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Contribution of Remote Sensing and Geographic Information System to Identify Potential Areas of Groundwater in the Department of M'Bahiakro (Central-East of Côte d'Ivoire)

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Authors' contributions

This work was carried out in collaboration between all authors. Author TL designed the study and performed analysis and interpretation. Author OSA wrote the primary draft of the paper. All authors read and approved the final manuscript.

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ABSTRACT

This study concerns an area located at central-east of Côte d'Ivoire and constituted by fractured crystalline and metamorphic rocks. In this area, problems of drinking water supply exist because of overpopulation and lack of knowledges about groundwater prospection. This study aims to highlight hydrogeological potentiality areas where drilling can provide a large discharge. Database is constituted by technical data from drillings and satellite images of Landsat ETM+. Remote sensing tools, multi-criteria analysis and geographic information systems (GIS) are used in this study. The results indicate that water resources are available in this area. GIS enabled to elaborate thematic maps of

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groundwater. Indeed, more than 80% of studied area has good to excellent availability of groundwater. Poor and bad groundwaters potentiality classes respectively cover 14 and 6% of the studied area. These resources are well exploited over 78% of the territory with good and excellent exploitability of groundwater resources. However, these resources are not easy to be reached because 67% of the territory presents difficult accessibility. Results of this study constitute an important element that must be considered for hydrogeological prospection.

Keywords: M'Bahiakro; fracturing; remote sensing; GIS; groundwater resources.

1. INTRODUCTION

Water is very unequally distributed across the globe and its accessibility can be problematic in certain area (depth, topography, location, etc.). With aspect such as the rapid economic development of regions, the overpopulation and its water needs, an inappropriate exploitation of water resources can lead to develop dramatic consequences [1].

For several decades, many complaints about quantitative and qualitative aspects of drinking-water arise with insistence in Africa generally and particularly in Côte d'Ivoire. Many official and private structures were established in Côte d'Ivoire to ensure water supply for populations. Society of Water Distribution in Côte d'Ivoire (SODECI) is responsible for water supply in urban cities. It is supervised by services of Water of Forest and Economic Infrastructures Ministries. These public services equipped villages with drinking water points. With the help of international partners, many drillings programs have been carried out. Actually, more than 19 500 drillings are exploited in the Country [2,3]. However, many drillings are unusable because of maintenance and mechanical failures. The basement of Côte d'Ivoire is essentially composed by crystalline and metamorphic rocks. The main aquifers are formed by weathered material, fissured layer and faults [4,5]. The two lastare protected from seasonal variations and possible accidental pollution [6,1,7,8,9].

Therefore, it appears necessary to know these fractured reservoirs for better use and management of their water resources because their hydrogeological importance is considerable [1,10].

The study of fracturing constitutes the first stage of the hydrogeological survey. Remote sensing reveals interesting reservoirs from its synoptic view and the various techniques of digital image process [11,12,13,14,9]. It is an ideal tool to study fracture networks. Hydrogeological, geological and structural knowledges are synthesized and processed through a Geographic Information System. That helps to understand the behavior of fissured aquifers, to map groundwater reservoirs and to implement drillings with large discharges.

The department of M'Bahiakro knew in the last decade an important increasing of its population. This overpopulation favored strong water pressure. This people meet serious water problems with harmful effect on subsistence activities and drinking water supply. It is in order to provide solutions about these problems that this study was undertaken. During last decade, the location of drillings in rural areas was based on geomorphological considerations [15,1]. This led to obtain low discharge and high failure rate. Geophysics and photo interpretation intervene as a last resort. The use of satellite images and radar gave satisfactory results in hydrogeological exploration of Precambrian basement of Côte d'Ivoire, even with exceptional discharges. Indeed, drillings generally located near or on the fractures delivered exceptional high discharges. In Man-Danané and Korhogo areas, very high discharges have been obtained respectively from 20 to 90 m^3/h [1,16] and from 18 to 66 m^3/h [17]. This study aims to highlight hydrogeological potentiality areas where drilling can provide a large discharge. It concerns Central-East area of Côte d'Ivoire, where tectonic events led to the installation of a very developed and dense fracturing pattern in these formations.

2. STUDY AREA

Located in Central-East of Côte d'Ivoire, the department of M'Bahiakro lies between latitudes 7º20 and 8º00 north and longitudes 3º30 and 4º40 west (Fig. 1). It covers an area of 5 460 km^2. Its climate is an equatorial transition one which is characterized by 2 rainy seasons and 2 dry seasons. This area is drained by 2 main rivers: The Comoé and the N'Zi. The low drainage density shows the influence of the long dry season on these rivers.

Geologic formations of this area are constituted by granites and volcano-sedimentary formations (Fig. 2). Their age is Birimian and they were structured during the Eburnean orogeny [18]. From a tectonic view, this areahas experienced several stages of deformation whose major tectono-metamorphic event is Eburnean orogeny. These deformations led to establish significant fractures in the Baoule-Mossi area of Côte d'Ivoire.

On hydrogeological view, 3 principals aquifers are distinguished: Unconsolidated alterite (saprolite or weathered material), fissured layer and faults of basement [4,19,3,20,5]. Weathered material essentially has capacitive function and fissured layer a conductive one. Fissured layer and faults of basement are exploited by drillings. The quality of these waters generally is better because of their protection from anthropogenic pollution and their great depth [1,21].

Fig. 1. Location of study area

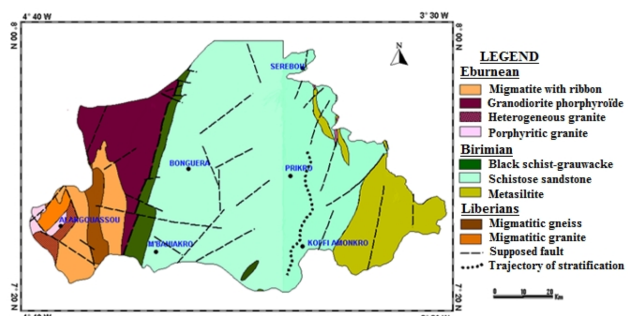

Fig. 2. Geological map of study area

3. MATERIAL AND METHODS

3.1 Data

Several data have been used in this study. These are cartographic, hydrogeological and satellite image data.

Cartographic data are constituted by topographic and geological maps of M'Bahiakro and Agnibilékrou-Kouamé-Dariareas. Topography and geology maps have been established respectively by Cartography and Remote Sensing Center (CCT) of National Office of Technical Studies and Development (BNETD) and Direction of Geology. These maps are established at 1/200 000 scale. On the topographic map, there are informations about the slope, relief and drainage networks. On the geological map there are informations about lithology and tectonic.

Hydrogeological data concern drilling from technical sheets. These data are discharge, depth of drillings, static level, thickness of weathered material, lithologic nature, etc. Over the last three decades, several researches about drilling programs have been carried out at M'Bahiakro area. These research aims to improve the supply of drinking water in the villages and, from a more methodological point of view, ata better knowledge of these reservoirs. A more quantitative hydrogeological approach was thus implemented to characterize these reservoirs [22].

Satellite images studied come from the satellite Landsat 7 with its powerful ETM + sensor, acquired on December 24, 1999, corresponding to the long dry season in the area. One scene 196-055 was used. The choice of this image is motivated by the lack of clouds in this area during the dry season, hence the lack of vegetation that covers outside forests galleries. Also, Landsat image have been selected for their spectral characteristics, structural analysis and large scale mapping [23]. The digital process of satellite images was carried out at the University Centre for Research and Application in Remote Sensing (CURAT) of University Felix Houphouet-Boigny (at Abidjan-Côte d'Ivoire) by using ENVI 4.1 software.

