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Remote Sensing and GIS Contribution for Groundwater Mapping Reservoirs in the Baya Watershed (Eastern Region of Côte d'Ivoire)

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Authors' contributions

This work was carried out in collaboration among all authors. Author MJM designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors KAK and GAD managed the analyses of the study. Authors IS and JB managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

This study is carried out in the Baya watershed in the eastern region of Côte d'Ivoire to highlight access to drinking water issue in the fratured areas of Côte d'Ivoire. It aims at mapping the groundwater reservoirs to optimize the future installment of new boreholes for a satisfactory success rate. For the methodological approach we use Landsat 7 satellite images to map fracture networks with the use of the directional filtering technique. The induced permeabilities from these fractures were calculated using Fanciss's method. The multicriteria analysis and Hydrogeological Information System with Spatial Reference were adopted to map groundwater reservoirs. Structural mapping by remote sensing permitted the development of detailed fractures maps with more than 6,998 listed fractures responsible for the formation of fracture aquifers in the Baya watershed. The

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size of these fractures is spread over two orders of magnitude. The main orientations are NE-SO (N70-80), corresponding to the Eburnean orientations, E-O (N90-100) and NO-SE (N100-120), associated with the Liberian orientation.
Induced permeabilities vary from $1.20.10^{-8}$ to $4.62.10^{-5}$ m/s with a regional average of about $5.32.10^{-6}$ m/s. The zones with strong induced permeabilities that coincide with those of high fracturing densities brought us to have five reservoirs in the basin, with two large reservoirs, two media and three small ones. This groundwater flows into the mainstream waters from two main directions.

Keywords: Induced permeability, Remote sensing, Groundwater, GIS, Côte d'Ivoire.

1. INTRODUCTION

Water is an indispensable natural resource in humans' life as well as for animals and plant life. As drinking water is vital, sufficient water quality and quantity contribute to the maintenance of safe drinking water. For the World Health Organization (WHO) statistics, about 1.1 billion people do not have access to clean water and 2.4 billion do not have access to adequate drainage system [1]. Today, water has become a worldwide stake strategy whose management must thoroughly be integrated within sustainable development perspective [2].

In Côte d'Ivoire (west Africa), the shortage of water is noticeable during dry seasons within certain localities, forcing populations to walk for long distances to fetch some permanent surface water whose quality is most of the time bad and its use leads to suffering from many diseases like dysentery, cholera etc [3]. This situation brought people to resort to groundwater. However, supply of good water quality with populations from every season is one of the main concerns of different governments [4]. Supply of safe drinking water is importantly directed to the search for groundwater whose quality meets the requirements of the WHO's international standards [5].

In rural areas like in the Baya watershed, d espite the measures taken by the government of Côte d'Ivoire, the campaign for sensitizing populations is a failure and many of the facilities are drying or do not meet populations' needs within certain areas. The rate of the families who have access to clean water was 24.8 % in 1998 against 32.4% in 1995 [6], which worsen the situation.

The solution for these various problems is certainly in the best knowledge of aquifers of fractures. Studies ([5,7,8,9,10]) have indicated that those aquifers can be real reservoirs for groundwater free from those seasonal fluctuations and to pollution. Therefore, there is a need to better appreciate those fractured reservoirs from new research techniques as their hydro-geological importance is considerable [11,12].

The fracture study is then the preliminary phase for groundwater reservoirs. Some works [13, [14,15,16,10] have shown that fracture field from satellite pictures reveal interesting information thanks to its synoptic vision and especially to the diverse techniques for processing digital pictures of high quality [17]. Thus, remote sensing could be a good tool for studying fractures' networks for water resources assessment. Hydro-geological information, geological and structural information are synthesized and analyzed thanks to multi-criteria analysis and to geographical information system (GIS) that helps for the understanding of the reaction of the aquifers of fractures, for the mapping of groundwater reservoirs as to optimize the future installation of new beholds to have a satisfactory success rate (boreholes with high debits).

2. MATERIALS AND METHODS

2.1 Study Area

Baya watershed is in the eastern region of Côte d'Ivoire between the longitudes 2°38' and 3°33' W and the latitudes 6°35' and 8°26' N. It covers a total area of about 6,324 square km (Fig. 1). The population size is about 478,327 people with a rise of 2.8% (INS, 2014). This basin is covered up with water table used for crops and trades (coffee, cacao, cashier nut) and food crops (Yves et al., 1995). The main geological formations can be divided into three big lithological groups (Youan Ta et al., 2015). A group of tarkwaien and volcano-sedimentary are mainly composed of schist, Amphibolite and of Metadolerite. From the hydrogeologic level, we can identify two types of aquifers within the study area. They are alliterating aquifers and fissured ones. The former is the reservoirs from physico-chemical alliterating processes and from the insular shelf. They are composed of clayey sand and coarse-grained and they represent the first level of reservoir in the board. Those aquifers are operated with rainfalls directly. The latter is to be found in areas and/or damage of the board. Thus, their water capacity is in relation with the board fractured density [18,5].

2.2 Material

Lineament mapping required two stages ETM+ (Enhanced Thematic Mapper plus) of the satellite Landsat 7. The stages are 195-54 and 195-55 of February 2nd, 2000. Those pictures taken in February 2000 are very lear as a whole. The period of the year corresponds to the big dry season where the almost lack of clouds and dampness (humidity) of air, which is conducive to the good visibility of sensors. Various geological and photo-geological cards have been analyzed for results validation from satellite images processing. Those geological cards are made for 1/50 000 for the regions of Agnibilékrou [19], Bondoukou [20] and Abengourou [21]. The photo-geological cards made for 1/200 000 for those areas [22] have also been used for geological accidents extraction.

Topographic maps (1/200 000) of square degrees from d'Agnibilékrou, d'Abengourou and Bondoukou (published by the center for mapping and remote sensing in 1994) to extract the hydrographic network and level curves.

The processing of satellite pictures for the mapping of fractures from the Baya watershed was done using the software ENVI 4.7. The statistical analysis was done using the following softwares: Linwin 2.0, MapInfosTM 8.0 and Excel.

