Available online www.jsaer.com

Journal of Scientific and Engineering Research, 2019, 6(12):90-101

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Analysis of Hydraulic Properties of Discontinuous Aquifers Basement of the Birimian Basin in Northern Togo

BOGUIDO Goumpoukini[1], GNAZOU Masamaéya D.T.[1], TAMPO Lallébila[1], BLEZA Aklesso[1], AYAH Massabalo[1], ZOUARI Kamel[2], BAWA L. Moctar, DJANEYE-BOUNDJOU Gbandi.

[1]Laboratory of Water Chemistry (LCE), Faculty of Science; University of Lomé, TOGO
E-mail address: boguival4@gmail.com
[2]Laboratory of Radio-Analysis and Environment (LRAE), National Engineering School of Sfax (ENIS), Tunisia

Abstract The main part of groundwater resources is contained in the discontinuous aquifers of the paleoproterozoïc basement in the extreme North of Togo. This study aims to evaluate the hydraulic properties of crystalline and crystallophyllian bedrock aquifers in Dapaong area (North of Togo). The hydrodynamic parameters of the aquifer are determined by the stepwise pumping tests using the various interpretation methods available that most of which derive from the methods of Théis and Jacob. Two methods were used in determining of aquifer transmissivities, Ecopage method and Logans method. The transmissivity values obtained range from $5.94.10^{-7}$ to $3.20.10^{-5}$ m²/s with Ecopage method. The values of transmissivity vary between $9.33.10^{-6}$ and $6.75.10^{-4}$ m²/s with Logans method. The values of the hydrodynamic parameters (transmissivity) are heterogeneous, reflecting the structural heterogeneity of the crystalline and crystallophyllian rock. The obtained results contribute to know the hydrogeological potentialities of the study area. The most productive depths in this area meet between 36 and 62 m while the weathering power is between 10 and 40 m with the most productive alteration layer of 10 to 25 m.

Keywords Paleoproterozoïc, hydrodynamic parameter, Ecopage method, Logans method

1. Introduction

The republic of Togo, like other African countries, under the effects of climate change is facing an ongoing shortage of drinking water despite the strong potential of surface water [1]. Water is an essential element for life, natural ecosystems, and a socio-economic valuable good. However, water shortage has become a crucial problem for all societies, especially those in developing countries [2]. Northern Togo is a part of the 94% of the national territory occupied mainly by the crystalline and crystallophyllous basement areas. The socio-economic life is focused mainly on agriculture (95%). Formerly, the most rural population obtained their supplies from surface waters and shallow wells. Under the effects of climate change, only groundwater is an alternative for drinking water supply in this region. The exploitation of groundwater is done meanly by two types of aquifers such as aquifer of alterites and aquifer of fracture tank. But the aquifers of cracks were most investigated during the hydrogeologic prospections, because they contain the main part of groundwater reserves and may be protected from seasonal fluctuations and surface pollution.

However, the boreholes exploiting these resources have generally low productivity, especially in rural areas. Some studies in crystalline basement areas of sub-Saharan region showed that majority of the studied catchment have low flow rates [3-5]. Similarly, the exploitation flows in the study area during water projects vary on average around 3,2m^3/h with a high rate of failure [6]. Lachassagne et al., [7] related that exploitation of these basement aquifers with low hydraulic conductivity is not easy. To answer this question, some studies have been conducted on this basement medium by several authors such as *Dewandel et al.* [8], Marechal et al. [9] and Lachassagne et al. [7]. Given the complex aspect of the fractured medium, several conceptual model proposals have been put in place, including model of Wyns et al. [10] which is commonly studied. In Togo, the development flow in basement area rates recorded in the drilling data sheets are between 0.4 and 16.3 m^3/h with a regional average of 4.94 m^3/h. The most frequent flows (46%) are between 0.8 and 2 m^3/h. The flows between 2 and 5 m^3/h and then between 5 and 10 m^3/h represent respectively 26% and 17% [11]. The objective of this study is to evaluate groundwater potential in aquifers of northern zone of Togo by determining the main hydraulic parameters determining the productivity of the critical fracture.

