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CONTRIBUTION OF REMOTE SENSING AND PIEZOMETRY TO THE STUDY OF THE TABLECLOTH BEHAVIOR OF THE HIGH BANDAMA BASIN AT TORTIYA (NORTHERN COTE D'IVOIRE)

CONTRIBUTION DE LA TELEDETECTION ET DE LA PIEZOMETRIE A L'ETUDE DU COMPORTEMENT DE LA NAPPE DU BASSIN VERSANT DU HAUT BANDAMA A TORTIYA (NORD DE LA COTE D'IVOIRE)

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ABSTRACT

The aim of this study is to investigate the tablecloth behaviour of High Bandama basin for the best management of groundwater. It was based on satellite Landsat TM images and piezometric data acquired during three campaigns (August 2009, April 2010, and May 2012) exploitation. Thus, the statistical analysis of fracturing shows that the main direction of fracturing is N0-10 with 14 percent. The most secondary direction is N70-80 with eight percent. These directions should allow water infiltration. Piezometric study reveals that seasonal variations of ranges do not exceed 4 meters unlike the structures of Dassoumgbo, Sépénédiokaha, and Fonnikaha (Côte d'Ivoire) which register respectively negatives variations of -4 m, -5.06 m and –5.485 m. At the opposite, there are small positives variations of water level ranging from +0.025 m (Koutiénédougou) to +0.9 m

(M'bolokakaha). They highlight some weak water upwelling levels and thus show that the tablecloth reaction is not immediate after the rainy season. These upwellings are gradual and seem to reflect difficult conditions of groundwater supply. The interannual ranges of the aquifer during the three campaigns are less than 5.5 meters. Piezometric map sketch during the high flow and less flow of water doesn't reveal some notice variations. The overlaying of the density map fracturing and the piezometric variations map for points followed during August 2009 and April 2010 campaigns shows that it is difficult to establish a relationship between piezometric and fracturing. This study constitutes important support for groundwater resource management in the basin.

Keywords: Fracturing, Piezometry, Variations ranges, High Bandama, Côte d'Ivoire

RESUME

La présente étude a pour but la connaissance du comportement de la nappe du bassin versant du Haut Bandama pour une meilleure gestion des eaux souterraines. Elle est basée sur l'exploitation des données images satellitaires Landsat TM et des données piézométriques recueillies au cours de trois campagnes (Août 2009, Avril 2010 et Mai 2012). Ainsi, l'analyse statistique de la fracturation montre que la direction majeure des fractures est N0-10 avec 14%. La direction secondaire la plus importante est N70-80 avec 8%. Ces directions favorisent l'infiltration des eaux. L'étude piézométrique révèle que l'amplitude des variations saisonnières n'excède pas 4 m en dehors des ouvrages de Dassoumgbo, Sépénédiokaha et Fonnikaha (Côte d'Ivoire) qui enregistrent respectivement des variations négatives de -4 m, -5,06 m et –5,485 m. A l'opposé, l'on note de faibles variations positives de niveau d'eau allant de +0,025 m (Koutiénédougou) à +0,9 m (M'bolokakaha). Elles traduisent de faibles remontées des niveaux d'eau et montrent ainsi que la réaction des nappes n'est pas immédiate après la saison des pluies. Ces remontées sont graduelles et semblent traduire les conditions difficiles d'alimentation des nappes. Les variations interannuelles de la nappe au cours des trois campagnes sont inférieures à 5,5 m. L'esquisse de cartes piézométriques en période hautes eaux et basses eaux ne révèle pas de variations notables. La superposition de la carte de densité de fracturation à celle des variations des niveaux piézométriques des points d'eau suivis au cours des campagnes d'Août 2009 et Avril 2010 n'a pas permis d'établir une relation entre piézométrie et fracturation. Cette étude constitue un support important pour la gestion des eaux souterraines du bassin versant.

Mots clés : Fracturation, Piézométrie, Amplitude des variations, Haut Bandama, Côte d'Ivoire.

INTRODUCTION

Considered a long time like inexhaustible, water resources are the subject of increased attention from the international community which rightly underlines the strategic and emblematic nature of sustainable management of these resources (Petit, 2004). In fact, since the second half of the twentieth century, the demographic pressure, the development of irrigation, and intensive agriculture has endangered this resource (Petit, 2004). Moreover, the climate changes with its unpredictable consequences constitute everywhere in the world a threat for water resources (surface, underground). The decrease of the piezometric level of groundwater can cause the temporary drying up of some outlets rivers (case of Conie, Beauce tablecloth outlet which was depleted in the middle of 1990 years). The prospects for growth in water consumption are indeed worrying and, if the estimated trend over the last century (multiplication by 10 of world water consumption) continues, the shortage could affect all the continents (Petit, 2004). According to Koutsoyiannis et *al*. (2020), the water storage in land has a total loss of 600 km^3 per year, which is a gain for storage in the sea. This mass gain corresponds to an increase in the sea level equal to 1.64 mm per year. Half of this (0.82 mm per year) corresponds to the groundwater depletion (example conversion of groundwater to seawater, as water mass, can not disappear nor be stored in the atmosphere, where it initially moves by evaporation in irrigated areas). This is clearly an anthropogenic effect in its entirety and is likely to remain if no increase in the foreseeable future. Over 650 million people suffer from water scarcity in almost 40 countries (Kurunthachalam, 2014). Concerning water sources for consumption, the main risks were linked to the assurance of good quality and sufficient quantity. To achieve this purpose, according Cencur Curk et *al*.(2020), several management options exist such as measures to support the uses of groundwater with optimization of water demand (Boutebba et *al*., 2014; Garnier et Holman , 2019; Wang, 2020), alternatives sources (Kurunthachalam, 2014, Fielding et *al*., 2015), the establishment of water areas protection involving land use planning (Amblard, 2019;. Pohlner, 2019). This reality doesn't escape Côte d'Ivoire, the West African country. In the High Bandama basin, groundwater is the main resource for feeding population through boreholes. The High Bandama basin is an agricultural region. Despite the government policy in the supply of potable water, water shortage remains in some areas. To reach the best management, the knowledge of tablecloth behavior is inescapable. It is with this in mind the study was initiated. This study is based on remote sensing which constitutes a powerful tool through the study of fracturing network and piezometry. The purpose is to show the importance of these two approaches in the comprehension of tablecloth behavior. The study was based on exploitation of satellite images of four scenes acquired in November 1986 from the Landsat TM satellite and piezometric data obtained during three campaigns carried out in August 2009, April 2010 and May 2012.