3.2 Methodology

The methodology includes2 approaches. The first approach is to study the fracturing map of studied area which is obtained after validation. It is based on structural lineaments mapping. The second is to identify favourable areas (high hydrogeological potentiality) for the establishment of productive drillings (large discharges) by using a Geographic Information System (GIS).

3.2.1 Methods of structural lineaments mapping

Several studies [6,24,25,7,26,14,27,28] in Côte d'Ivoire showed the contribution of remote sensing and GIS in the identification of water resources.

The mapping of structural lineaments is more or less depending on the ability of operator. It begins with the pre-treatment which consists of radiometric and geometric corrections. Then, contrast enhancement, enhancement of contours, spatial filtering and retrieval lineament networks constitute the treatment. The different steps for extraction of lineament networks are summarized in Fig. 3.

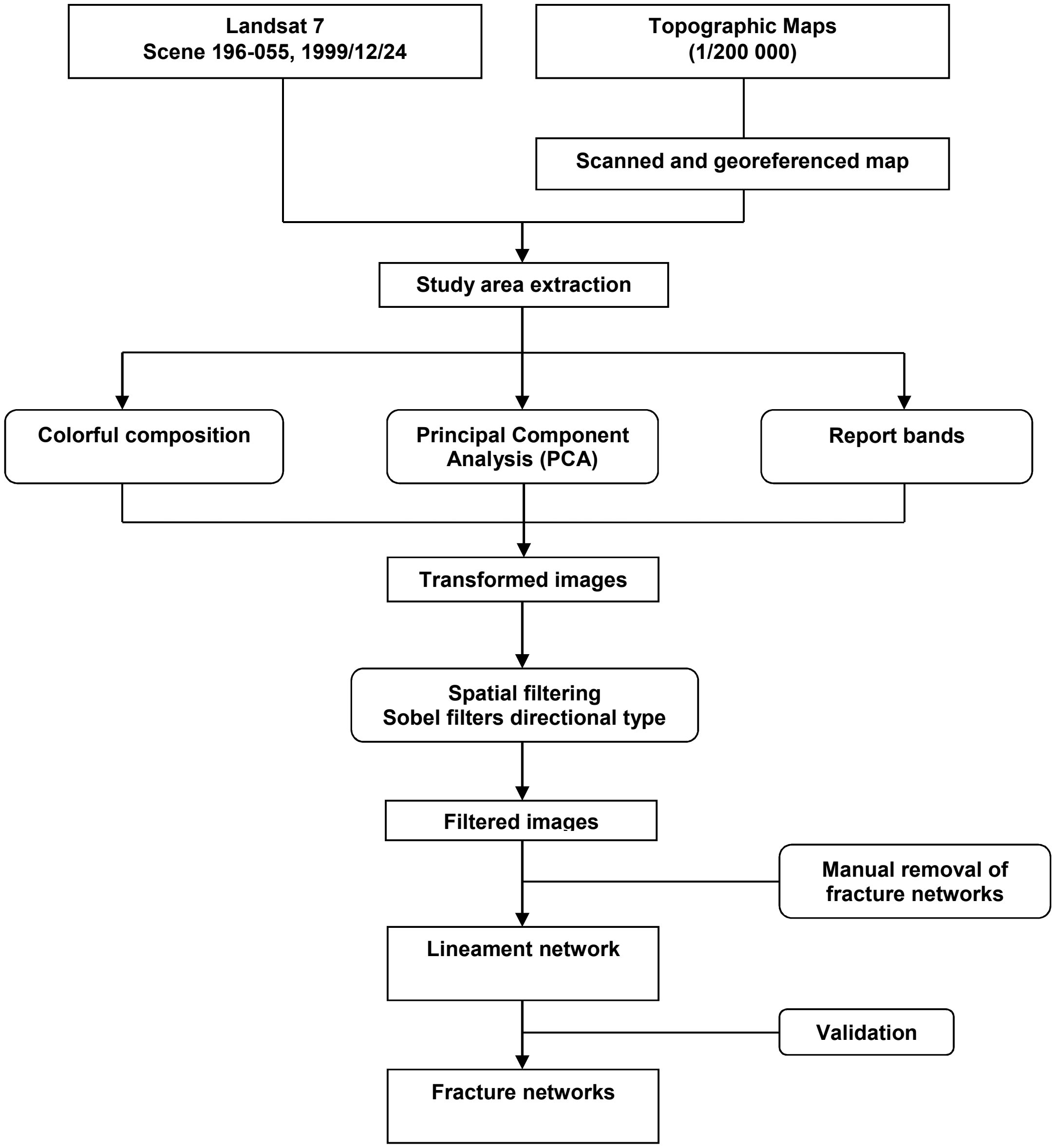

Fig. 3. Procedure of lineaments extraction

3.2.2 Control and validation of lineaments

Evaluation and validation of the extracted lineaments from digital processing stage of satellite images are essential to judge the efficiency of the method used [29,30,31,25].

Identified lineaments from Landsat ETM have been a frequency analysis to highlight the directional maxima. These directions are then compared to those identified during the field campaign or existing geological maps accidents [10,14]. Lineaments mapped by satellite imagery used in this study have a value of fracturing and could be related to fractures or tectonic discontinuities [1,32,10]. Indeed, during the validation phase, lineaments withan origin other than tectonics were removed [10,14].

3.2.3 Design of geographic information system

The methodology design of the Geographic Information System requires 5 main steps:

i) Design and data generation, data acquisition,
ii) Data management,
iii) Processing and analysis of data,
iv) Display of data,
v) And interpretation of data.

3.2.3.1 Definition of factors

Six factors were selected in this study as recommended by several authors [24,33,34,7,17]. They are:

- The slope, it is determined from topographic maps at 1/200 000;
- The fracturing density, it is determined by using the fracturing map made from satellite images. It identifies areas that facilitate infiltration;
- The drainage density, it is obtained through the hydrographic networks from topographic maps at 1/200 000;
- The thickness of weathered material, it is determined from the data sheets of drillings;
- The static level determined from the data sheets of drillings;
- The depth of drillings obtained from data sheets.

3.2.3.2 Data processing

3.2.3.2.1 Classification factors

Five classes were selected for each factor as it has been suggested by various authors [24, 34,17] in crystalline and metamorphic environments: very low, low, medium, high and very high. Table 1 provides information on the limits based on classes of 6 factors selected.

Table 1. Limit of factors

Factor	Class				
	Very Low	**Low**	**Average**	**Strong**	**Very strong**
Slope (%)	< 0.1	0.1-1	1-3.5	3.5-5	> 5
Fracture density (km/km^2)	<11	11-21	21-31	31-40	40-50
Drainage density (km/ km^2)	< 07	7-9	9-11	11-17	17-21
Weathered thickness (m)	< 10	10-15	15-25	25-40	40-67
Static water level (m)	< 10	10-25	25-35	35-45	45-57
Drilling depth (m)	< 15	15-30	30-70	70-90	90-110

3.2.3.2.2 Evaluation of factors

The factors are evaluated according to their importance from hydrogeological point of view. Assessment of factor considered here are classified into 4 classes: bad, poor, good and excellent (Table 2).