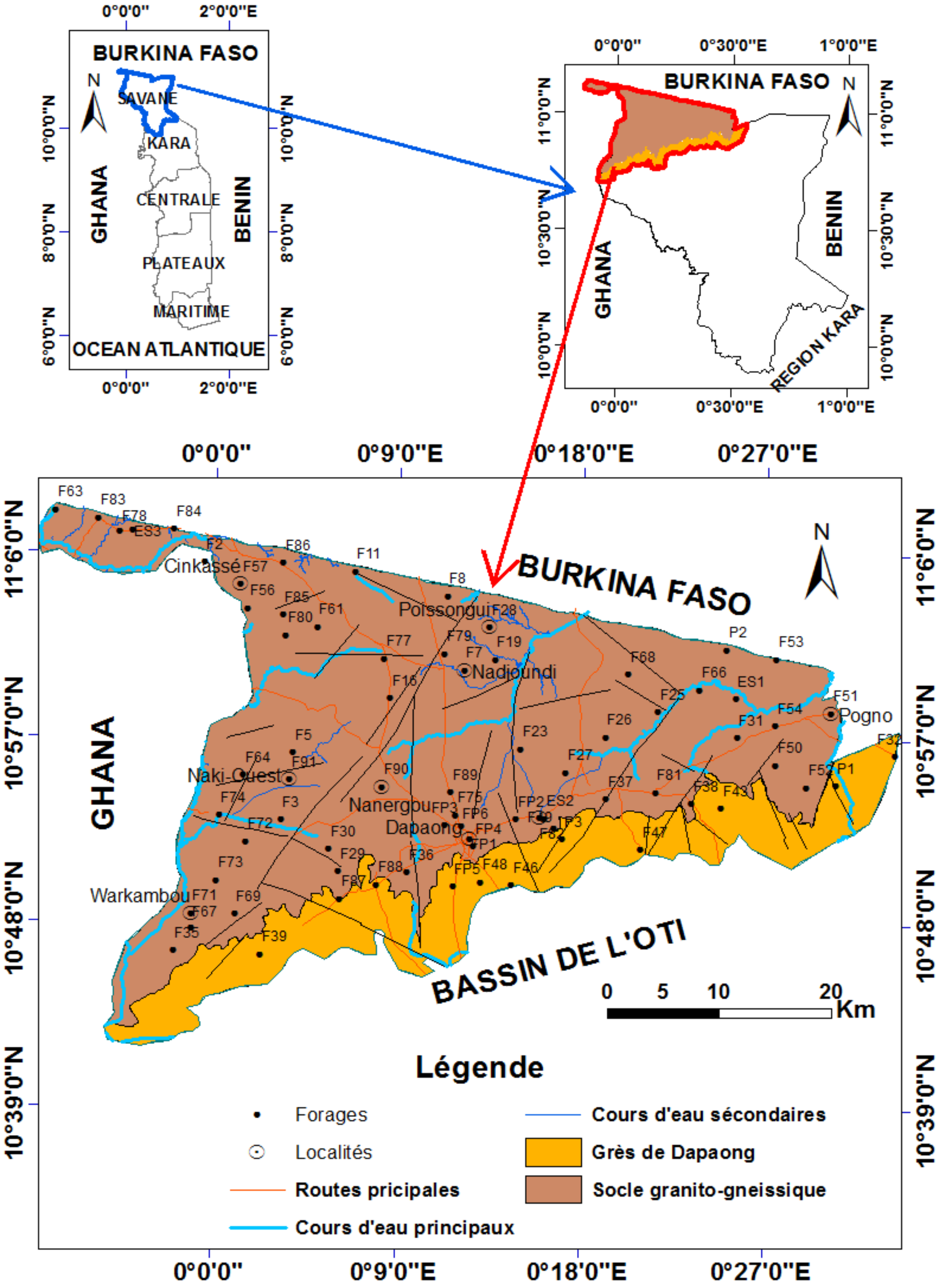

Figure 1: Location map of the study area

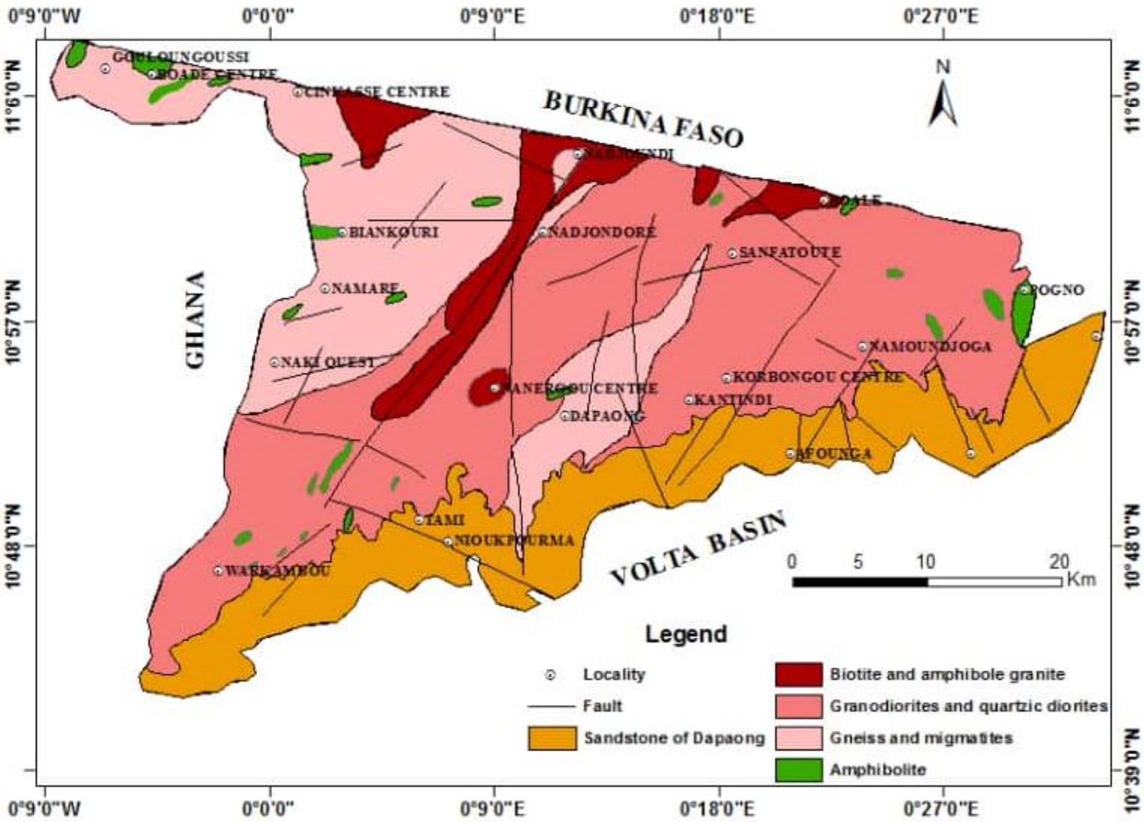

Figure 2: Geological map of the study area

2. Material and Methods

2.1. Study area

The study area is the Birimian bedrock in North-West Togo, located between latitude 10 ° 43 'and 11 ° 08' North, longitude 0° 09 'West and longitude 0 ° 33' East with elevation above sea level ranging from 260 m to 330 m (Fig 1).

The formations in the study area belong to the eastern edge of West African Big Craton Man Ridge. This ridge which develops largely in the North-West of Togolese part, is a vast geological set well represented in West Africa. It covered an area about 1345 km^2, belonging to the so-called stable area, and is situated about 600 km north of the capital city Lomé. It is the oldest formation represented in Togo, and attributed to Birimian in comparison to the Birimian formations observed in Ghana, Burkina Faso and Ivory Coast. It consists by granito-gneissic basement and includes diverse crystalline formations. In comparison to similar formations of the same type in Burkina Faso, they are considered from Archean (or pre-Birimian) to earlier Proterozoic (Precambrian C or Birimian) [12]. There are gneisses, migmatites, amphibolites, granites, granodiorites and diorites [1]. The geological map is shown in Figure 2.

The main hydrogeological formations of granito-gneissic basement are those of the large unit eastern edge of West African craton. The fissured medium that constitutes this region is the granito-gneissic domain whose hydrogeological conditions are relatively homogeneous and corresponding to the lithological families [12]. In crystalline and crystallophyllian environments, the aquifer zones corresponding to the altered surface levels (alterites and alluvium) and depth basement levels (fissures and / or fractures), which are in many cases superimposed and form the same aquifer system [8]. There are two types of aquifers: the aquifer of alterites exploited by modern or village wells, the aquifers of fissures and fractures captured by the boreholes within the framework of the programs of drinking