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Characterization of the Hydrogeological Functioning of Fissured Aquifers in a Mining Context: The Case Study of the Yaoure Gold Project (Central-West Ivory Coast)

Yao Kouadio Michel[1, *], Dibi Brou[1], Mangoua Oi Mangoua Jules[1], Konan Oi Yao Noel Xavier[1], Adjoro Serge[1], Ble Jean Fidele Yrro[2]

[1]Environmental Sciences and Technologies Laboratory, Department of Environment, University of Jean Lorougnon Guedé, Daloa, Ivory Coast

[2]INational Institue of Scientific Research, Department of Water-Earth-Environment, Quebec, Canada

Email address:

michel.yaok@gmail.com (Y. K. Michel), dibrou2003@yahoo.fr (D. Brou), mjul_2@yahoo.fr (M. Oi M. Jules), xavierkonan8@gmail.com (K. Oi Y. N. Xavier), adjoroserge@gmail.com (A. Serge), bleyrro@gmail.com (B. J. F. Yrro)

[*]Corresponding author

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Abstract: Mining is a major concern for the availability of groundwater resources due to the continual pumping out for pit dewatering. The objective of the study is to assess the impact of mining on the functioning of the aquifer system of the Yaoure Gold Project area. The methodology adopted was to first caracterize the aquifer system by producing the fracturing map from remote sensing. Endeed, the water level in the aquifer system was determined by the Castany method. The piezometry was studied in low and high water in order to determine the recharge and discharge zones and to follow the behaviour of the water in the aquifer system. Finally, the analysis of pumping test sheets was used to determine the hydrodynamic characteristics of the aquifer. The results obtained show 170 lineaments oriented in the N-S, NE-SW and NW-SE directions. The recharge of the aquifer is 46.5 mm/year with discharge zones observed in the north-east and south sectors and a recharge zone in the north of the study area. Water level variations in some boreholes and the determined transmissivity values varying between $1.85.10^{-6}$ and $3.5.10^{-4}$ m^2/s (average of $2.47.10^{-5}$ m^2/s), indicate a probable influence of pumping on the water level in the aquifer. Groundwater flows preferentially in a west-east direction and could generally discharge into the Bandama River. The hydraulic conductivities vary between $1.23.10^{-7}$ and $1.32.10^{-5}$ m/s with an average of 3.3710^{-6} m/s. The specific flow rates vary between 0.05 and 3.6 m^3/h/m and the average value is 0.61 m^3/h/m.

Keywords: Characterization, Hydrogeology, Fissured Aquifers, Gold Mine, Yaoure

1. Introduction

Water, the source of life, is necessary for the economic and social development of every nation. It's absence and/or presence can be a source of potential conflicts. In fact, where the water resources are scared and various interest groups are involved, concurrent and conflictual relationships could appear [1]. Everywhere in the world, the stress on water resources, especially on ground water resources, is increasing due mainly to the growth of demands, the surface water quality degradation [2] and the climate change effects [3]. In contrary to surface water, the ground water is considered to be the appropriate potable water supply due to its huge capacity of storage and low exposition to the pollution risks [4, 5]. However, this water resource is still deeply threatened at its availability, including around mining operation areas where it is pumped up for pit dewatering.

In the Marahoue Region, Centre-west of Côte d'Ivoire, where the Angovia Mine is located, these findings are often observed causing water shortages in some communities. Indeed, during the previous mining operations, the water was pumped out for pit dewatering in order to dry up the pits. This method could have lowered the water table, affecting underground runoff and causing some community consumption boreholes to be dried up [6]. It's therefore necessary to better understand the functioning of the aquifer system of the mine area through the structural and hydrogeological characteristics. It is in that context that this study is initiated on the objective of characterizing the hydrogeological functioning of the aquifer system impacted by the mining operations in the study area.

2. Study Area Presentation

The study area includes the Yaoure Gold Project's Exploration Permit, located in the Centre-West of Côte d'Ivoire, in the Marahoue Region and comprises between the longitudes 5° 19 and 5° 31 West and Latitude 6° 53 and 7° 65 North, covering an area of 50 km^2 (Figure 1). This area is located in a transitional tropical climate zone and is characterized by a very low-hilly terrain. The average annual temperature is 26.9°C and the average annual rainfall is 1907 mm over the period 1983 to 2015. The surface water system consists mainly of a small affluent of white Bandama River and a few temporary streams. As far as geological context is concerned, the site is located at its base area in a synclinal of meta-volcanic tholeiitic areas covered by more acidic volcanic sediments [7]. Hydrogeologically, two types of aquifers have been identified in previous work. These are alterite aquifers and fissured aquifers.

