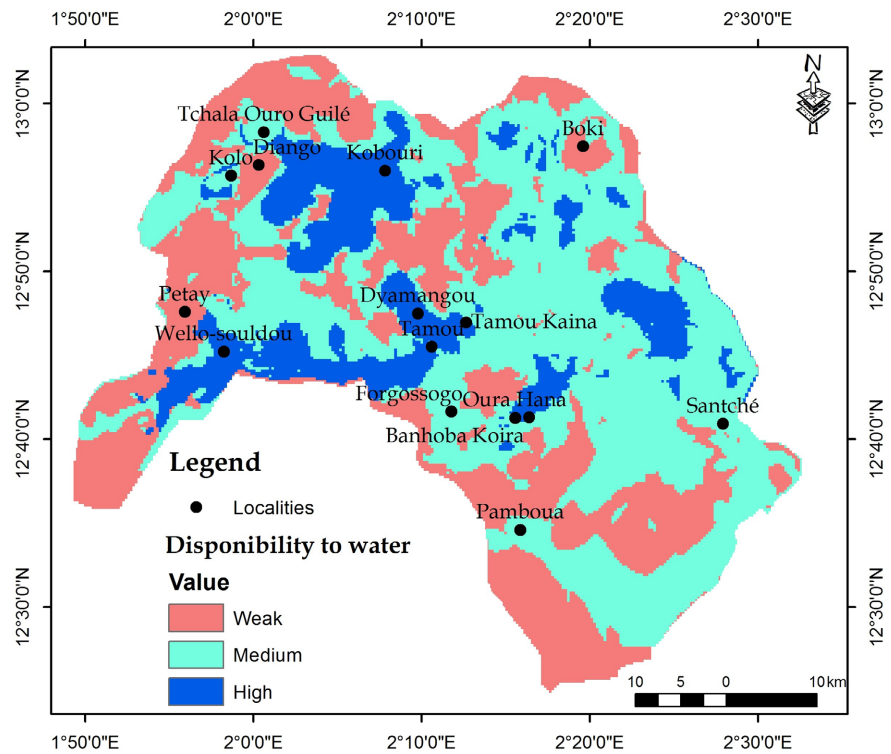


Figure 3. Groundwater availability map of the study area.

- The high availability class covers 16% of the study area. It is observed in the Diamangou valley, in the northwest on the Burkina-Faso border, towards Bala Rimaibé and in the eastern part, around the Niger River valley. This class is characterized by the type of stony or boulder soils. In addition, fault nodes and kilometer-sized faults have been identified through the Landsat ETM+ satellite image in these areas. These factors undoubtedly contribute to the recharge of aquifers, and will help explain the high availability of water resources in this area. This class is sought by hydrogeologists.

The summation of the class of medium and high availability, gives a coverage rate of 66% of the total area of the study area. These results confirm that the study area is moderately covered with a medium availability of groundwater resources, hence the need to map the accessibility of groundwater, in order to identify areas where this availability is easy access.

4.3. Accessibility to Water Resources in the Study Area

The analysis of the accessibility map (**Figure 4**) shows 3 classes of unequal distribution.

Areas of low accessibility occupy 40% of the study area. The structures located in these areas are characterized by high depths, with low probabilities of finding positive boreholes. These zones are mainly found in Bamboma, Dori, Lélé, Lilo, Petay, Tchala Ouro Guile, Yangana, Weressouldou, etc.

The medium and high accessibility classes are relatively important and represent 29% and 31% respectively, or 60% of the total area of the study zone. These