PRESENTATION OF THE STUDY AREA

The study area which is the High Bandama basin at Tortiya outlet is a sub-basin of White Bandama called Bandama blanc. It is located between longitudes 5° and 6°20'West and latitudes 8°40' and 10°20' North (figure 1). It extends on square degrees of Korhogo, Katiola, Niellé, Tengréla, and Boundiali and covers an area estimated to 14500 km^2. Most part of the area (86%) was centered on Korhogo square degree.

Overall, it's a huge plateau characterized by planar areas which altitudes range between 300 and 400 meters. However, this monotony of plateau was interrupted by granitic domes with inselbergs allures (Géomines, 1982). The basin is largely drained by the Bandama and its main tributaries (Solomougou, Lopkoho, Yoréloro, Lafigué, Badénou, etc). Agriculture is the main activity followed by breeding. The climate is soudanian type (tropical regime of transition) with two contrasting seasons: a rainy season and the dry season with an annual average of rain evaluated to 1230 mm during the 1950-2000 period (Soro et *al*., 2013). Hydrologic regime is modelled on that of rainfall. The basin was constituted in most part of ferralitic soils meanly and strongly desaturated. One can encounter next these last, a complex of ferralitic weakly desaturated and tropical bruns eutrophic soils derived from basic rocs (Perraud, 1971). From geologic point of view, the weak intensity of metamorphism allows to distinguish two high groups of formations (Arnould, 1961): sedimentaries formations and those of volcanic origin and most accessory eruptive.

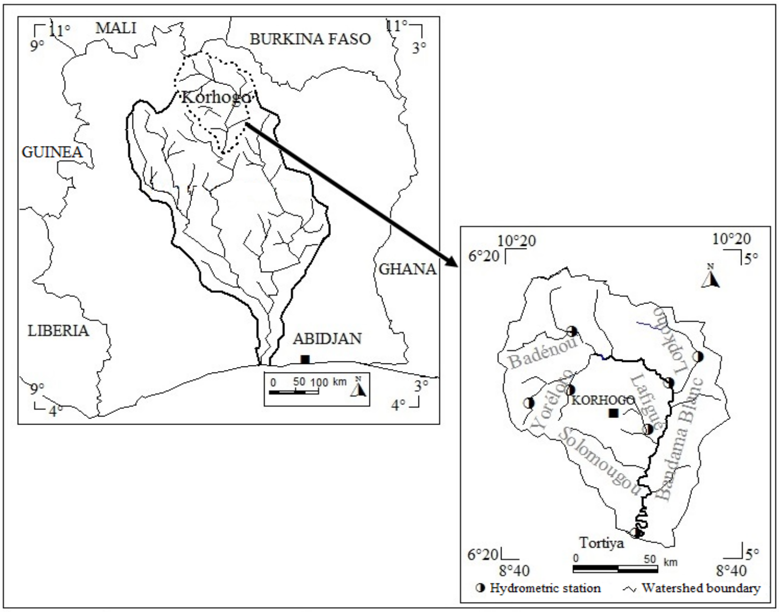


Figure 1: Location of the study area

MATERIAL AND METHODS

Data and material

The data used in this study are piezometric data and satellite images. The piezometric data were obtained following three campaigns carried out in the area in August 2009, April 2010 and May 2012 from around twenty structures. We used a sound piezometric probe whose characteristics are: Type 010,100 Meter, 229773 for water levels measurement and a GPS of Garmin 12 type to note the measurement points coordinates and their altitude. These coordinates have been compared to those contained in archives of Géomines (1982).

The satellite optic images used come from captor TM (Thematic Mapper) of Landsat. Four scenes images (197-053, 197-054, 198-053 et 198-054) centred on Korhogo town were needed to cover the study area. They were acquired on the 16th November 1986. These images have a global resolution of 30 m and were obtained from the site http: //glcfapp. umiacs.umd. edu: 8080/esdi. The images treatment was made with Envi 4.1 software.

Method of fracturing study

Establishment of lineamentary map

The treatment methodology is that used by several authors including Biémi (1992), Savané (1997), Kouamé (1999), Saley (2003), Jourda (2005) and Youan Ta (2008). From their work, we note that lineaments treatment and extraction includes several operations. There is first the geo-referencing and geometric corrections which are part of the pre-treatment, then the improvement of the contrast of images, and finally the filtering techniques. We are not going to outline all these steps here. For more information, we bring the reader back to these works.

Statistical analysis of the fracturing

The general stochastic DFN (Discrete Fracture Networks) approach assumes fractures to be straight lines (in 2D) or planar discs/polygons (in 3D), and treats the other geometrical properties (e.g. position, frequency, size, orientation, aperture) as independent random variables obeying to certain probability distributions (Lei et *al*., 2017). Fractures map may exhibit a negative exponential, lognormal, gamma, or power-law distribution (Lei et *al*., 2017).

The statistical treatment of lineaments was made using Linwin software. We adopted the methodology of fractures field of Brières and Razack cited *in* Saley (2003). The main parameters considered are:

- the distribution of alignments by directional classes in frequencies and in cumulative lengths
- the distribution of alignments by length classes in frequencies.

This study gives respectively the directional rosette and the histogram of number and cumulated length of lineaments. The analysis of field fracturing gives directional families subdivided by intervals classes of 10°. The directional rosette allows observing the distribution of lineaments number percentage and that of cumulated length.

Study of fracturing intensity

To observe best the spatial distribution of fracturing density following the two modes to know the number of fractures and the cumulated length, we are going to build the iso values map of these two parameters. These distributions reflect spatial variability of fractures in number of fractures and cumulative fracture length on the study area. Linear regression study will be made between the intensity in the number of fractures (NF) and the intensity of cumulated length (LC) by meshes. One or another of these parameters can be used if there is a correlation for the following of the analyses. The fracturing study allows disposing a map of density fracturing which will be crossed with piezometric variations map for the two campaigns (low flow and high flow). This may allow seeing the possible relationship between piezometry and fracturing.

Method of piezometry study

The piezometry study was made passing by piezometry monitoring, the piezometric cotes calculation, and the amplitude of fluctuations and the piezometric maps drawing.

Piezometric monitoring

Figure 2 shows the distribution of the waters points monitored during the campaigns of August 2009 (high flow), April 2010 (low flow), and May 2012 (starting rainy season) when observation piezometric were absent. Thirty localities were visited. The number of restreint of structures visited is explained in general by logistic means.