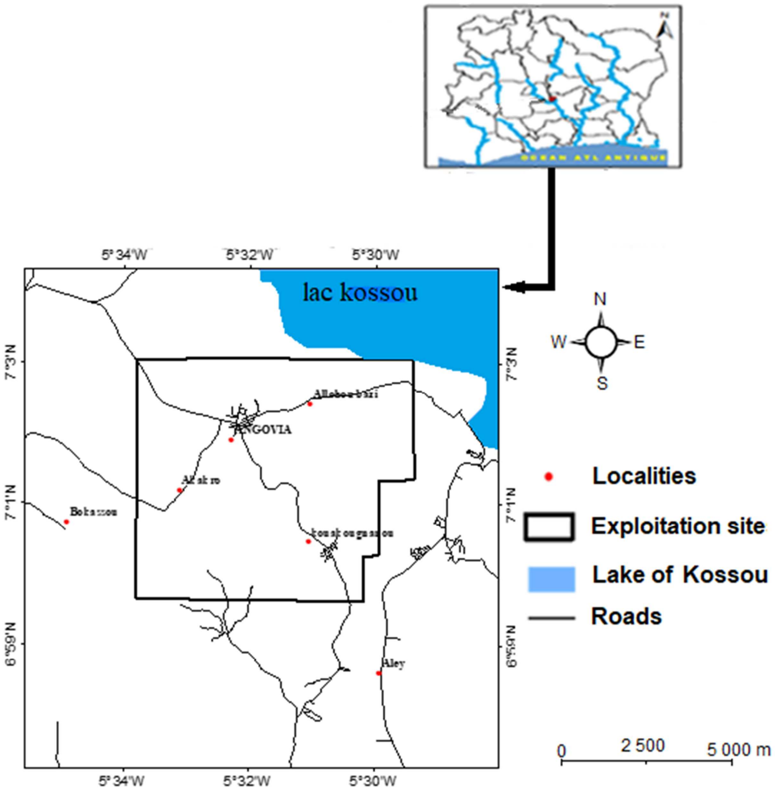

Figure 1. *Location of Study Area.*

3. Material and Methods

3.1. Data Acquisition

To complete this study, it was used climate, mapping and drilling data as well as image data. The climate data comes from the national Aerospace and Meteorological Development and Operations Corporation (SODEXAM). This is the rainfall and temperature data observed in the Zuénoula's sugar complex plant from 1983 to 2015 and at the Angovia mine station over the period 2009–2018. These data allowed to assess the hydrological balance of the Zone. The image data used are those of Landsat Oli 8 recorded on 17/02/2020 and relating to Zone 30 of the Northern Hemisphere. They allowed us to map the lineaments' network. Drilling data includes 11 boreholes located at the mine site as well as some boreholes from surrounding communities (Figure 6). These data were used to determine the piezometric level from the measured static levels.

3.2. Methods

3.2.1. Reservoir Structure Characterization

The study of fracturing is the preliminary phase for the search for groundwater reservoirs [8]. Studies have shown that the fracturing field from satellite images brings out a lot of interesting information, especially due to its synoptic vision and mostly the various techniques for processing high-quality digital images [9, 10].

Mapping of the lineaments in the study area was made possible by the various treatments applied to the Landsat ETM raw image scene 197-056 of 08-03-2003. From the geo-referenced Landsat image ETM-scene 197-056 of 18-02-2001, we geo-referenced the raw image. We applied to this image the treatment techniques of enhancements, principal component analysis [11], waves report, colored composition, data spatial filtering (directional and non-directional filter). Different filters have been applied to enhance all discontinuities images similar to geological lineaments [12]. In terms of the survey of structural lineaments, two methodological approaches are to be considered according to Kouamé [13]. The first one is to automatically extract lineaments by mathematical morphology [14, 11] cited by Kouamé [13]. The second one, which was used to extract the lineaments of the study area, is a manual extraction methodology by photo-interpretation [13, 15].

3.2.2. Lineament Map Validation

The monitoring and validation phase of lineaments extracted from the digital processing of satellite images are necessary to clarify their structural significance [16]. The lineaments identified from Landsat 8's OLI images were the subject of frequent analysis to highlight the main directions. Indeed, the orientation of fractures is one of the essential parameters involved in the flow of groundwater in the rocky basement. Depending on their orientation, fractures can promote and facilitate groundwater drainage. For the validation of these lineaments, the directions obtained are firstly compared to those obtained in previous work carried out by Adon et al. [17] in the Marahoué, by Affian et al. [18] and by Koffi et al. [19] in the Angovia gold mine area. Secondly, the overlay of the lineament map with that of geophysical implanted drilling [20] reveals the coincidences between the major tectonic lines and the most productive drillings. Indeed, according to Jourda [20], the most productive boreholes are located on major accidents and can therefore be an essential factor for the validation of lineaments.