Table 2. Assessment of factor

Factors	Class			
	Bad	**Poor**	**Good**	**Excellent**
Slope (%)	> 5	3.5-5	1-3.5	<1
Fracture density (km/km^2)	< 11	11-21	21-31	31-50
Drainage density (km/km^2)	>17	11-17	9-11	<9
Weathered thickness (m)	< 10	10-15	15-25	25-67
Static water level (m)	> 45	25-45	10-25	< 10
Drilling depth (m)	> 70	30-70	15-30	< 15

3.2.3.2.3 Developing indicators

Indicator development consists to involve factors even 2 by 2,3 by 3or5 by 5. It allows to evaluate different factors in the same map [24] in order to get a better interpretation. Three indicators are achieved:

- Availability indicator is a combination of slope, thickness weathered material, fracture density and drainage density factors. This indicator provides information about open fractures [17]. It will also indicate the existence of an aquifer;
- Accessibility indicator combines the static level and depth of drillings. It reflects the access to groundwater problems. These challenges are economic [24]
- Exploitability indicator, the exploitability of groundwater resource depends on water discharge and the piezometric water level of the aquifer [28]. This indicator determines the existence or not of the productivity of the reserve.

3.2.3.2.4 Evaluation, codification and crossover factors

In Côte d'Ivoire, the GIS first works are those of [6]. Subsequently, several studies have been made [24,25,34,7,35,36]. However, the choice of aggregation methods varies according to the authors. Weighting and codification methods have been used respectively by [24,34] and [7,17].

Codification is to match each class with a "code". The scoring system used is the arithmetic progression within the "points" obtained can be added with those from classification on other factors [17]. Assignment of codes 1, 10, 100 was adopted to facilitate the distinction of variants after crossing thematic maps. This concept was called "traceability". Indeed, after crossing, distinction is facilitated in this case variant 11 results from intersection of 10 and 1 variants. So, variants are tracked down. Table 3 summarizes various indicators, factors, classes and codes of these classes.

Table 3. Classes and codes of factor indicator

	Indicators	Factors	Classes	Codes
Water potentiality of drillings	Availability	Drainage density (km/km^2)	< 7	50
			07-09	40
			09-11	30
			11-17	20
			17-21	10
		Fracture density (km/km^2)	< 11	1
			11-21	2
			21-31	3
			31-40	4
			40-50	5
	Accessibility	Static water level (m)	< 10	50
			10-25	40
			25-35	30
			35-45	20
			45-57	10
		Drilling depth (m)	< 15	5
			15-30	4
			30-70	3
			70-90	2
			90-110	1
	Exploitability	Slope (%)	< 0.1	50
			0,1-1	40
			1-3.5	33
			3.5-5	20
			5-9.5	10
		Weathered thickness (m)	< 10	1
			10-15	2
			15-25	3
			25-40	4
			40-67	5

As an example, we present values of each variant after crossing of the factors according to their classes (Table 4).

The crossing of factors sensitivity class was made by taking into account environmental field, dominant and minus factor.

Thus, for the example (see Table 5):

- A class of excellent sensitivity results from crossing the very small class of high (drainage density) and the very strong factor of minus (fracture density).

- A class of good sensitivity is obtained from the crossing of the lower class and the important factor of minus strong factor;
- A class of poor sensitivity comes from the crossing of the middle class of the most important factor and the middle class to the very low minus factor;
- A class of very bad sensitivity results from the crossing of the strong class of the most important factor and the very low one. It can also be obtained by the crossing of the high class of the dominant factor and the factor of minus strong factor.

Interpolation and crossing factors are made from the module «Spatial Analyst" of ArcView 3.2 software.

Table 4. Values taken by each class after crossing of factors

Fracture density (km/km^2)	**Drainage density (km/km^2)**				
	Very low 50	**Low 40**	**Middle 30**	**Strong 20**	**Very strong 10**
Very low	51	41	31	21	11
Low	52	42	32	22	12
Middle	53	43	33	23	13
Fort	54	44	34	24	14
Very strong 5	55	45	35	25	15

Table 5. Assessment factor of water availability map

Fracture density (km/km^2)	**Drainage density (km/km^2)**				
	Very low 50	**Low 40**	**Middle 30**	**Strong 20**	**Very strong**
Verylow 1	Good	Good	Poor	Bad	Bad
Low 2	Good	Good	Poor	Bad	Bad
Middle 3	Good	Good	Poor	Poor	Bad
Fort 4	Excellent	Good	Good	Poor	Poor
Verystrong 5	Excellent	Excellent	Good	Poor	Poor

3.2.3.2.5 Potential water validation map

The crossing maps about availability and exploitability in water allowed to obtain the map of groundwater recharge. Then this map was crossed with the one of water accessibility to obtain the final map of potentiality. For the validation of thematic map of potentiality, we used drillings discharge data because of their independent nature. Indeed, the endpoint must obey 2 principles which are independence and compliance [17]. Discharge of drillings is not involved in the production of potential water map. The principle of compliance has been met. It requires that discharges are grouped into class with the same characteristics as potential map for assessment.

3.2.3.2.6 Validation mode: Trendlines curve sensitivity

Map of drillings discharge has been subdivided into 5 classes (very high, high, medium, low and very low) and was superposed on the thematic map of potential water. It was noted then, for each class of sensitivity: The map of potentiality in water, and the number of drillings therein according to their class. This produces a number of drillings for each sensitivity class of map of potentiality in water. The percentage of each class and the sensitivity factor were calculated relatively to the total number of drillings obtained by class factor (discharge). Curves (trend sensitivity) frequency expressed as a percentage (%) by sensitivity classes according to the classes of discharges have been built. Finally, the shape of the trendlines sensitivity obtained is compared with theoretical curves trend sensitivity classes (Fig. 4) for validation [17].

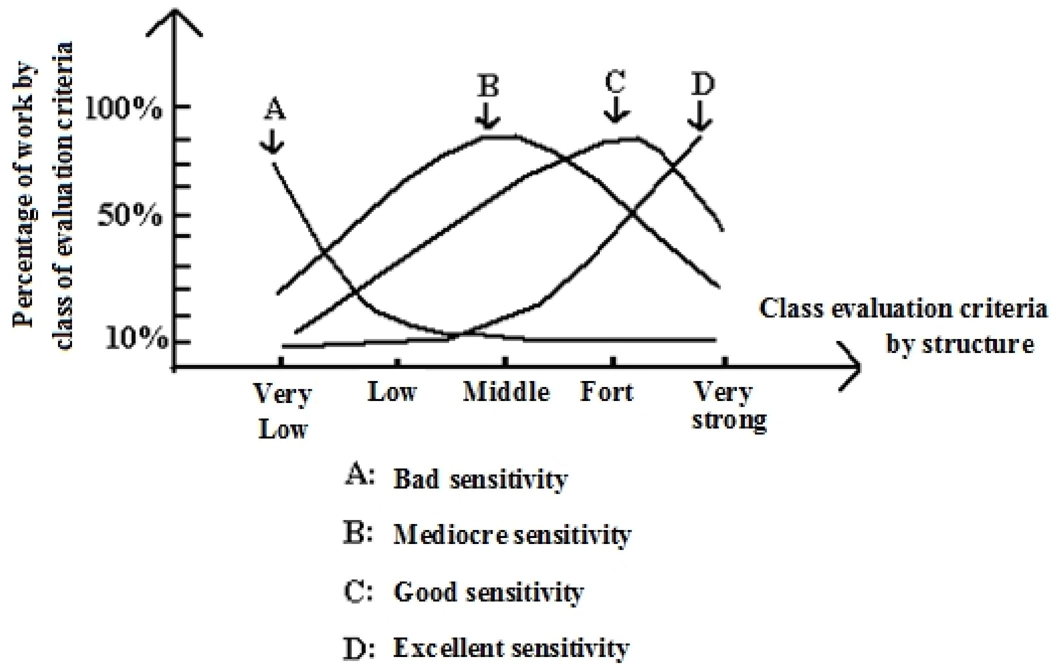

Fig. 4. Standard curve trend of sensitivity classes according to the discharges ([17])

According to these authors, each trend materializes sensitivity behavior of a given sensitivity class opposite to an assessment factor. For a given sensitivity class theme is a reflection of the reality on the field, and the trend is of the form of one of the theoretical curves defined above corresponding to the class:

- Trend of excellent sensitivity class must be the unimodal shape (D);
- Trend of good sensitivity class must be the unimodal (C);
- Trend of poor sensitivity class must be Gaussian curve (B);
- Trend of the sensitivity class of the poor must have unimodal shape focused on the low class factor (A).