water supply in these localities. The alteration of these formations produces a thick layer of alterites which varies between 2 and 40 m or more [13]. The climate is of Sudanian type characterized by a unimodal rainfall regime with a rainy season from April to October and a dry season during the other months of the year. The average annual rainfall is about 1000 mm to 1200m of water with a temperature that varies between 25.4 ° C and 31.6 ° C. The total annual evapotranspiration varies between 1800 to 2000 mm.

2.2. Hydrodynamic methods

This study was carried out with help of hydrodynamic drilling data obtained during the rural and semi-urban drinking water supply and sanitation project in savannah region executed by Japan International Cooperation Agency (JICA). The PASSCO project in Savannah region and the Base Progress (regrouping all the hydraulic structures in Togo) also made it possible to obtain drill cuts, hydrodynamic data and drilling depths. The JICA project was implemented in 2013-2014 and the PASSCO project in 2016-2017.

Each well having its technical file is identified by:

- its location sheet giving information on its situation (Prefecture, township, village), on its location (geographical coordinates, number); its geological section; its technical sheet listing the parameters and characteristics of the structure (depth, flow, water inflow, static level, geology, etc.); its pumping test sheet.

The hydrodynamic parameters of the aquifer are determined using the stepwise pumping tests using the various interpretation methods available, most of which derive from the methods of Théis and Jacob [5]. Various studies have shown that it is possible to calculate these parameters using short-term pumping or step pumping provided that they reach a plateau during each cycle. The minimum number of steps required to achieve satisfactory results is three (3). Several authors in West Africa have used short-term pumping for the evaluation of hydrodynamic parameters and have shown that the values of hydrodynamic parameters obtained by step pumping do not differ significantly from those obtained from conventional pumping [5, 14].