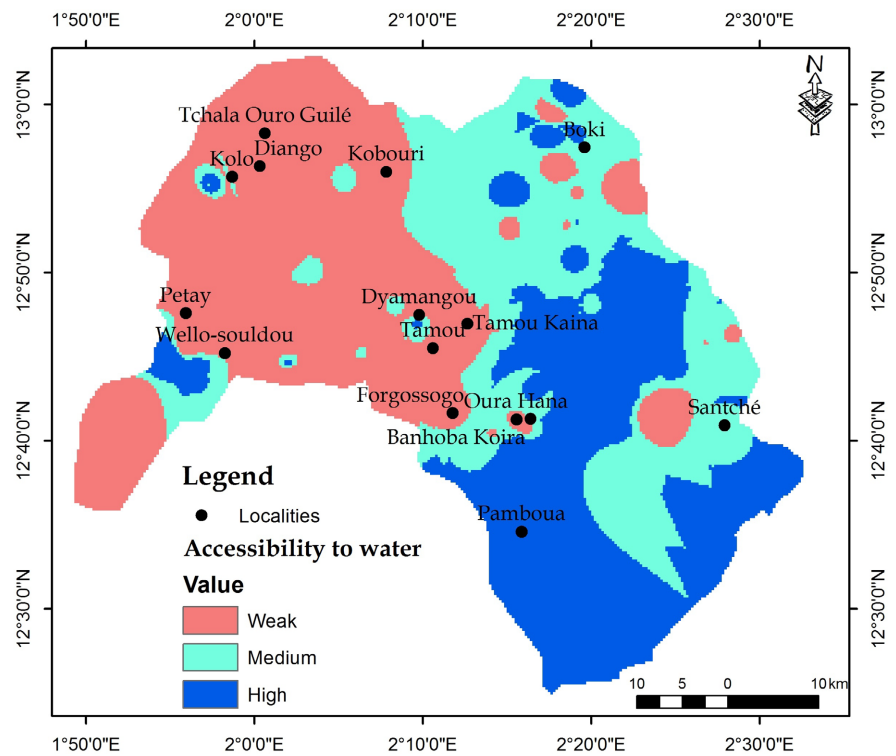


Figure 4. Groundwater accessibility map of the study area.

classes are found throughout the study area, with the exception of the northwestern part of the study area, corresponding to the sub-surface portion of the Birimian basement. These areas are the most sought after for the implementation of large flow structures. Thus, this map is a guide for hydrogeologists.

4.4. Exploitability of Groundwater Resources

The map generated from the exploitation rates and piezometric levels (**Figure 5**) shows three distinct classes, as follows:

- The low exploitable class covers about 69% of the total area of the study area. This is the dominant class and is widespread throughout the study area. This class is characterized by low to very low flow rates;
- The class of average exploitability covers a quarter (1/4), or 25% of the total area of the said zone. It extends from the central part to the NE - SE of the study area;
- The strong class represents only 6%, and is found in the extreme east of the study area, corresponding to the edge of the basin of Iullemmeden. This class is found in the villages of Bolé, Diagoga, Bonkoukou kouara, Forgossogo and Yambidiana.

4.5. Areas Suitable for the Installation of Large Flow Boreholes

The map for the location of high flow boreholes (**Figure 6**) is obtained by combining the availability, accessibility and exploitability maps. It also shows three different classes.

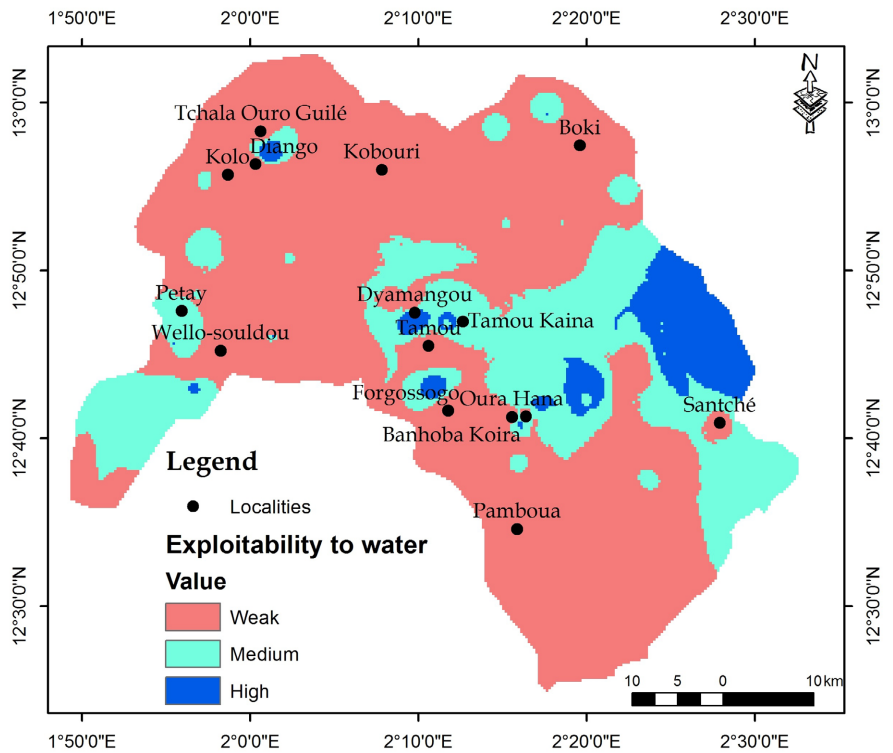


Figure 5. Groundwater exploitability map of the study area.