Fig. 5 summarizes steps for establishing the map of groundwater potential of M'Bahiakro area.

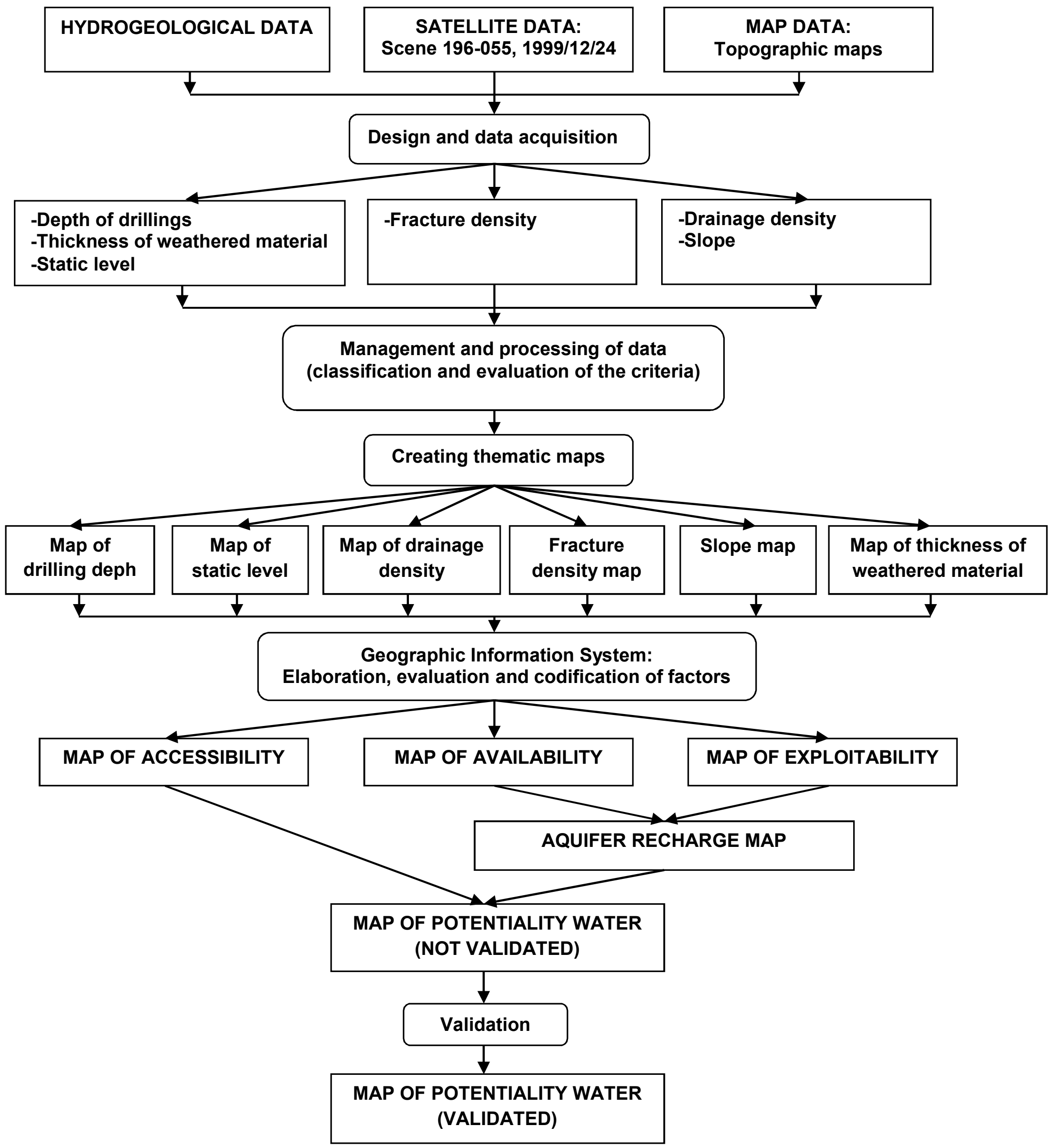

Fig. 5. General organization of the major steps in a GIS

4. RESULTS

4.1 Lineament Map

Lineament networks map of M'Bahiakro area is illustrated in Fig. 6. This map has been validated with field knowledge, geological and structural maps. So, map of lineament networks has fracturing value. Fracturing map contains numerous fractures with sizes ranging from several hundred meters to several kilometers. Although it is not exhaustive, this map can be representative of geological structures of the study area. This map of fracturing can be a useful aid in the search for better knowledge and understanding of the geometric properties of fracture networks for hydrogeological purposes and / or mining. Fracture density is unevenly distributed across the studied area. South, center, south-east and north-east areas are densely fractured (see localities of Prikro, Kofi Amonkro and Eastern of M'Bahiakro).

This difference of fracture density can be interpreted by geological constraints those have affected the area on the one hand and on the other hand by petrographic nature of the rocks.