2.3 Methods

2.3.1 Mapping of des lineaments

To boost images discontinuities for their mapping, directional filtering technique through the application of mobile window on the one hand on primary images ETM+ of Landsat 7 (ETM+5 and ETM+7) was used and on the other hand on new images provided by the analysis with selective main components ACP1567), images combination (ETM+5/ETM+4 and ETM+7/ETM+6). It is mainly about directional filtering for 7x7 size of Sobel type and gradient filtering of [23].

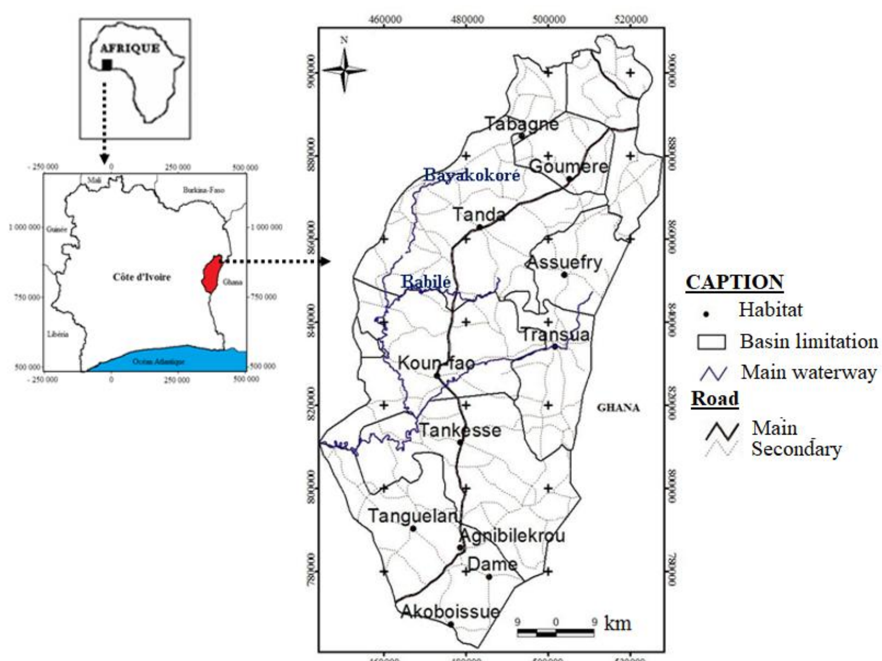

Fig. 1. Map of the study area

The application of those methods leads to the elaboration of the detailed card and the validation of the Baya fractures watershed. For more information about the methods principles, their application and about the validation procedure of the fracture card, we invite the readers to check the documents of [24,5,25,26,16,10,27,17]. This path is indicated in the figure.

2.3.2 Determination of induced permeability

Induced permeability determination from Francis' method has already been used through many applications in the sub-regions and in Côte d'Ivoire ([18], [5], [26], [28], [7], [29], [3]). We here represent the simplified theory and for more details, we invite readers to refer to the works of [30]. Induced permeability estimation by fracture gives room to flow modeling in fissured area. The following simplified hypotheses are proposed by [30] for the application of the method.

- Fractures are vertically orientated toward sub-vertical ones to analyze the data within the dimensional area.
- The thickness of the crushed area, average distance between the two lips of a fracture) is a linear empirical function of the length (L) of the fracture in meter.

Two variables are indispensable for the induced permeability calculation. They are hydraulic conductivity (Kf) of the region and the ratio

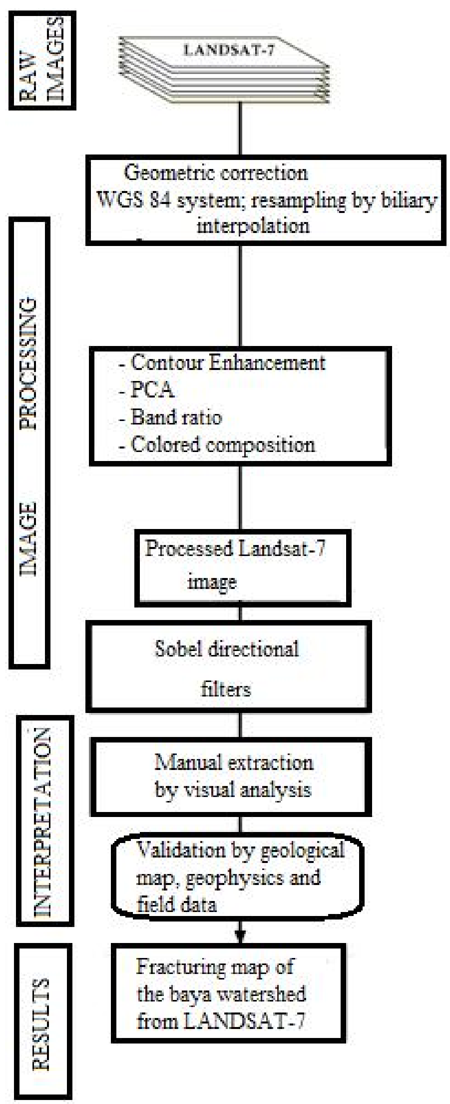

Fig. 2. Chart for picture assessment techniques ETM+ Landsat 7

coefficient between the openness and the length of fractures.

The second hypothesis is used to calculate this coefficient using length measurements and fractures openness done on outcrops during fieldworks.

« C » is defined by the following equation:

$$C_i = \frac{e_i}{L_i} \quad (1)$$

With;

C: Empirical Coefficient ratio;
e_i : thickness of crushed area (m) ;
L_i : Length of fracture (m).

Hydraulic conductivity is easily assimilated to average permeability characterizing all the surface analyzed [26]. It is determined by the following relation:

$$T_i = K_i e_i \quad (2)$$

With;

T_i : transmission of fractured area (m^2/s)
e_i : thickness of fractured area (m)
K_i : conductivity of the area (m/s) representing K_f which is an average value

Kf corresponds to average value of Ki. The thickness of the fractured zone is assimilated to the length of the filter (strainer) in case the borehole should have a unique water point. If the borehole has many water points, the thickness of the fractured area is determined making the difference between the first water point and the last one.