3.2.3. Statistical Analysis of the Fracturing

The statistical analysis of the fracturing field of the Angovia gold mine aims to build the directional rosette. The approach adopted here is the discretion of the mesh fracturing field by considering the representative elemental surface (SER). The dimensions of the latter for which the directional distribution of lineaments (fractures) is consistent in the fracture field achieved is 5 km×5 km (regular mesh). Indeed, when the size of the mesh increases, the integrated data (numbers of lineaments) are very numerous and there is a variation in the directional distribution. Beyond 10 km, directional information is stomped. In each mesh, the total number of fractures and the length of each fracture are determined. The interest of this map is to highlight the spatial variability of the intensity of small-scale fracturing investigation. To do this, the fracturing map is georeferenced in order to be recognized by the Linwin 2.1 software. This software establishes at the same time the histogram, the rosette, the cumulative length and the number of lineaments.

3.3. Determination of Aquifer Recharge and Discharge Zones

3.3.1. Assessment of the Recharge

The hydrological balance allows knowing the water inflows and losses of the basin and thus to quantify the water resources in a comprehensive way. It relates to a quantifiable water cycle at the level of a region or watershed. It expresses the sharing of rainfall between the different components of the water cycle (Equation 1).

$$P = R + ETR + I \quad (1)$$

with:

P: Precipitation (mm)

R: Runoff water slide (mm)

ETR: Real Evapotranspiration (mm)

I: water slide infiltrated (mm)

Runoff (R) is the portion of the rain that feeds the surface network. It allows calculating the region's runoff coefficient (r). The respective expressions of these parameters are as follows (Equation 2):

$$R = \frac{P \times t}{S} \text{ and } r = \frac{R}{P} \times 100 \quad (2)$$

R: The Runoff water slide;

P: average annual precipitation of the observation period;

t: time in second of an observation year (t - 3,155,600s);

S: the total surface area of the region;

r: runoff coefficient in percentage (%).

Actual Evapotranspiration was determined from Thornthwaite's method. The assessment of infiltration in the region is very important for an understanding of the amount of water that feeds groundwater each year. The determination of the recharge or replenishment of aquifers is based mainly on the water balance. Thus, the formula of infiltration (Equation 3) is derived from that of the hydrological balance equation:

$$I = P - (ETR + R) \quad (3)$$

3.3.2. Piezometric Study

This study allows identifying the directions of flow, thus determining the preferred recharge and discharge zones. This requires the creation of a piezometric map that scans the conductive function of the reservoir and the hydrodynamic characteristics of the aquifer. It represents, on a given date, the spatial distribution of loads. In this study, two piezometric maps were made to assess the variation in water levels during periods of low and high water.

A monitoring of the variation in piezometric levels was carried out over time to assess the potential impact of pumping on the change of water level in the aquifer.

To calculate piezometric level, priority is given to the accuracy of the leveling and the date the measurements were made. Piezometric ratings are determined from the formula of Castany [21] (Equation 4).

$$H = Z - (P - H_m) \quad (4)$$

with:
H: Piezometric level (m)
Z: Soil level or natural terrain elevation (m)
P: Measured depth (m)
Hm: Height of the margin (m)

4. Results

4.1. Lineament Maps

The processing of the images using image combination techniques and the application of Sobel filters (Figure 2) have revealed many image discontinuities. These images have enabled the vectorization of the fractures governing some tributaries of the stream and the largest number of lineaments in the Angovia area. Directional filters enhance lineaments perpendicular to their convolution direction.