On the thirty structures visited, we can make the measures of twenty. In fact, there is a refusal of some localities like Nambonkaha inhabitants to accept measures because they fear their water contamination. Sometimes, the village chief absence (case of Nagniévogo) or the youngsters in charge of water points management (Nagbanwavogo), the drying up of the water point (case of Ourossantiakaha village) or structure absence (example: Momirasso) or blind boreholes existence (Nangounonkaha, Lokaha 1) haven't allowed the measurements. However, this campaign far to cover the study area is very important. It gives an idea of seasonal variations of water tables. For piezometric measures, we remove electrode of piezometric probe which is the end of the bearing. This end is then plugged in structures and we continue to unwind the probe by means of the crank. Once the electrode reaches the level of water, the probe emits an audible noise. We stop unrolling it and to register the measured level, the coiled rope tape being graduated. Water levels in the structures were measured very early in the morning to avoid any disturbance of the aquifer.

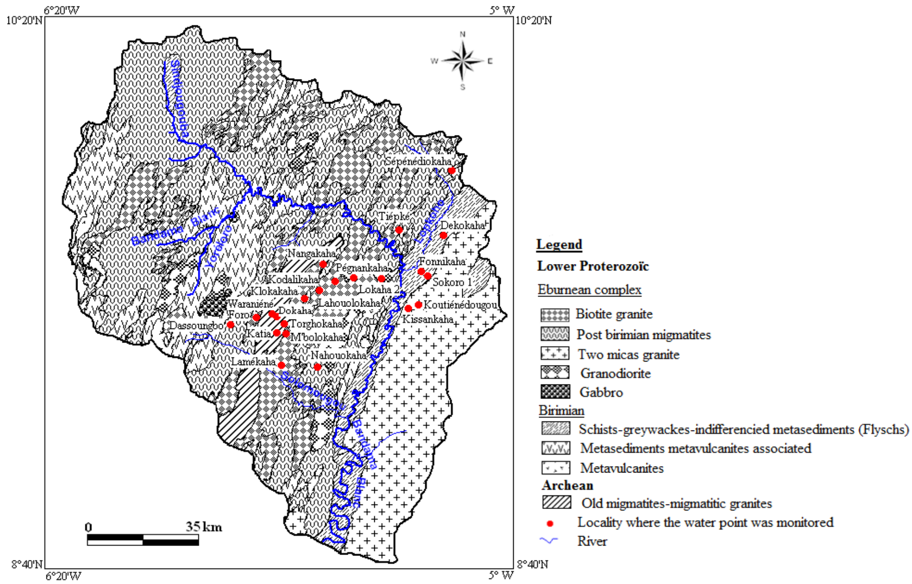


Figure 2: Map of spatial distribution of monitored water points

Calculation of piezometrics alitudes and fluctuations amplitudes

The piezometric levels (NP) measured in the structures with respect to the ground after having subtracted the heights of the copings were translated into piezometric level ratings taking into account the altitudes (Z) of the measured points. Likewise, the amplitudes of seasonal fluctuations (variation of the piezometric level noted ΔNP) were calculated to get an idea of the behavior of the water tables in the region according to the formula of equation 1:

$$\Delta NP = NP1 - NP2 \quad (1)$$

with:

ΔNP the variation of piezometric level in meter (m);

NP1 the piezometric level of water point during the first campaign and NP2 this of the same structure during the second campaign.

The piezometric altitude (PA) was calculated based on equation 2 like this:

$$PA = Z - NP \quad (2)$$

Where

NP= Piezometric level in meter (m);

Z= Cote (altitude) of structure in meter (m).

Piezometric maps drawing

The values of the piezometric altitudes obtained (PA) made it possible to construct the piezometric maps using the Surfer 8 software. The interpolation method used is kriging. These maps were produced in the high water period (rainy season) and in the low water period (dry season).

The methodology of study is summarized in the flowchart (figure 3) where HWP and LWP mean respectively High Water Period and Low Water Period.

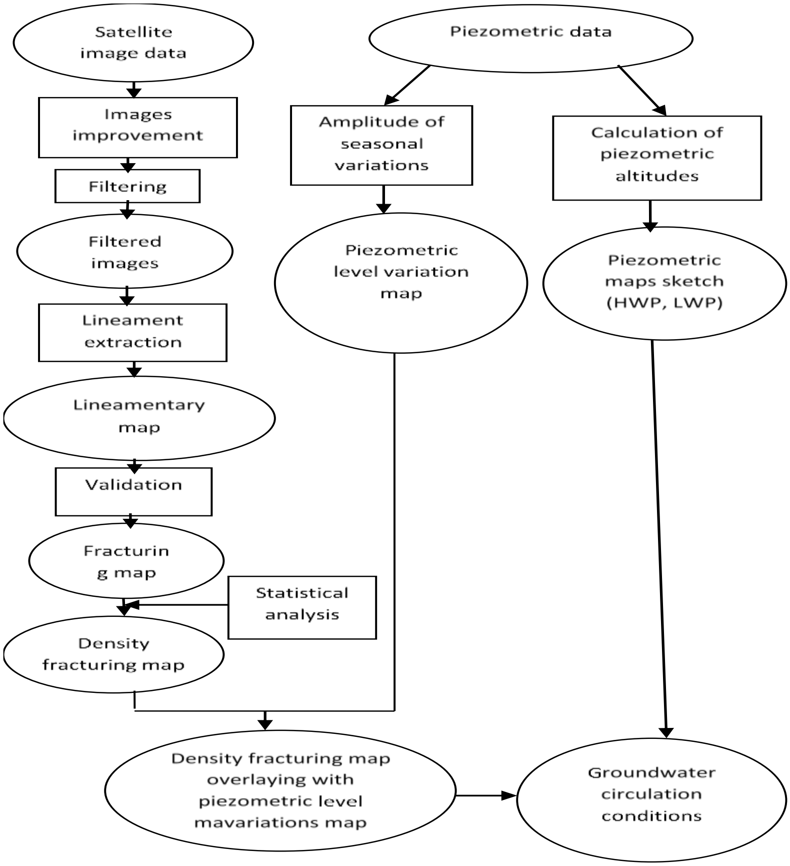


Figure 3: Flowchart showing the study methodology

RESULTS AND DISCUSSION

Lineamentary network map

The manual extraction of lineaments (image discontinuities) from the filtered images made it possible to establish a map of the lineament network (figure 4). Although not exhaustive, the map obtained is representative of the geological linear structures of the region. Analysis of this map shows that the lineament network is dense throughout the basin. It has 7426 lineaments of varying lengths and directions.