For more details about Francis' method, the reader could read the works of [30,5,28,7]. The application of this method used an underdeveloped zone of study for a total area of 6,324,041 sq km, in 372 circles of 5,000 meters of diameters (D = 5000), each one of them registered within the square whose side is equal to the diameter of the corresponding circle. Within each circle, the total number of fractures and its direction has been calculated.

2.3.3 Determination of reservoirs and groundwater flow gully

The permeability values determined through this method (Kmin, Kmax et Kmoy) are represented on a mapping stand with two measurements. Thus, iso-value cards that explain spatial variability of those parameters have been made. The digital processing and interpretation of those cards within the hydro-geological information system with spatial reference will bring about the identifications of underground flow areas or groundwater flow gully. In fact, induced permeability assessment through the method of [30] leads to the identification of groundwater flow gullies and groundwater reservoirs.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Emphasis on structural lineaments

Spatial filtering used for the framework of this study was useful for the image (vectoring) of images discontinuities even the most subtle. Two window images analyzed are presented below (Figs 3 and 4) to illustrate the discriminate power of filters from gradient and Sobel types. Therefore, many lineaments were mapped on analyzed images.

Lineaments are made through limitation of dark and clear zones. They can sometimes range from many kilometers. The Sobel filters have this particularity of boosting the lineaments that are perpendicular to their convolution direction. As for the gradient filters, they boost the lineament all over the place.

Lineaments detailed maps (Figure 5) have been drawn thanks to an interpretation of derived images from different processing techniques. This card contains 6,998 lineaments manually extracted from the interpretation of derived items. It presents an important density of sized lineaments and changeable direction ranging from some hundred meters to many kilometers. Their interconnections form a very dense network. The fracture density shows that the Baya watershed had undergone the influence of many tectonic phenomena which led to geological formation fragmentation.

The lineament card highlights the various knots of fractures. These knots had some hydrous potential which cannot be neglected. They sometimes appear with a gap more or less marked but from satellite observation, they are sometimes difficult to be observed.

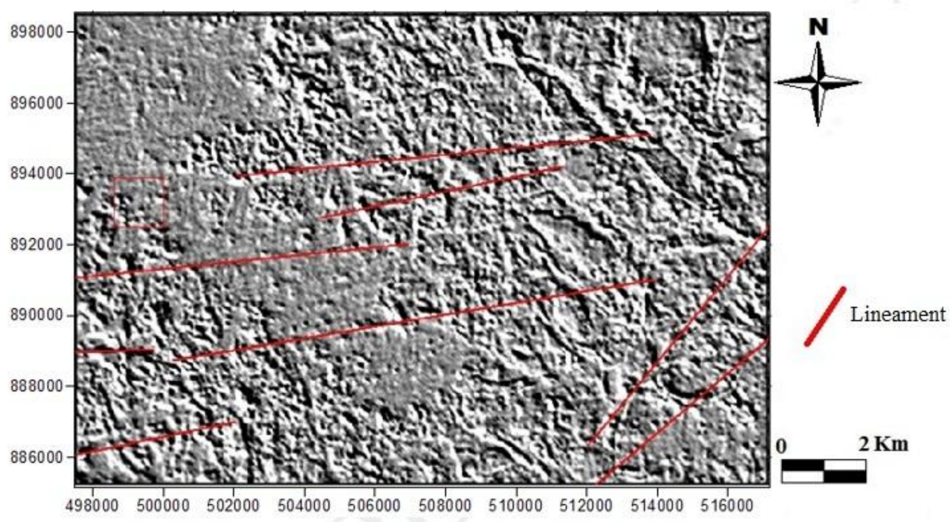

Fig. 3. Analyzed image by Sobel filtering of direction NO-SE applied with ETM+5/ETM+4 indices boosting the accidents NE-SO

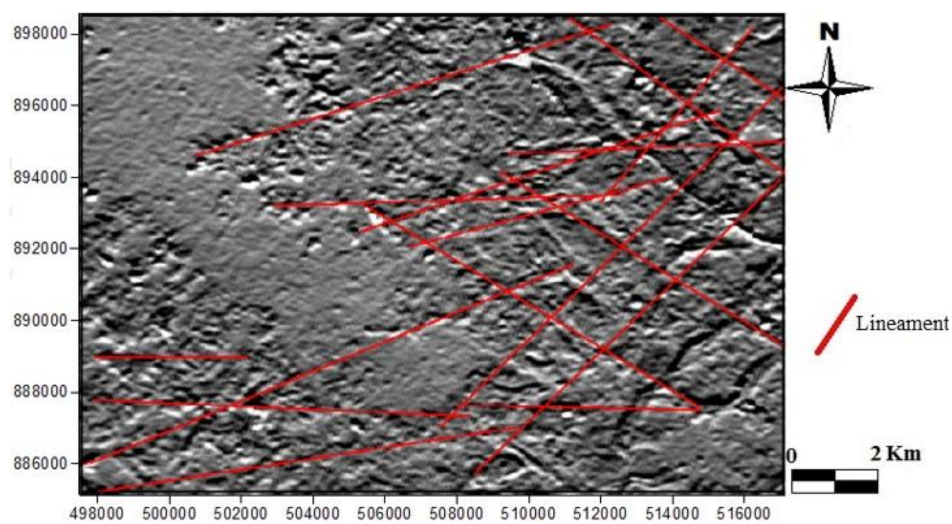

Fig. 4. Main Accidents boosted by gradient filtering, [23] applied to the image ETM+7

3.1.2 Validation of lineament card

Fig. 6 presents the circular histograms in number of lineaments from satellite images processing (A) and the fracture identified on the photo-geological card (B). The main direction of identified lineaments on A are: N70-80 (NE-SO), N90-100 (E-O), N100-110 and N110-120 (NO-SE). However, the analysis of the fracture of the histogram on B shows that the directions N100-110 (E-O), N110-120 and N120-130 (NO-SE) are the most represented.