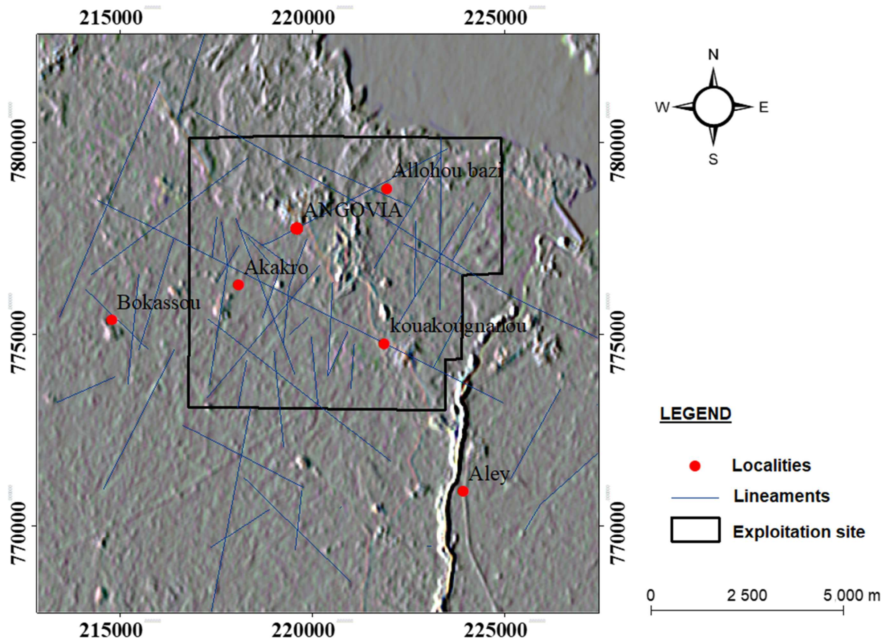

Figure 2. *Treated image by Sobel Filter at NO-SE direction enhancing the lineament.*

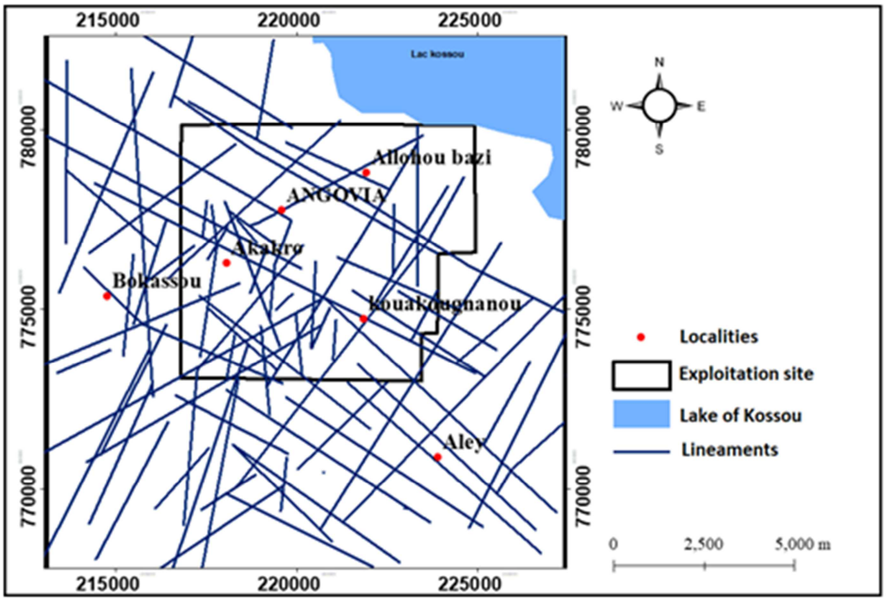

Figure 3. *Detailed lineament map of Angovia Mine site.*

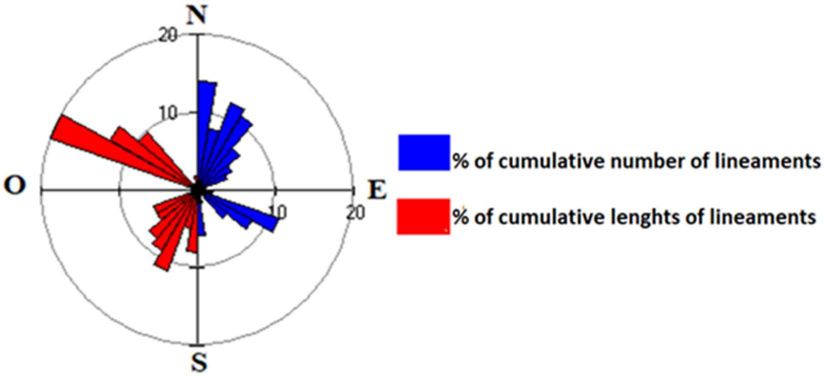

Figure 4. *Directional Rosace of lineaments.*

The detailed map of lineaments (Figure 3) includes 170 lineaments manually extracted from the interpretation of images derived from different processing techniques. The cumulative length of the lineaments is equal to 266 km. The analysis of the map of detailed surveyed lineaments allows the development of many thematic files from which is defined and characterized the geometry of underground aquifers (density of fracturing, distribution of lengths and orientations of lineaments).

4.2. Statistical Analysis of Lineament

Statistical analysis of fractures determined percentages in number of lineaments and cumulative lengths of lineaments. It also led to the realization of a directional rosette (Figure 4). The distribution of fracking expressed in number and cumulative length on the directional rosette is almost homogeneous. The dominant directions are those with 10% or more. These directions define three major directions: the N-S (N 0–10) directions. The most dominant direction is the N-S direction.