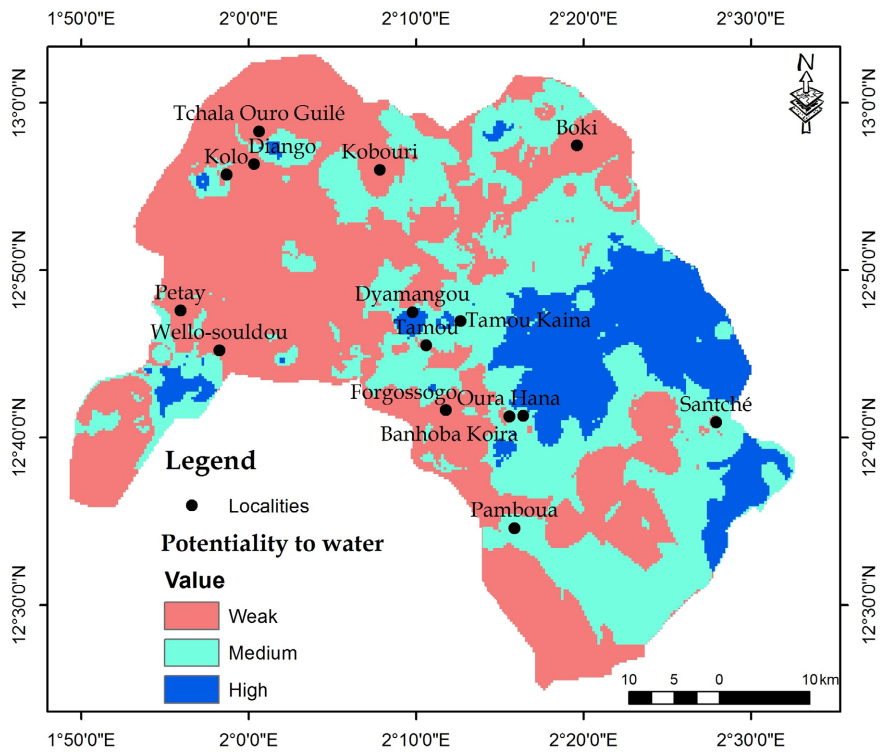


Figure 6. Map of areas suitable for the installation of high flow boreholes.

The low class occupies 54% and is found almost everywhere in the study area, with the exception of the eastern part and the extreme south. It is characterized

by low availability, accessibility and exploitability of groundwater resources. Nevertheless, in this class, the structures can have a flow of about 1 m³/h.

The low flow areas dominate the study area, and are characterized by high drainage densities and low induced permeabilities.

The middle class represents 26%, and is unevenly distributed over the territory. Indeed, it is mostly observed in the South, South-East and North-East parts.

The strong class has a portion estimated at about 20%, and is found in the eastern and southeastern parts of the study area. It is characterized by a good accessibility and exploitability, and corresponds to the most favorable area for the implementation of drilling with large flows.

4.6. Validation of Thematic Maps

The thematic maps were validated by calculating the uncertainty associated with the criteria of the different indicators (**Table 8**).

The uncertainties calculated on the availability evaluation parameters vary from ± 0.076 to ± 0.671 . However, it appears that on all the criteria of this indicator, the errors committed are negligible, apart from that of the infiltration, which is ± 0.67 . The level of confidence is significant with a rate of 95% for all the criteria defined for the elaboration of the thematic map of groundwater availability.

Regarding the accessibility indicator, the depth and success index parameters have uncertainties of ± 1.221 and ± 0.407 respectively, and confidence levels of 95%.

The exploitability map has a margin of error of ± 0.814 with a 95% confidence level.