We notice that histograms from satellite images also have directions E-O and NO-SE and they are found on the histogram from the photo-geological, the direction NE-SO. From this analysis, we see that the directional roses are almost similar. Lineament orientation in general and the main orientation classes in particular are almost identical for the two roses. This similarity confirms the validation of the detailed card of lineaments of the Baya watershed. These lineaments have a fracture value as during the phase of validation, the lineaments with different origin from tectonic one were cancelled.

We have also superimposed boreholes dug with geophysics with main lineament from images ETM+ from LANDSAT 7 (Fig. 7). Those boreholes are for the most part on lineaments or close to them even if sometimes the debit of some of those boreholes is weak. We remark that the majority of the boreholes located next to or on the lineaments provides high debit. Therefore, those lineaments have fracture values.

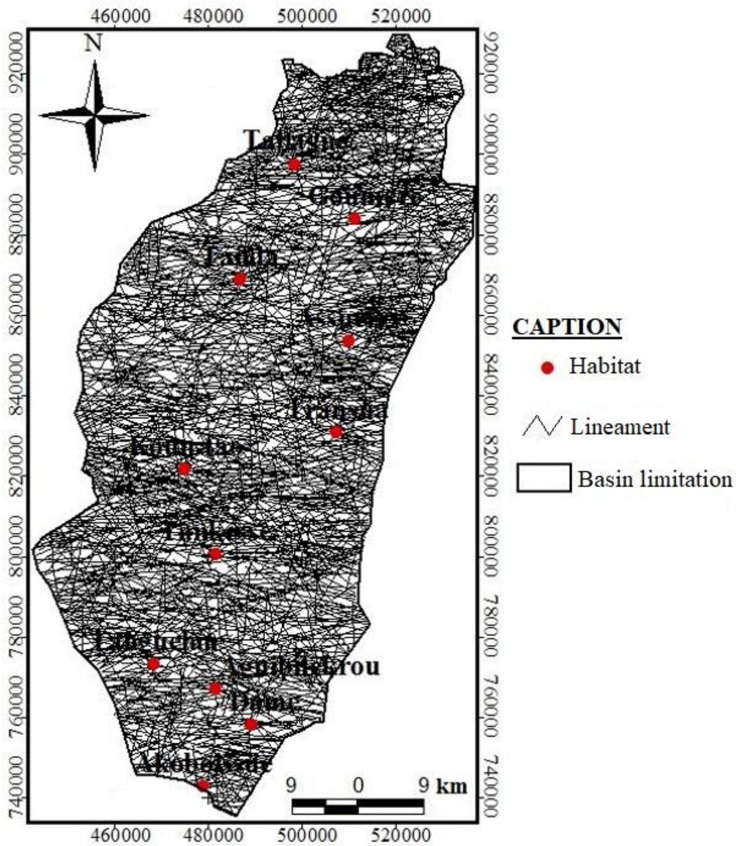

Fig. 5. Detailed card of the Baya watershed lineaments

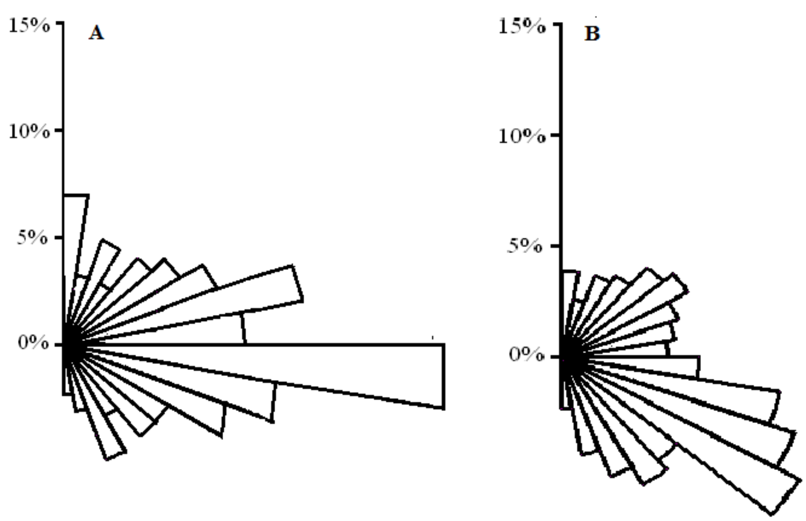

Fig. 6. Comparison of diagrams: A)-from satellite images and B)- from photo-geological card [31]

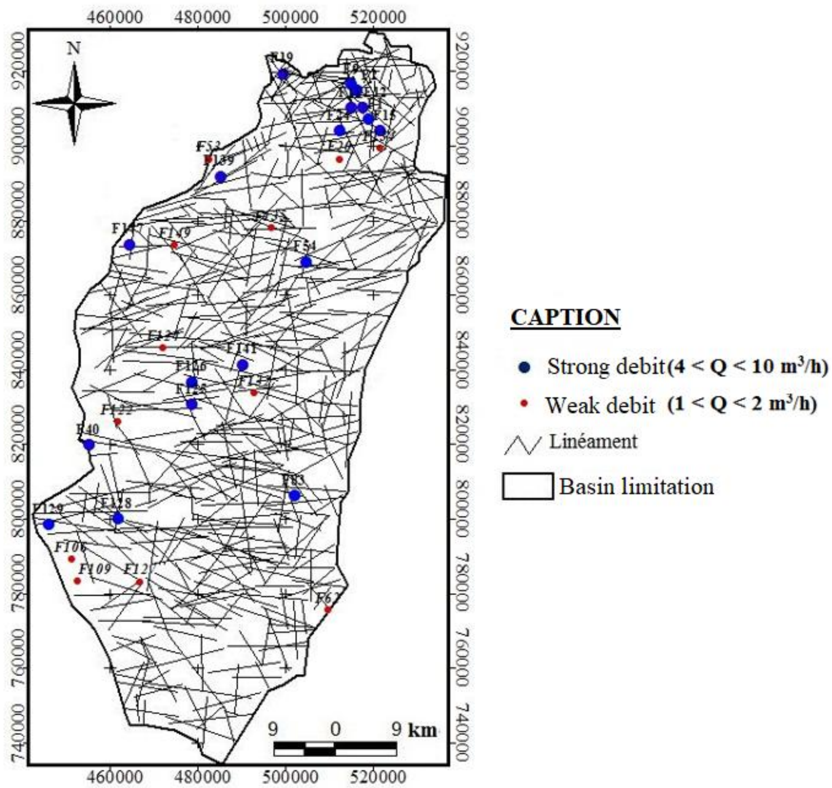

Fig. 7. Superimposition of boreholes with geophysics and lineaments

3.1.3 Fracture intensity study

To better observe the spatial distribution of fracture density from the number of fractures per unit of surface, we built the is-value card of distribution for this parameter (Fig. 8). The density is changeable on the watershed. Therefore, the fractures are differently distributed on the entire zone of study.