4.3. Fracture Intensity Distribution

The fracking density distribution map (Figure 5) shows spatial variability in fracking intensity. A comprehensive analysis of this map suggests that the Angovia mine site is weakly fractured. Indeed, the spatial distribution of fracking intensity shows that the low and medium fracking density classes represent 92% of the study area with 65% for the low class and 27% for the middle class. On the other hand, areas with high fracking density occupy 8% of the study area.

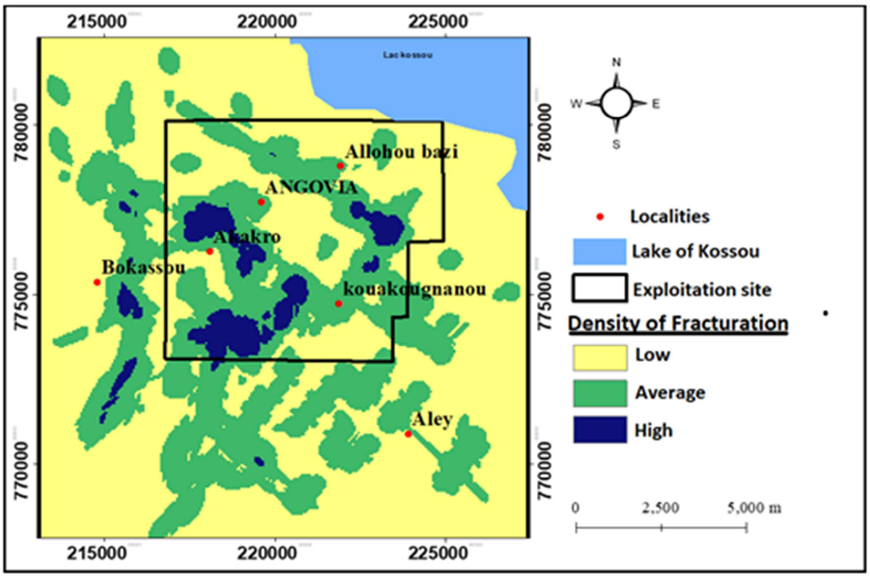

Figure 5. *Fracturing density map expressed in cumulative length (5 km×5 km) per grid.*

4.4. Water-level Variation

4.4.1. Estimated Recharge

The total infiltration that contributes to the recharge of the aquifers is about 46.5 mm/year (Table 1). This water slide accounts for about 4% of the rainfall.

4.4.2. Piezometric Study

The results of the piezometric study are presented in two parts. The first is the spatial analysis of piezometric levels and the second part deals with the analysis of interannual fluctuations in piezometric loads.

Table 1. *Aquifer Recharge parameters of study area.*

	P (mm)	ETP (mm)	ETR (mm)
January	4	234	4
February	54	186	54
March	121	202	117
April	165	174	132
May	179	167	156
June	136	146	124
July	72	125	93
August	107	125	93
September	121	128	107
October	152	139	125
November	56	141	94
December	8	140	24
TOTAL	1174	1907	1124
R	3.5		
I	46.5		

(i). Spatial Variation of Piezometry

This analysis was made from piezometric maps with low water and high-water data from the study area. These maps provide an account of the state of the aquifer during the extreme periods of the high and low waters of the hydrological cycle. The maps in Figures 6 and 7 below show the piezometry of the study area for the period of low water (January 2015) and high water (May 2015) made from water level measurements, respectively. There is no noticeable difference between these two maps. They have one recharge zone and two discharge zones with a flow that takes place in several directions including the west-east, north-south and south-north directions, but preferably the west-east direction (Figures 6 and 7). The recharge zone is characterised by a concentration of water in a specific location. It is located in the northern part around boreholes ESIAG1, ESIAG2, and YRC0766 (Figures 6). The two discharge areas are characterised by zones where the main flow paths start. The first is located in the north-eastern part around borehole ESIAG7 and the second in the southern area at ESIAG5 (Figures 6).