For estimation of transmissivity, several methods generally exist close to method of Théis (Cooper-Jacob method, Thiem method, the Gringarten method, Gringarten-Ramey method, Thiery method, etc.). These methods have generally been used to estimate hydrodynamic parameters in Ivory Coast and elsewhere in the world. However, these methods do not always give the expected results because of many assumptions that are not always verified and therefore remain limited.

The fundamental question raised by this study is whether other methods whose mathematical bases differ from the methods mentioned above cannot lead to similar or even better results than those produced by the former? It is therefore necessary to use methods other than those commonly used and derived from the method of Théis to evaluate the hydraulic properties of aquifers [15] granito-gneissic basin northwest of Dapaong in Togo. The different methods used to estimate transmissivity are the Ecopage method and the Logans method.

2.2.1. Ecopage method

The calculation of transmissivity using Ecopage (T1) method was based on the following formula (equation 1) [16]

$$T_1 = \frac{V}{4\pi s' t} \qquad (1)$$

with:

T: transmissivity (m² / s);

V: volume of pumped water (m^3) (product of pumping rate over time);

s': residual drawdown in the borehole (m);

t: time elapsed since the extraction of the volume of pumped water (s).

2.2.2. Logans method

Estimate of transmissivity from Logans method (T2) is based on the following expression (Equation 2) [17]:

$T_2 = 1,25*q_s$ (2)

With:

T: transmissivity (m^2/s);

qs: specific flow (m^2/s);

3. Results and Discussion

3.1. Characteristics of boreholes and thicknesses of alterites in basement aquifer systems

3.1.1. Depth of boreholes

In general, all the boreholes in the study area reached the sound basement. The productivity of a borehole is both related to the density and nature of cracking and the thickness of cracked fringe. Thus, beyond a certain depth, cracks close or become rare. The distribution histogram (Fig. 3) shows the results.

The arithmetic mean values and the median of total depths are respectively 50,51 m and 49,15 m and the standard deviation is 13,12 m; 74,3% of the boreholes have a depth of 30 to 60 m, and 10% have a depth between 70 and 100 m.

Considering the standard deviation about 13 m and the median of 49 m, we can say that the good flows are generated between 36 and 62 m of depth. Approximately 22% of the boreholes exceed 62 m depth and despite this, their flow rates remain below a desirable flow rate.

According to Savadogo [18], the great depths do not always guarantee a high productivity of the works, which is in perfect agreement with the observation made by more recent studies in Uganda on the permeability of fractures in the basement aquifers which have shown that no fractured with a permeability better than 10^{-5} m/s was found below 57 m. This suggests that the actual aquifer base is about 60 m below the surface of the soil.

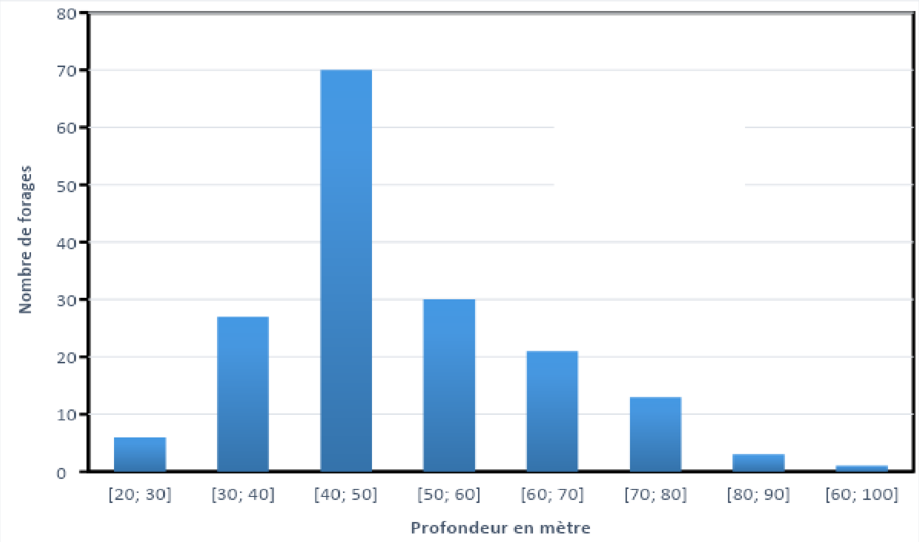

Figure 3: Frequency of number of boreholes according to the depth

3.1.2. The thicknesses of total alteration

The nature and thickness of alteration products are determined by mineralogical composition of the rock source, climatic conditions and intensity of the fracturing. Alterites in this study are predominantly clay-porous but not very permeable. This level is due to a complete destruction of altered rock which has given way to a sandy-clay formation gradually passing to clay materials towards the summit. The structure of the original rock preserved in the underlying level disappears definitively by a complete dissociation of the crystals. The phenomena of hydrolysis and destruction of minerals transform feldspars and micas into clay leaving quartz very sparingly soluble in this clay matrix.