A global analysis of the card brings us to assert that the Baya watershed is strongly fractured. Zones with very strong density represent 12% of the study area and are to be found in the northern part of the watershed within the sub-prefecture of Bondoukou (North of Tabagne). It is about a crushed zone where volcano-sedimentary rocks are located. It is an area where the relief is uneven ground. Areas with strong and average density of fracture represent the biggest part of the watershed about 83% of the zone investigated. The areas with strong density form two big blocks. The former is in the center between the localities of Koun-fao and Tankéssé and the latter is located in the north. The latter ranges from the east in the departments of Transua and d'Assuefry.Lastly, a zone with weak density is located between Koun-Fao and Tanda. It represents 5% of the watershed.

3.1.4 Permeability induced by fractures

The useful parameters for the determination of induced permeabilities are: the coefficient ratio (Ci= 5.59.10-3) and hydraulic conductivity (Kf = 1.61.10-4m/s). The results of induced permeabilities are presented in Table 1.

Table 1. Summary of induced permeability values

	Permeability induced (m/s)		
	Kmax	**Kmin**	**Kmoy**
Minimum	$2.40.10^{-8}$	$7.55.10^{-10}$	$1.20.10^{-8}$
Average	$8.23.10^{-6}$	$2.55.10^{-6}$	$5.32.10^{-6}$
Maximum	$8.84.10^{-5}$	$9.73.10^{-6}$	$4.62.10^{-5}$

Induced permeability by fractures on the Baya watershed varies from 1.20.10-8 to 4.62.10-5 m/s. The regional average of induced permeability in that region of the country is 5.32.10-6 m/s. This induced permeability is average on the Baya watershed.

The different values of average induced permeability (Kmoy) permitted to generate permeability card of the watershed (Figure 9). This card shows spatial permeability variability. We clearly notice that areas with strong induced permeability coincide with those with strong fracture density. Areas with strong permeability form two big blocks and five small blocks. The big blocks are located in the north and in the center for fracture density. The five others are distributed on the watershed. These different blocks indicate that the Baya watershed has two (2) big reservoirs, two (2) average and three (3) small ones.

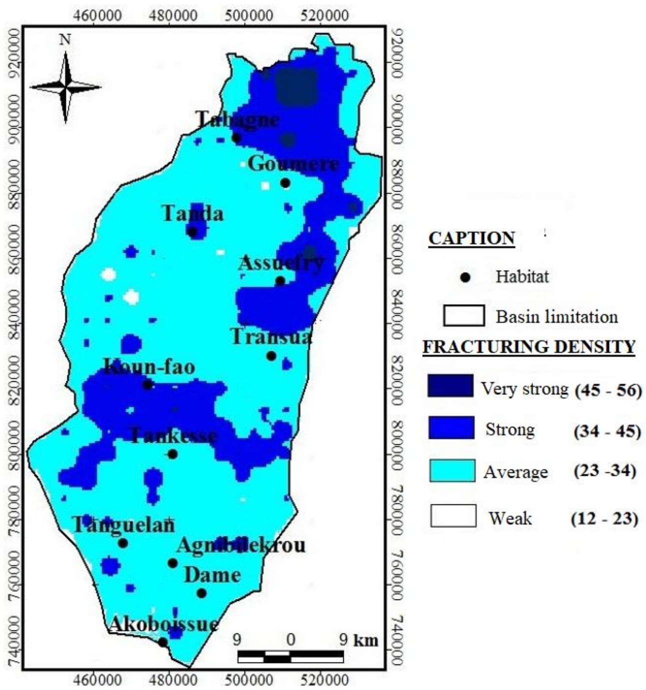

Fig. 8. Carte de densité de fracturation exprimée en nombre par maille de 5 km x 5 km

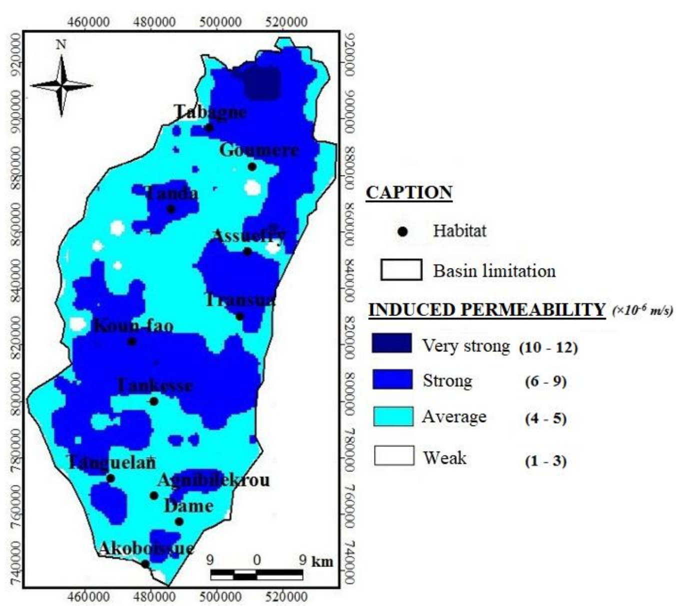

Fig. 9.Average induced permeability card

Likewise, we notice that water from those different reservoirs flow in the main river through two main directions which are the directions of NE-SO and SE-NO (Figure 10). The direction NE-SO goes from Tabagne to Koun-Fao and from Gouméré to Koun-Fao and the direction SE-NO is from Damé and Agnibilékrou to Tenguelan. As a whole, those water flow to the outlet of the watershed to Comoé River.