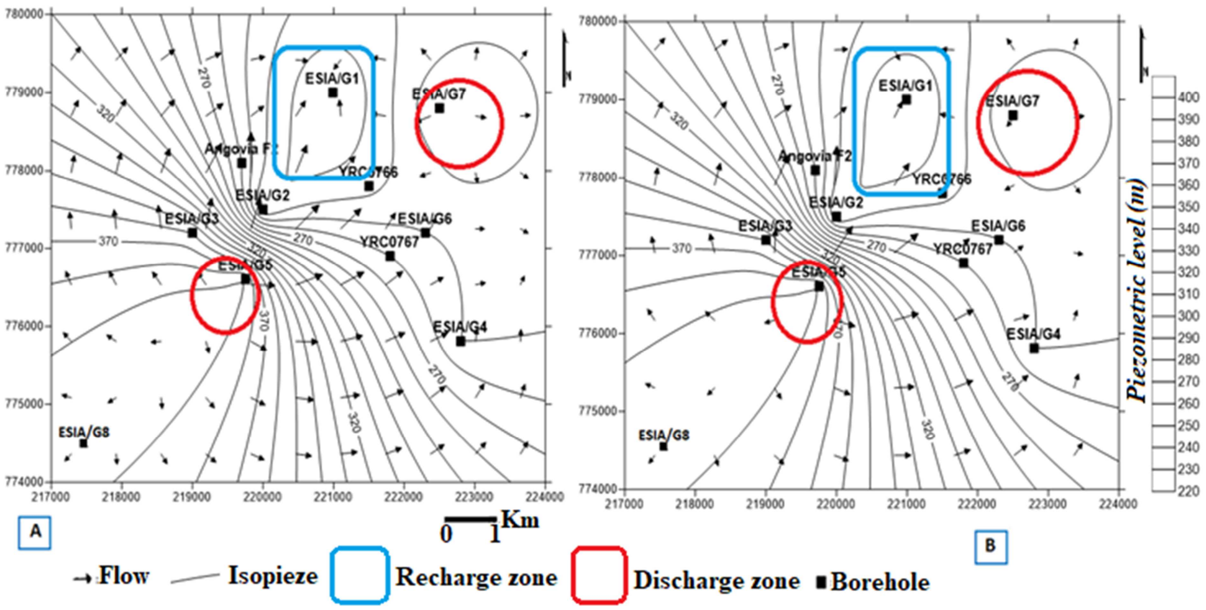

Figure 6. *Piezometric map of low water January 2015 (A) and high water May 2015 (B).*

(ii). Temporal Variation of the Piezometry

The temporal evolution of water levels in boreholes (Figure 7) provides information not only on the impact of climate variability but also on the influence of pumping for drying out pits could have on groundwater. The analysis of Figure 7, which represents water levels from borehole ESIAG1, ESIAG2, ESIAG4, ESIAG5, ESIAG6 and YRC0765, shows an alternating variation of water levels in the borehole, from one year to another. Thus, in figures 7a, 7b and 7c, we see that from January to March or April, there has been a decrease in water levels in 2017 compared to 2016 with an upward trend until this trend is reversed. However, water levels in these two years remain lower than in 2015. In Figures 7d and 7e, this same variation is observed at the level with a trend for 2017 that sometime exceeds the water level of 2015 especially from August and September.

Of all the boreholes shown in Figures 7 and 8, we generally find that the 2015 piezometric rating curve is above those of 2016 and 2017. On all boreholes, this drop in water level is between 2 m and 4 m. We also note the presence of two different aquifers at the Angovia gold mine site:

At figure 8, unlike previous boreholes, the water level remains almost constant in the water table over the three years with a high amplitude of change in water levels in the dry and rainy seasons. If this variation is less noticeable in figures 8a, 8b and 8c, this is not the case for figures 8d and 8e. In these last two figures, we see a net difference in level at each year. However, pics are observed each time practically the same periods corresponding to heavy water losses in the dry season as seen in borehole ESIAG 3 and 7. For Figures 8 c, d and e, the pics observed are obtained during the rainy seasons showing a spectacular rise in the level during rainy seasons.