Total average alteration thickness is 18.6 m with a standard deviation of 9.8m (Fig 4). The alterations whose thickness exceeds 10 m can constitute aquifer resources, the alterites slices between 15 and 40 m have the best flow rates while the overlays whose thickness exceeds 45 m are dominated by clay and cause flow rates insignificant or even null.

The map of thicknesses saturated alterations realized with Surfer software using the interpolation method appreciate their spatial variability. The thickness of alteration level is very variable: sometimes none at some rock domes released by erosion, it can be considerable and reach 40 meters or more. On average, this level of alteration has a power about 2 to 15 meters in the study area.

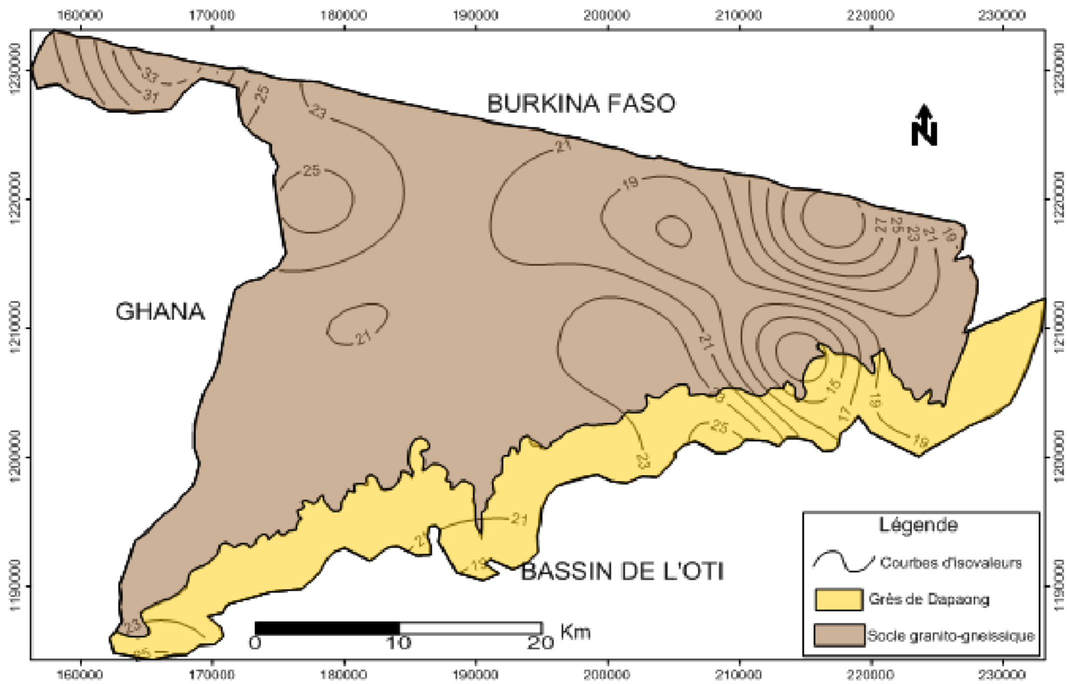

Figure: 4: Thickness map of the alteration of the study area

3.2. Hydrodynamic characteristics of boreholes in Dapaong area

3.2.1. Productivity and physical parameters

The relationship between productivity and boreholes depth is represented by Figure 5. Analysis of this graphic indicates that the highest flows (> 5 m^3/h) occur between 40 and 60 m depth. On the other hand, examination of the same graph shows that low flows at depths beyond 70 m. This indicates the existence of unproductive fractures at great depths. Thus, in the light of this analysis, it can be noted that the most productive depths are between 40 and 60 m.

In order to determine the class of alterites thicknesses that provides the most interesting flow rates, a study of relationship between productivity rates and the thickness of alterites was conducted. The analysis of Figure 6 indicates an influence of alterites thicknesses on the flows of the structures. Indeed, the strong flows are provided by alterites thicknesses ranging from 10 to 37 m and the very high flows between 10 and 25 m. Beyond 25 m, there is a downward trend in drilling flows. A significant thickness of alterites can become a factor of productivity in the recharge of cracked aquifers provided that they have a good permeability. In the opposite case, they tend to oppose the recharging of the underlying fractures [19].