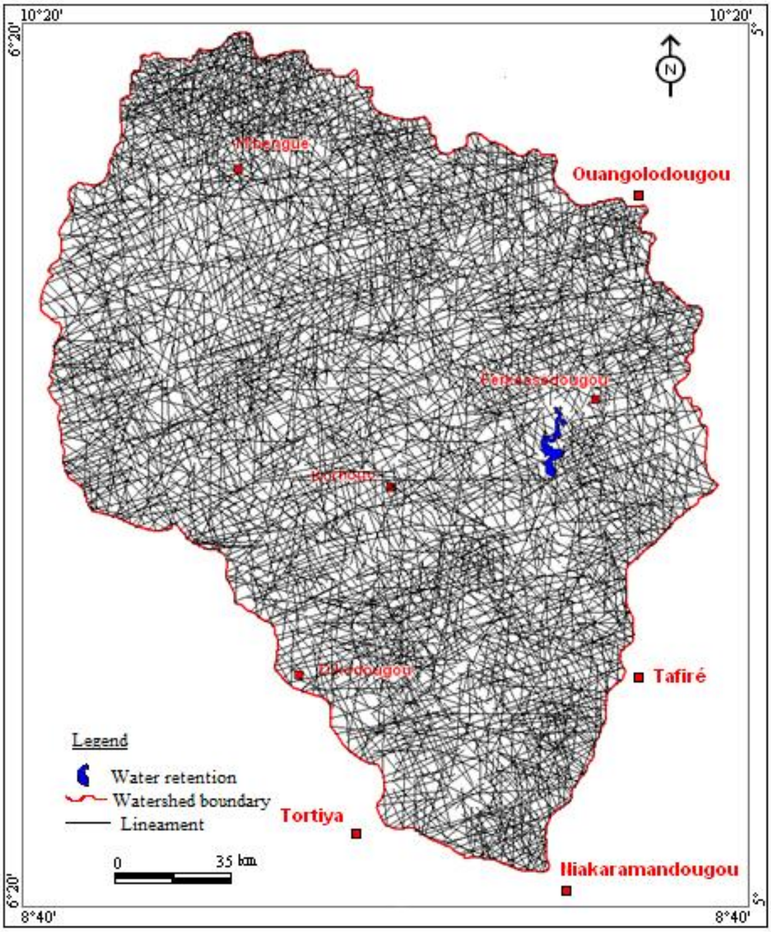


Figure 4: Map of lineament network of High Bandama watershed obtained from satellites images

Statistical analysis of lineaments network

The number of lineaments obtained in the High Bandama basin stands at 7426. Directional rosette allows observing the distribution of the percentage of lineaments number percentage and that of cumulative lengths (figure 5). Analysis of the results of the statistical study shows that the predominant lineaments in this region vary between N0-10 with a proportion of 14%. The secondary directions are N60-70, N70-80, N90-100, and N150-160. The highest percentages in cumulative lengths belong to classes N0-10, N50-60, N60-70, and N70-80.

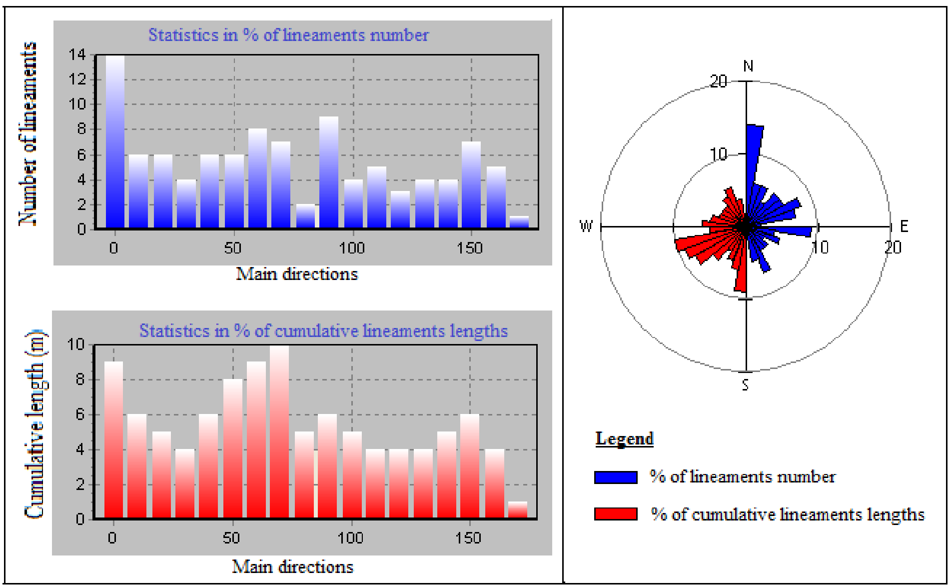


Figure 5 : Histograms of the number and cumulative lengths of lineaments (left) and directional rosette (right)

Validation of lineamentary map

The lineamentary map has been validated using work already carried out in the area. The main directions noted on the lineamentary map N0-10 (14%) and N70-80 (8%) are in agreement with those resulting from measurements on outcrops (figure 6). Of these, the N70-80 direction is the most dominant. Directions N0-10, N70-80, N90-100, and N130-140 represent major fractures. This rosette validates the lineamentary map of the High Bandama basin in its large western part.

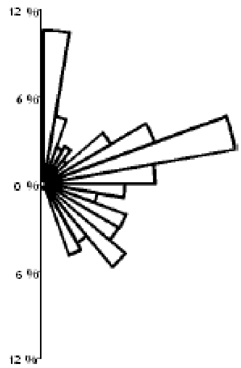


Figure 6: Rosette of global outcrop fractures in the Korhogo region (N=2853) (Jourda, 2005)

Correlation between fracture intensity and number of fractures

The cumulative fracture lengths and the number of fractures per mesh can both express the severity of fracturing in a given region. Determining a correlation between these two parameters makes it possible to use one or the other. Linear regression (least-squares line) applied to the projection of points in an arithmetic diagram was used to establish this correlation. These points align more or less along a straight line characterizing a correlation between these two parameters (figure 7). The relation is of positive linear type with the following characteristics:

- least-squares equation: LC (km) = 1.735 NF;
- the linear correlation coefficient is $R^2 = 0.515$.