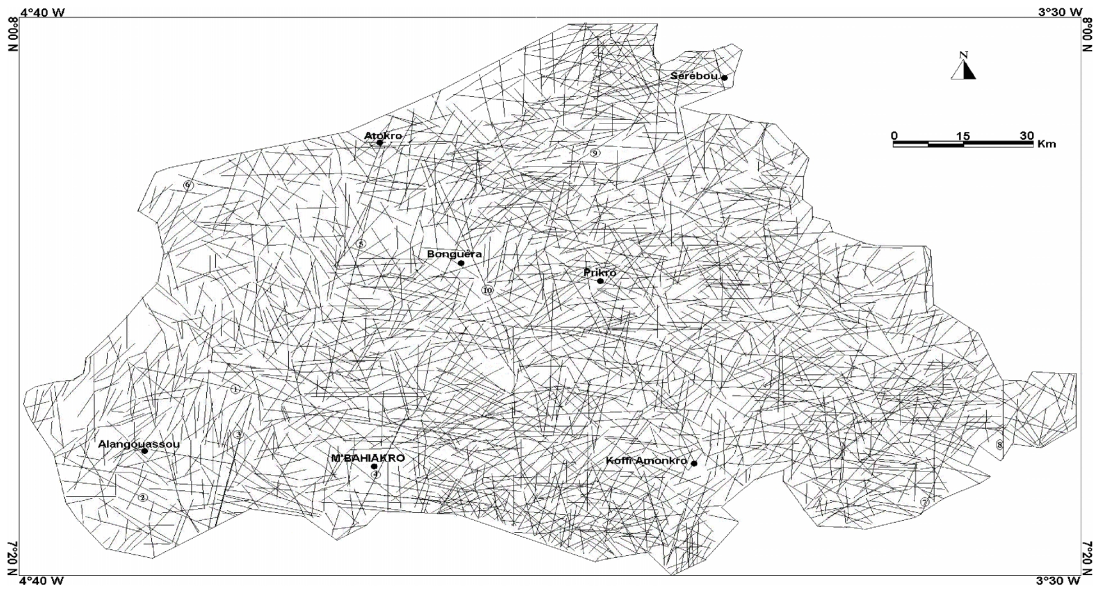

Fig. 6. Fracturing map of department of M'Bahiakro

4.2 Statistical Analysis of Fracture Networks

Circular histograms of fracturing expressed in number and cumulative length are shown in Fig. 7. The analysis shows that the classes of fracturing N-S (N00-10 and N170-180), NE-SW (30-50), EW (N90-110) and NW-SE (N130-150) constitute major classes of fracturing in M'Bahiakro area. The other classes are secondary directions of fracturing with less than 6% frequency. The analysis of the frequency distribution of lengths accumulated indicates a similarity with the frequency distribution of the number of fractures. This result shows that the main directions of fracturing are also longer.

Fracturing map has several hundred fractures whose sizes vary in the interval [0.698 km; 47.114 km] with an average length of 7.06 km. The lengths of fractures extend over 3 orders of magnitude. The total length of lineaments mapped on the study area is 11 306.99 km. The area generally has numerous long fractures (>5 km) corresponding to 61.5% of all lineaments.

Frequency in number Frequency in cumulated length

Fig. 7. Circular histogram of fracturing

4.3 Hydrogeological Characteristics

The analysis of Table 6 indicates that medium to very high discharges are 45%. This result shows that about half of the discharges exceed 2m^3/h. That can be considered as satisfactory, because only 1 m^3/h is considered sufficient to supply drinking water for rural communities. Drillings less than 1 m^3/h represent 55% of drillings studied.

Table 6. Classification of discharges

Discharges classes (m^3/h)	**Number of Drillings**	**Discharge %**	**Productivity**
< 1	48	22.54	VeryLow
1-2	70	32.86	Low
2-5	76	35.68	Average
5-10	16	07.51	Strong
> 10	3	01.41	Verystrong
Total	**213**	**100**	

The influence of weathered material thicknesses on drilling discharges can be seen in Fig. 8. Drilling discharge increases with the thickness of weathered material from 2.73 to 3.38 m^3/h respectively for thicknesses from 20 to 40 m (Table 7). After 40 m, average discharge gradually has been decreasing and reached 2.48 m^3/h to 80 m. Most of large discharges were recorded in weathered material of less than 40 m. This result shows that the weathered material thickness is more important at low discharges. The better weathered material thickness for the producing of large discharge can be fixed at 40 m.

Therefore there is no proportionality between these two parameters. That justifies low discharges at significant weathered material thicknesses.

Table 7. Distribution of average discharge according to weathered thicknesses

Weathered thicknesses classes (m)	Average discharge (m^3/h)	Number of drillings	% of the number of drillings
0-20	2.73	75	54.35
20-40	3.38	38	27.54
40-60	2.96	20	14.49
60-80	2.48	5	03.62

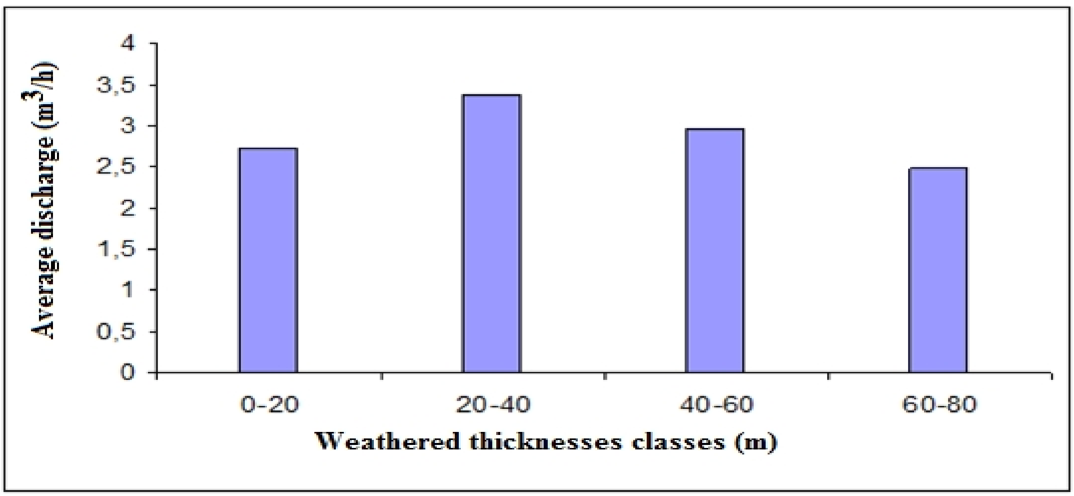

Fig. 8. Variation of average discharge according to weathered layer

Fig. 9 illustrates the relationship between the depth of drillings and the average discharge. This graph shows that average discharge weakly varies at the first 40 meters. This discharge gradually increases between 40 and 80 m (Table 8). Beyond 80 m, there is significant decreasing of discharge. Drilling whose depths are between 40 and 80 m likely encountered acceptable discharges. This result shows here the limit of drilling depths for water supply in rural areas. Lower discharges to great depths may be related to the gradual closure of open fractures. This is not always true because the probability to encounter hydraulically active fractures at great depths sometimes reaching more than 400 m is not null. This is the case of inflows encountered in the mines came to great depths sometimes with even exceptional high discharge. In our regions, it is mainly for economic reasons that drilling depths are limited to less than 100 m.

The statistical analysis conducted with the data of discharges exceeding 1 m^3/h in relation to the type of rock indicates that schists are more productive than granites in this part of the country. Indeed, 11 and 54% of drillings produce more than 1 m^3/h respectively on granites and schists.

This productivity of schists can be explained by the presence of schistosity plans arranged vertically in this area in one hand and with good geometrical properties of its fracturing in the other hand.