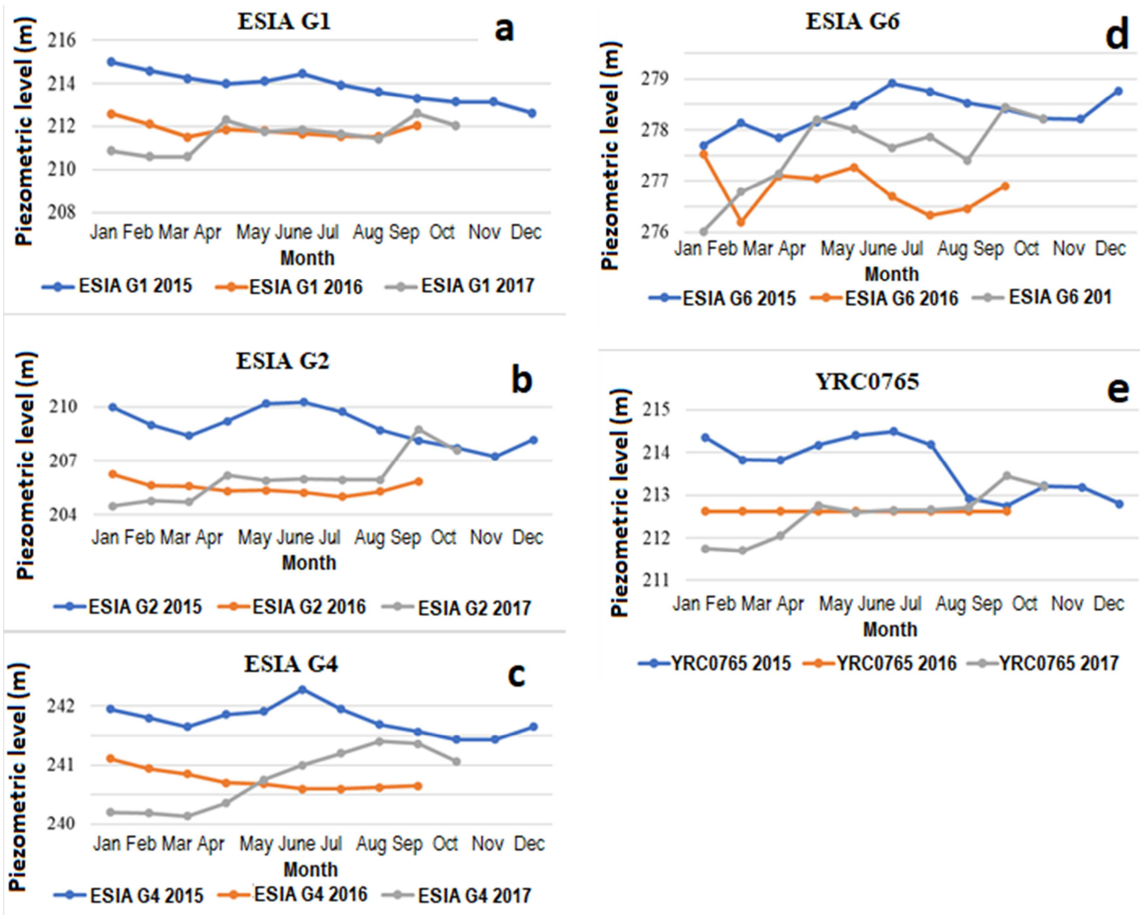

Figure 7. *Water table with low amplitude of variation of piezometric values.*

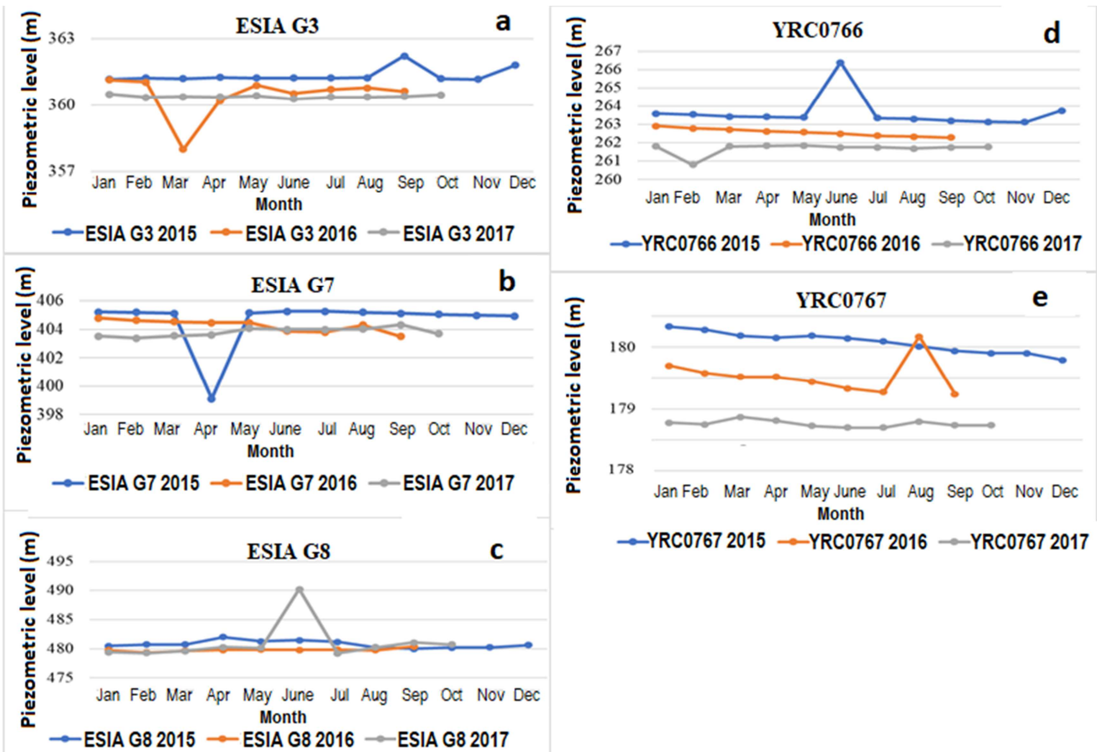

Figure 8. *Aquifers with piezometric level at high amplitude variation.*

5. Discussion

The results of the manually obtained linear structures mapping showed that the Angovia mine site is weakly fractured. This low fracking may imply low groundwater availability because in the bedrock foundation area, fractures are the best reservoirs. In addition, statistical analysis of the fracture network revealed three main directions: the N-S (N-0-10), NE-SO (N 30–40) and NO-SE (N 50–60) directions. These results are similar to those obtained by Adon *et al.* (2019) in Upper Marahoué and by Affian *et al*. and Koffi *et al* [18, 19] in the Angovia gold mine site. The main directions obtained by Adon *et al*. [17] are N-S; E-O and NE-SO. Affian *et al*. [18] were given directions N 0–20 (N-S), N 45–50, N 90–120 (NE-SO), and N 160–170 (NO-SE). Not all fracture directions obtained have the same hydrogeological interest. Thus, the fieldwork carried out by Affian *et al*. [18] showed that on observed rocks, the N 0–20 direction corresponds both to fracture directions, fracture schistosity and quartz veins. Direction N 45–50 degrees are scenester shear corridors that often result in fractures and crenulation schistosities. Direction N 160–170 is scenester shear corridors on some observed rocks and dextres on other observed rocks. The direction N 90–120 is that of fractures filled in some places by aplite. These fractures are intersected by shears N 45–50 and N 160–170.

The overall hydrological balance assessment shows that real evapotranspiration (ETR) is the most dominant term with a value of 1124 mm (or 95.7% of precipitation). The importance of this term on the water basin is due to the stripping of soils converted into agriculture lands and gold mining activities as well as the destruction of the forest cover [18]. This value remains substantially the same as that obtained by Kokobou [22] in the same study area, which is 1045.76 mm (or 94% of precipitation). The small quantity of infiltrated water, which is 46.5 mm, remains substantially the same as that obtained on the Marahoué (46 mm) by Biemi [23]. This low value of the infiltrated water slide could be due to the low rainfall (1174 mm) in the area. All this confirms the importance of precipitation in recharging, as pointed out by Hugues [24] in South Africa. The latter showed that the aquifers recharge in proportion to precipitation.