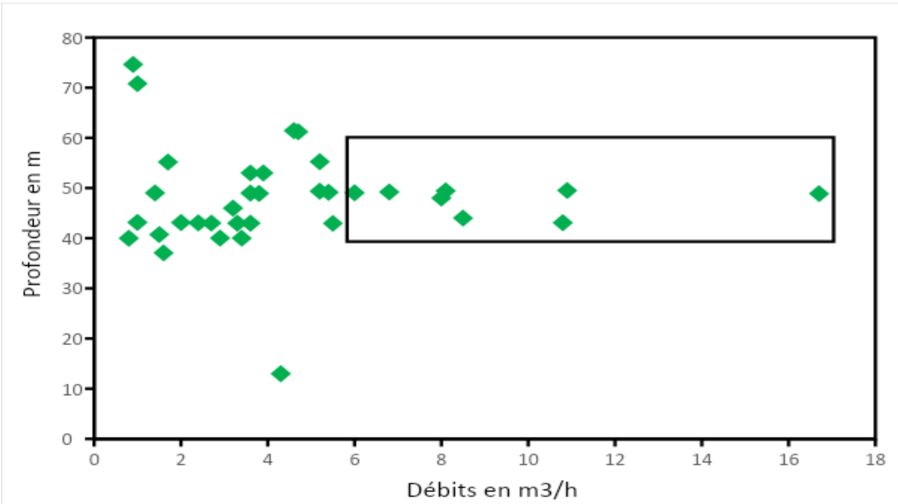

Figure 5: Relationship between flow rates and total boreholes depth

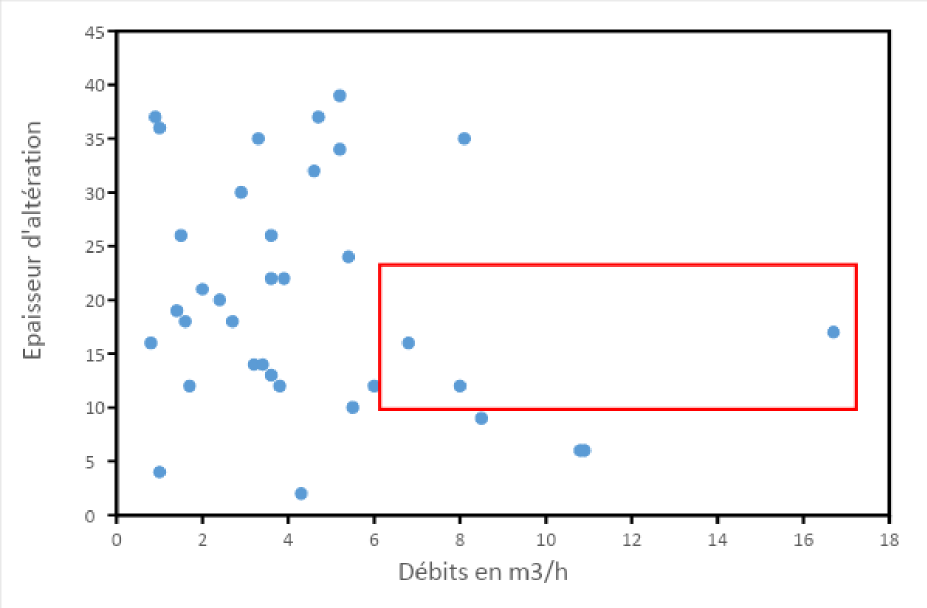

Figure 6: Relationship between flows and alterites thickness

3.2.2. Specific flows

Flow is generally used for assessment of aquifer productivity. However, this approach can lead to underestimates or overestimates of real potentials in that the flow rate only evaluates the capacity of water to move in aquifer, contrary to the transmissivity that evaluates the capacity of aquifer to transmit water and satisfy the needs of abstraction [11]. The specific flow rate, which represents the rate per unit width of the hydraulically active layer thickness, is also considered the most representative parameter for assessing the productivity of structures when transmissivity data are [20-21]. The specific flows vary from 0,027 to 1.44 m^3/h/m with a geometric mean of 0.358 m^3/h/m and a coefficient of variation of more than 74.25%. The high coefficient of variation reflects the heterogeneity of the geological environment and that hydrogeological environment. All these specific flow rates are less than 1 m^3/h/m, except for one borehole which gives 1.44 m^3/h/m. According to Engalenc [22], to obtain specific flows > 0.2 m^3/h/m, kilometer fractures must be investigated. Abdoubabaye [23] in Niger obtained a variation of the specific flow in the Dargol basin between 0.004 and 1.69 m^3/h/m with an average value of 0.23 m^3/h/m. These results are in the same order of magnitude as those found by other authors in the West African basement [24].