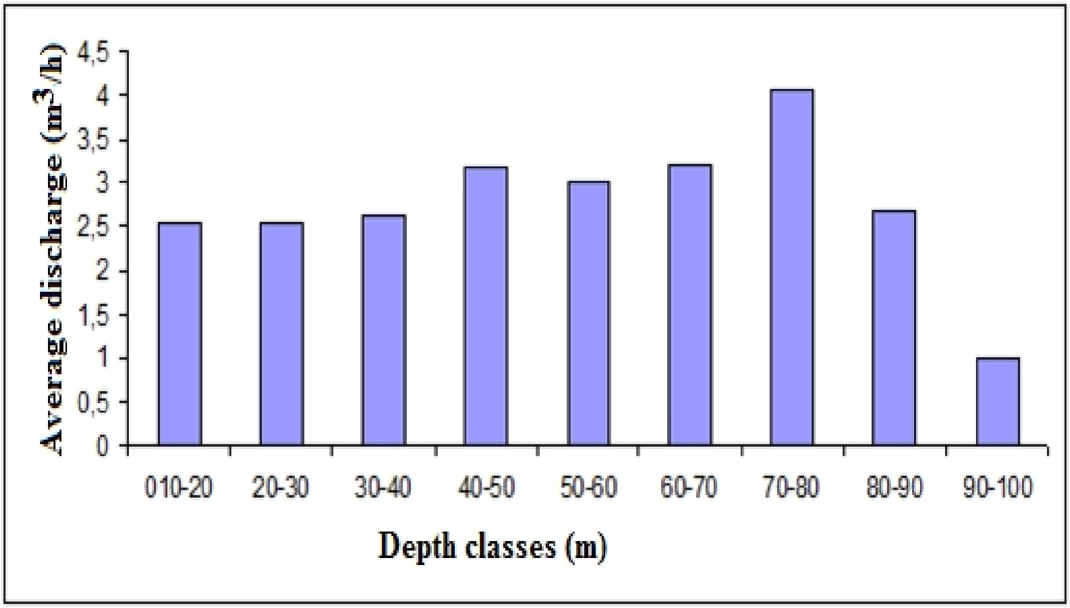

Fig. 9. Variation of average discharge according to drillings depth

Table 8. Distribution of average discharge according to depth classes

Depths classes (m)	Average discharge (m^3/h)	Number of drillings	% of the number of drillings
10-20	2.56	8	05.84
20-30	2.55	18	13.14
30-40	2.64	22	16.06
40-50	3.18	32	23.36
50-60	3	29	21.17
60-70	3.2	18	13.14
70-80	4.05	4	02.92
80-90	2.67	4	02.92
90-100	1	2	01.46

4.4 Thematic Maps

Different hydrogeological, satellite and map data were integrated in a GIS to produce maps of availability, exploitability, accessibility and potentiality water.

4.4.1 Availability map of M'Bahiakro area

Map of water availability is presented on Fig. 10a. It is defined by 4 classes which are:

- The class of bad availability: this class represents 9% of the study area and occupies the northern areas of Serebou and Bonguera and southern of M'Bahiakro. These are areas with very low fracture density and high density of drainage;

- The class of poor availability: it covers 10% of the territory and occupies parts of the area including small beaches south, west and north. These areas have significantly better availability than the previous class in water;
- The class of good availability: this class covers about 35% of the study area. It occupies the central band generally oriented N-S outside the southern M'Bahiakro, northern Bonguera, and some beaches in the south-east and west of the area.
- The class of excellent availability: this class covers most of the area, about 46% of the study area. It is located in the eastern and western parts of the area. These sectors are characterized by high fracture density and very low drainage density. They indicate the presence of very shallow water. In general, the study area has good and excellent availability of groundwater which represents 81% of study area.

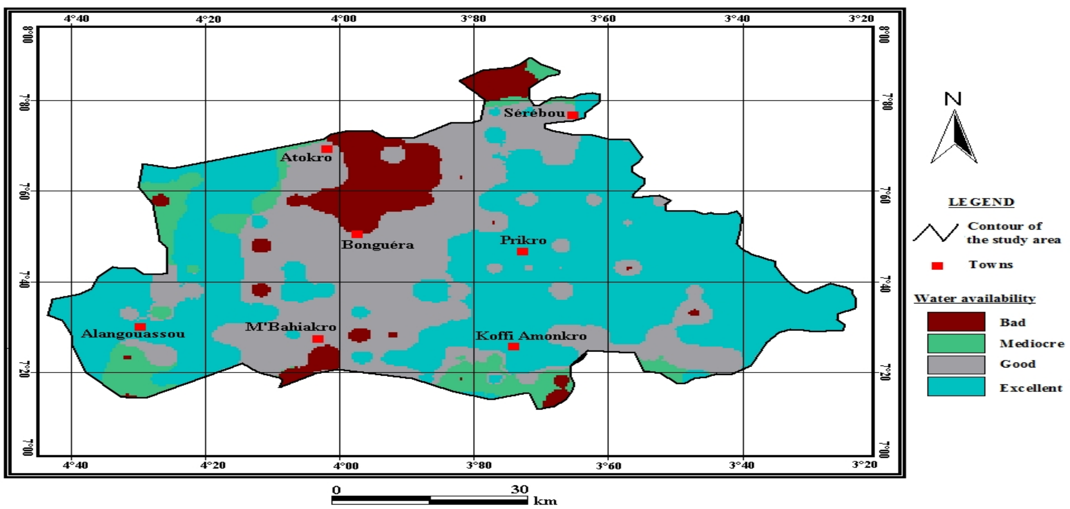

Fig. 10a. Water availability map in M'Bahiakro department

4.4.2 Exploitability map area of M'Bahiakro

The exploitability water map is presented on Fig. 10b. It consists of 4 classes:

- The class of bad exploitability: it represents only 3% of the territory. These areas are characterized by low thickness of weathered material and very steep slopes. These areas are not favourable to urban hydraulic;
- The class of poor exploitability: this class covers about 20% of the territory. It is in the form of thin and winding strips at east, center and slightly to the west. The drillings of these areas feed small towns;
- The class of good exploitability is about 32% of the area, it's scattered on the area. These areas are favourable for small-scale irrigation and drinking water for the population;
- The class of excellent exploitability is the most important, it represents 45% of the territory and occupies almost the whole area. These sectors are characterized by very low slopes and high thickness of weathered material. These sites are important in hydrogeology prospecting and for motorized agriculture.

The groundwater resources of M'Bahiakro area have good conditions for exploitation, and involve more than 75% of the study area.

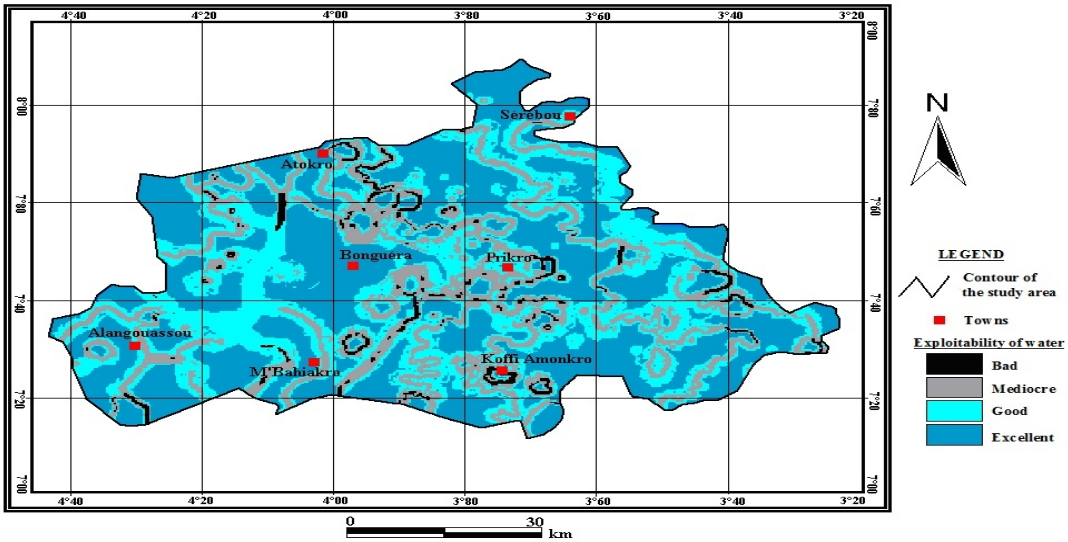

Fig. 10b. Water exploitability map in M'Bahiakro department

4.4.3 Groundwater accessibility map of M'Bahiakro area

The accessibility water map is presented on Fig. 10c. It is defined by 4 classes:

- The class of bad accessibility: characterized by a big depth of drillings, this class represents 35% of the study area. It occupies the center, south and north-west of the area. These sectors have difficult access, water is very deep and their extraction financial supports are expensive;
- The class of poor accessibility: it covers 32% of the territory. It occupies the center, north and South-East of the area. These are sectors where cost of extraction will be expensive.
- The class of good accessibility: this class covers 32% of the study area. It covers the western and eastern areas. These areas are characterized by shallows drilling and good groundwater recharge when the fracture density favours water infiltration;
- Class of excellent accessibility: this class covers 1% of the study area and is located at South-western of studied area. In this area, drillings exploit groundwater from shallow depth.