The card of synthesis involving gully flow, hydrographical network, induced permeability and sub-watershed permitted to identify water reservoirs of the Baya watershed (Fig. 11). The analysis of this card shows that the Baya watershed contains two big reservoirs, two average and three small ones. The reservoirs are between the different underground identified gullies from structural origin. Groundwater of the watershed all flow to Comoé River with different directions following the sub-watershed in question. Generally, the big directions are NE-SO and SE-NO.

3.2 Discussion

The appropriateness between the main directions of processed lineaments, from the fracture of the photo-geological card and the set up boreholes with geophysics and with the fracture card, confirm that the lineaments identified are associated with fracture. This helps in validating the methodological cartography.

The fractures charted do not have the same hydro-geological importance because of the different permeability developed. Works by many researchers like [31,32,11,12,8,16] revealed that within the fracture of massive rocks, all the directions of fractures are not productive. Some are consolidated and others are not. The direction N40 being considered by those researchers like the one referring to tension distortion. The direction close to him is favorable and those perpendicular to him are closed. Boreholes set up on fractures of direction NO-SE (N100-120) and E-O (90-100) cannot give expected debits. This would explain the high rate of boreholes with weak debit and shortage of water is due to the bad setting of the boreholes. In this case, fracture productivity is connected with its geometry. From the structural level, strong fracture intensity correspond to the shearing of gullies shown by the direction NO-SE

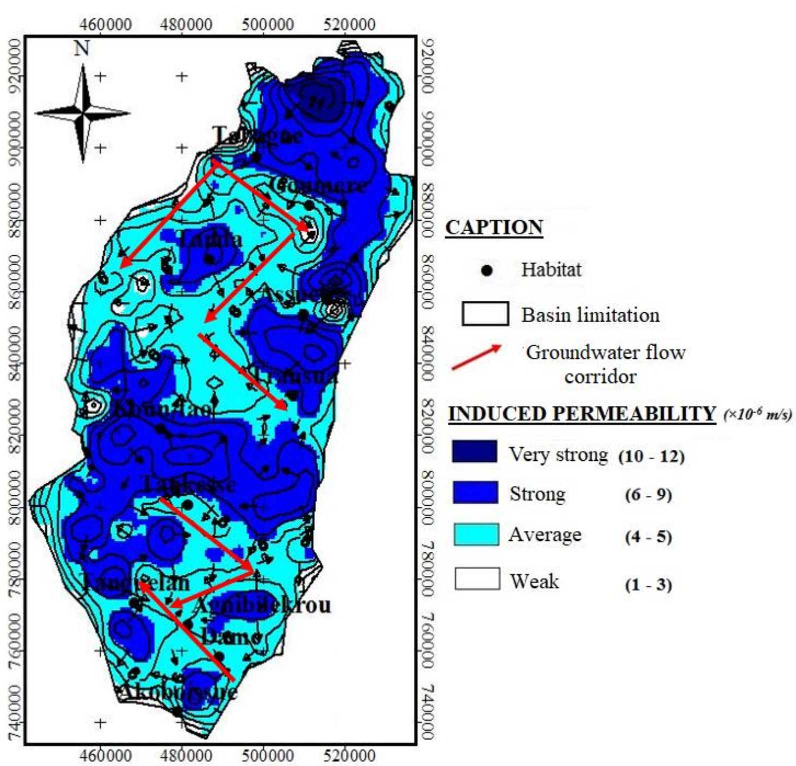

Fig. 10. Average induced permeability and preferential axis of underground water

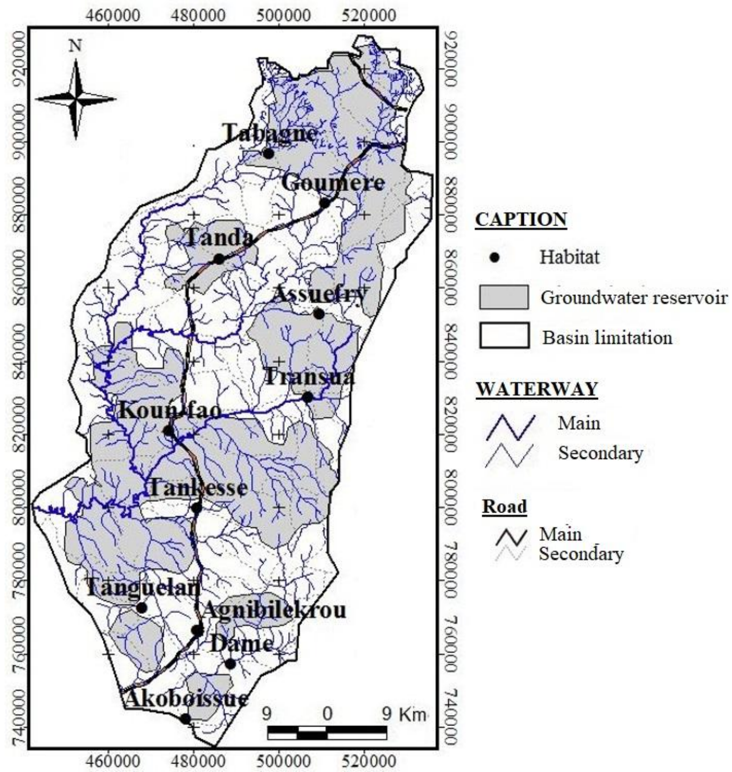

Fig. 11. The different groundwater reservoirs

(N110 and N140) of the gully composed of an accidental beam corresponding to faulty geological card [33] from the village of Bilaodi [34]. This fault is noticeable in tarkwaïen formations of Zanzan [35] and moves through the volcano-sedimentary formations, which represent the separation barrier of volcano-sedimentary schists from granitic formations located in the north of Tabagne.