The piezometric study produced two maps for 2015, one in low water and one in high water. These maps reflect how the water table works during periods of extreme water. Also, piezometric fluctuations over time revealed two different behaviors of the aquifers. In the first case, there are large fluctuations from month to month over the three years. In this case, these variations could be attributed to climate variability. The importance of climatic variability was shown by the works of Soro *et al*. [25]. In their work, they showed the impact of rainfall on changes in water levels of boreholes. Thus, the higher the rainfall, the higher the water levels in the boreholes. In the second case, we observe the water level remains substantially decreasing constantly over the three years. This steady decline could be explained by the lack of influence of rainfall fluctuations and therefore of climate variability. It could probably come from pumping that would cause a regular drop in water levels in any season. Work by Ouedraogo [26] in the Bandama Blanc catchment highlighted the importance of pumping on the variation of water levels in boreholes. In fact, this work showed that greater water level fluctuations are observed in the structures that are heavily pumped for groundwater supply (daily pumping), unlike in other localities. Thus, the drops in water level would be attributed to the chronic rainfall deficits identified. Similarly, Maréchal *et al.* [27] in their work showed that this drop in piezometric level is due to drainage to perennial streams or other sources.

6. Conclusion

At the end of this study, it is noted that the map of the lineaments network of the Angovia Gold Mine revealed the existence of 170 fractures spread over a length of 266 km. Three preferred directions of the lineaments were obtained: the N-S, NE-SO and NO-SE with a dominated N-S direction. The piezometric study provided maps that reflect the behavior of groundwater in the Angovia aquifer system. These maps showed two discharge zones of the aquifer (one in the North-east and the other in the South) and one recharge zone in the North. Groundwater generally flows in a West-East (W-E) direction and could possibly flow into the Bandama. The observed variations in boreholes show, on the one hand, the impact of climate variability and, on the other hand, the likely influence of pumping on certain boreholes such as YRC0766 and YRC0767.

Acknowledgements

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