In general, the study area has poor accessibility (more than 35% of the territory).

4.4.4 Map of groundwater potentiality of M'Bahiakro area

The map of groundwater potential of M'Bahiakro area has been developed after the coupling of different types of data. It indicates favourable and unfavourable sites of drilling implementation (Fig. 10d). The analysis of map of water potential indicates that good to excellent classes are the most dominant. They occupy about 80% (26 and 54% respectively for good and excellent classes) of the study area. These classes are most popular during the hydrogeological studies. The sectors are characterized by high density of fracture, many basins of weathered material, many shoals and the presence of very low slopes.

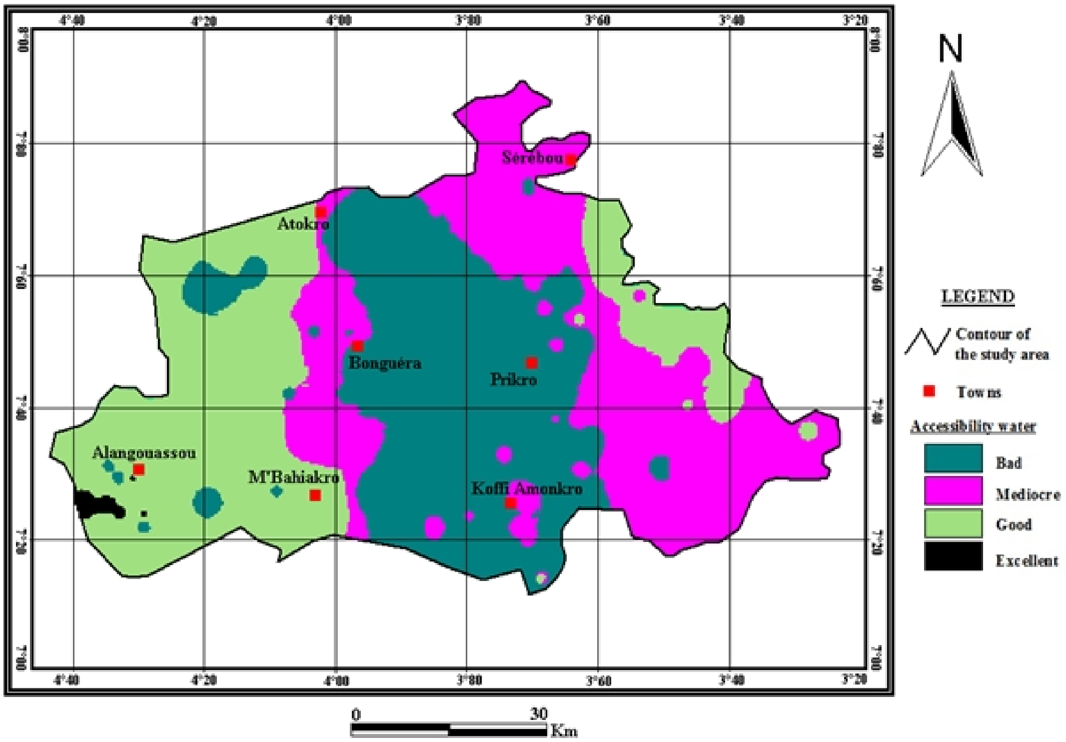

Fig. 10c. Water accessibility map in M'Bahiakro department

The class of poor potential is usually found in west of the study area and disseminated between excellent and good classes areas. We met it around the localities of Atokro, Bonguera, south of M'Bahiakro and in north-west of Serebou. This class covers 14% of the area. These areas are not appropriate to carry out the drillings because it is likely to obtained very low discharges for water supply of rural population. This result can be interpreted in terms of low fracture density in one hand and the presence of high thickness of weathered material in other hand.

Finally, bad potential areas represent only 6% of study area. These areas are presented in small beaches on the whole study area and especially in northern Bonguera. These sites are characterized by steep slope and low fracture density. Infiltration in these areas is difficult because of the lack of shallows.
The execution of drilling in these areas requires further geophysics methods to target major accidents identified by satellite imagery methods.

M'Bahiakro area has a great potential groundwater may constitute sources of drinking water supply for population. It is the result of several factors including the intensity of fracturing and low slope.

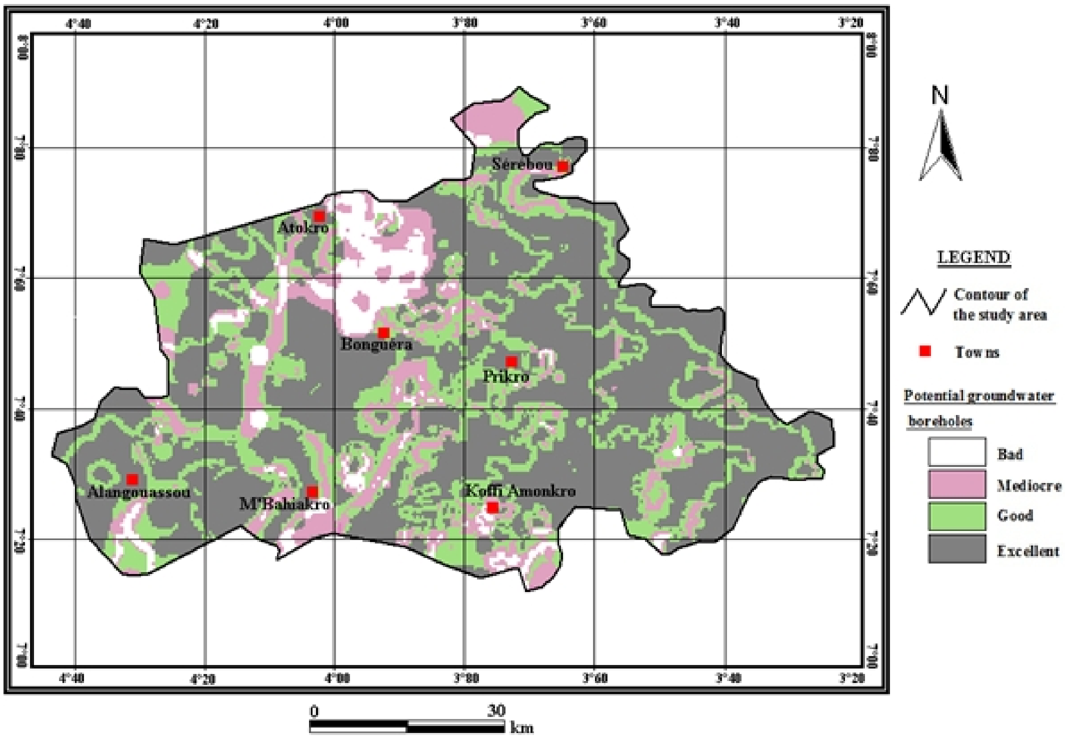

Fig. 10d. Map of water potentiality in M'Bahiakro department

4.5 Validation Map of Potentiality Groundwater

Discharges were superimposed on the thematic map of potential drilling to raise the number of drillings in each sensitivity class of water potentiality. With the number of drillings class, the percentages are calculated (Table 9). The percentages by curves of water potential sensitivity classes depending on discharges have been constructed (Fig. 11). Finally, these curves are compared with standard curves trend sensitivity classes according to the discharges for their validation.