The shearing gully named (KA) by Savanéet al. [34] from direction N20 from Koboko to Assouanyé is a zone with strong structural trend [36]. The latter can be assimilated with an important area of shearing in contact with Bondoukou [27] porphyroïd granodiorite and amphibolites formation. Lastly, the direction E-O is marked by the shearing gully formed by volcanic ashes form Bradrai Mountain from the department of Koun-fao.

The spatial distribution of average induced permeability highlights some axes along which induced permeability variations are good. These axes are assimilated with underground preferential flow or groundwater flow gully. Those areas with strong induced permeability are characterized by high fracture density. Thus, the more a region is fractured, the more induced permeabilities are improved. The main waterway superimposes to different underground flow axes. This result is in line with [5] in the region of Marahoué, by Lillesand [28] in the region of Man, by Jourda [7] in Korhogo, by Ahoussi [36] in Bondoukou and by Toure [35] in the region of l'Agnéby, bring us to think about the drainage-supply type between the hydrographic network and groundwater flow gullies. These axes correspond to major fractures within the insular shelf. These results shed light upon some problems of provision in groundwater in dry season. The analysis of the hydrographic network has indicated that the hydrographic is less dense in dry season. The provision of underground fracture reservoirs from that relation is in connection with seasons. Therefore, gullies with strong induced permeability represent areas for supply and provision of underground water table.

4. CONCLUSION

Satellite image processing has permitted to identify 6,998 fractures. The size of these fractures is spaced out with two big orders. The cumulated length of these fractures is 12,400 km. The main directions are:

- NE-SO (N70–80), corresponding to eburnean directions;
- E-O (N90-100) ;
- NO-SE (N100-120), associated with Liberian direction

Fracture density is changeable from one area to another one because of the heterogeneity of the environment and is characterized by variable productivities.

Induced permeability varies from $1.20.10^{-8}$ to $4.62.10^{-5}$ m/s. These induced permeabilities have permitted to characterize flow gullies of underground water, which are in close relation with the hydraulic network

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. OMS, Rapport sur la sante dans le monde, Les soins de santé primaires-maintenant plus que jamais, Genève OMS. 2008;149.
2. Servais P, Billen G, Garcia-Armisen T, George I, Goncalvez A, Thibert S, La contamination microbienne dans le bassin de la Seine, Edition. Agence de l'Eau Seine Normandie. 2009;50.
3. Mangoua MJ. 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 Nangui Abrogoua, Abidjan (Côte d'Ivoire). 2013;170.
4. Hawa S. Analyse physico-chimique et bactériologique au L.N.S des eaux de consommation de la ville de Bamako durant la période 2000 et 2001. Thèse de Doctorat en pharmacie, Université de Bamako (Mali). 2002;177.
5. Biémi J, Contribution à l'étude géologique, hydrogéologique et par télédétection des bassins versants subsahéliens 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. ès Sciences Naturelles, Université. Abidjan. 1992;493.
6. Koita M, Caractérisation et modélisation du fonctionnement hydrodynamique d'un aquifère fracturé en zone de socle. Région de Dimbokro-Bongouanou (Centre Est de la Côte d'Ivoire). Thèse de Doctorat, Université de Montpellier II (France). 2010; 220.
7. Jourda JP, 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. 2005;430.
8. Kouadio EK, Savané I, Lasm T, Biémi J, Hydrogéology prospecting in crystalline and metarmorphic area by spatial analysis of productivity potential. European Journal of Scientific Research. 2008;22(3):373-390.
9. Niamké KH, Saley MB, N'dri BE, Ouattara A. et BIÉMI J, Contribution a l'interprétation des linéaments par L'exploitation des Pseudo Images, de L'hydrographie en Région Tropicale Humide: Cas du N'zi-Comoe (Centre de la Cote D'ivoire). European Journal of Scientific Research. 2008;24(1):74-93.
10. N'go YA, Lasm T, Koita M, et Savane I, Extraction par télédétection des réseaux de fractures majeures du socle précambrien de la région de Dimbokro (Centre-est de la Côte d'Ivoire). *Revue Télédétection*. 2010;9(1):33-42.
11. Lasm T, Hydrogéologie des réservoirs fracturés de socle: Analyses statistiques et géostatistique de la fracturation et des propriétés hydrauliques. Application à la région des montagnes de Côte d'Ivoire