3.2.3.Transmissivity

Statistical characteristics of the transmissivity calculated from the Ecopage (T1) method and the Logans (T2) method are given in Table 1. Analysis in this Table shows that transmissivity values obtained with the Ecopage (T1) method vary between $5.94.10^{-7}$and $3.20.10^{-5}$ m²/s with an average value of $7.85.10^{-6}$ m² s. Those obtained with the method of Logans (T2) varied between $9.33.10^{-6}$ and $6.75.10^{-4}$ m²/s for an average of $1.40.10^{-4}$ m²/s.
Analysis of transmissivity values obtained by the two methods shows that, standard deviations vary increasingly from the Ecopage method ($5.98.10^{-6}$) to the Logans method ($1.25.10^{-4}$). The coefficients of variation fluctuate in the same order and range from 0.76 (Ecopage method) to 0.83 (Logans method). The coefficients of variation obtained are all less than 1 but remain greater than 0.25. However, these values therefore reflect a strong dispersion of transmissivity values in space. Transmissivities obtained are generally heterogeneous.

Table 1: Statistical characteristics of transmissivity

	Average	**Min**	**Max**	**Stand. deviation**	**Coefficient of variation**
Method of copage (T1)	$7.85.10^{-6}$	$5.94.10^{-7}$	$3.20.10^{-5}$	$5.98.10^{-6}$	0.76
Metchode de Logans (T2)	$1.40.10^{-4}$	$9.33.10^{-6}$	$6.75.10^{-4}$	$1.25.10^{-4}$	0.89

Analysis of Table 2 shows the different transmissivity classes of the different methods:
- Ecopage method reveals that a good part of transmissivities is in weak class (70.60%) and the rest of middle class (29.40%) while no value of transmissivity is in the class strong;
- Logans method transmissivities values are almost distributed in the middle and strong classes with respective values of 38.20% and 58.90%. The weak class represents only 2.90%.

Distribution of transmissivities shows that they are all concentrated in the low and medium classes for Ecopage methods, while they are more concentrated in the middle and high classes for Logans method.

Table 2: Distribution of transmissivities according to defined classes

		Low	**Medium**	**High**
Méthodes	Classe deT	$< 10^{-5}$	$[10^{-4}; 10^{-5}]$	$> 10^{-4}$
Ecopage	% of classes	70.60%	29.40%	0
Logans	% of classes	2.90%	38.20%	58.90%

The transmissivities calculated from the two methods are in the range $5.94.10^{-7}$ and $6.75.10^{-4}$ m²/s with average values in the range of 10^{-6} to 10^{-4} m^2/s. Good transmissivity values could be explained by the high density of fracture networks and especially the importance of their connection to allow easier water circulation [25]. But the existence of a high fracturing density is not enough on its own to guarantee good hydrodynamic properties if there is not a good connection of the fracture networks.

According to Faillat [26] only intense tectonic activity characterized by reactivation of old fractures or the establishment of new fractures could be at the origin of these hydrodynamic properties. Indeed, alteration plays a key role in the origin of fractures and consequently influences the hydrodynamic parameters of aquifers [27].

Work carried out by Kouassi et al, 2012 in Côte d'Ivoire in the N'zi-Comoé zone has made it possible to obtain transmissivity results ranging from 1.72×10^{-6} to 3.62×10^{-4} m²/s. average of $5.45.10^{-5}$ m²/s from the Cooper-Jacob method. The transmissivity values obtained by Soro [5] in the Lake District (Yamoussoukro) ranged from 1.15×10^{-6} to 4.48×10^{-4} m^2/s, or three orders of magnitude, with an average of $4.95.10^{-5}$ m^2/s. Lasm [4] obtained values ranging between $8.33.10^{-5}$ and 10^{-4} m²/s in the Korhogo catchment and Engalenc [22] obtained values that fluctuate between 1.10^{-6} and 1.10^{-5} m²/s. Values ranging from 10^{-6} to 10^{-4} m²/s were found by Soro [6] in the Mé basin. Biémi [24] obtained transmissivity values oscillating between 10^{-4} and 10^{-7} m²/s in the region of Haute Marahoué. Values ranging between $1.09.10^{-6}$ and $2.32.10^{-3}$ m²/s were obtained by Soro [6] in the west mountainous in Ivory Coasta and in the Ivorian crystalline domain (Biankouma-Man) shows that the transmissivity average is 5.62×10^{-6} m²/s with the Théis method and 1.60×10^{-5} m²/s with Jacob's method. Average values of 2.3×10^{-4} m²/s in shale and 2.6×10^{-4} m²/s in granites at Agboville were obtained. The results of Ahoussi [28] give values that oscillate between 1.6×10^{-6} and 1.11×10^{-3} m²/s in basement region of Agboville. The transmissivity values obtained in the old cocoa loop vary between 6.10^{-6} and 6.10^{-3} m²/s (Ahoussi, 2008) while values obtained by [19] in the Toumodi region vary between 1.34×10^{-6} and 6.93×10^{-4} m²/s and are close to those obtained by Jourda [29].