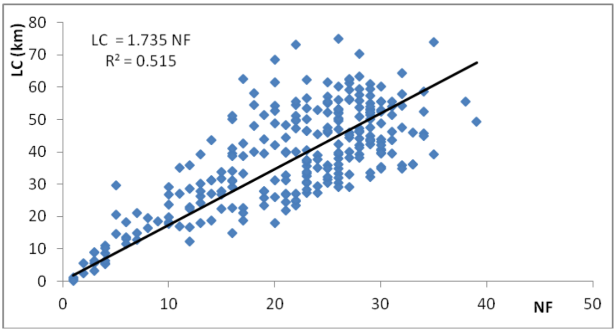


Figure 7: Correlation between fracturing intensity in fractures number (NF) and in cumulative length (LC)

These results show that these parameters are correlated. Thus, either of these parameters can be used to estimate the intensity of fracturing. In the remainder of the study, the cumulative length intensity of mesh fractures (LC) will be used.

Piezometric study of water table

Seasonal variations of piezometry

The values of piezometric altitudes, as well as piezometric levels in the structures, are recorded in tables 1 and 2. The calculation of the variations in piezometric levels reveals structures with negative variations and others with positive variations (table 3). In general, the amplitude of the variations in level is quite low (less than 4 m) apart from the structures of Dassoumgbo, Sépénédiokaha and Fonnikaha where we obtained respectively -4 m, -5.06 m and - 5.485 m. The majority of the structures recorded negative variations in water level between –5.485 m, and -0.1 m. These negative variations could reflect either a drying up of the water table following excessive withdrawals or a rise in the water table that has not yet started. In contrast, there are small positive variations in water level ranging from +0.025 m (Koutiénédougou) to +0.9 m (M'bolokakaha). They reflect weak rises in water levels, and thus show that the reaction of the water tables is not immediate after the rainy season. These rises are gradual and seem to reflect the difficult conditions of the groundwater supply.

Table 1: Results of piezometric measures during August 2009 campaign (high water period)

Locality	Type of structure	X(km)	Y(km)	Z(m)	NP(m)	Piezo. alt. (m)
Dokaha	PM	208.523	1041.68	401	16.1	384.90
Waraniéné	PM	206.965	1042.514	408	21.3	386.70
Foro	PM	201.915	1041.456	377	8.1	368.90
Dassoumgbo	PT	193.914	1039.237	384	8.8	375.20
Torghokaha	PT	210.558	1039.326	362	9.1	352.90
Katia	PM	208.256	1036.612	368	11.6	356.40
M'bolokaha	PM	211.305	1036.108	373	17.3	355.70
Laméhékaha	PT	209.82	1026.067	330	6.5	323.50
Nahouokaha	PM	221.054	1025.42	368	10.84	357.16
Klokakaha	PM	217.177	1047.377	360	15.1	344.90
Lahouolokaha	PT	221.719	1049.996	361	12.7	348.30
Nangakaha	PM	222.829	1058.661	368	10	358.00
Kodalikaha	PT	226.597	1052.969	357	9.35	347.65
Pégnankaha	PM	232.466	1054.105	370	15.8	354.20
Tiégbé	PT	246.814	1069.433	326	18.53	307.47
Dekokaha	PT	260.806	1067.737	318	2.95	315.05
Sépénédiokaha	PM	263.458	1088.531	325	3.14	321.86
Kissankaha	PM	249.856	1044.397	326	14.7	311.30
Koutiénédougou	PM	253.021	1045.,288	347	11.2	335.80
Sokoro 1	PM	255.934	1054.552	360	12.1	347.90
Fonnikaha	PT	253.87	1056.262	331	0.95	330.05
Lokaha 2	PM	241.205	1053.804	345	15.15	329.85

PM : Modern well ; PT : Traditional well ; NP : Piezometric level; Piezo. : Piezometric alt.: altitude, .X and Y : UTM coordinates, Z: Altidude

Table 2: Results of piezometric measures during April 2010 campaign (low water period)

Locality	Type of structure	X(km)	Y(km)	Z(m)	NP(m)	Piezo. alt. (m)
Dokaha	PM	208.523	1041.68	401	16.475	384.53
Waraniéné	PM	206.965	1042.514	408	20.75	387.25
Foro	PM	201.915	1041.456	377	8.72	368.28
Dassoumgbo	PT	193.914	1039.237	384	12.80	371.20
Torghokaha	PT	210.558	1039.326	362	*	*
Katia	PM	208.256	1036.612	368	12.53	355.47
M'bolokaha	PM	211.305	1036.108	373	16.40	356.60
Laméhékaha	PT	209.82	1026.067	330	7.15	322.85
Nahouokaha	PM	221.054	1025.42	368	12.35	355.65
Klokakaha	PM	217.177	1047.377	360	14.215	345.79
Lahouolokaha	PT	221.719	1049.996	361	12.40	348.60
Nangakaha	PM	222.829	1058.661	368	12.73	355.27
Kodalikaha	PT	226.597	1052.969	357	9.45	34.55
Pégnankaha	PM	232.466	1054.105	370	17.05	352.95
Tiégbé	PT	246.814	1069.433	326	*	*
Dekokaha	PT	260.806	1067.737	318	2.72	315.28
Sépénédiokaha	PM	263.458	1088.531	325	8.20	316.80
Kissankaha	PM	249.856	1044.397	326	13.99	312.01
Koutiénédougou	PM	253.021	1045.288	347	11.175	335.83
Sokoro 1	PM	255.934	1054.552	360	12.45	347.55
Fonnikaha	PT	253.87	1056.262	331	6.435	324.57
Lokaha 2	PM	241.205	1053.804	345	14.90	330.10

*PM : Modern well ; PT : Traditional well ; NP : Piezometric level ; Piezo. : Piezometric ; * : Dry well, alt.: altitude, X and Y : UTM coordinates, Z: Altidude*

Table 3: **Amplitude of piezometric levels variation of structures**

Locality	X(km	Y(km)	Z(m)	NP 2009 (m)	NP 2010 (m)	ΔNP (m)
Dokaha	208.523	1041.686	401	16.1	16.475	-0.375
Waraniéné	206.965	1042.514	408	21.3	20.75	+0.55
Foro	201.915	1041,456	377	8.1	8.72	-0.6
Dassoumgbo	193.914	1039.237	384	8.8	12.8	-4
Torghokaha	210.558	1039.326	362	9.1	*	-
Katia	208.256	1036.612	368	11.6	12.53	-0.93
M'bolokaha	211.305	1036.108	373	17.3	16.4	+0.9
Laméhékaha	209.82	1026.067	330	6.5	7.15	-0.65
Nahouokaha	221.054	1025.42	368	10.84	12.35	-1.51
Klokakaha	217.177	1047.377	360	15.1	14.215	+0.885