Table 9. Percentage of discharges sensitivity classes

Sentsitivity class	Discharge classes				
	VeryLow	Low	Average	Strong	Very strong
Excellent (%)	21	28	37	31	67
Good (%)	15	17	39	44	33
Poor (%)	26	34	16	19	0
Bad (%)	38	21	8	6	0

The analysis of the different curves points out:

- 67% of very high discharge of drillings superimposed on the excellent sensitivity class;
- 44% of high discharge of drillings overlapped with good class sensitivity;

- 50% drillings with average and low discharges are overlapped classes of poor sensitivity;
- 38% of very low discharge drillings are superimposed on the poor sensitivity class.

This graph reflects the sensitivity of the field. The different sensitivity classes are covered largely by the corresponding discharge of drillings.

Analysis of the results (Table 10) shows that 18 drillings with discharges superior to 5 m^3/h, we have 14 drillings overlap with good to excellent potentiality.

Table 10. Excellent sensitivity classes of drilling discharge

N°	Locality	Class of discharges	Class of sensitivity	Discharges of drilling (m^3/h)
1	Kouamékro	Strong	Excellent	5.1
2	Amankro	Strong	Poor	5.4
3	Attokro	Strong	Good	5.4
4	Donguikro	Strong	Excellent	5.4
5	Anyanou	Strong	Good	5.7
6	Kouadiokro	Strong	Bad	6
7	Bofouimbo	Strong	Good	6
8	Famienkro	Strong	Good	6
9	Sérébou	Strong	Poor	6
10	Essuikro	Strong	Good	6.5
11	Aouan	Strong	Poor	6.7
12	M'Bahiakro	Strong	Excellent	7
13	Kora	Strong	Good	7.7
14	Agbakro	Strong	Excellent	7.8
15	Bendessankro	Strong	Excellent	9
16	Bognankro	Verystrong	Excellent	10.8
17	Koffikro	Verystrong	Good	11
18	Prikro	Verystrong	Excellent	16.8

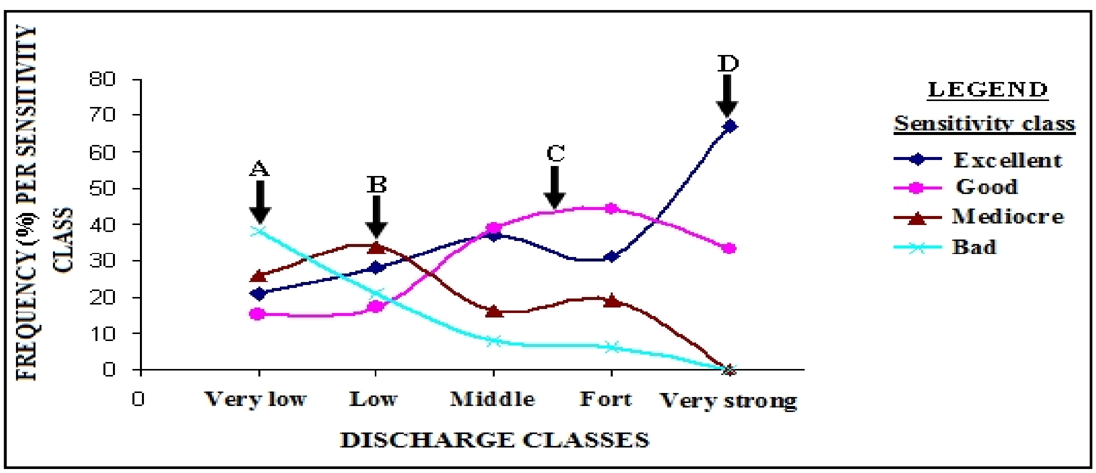

Fig. 11. Trend curves of sensitivity according to discharge classes.

However, 4 drillings in high and very high discharges classes are superimposed on the bad and poor classes. These results demonstrate that the sensitivity classes “excellent and good areas” strongly reflect good potential groundwater reservoirs of the department of M'Bahiakro.

5. DISCUSSION

Lineament Map of M'Bahiakro area is the result of processing performed on Landsat ETM + images. These lineaments reflect the state of fracturing in the basement environment and can provide information about the presence of groundwater in the aquifers of this area.

The numerous structural elements and validation map demonstrate the relevance of the adopted methodology. The various technical process used in this study have provided excellent results. These techniques were used to update the map of existing fracturing. Indeed, many additional fractures have been mapped. This map is representative of fracturing area of M'Bahiakro.

From the fracturing map and hydrogeological data of M'Bahiakro area, several thematic maps were produced within a Geographic Information System (GIS). Similar studies were carried out in Côte d'Ivoire by [34,17,36] respectively in Man, Korhogo and Bondoukou areas.

Thematic maps are made actually and represent a relative assessment of the phenomena. These maps provide useful information that can guide decision making for efficient management of groundwater resources.

Water resources are available in abundance in the area. The availability of water is due to a high density of drainage and good fracture density, which results to a good infiltration of water into the aquifer [37]. The availability of this resource can be difficult. Generally in M'Bahiakro area, the accessibility of groundwater resources is average to good. Good accessibility (32%) linked to depth average of drillings. In addition, discharge of exploitability permits determination of success index which is often greater than 4 m^3/h. This discharge corresponds to an index which is greater than or equal to 80% of success [28]. The exploitability is dominated by excellent (45%) and good (32%) classes. These classes are respectively met on schists and granites. The good exploitability in water of granites could be related to their high fracture density [28].

The importance of potentiality water map obtained is to help prediction of success likelihood in the carrying out of new drillings with large discharge. Indeed good potentiality results from high probability for detecting productive aquifer [17]. Potentiality groundwater map produced by the method of codification reflects the productivity of reservoirs in M'Bahiakro area, as it is shown by the assessment test used to validate this map.

6. CONCLUSION

Studies in the department of M'Bahiakro about the location favourable for the implementation of drillings gave the followings results:

The best discharges are found in the drilling with a weathered material thickness between 0 and 40 m. The depths of economic profitable drilling would be between 40-80 m above the top of the basement. There is no proportional relationship between weathered material thicknesses and discharges in one hand and between depth of drillings and discharges in other hand.

Fracturing map contains numerous fractures with varying sizes, highlighting heterogeneity of studied area. The main directions of fracturing are N-S (N00-10 and N170-180), NE-SW (30-50), EW (N90-110) and NW-SE (N130-150).

The map indicates that 80% of M'Bahiakro area has good potentiality of water resources. Areas concerned are mainly in Central-west and East of the department. This map of groundwater potentiality is a major contribution for knowledge, the optimal use and sustainable management of these resources. It must be taken into account by local authorities for the development director plan of this area. It offers the advantage of considerable reducing of the costs of hydrogeological prospecting and providing of drillings with large discharge.

The potentiality map carried out from the coding method reflects the productivity of discharge of drillings in M'Bahiakro area.

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COMPETING INTERESTS

Authors declare that no competing interests exist.

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