(Domaine Archéen). Thèse unique de doctorat Université de Poitier. 2000;272.
12. Lasm T, Kouame F, Soro N, Jourda JPR, et Biemi J. Analyse géostatistique de la fracturation extraite de l'imagerie spatiale aéroportée et satellitaire. Application à la région de Man-Danané (Ouest de la Côte d'Ivoire*).* Revue Ivoirienne des Sciences et Technologie. 2004;5:135-154.
13. Maréchal JC, Dewandel B, Subrahmanyam K. Use of hydraulic tests at different scales to characterize fracture network properties in the weathered-fractured layer of a hard rock aquifer. Water resources Research. 2004;40. DOI: 10.1029/2004WR003137
14. Galanos I, Rokos D. A statistical approach in investigating the hydrogeological significance of remotely sensed lineaments in the crystalline mountainous terrain of the island of Naxos, Greece. Hydrogeology Journal. 2006;14:1569-1581.
15. Giao PH, Weller A, Hien DH, et Adisornsupawat K. An approach to construct the weathering profil in hilly granitic terrain based on electrical imaging, Journal of Applied Geophysics. 2008;65: 30-38.
16. Youan Ta M, Lasm T, Jourda JP, Kouame KF, et Razack M. Cartographie structurale par imagerie satellitaire ETM+ de Landsat-7 et analyse des réseaux de fractures du socle précambrien de la région de Bondoukou (Nord-Est de la Côte d'Ivoire). Revue Télédétection. 2008;8(2):119-135.
17. Tagnon BO, Assoma VT, Mangoua JM, Douagui A G, Kouamé FK, Savané I. Contribution of SAR/RADARSAT-1 and ASAR/ENVISAT images to geological structural mapping and assessment of lineaments density in Divo-Oume area (Côte d'Ivoire). The Egyptian Journal of Remote Sensing and Space Sciences; 2018; DOI.org/10.1016/j.ejrs.2018.12.001
18. I.N.S. Institut National de la Statistique, Recensement général de la Population et de l'Habitat. www. ins.ci ; 2014.
19. Yves S, Delor C, Zeade Z, Kone Y, Yao BD, Vidal M, Diaby I, Konan G, Irié DB, N'da D, Dommanget A, Cautru JP, Guerrot C, et Chiron J-C, Carte Géologique de la Côte d'Ivoire à 1/200 000 ; Feuille AGNIBILEKROU. Mémoire de la Direction des Mines et de la Géologie, Abidjan, Côte d'Ivoire. 1995;19(8).
20. Youan Ta M, Lasme OD, Baka D, Lasm T, Jourda PJ, Biemi J, Analyse des propriétés hydrodynamiques de l'aquifère fissuré du socle paléoprotérozoïque: Aide à l'approvisionnement en eau potable des populations de la région de Bondoukou (Nord-est de la Côte d'Ivoire). 2015;13: 563-564.
21. Sawadogo AN, Géologie et hydrogéologie du socle cristallin de la Haute Volta : Etude régionale du bassin versant de Ima Sissili. Thèse de Doctorat d'Etat ès-Sciences Naturelles, Université de Grenoble (France). 1984;350.
22. Simeon Y, Delor C, Zeade Z, Kone Y, Yao B, Vidal M, et al. Notice explicative de la carte géologique de la Côte d'Ivoire à 1/200 000, feuille Agnibilékrou, Mémoire de la Direction des Mines et de la Géologie de la Côte d'Ivoire, Abidjan (Côte d'Ivoire). 1995;19(8).
23. Zeade Z, Delor C, Yves S, Yao BD, Vidal M, Sonnendrucker P, Diaby I, et Cautru JP. Carte Géologique de la Côte d'Ivoire à 1/200000 ; Feuille Bondoukou, Mémoire de la Direction des Mines et de la Géologie, Abidjan, Côte d'Ivoire. 1995; 17(10).
24. Adou M, Delor C, Yves S, Zamble BZ, Konan G, Yao BD, Vidal M., Diaby I, Cautru JP, Chiron JC, Dommanget A., et Coherie A. Notice explicative de la carte Géologique de la Côte d'Ivoire à 1/200 000, Feuille Abengourou, Mémoire de la Direction des Mines et de la Géologie de la Côte d'Ivoire, Abidjan, (Côte d'Ivoire). 1995; 19(7).
25. Caldini FG, Posavec M, et Azuelos MJ. Carte photo-géologique de la Côte d'Ivoire à 1/200 000, Feuille de Nassian, Commission du Canada, Société pour le Développement Minier de la Côte d'Ivoire (SODEMI). 1978;17.
26. Yesou H, Pion JC, Besnus Y, Saint Jean R. Amélioration des données SPOT pour la cartographie structurale en milieu tropical. Exemple de la région des chapeaux de fer de Pagala (Togo). IIIèmes Jour. Scient. Rés. Télédét. UREF, Toulouse, In: J.M. Dubois, F. Blasco (dir), Outil microinformatique et Télédétection de l'évolution des milieux, PUQ/AUPELF UREF. Ed. 199;492.
27. Bonn F, et Rochon G. Précis de télédétection : Principe et méthodes. Press. Université Quedec. AUPELF-UREF. 1992; 1:485.

28. Lillesand T, Kiefer R. Remote sensing and image interprétation. 3ème Edition. 1993; 750.
29. Savane I. Contribution a l'étude géologique et hydrogéologique des aquifères discontinus du socle cristallin d'Odienné (Nord-Ouest de la Cote d'Ivoire) : Apport de la télédétection et d'un système d'information hydrogéologique a référence spatiale. Thèse de Doctorat d'Etat es-Sciences Naturelle. Université de Cocody, Abidjan (Côte d'Ivoire). 1997;398.
30. Kouamé KF. Hydrogéologie des aquifères discontinus de la région semi-montagneuse de Man-Danané (Ouest de la Côte d'Ivoire). Apport des données des images satellitales et des méthodes statistique et fractale à l'élaboration d'un système d'information hydrogéologique à référence spatiale. Thèse de Doctorat 3ème cycle. Université de Cocody, Abidjan, (Côte d'Ivoire). 1999; 194.
31. Dibi B. 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 de Doctorat, Université de Cocody, Abidjan (Côte d'Ivoire). 2008; 164.
32. Franciss FO. Contribution à l'étude du mouvement d'eau à travers les milieux fissurés. Géomorphologie et Géologie du Brésil. Thèse de Doctorat d'Ingénieur, Université de Grenoble I (France). 1970; 108.
33. Engalenc M. Elément de quantification des ressources hydrauliques dans les roches cristallines. Bulletin BRGM, Série 2I, Section III. 1981;4:325-326.
34. Savané I, Benié GB, Hugh Gwyn JQ, et Biémi J. Application de la télédétection à la recherche des eaux souterraines en milieu cristallin : cas d'Odienné, Côte d'Ivoire. Télédétection des ressources en eau. Actes Journées Scientifiques, Tunis. 1993; 111-120.
35. Toure S. Pétrologie et géochronologie du massif de granitoïdes de Bondoukou (Nord-est de la Côte d'Ivoire) : Evolution magmatique et contexte géodynamique au protérozoïque inférieur (Paléoprotérozoïque); relation avec les formations volcaniques et volcano-détritiques du Zanzan, Koun, Tanda ; implications paléogéographiques. Thèse de Doctorat d'Etat ès-Sciences Naturelles, Université d'Abobo-Adjamé, Abidjan (Côte d'Ivoire). 2007;467.
36. Ahoussi KE. Evaluation quantative et qualitative des ressources en eau dans le Sud de la Côte d'Ivoire. Application de l'hydrochimie et des isotopes de l'environnement à l'étude des aquifères continus et discontinus de la région d'Abidjan-Agboville. Thèse de Doctorat, Université de Cocody, Abidjan (Côte d'Ivoire). 2008;237.
37. Youan TM. 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 de Doctorat, Université de Cocody, Abidjan (Côte d'Ivoire). 2008;237.

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