Lahouolokaha	221.719	1049.996	361	12.7	12.4	+0.3
Nangakaha	222.829	1058.661	368	10	12.73	-2.73
Kodalikaha	226.597	1052.969	357	9.35	9.45	-0.1
Pégnankaha	232.466	1054.105	370	15.8	17.05	-1.25
Tiégbé	246.814	1069.433	326	18.53	*	-
Dekokaha	260.806	1067.737	318	2.95	2.72	+0.23
Sépénédiokaha	263.458	1088.531	325	3.14	8.2	-5.06
Kissankaha	249.856	1044.397	326	14.7	13.99	+0.71
Koutiénédougou	253.021	1045.288	347	11.2	11.175	+0.025
Sokoro 1	255.934	1054.552	360	12.1	12.45	-0.35
Fonnikaha	253.87	1056.262	331	0.95	6.435	-5.485
Lokaha 2	241.205	1053.804	345	15.15	14.9	+0.25

ΔNP : Piezometric level variation ; : Dry well, X and Y : UTM coordinates, Z: Altidude*

Spatio-temporal evolution of the piezometry of the basin

A piezometric map sketch was carried out for the two campaigns (August 2009 and April 2010) (figure 8). The choice of these dates is justified by the fact that these months fall respectively into the period of high water and low water. The examination of the maps obtained does not reveal any notable difference between the two periods. The isopièzes keep the same shape and however show an evolution following an increasing East-West gradient.

Interannual evolution of the piezometry of the basin

The evolution of the piezometric level of the structures which did not fall dry during the three piezometric campaigns (August 2009, April 2010 and May 2012) is illustrated by the graph in figure 9. The analysis of the graphs shows a strong variation of the piezometric level in each structure over the three campaigns. This variation shows the complexity of the hydrodynamic functioning of the aquifers in the region.

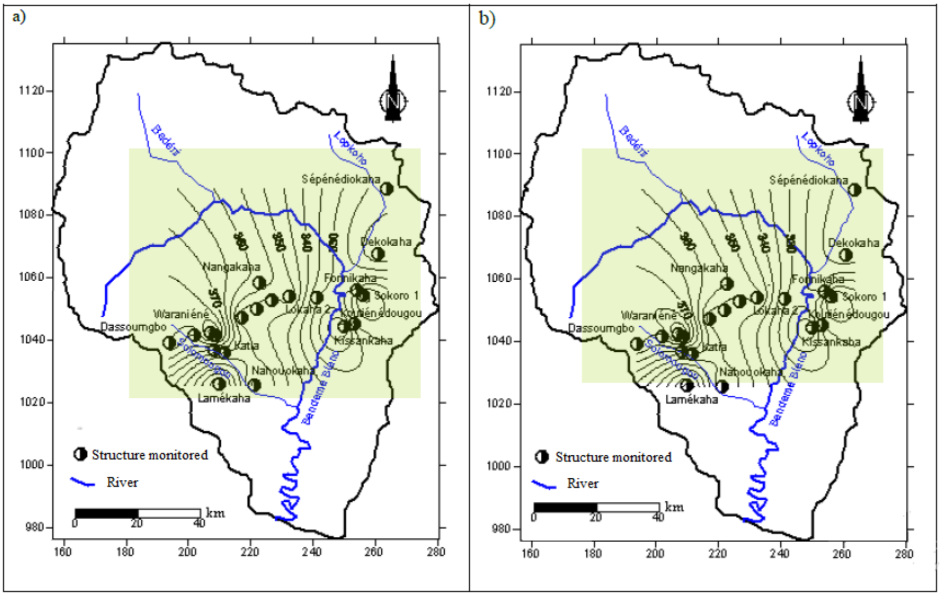
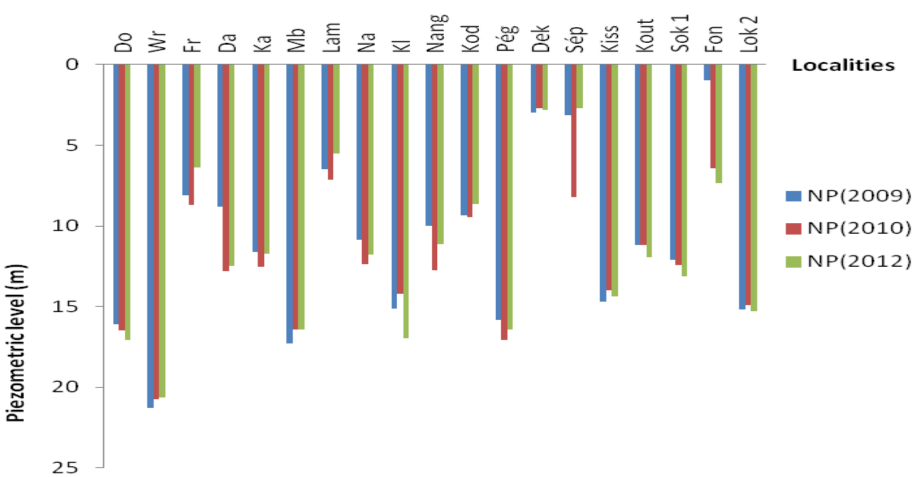


Figure 8: Piezométric esquisse of August 2009 campaign (high water) (a) and April 2010 (low water) (b) in the alterites



Do : Dokaha ; Wr : Waraniéné ; Fr : Foro ; Da : Dassoungbo ; Ka : Katia ; Mb : M'bolokaha ; Lam : Lamékaha ; Na : Nahouokaha ; Kl : Klokakaha ; Nang : Nangakaha ; Kod : Kodalikaha ; Pég : Pégnankaha ; Dek : Dekokaha ; Sép : Sépénédiokaha ; Kiss : Kissankaha ; Kout : Koutiénédougou ; Sok1 : Sokoro 1 ; Fon : Fonnikaha ; Lok 2 : Lokaha 2

Figure 9: Variation of piezometric level of structures (wells) during three campaigns (August 2009, April 2010 and May 2012)

Relation between fracturing and piezometry

The cumulative length fracturing density map of lineaments per 10 km x 10 km mesh was constructed and superimposed on that of the variations in the piezometric levels of the water points monitored during the campaigns of August 2009 and April 2010 (figure 10). It is noted that the high fracturing densities are located in the center of the zone. Otherwise, it is difficult to establish a relationship between the evolution of the amplitude of the piezometric variations and the fracturing density. As proof, the structures of Fonnikaha and Sépénédiokaha which record the greatest drops in water levels with respective seasonal variations of -5.485 m and -5.06 m are located in areas of a high density of fracturing. However, we expected a rise in the piezometric level of these structures since the fractures facilitate water infiltration and therefore recharge. It seems important to us to know the position of the structures in the areas mentioned in relation to the fractures. The structures monitored were therefore positioned on the map of major fractures in the area (figure 10). Analysis of the map shows that Sépénédiokaha's structure lies between the open fractures and that of Fonnikaha in the continuation of a fracture. The sealing of the fractures could explain the difficult water circulation conditions for these structures.