As for the parameters of the map of potential high flow sites, the errors vary

Table 8. Statistical summary of indicator evaluation criteria.

| | Parameters | Min | Max | Medium | Standard Deviation | Uncertainty | K | NC (%) |
|-----------------------------|----------------|------|------|--------|--------------------|-------------|---|--------|
| Disponibility | Infiltration | 0.43 | 4.3 | 2.236 | 1.5 | ± 0.671 | 2 | 95 |
| | Slope | 0.26 | 2.6 | 1.35 | 0.91 | ± 0.407 | 2 | 95 |
| | DD | 0.05 | 0.5 | 0.26 | 0.17 | ± 0.076 | 2 | 95 |
| | FD | 0.10 | 0.7 | 0.52 | 0.35 | ± 0.157 | 2 | 95 |
| | Pi | 0.10 | 1.1 | 0.57 | 0.38 | ± 0.170 | 2 | 95 |
| | AT | 0.05 | 0.5 | 0.26 | 0.17 | ± 0.076 | 2 | 95 |
| Accessibility | TD | 0.75 | 7.5 | 4.05 | 2.73 | ± 1.221 | 2 | 95 |
| | Is | 0.25 | 2.5 | 1.35 | 0.91 | ± 0.407 | 2 | 95 |
| Exploitability | Qexp | 0.75 | 7.5 | 4.05 | 2.73 | ± 1.221 | 2 | 95 |
| | NS | 0.25 | 2.5 | 1.35 | 0.91 | ± 0.407 | 2 | 95 |
| Potential at High Flow Rate | Disponibility | 0.17 | 1.62 | 0.87 | 0.58 | ± 0.259 | 2 | 95 |
| | Accessibility | 0.5 | 5 | 2.7 | 1.82 | ± 0.814 | 2 | 95 |
| | Exploitability | 0.5 | 5 | 2.7 | 1.82 | ± 0.814 | 2 | 95 |

from ± 0.259 to ± 0.814 . It should be noted that all these criteria have a 95% confidence level.

All these thematic maps have a low uncertainty error and a high confidence level (95%), which means that these maps are close to the reality of the field.

5. Discussion

The study area has overall medium to high groundwater availability (66%) which is satisfactory. This good availability is due to the low slopes and significant fracturing density. These two parameters are likely to favor aquifer recharge [28]. This good water availability, observed throughout the study area, could be explained by the presence of agricultural land, possessing a high infiltration capacity. These results are in line with those obtained in the Korhogo department in Côte d'Ivoire by [29] in the Tamil Nadu area in China, by [30] in the Lobo watershed in Côte d'Ivoire, by [18] and finally in the Bandama watershed in Côte d'Ivoire by [9]. Nevertheless, it is important to know that the identification of areas with medium and high potential does not guarantee a 100% success rate of drilling, even if the probability seems high [14]. In addition, the geophysical study and other socio-cultural data (proximity of cemeteries, places of worship etc.) must be integrated.

Accessibility is dominated by the middle and strong classes, with a cumulative 60% coverage of the study area. This would indicate that the majority of boreholes in these areas have depths, more or less average, between 30 and 60 m, with high success rates (greater than or equal to 70%). These results are in agreement with the work of [18] [21].

The groundwater exploitability of the study area is difficult, as 69% is dominated by the low class. In fact, according to [31], granites and shales represent the most productive lithological formations in fractured or altered basement zones. Nevertheless, the weak class remains dominant in this sector. This observation can be explained by the absence of serious studies before the implementation of drilling [13]. However, the areas of medium and high exploitability are favorable for urban hydraulics and agricultural development [11]. These classes, which represent 31%, correspond to areas where boreholes generally have more or less important flows. On the other hand, the remaining 69% of the zones are characterized by structures with low or even negative flow rates.

The zones that are favorable for the installation of large flow boreholes are dominated by the low class. In this class, the flow rates of the wells are around 1 m³/h, which is sufficient to supply the populations of small villages [32]. Thus, the medium class, relatively low (26%), may correspond to acceptable areas for the establishment of boreholes in the context of improved village hydraulics [16] [18].

6. Conclusions

This multi-criteria analysis study, whose objectives were to develop maps of

fracture networks and assess the availability, accessibility and exploitability of groundwater resources, in order to help improve knowledge of areas potentially favorable for the establishment of boreholes likely to give more satisfactory flows, shows that: more than half (66%) of the Tamou area has good hydraulic potential, good accessibility and a low class of exploitability.

The areas suitable for the installation of large flow boreholes (medium and high class) cover less than half (46%) of the study area. These areas are mainly concentrated in the eastern and southeastern sectors, in accordance with the distribution of alluvial plains and agricultural land with high infiltration capacity. These thematic maps remain as a guide and can help in the decision-making process during future hydrogeological prospecting campaigns while avoiding intense failures in the realization of hydraulic works.

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Conflicts of Interest

The all authors declare no conflict of interest in this publication.

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