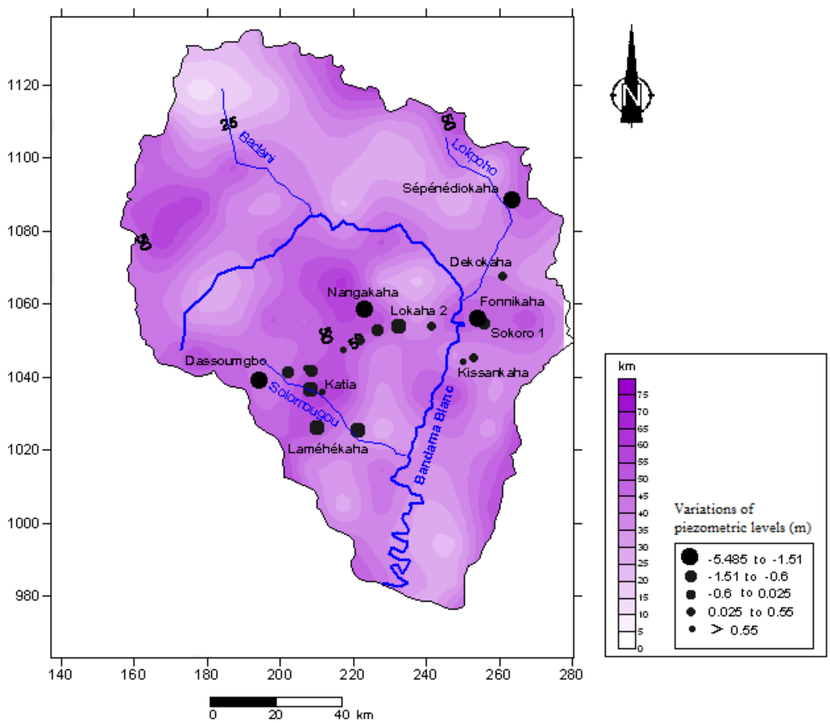


Figure 10: Overlay of fracturing density in LC (10 x 10) and piezometric levels variations map (2009-2010)

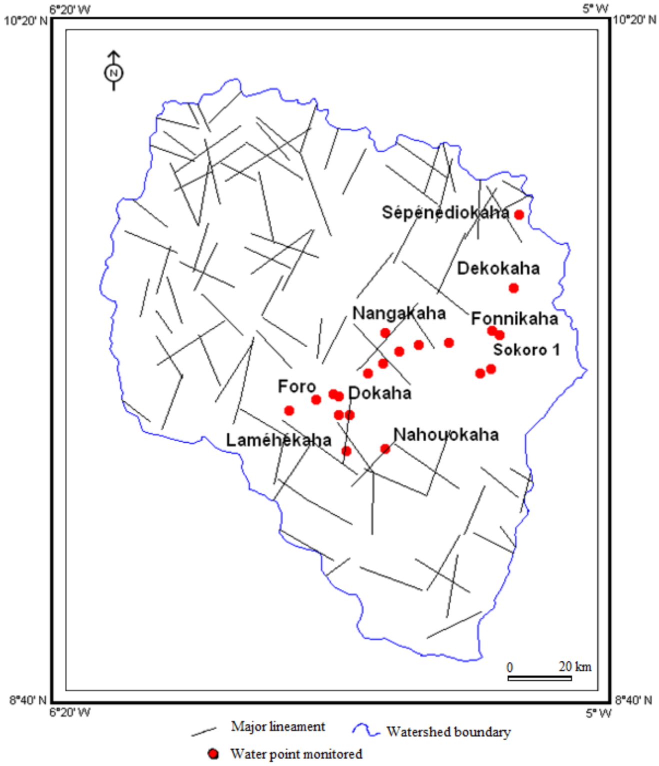


Figure 11: Positioning of structures monitored on the major fractures map

Groundwater recharge mechanism

The results of a study of the water table carried out, over the entire basin of Korhogo over a period of more than ten years, by the BRGM then by the ORSTOM *in* Roose (1979) provide an even better understanding of the behavior of the water table. We notice that the water table is at its lowest at the end of July (-9 to -13 m) and begins to rise at the beginning of August when the soil stock has been replenished (figure 12). The highest level is reached between early October (05 October) and late November (26 November) and is between -11 and -6 m. The fluctuations of the water table vary according to the year from 1.5 to 5.7 m with an average of 3.5 m.

The groundwater recharge in this basin takes place in two phases (Lenoir, 1972). The first, at the start of the rainy season, consists of adding up the rainfall amounts from top to bottom. This is the latent phase, during which water percolates by gravity into the coarse and fine pores and capillaries from the surface. With each rain, a slice of soil is soaked and the descent of the wet fringe takes place in jerks. When all the layers are rewetted to the top of the water table, the second phase or apparent phase occurs. Thus, the rise of the piezometric level can be done by cumulating the contributions from bottom to top.

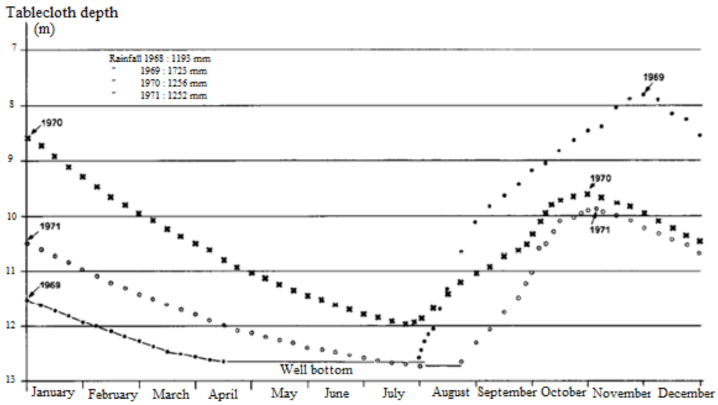


Figure 12: Evolution of the water table at well n° 10 of Korhogo basin over the 1969-1971 period (Roose, 1979)

DISCUSSION

The amplitude of the seasonal variations does not exceed 4 m apart from the structures of Dassoumgbo, Sépénédiokaha, and Fonnikaha which record respectively negative variations of -4 m, -5.06 m and -5.485 m. Besides, there are weak positive variations in water level +0.025 m in Koutiénédougou and +0.9 m in M'bolokakaha. These same variation trends (positive and negative) were observed by Soro (2002) for structures of the Grand-Lahou square degree. The author notes variations of + 4.14 m, + 5.88 m, and + 8.45 m respectively for the structures of Sur-rails, Séliboua and Guiméyo. The interannual variations of the water table during the three campaigns (August 2009, April 2010, and May 2012) are less than 5.5 m. These results are in agreement with the work carried out by BRGM and then ORSTOM on water table n ° 10 of the Korhogo basin over a period of ten years. The interannual fluctuations depending on the year are between 1.5 m and 5.7 m with an average of 3.5 m. Moreover, the analysis of the sketches of piezometric maps during periods of high water and low water does not reveal any notable variations. This finding is similar to that carried out in the Korhogo investigation basin by BRGM-CIEH (1972) in CEFIGRE (1990). Indeed, a series of maps reproducing the state of the piezometric surface of the alterite layer has been produced. The variability in the shape of the piezometric surface is minimal. The natural drainage axis and flow directions are stable.

The piezometric study of water tables in Côte d'Ivoire is still fragmentary. During the decade 1965-1975, only the regime of the layers of alterites was the subject of various studies (Lelong and Lemoine, 1968 *in* Grillot, 1992; Joseph, 1969). In 1980, an experimental site was set up at Yamoussoukro comprising several boreholes reaching the basement and dark piezometers at different levels in the alterites. Many measurements have been carried out by Faillat (1986) on this site. We will retain from the work of Faillat (1986) that the seasonal piezometric variations observed over two successive climatic cycles (1980-1982) are marked by maximum amplitudes of the order of one meter for the boreholes reaching the base, the evolution curves being similar to each other. The factors which influence the piezometric variations are diverse. The work of the authors in Côte d'Ivoire noted the influence of rainfall, the nature, and thickness of the alterations as well as the geomorphological position linked to the depth of the water table on the piezometric variations. These same observations were made in other countries in the sub-region and in the world. It emerges from the comparison of fluctuations over several boreholes during four consecutive years (1976-1979) in Ghana by Wardrop and Associates Ltd (1980) *in* Grillot (1992) that overall the piezometric levels are dependent on rainfall inputs. Likewise, the work of Grillot (1992) on the groundwater regime in an altered crystalline medium in Madagascar confirms the influence of precipitation on piezometric variations. The author notes a rapid response of the alterite slicks to the rain signal (10 days) for cumulative precipitation of 100 mm. Ouis (2012) in the study on impact of climate fluctuations on quantity and quality of Ghriss plain groundwater (northwestern algerian) noted a decrease of piezometic levels linked to precipitations decrease. The work of Lallahem (2002) on the chalky aquifer of the Paris basin confirmed these listed factors while showing the influence of fracturing on the responses of piezometers. Ngouala et *al*.(2016) in their study made in Loémé watershed in Congo republic confirmed also that the dependence of piezometric levels to precipitations is function of soils nature, relief, etc. The lack of rainfall data did not allow us to link piezometric and rainfall trends, which would have enabled this relationship to be confined.

The amount of rainfall from which the groundwater supply is visible depends on the bioclimatic conditions. According to Lelong and Lemoine (1968) *in* Lenoir (1972), in the savannah region near Korhogo, for an annual rainfall of 1400 mm, the rise only becomes visible after rainfall amounts greater than 600 mm. The rise in the piezometric surface of the water table therefore occurs quite clearly behind the start of the rainy season because of the time required for the dry soil to moisten.

Apart the role played by fracturing on the variation in piezometric levels, its study is of considerable importance. Koudou et *al*.(2017) showed the influence of fracturing in aquifers pollution susceptibility study in the contact zone bedrock-sedimentary in southeast of Côte d'Ivoire. Many authors like Saley (2003), Jourda (2005), Youan Ta (2008), Mangoua et *al.* (2019) mentioned fracturing density as an important parameter in the evaluation of disponibility indicator for groundwater potentialities study in fissured aquifers.

CONCLUSIONS

This study allowed us, using remote sensing and piezometry, to get an idea of the behavior of the water table in the Hight Bandama watershed. The fracturing study showed that the major direction of fracture is N0-10 with 14%. The secondary directions are N60-70, N70-80, N90-100, and N150-160. These directions would promote water infiltration. In general, the amplitude of the variations in level is quite low (less than 4 m) apart from the structures of Dassoumgbo, Sépénédiokaha and Fonnikaha where we obtained respectively -4 m, -5.06 m and -5.485 m. The majority of the structures recorded negative variations in water level between –5.485 m and -0.1 m. These negative variations could reflect either a drying up of the water table following excessive withdrawals or a rise in the water table that has not yet started. In contrast, there are small positive variations in water level ranging from +0.025 m (Koutiénédougou) to +0.9 m (M'bolokakaha). They reflect weak rises in water levels and thus show that the reaction of the water tables is not immediate after the rainy season. These rises are gradual and seem to reflect the difficult conditions of the groundwater supply. The superposition of the map of the cumulative length fracturing density of lineaments on that of the variations in the piezometric levels of the water points monitored during the campaigns of August 2009 and April 2010 shows that it is difficult to establish a relationship between the evolution of the amplitude of the piezometric variations and the fracturing density. The study is of undeniable importance because it constitutes support and a contribution to better management of groundwater in the watershed. It permitted to know: the fractures density, the amplitude of piezometric head, and the conditions of groundwater supply. However the presented study has some limitations. There are the lack of rainfall data during the period 2001-2012 which includes piezometry monitoring and the short series of piezometry data. For future works, we suggest the installation of observation piezometers in all the study area and near each piezometer, the presence of rainfall station.

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