Moreover, in Burkina Faso, in the same contexts of crystalline and fissured environments like our study area, the transmissivity ranging respectively from 10^{-6} and 10^{-3} m²/s were found by Vouillamoz [30]. In the same context, values ranging from 5.78×10^{-4} to 5.7×10^{-1} m²/s in cracked basalts from Djibouti were obtained by Houmed-Gaba [31] while Aïssata [32] obtained values between 3×10^{-5} and 1×10^{-2} m² / s.

The orders magnitude of transmissivity obtained from the Ecopage method are therefore in the values obtained by several authors in Ivory Coast and elsewhere, in crystalline and crystallophyllian media. However, the transmissivity values obtained by the Logans method, which are in the middle and high classes, show that this method has the disadvantage of overestimating transmissivity.

It emerges from this study that the transmissivity values are acceptable and vary between 10^{-6} and 10^{-4} m²/s, which corroborate with the results obtained previously on cracked aquifers, in West Africa in general and in Ivory Coast in particular, in fractured rocks.

The transmissivities obtained in our study area are heterogeneous (coefficient of variation greater than or equal to 0.76). This heterogeneity of transmissivity values was also found by Soro [5] with a variation of $5.97.10^{-6}$ to $7.45.10^{-4}$ m²/s for the granitic basement and $1.83.10^{-5}$ m²/s at 2.69×10^{-4} m²/s on metasediments and metavolcanites. The dispersion of the transmissivity values is in line with the results already obtained in analogous formations, both in Ivory Coast and in West Africa by many other authors such as Savadogo [18], Traoré [33], Biemi [24], Tapsoba [34], Savane [3], Lasm [4] and Ahoussi, [28]. The wide dispersion of the values of various hydrodynamic parameters results from the large heterogeneity of lithological facies encountered at each aquifer level and above all the quantitative and qualitative variations of the fracturing [35].

3.3. Piezometry

The objective of the piezometric study is to follow level variation of free surface in aquifer (its fluctuation), to elaborate the map of water level.

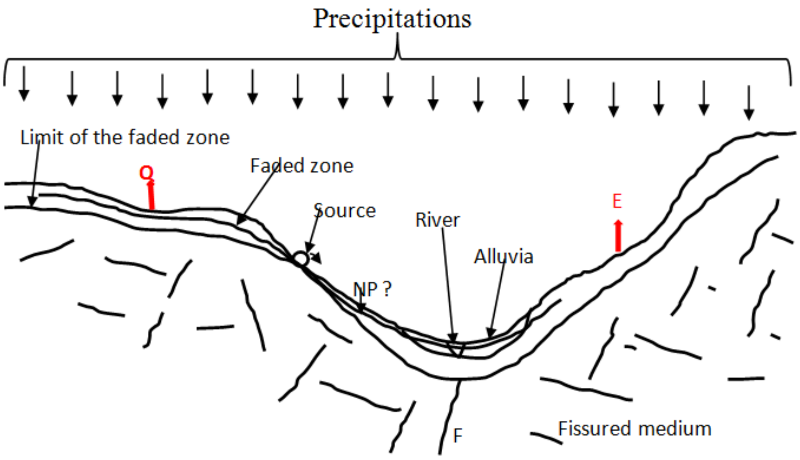

Figure 7: Diagram of the operation hydrogeologic of the aquifers of base

Static data levels acquired during the measurement campaign of Sept 2017, were only raw data so not directly usable in the state. Thus, for the realization of the piezometric map, a series of measure treatment of water depth in the structures was necessary. The first phase of the treatment consisted of bringing all the static levels back to a common measurement mark which is the ground. As a result, measurements of water depth, which have been made relative to the curbs of the structures, have been brought back from ground level. In fact, for structures with a curb, the heights of the curbs have been subtracted from static level measurements. The second phase consisted in determining the piezometric levels by the formula below [17, 36]:

$H = Z\text{-}Hp$

H = piezometric level,

Z = altitude of the natural area at the right of the structure,

Hp = depth of water in the structure (relative to the ground).

The piezometric map in Figure 8 is based on data from the piezometric survey conducted in September 2017 on hydraulic structures. We note on this map that:

- The isopipe curves are concentric in the west and progressively spaced east of the study area;
- A groundwater divide is emerging (north-south) west of the study area.

The isopipe more or less tight to the West translate a high hydraulic gradient and conversely to the East, a lower hydraulic gradient. According to Darcy's relation (Q = T.i.L), the hydraulic gradient is inversely proportional to Transmissivity (T = K.e) of the tablecloth. Thus, the sectors of low hydraulic gradient are the most interesting in terms of productivity, and therefore the most favorable for implementation of operating structures. Groundwater divide also reflects that of sharing natural flow of surface water. From the watershed line, the natural flow of water table is carried out on both sides towards watercourses and depressions by generating sources. There is an exchange; either groundwater feeds surface water or vice versa. The hydrodynamic functioning of basement aquifers can be summarized by the diagram below (Fig.7). They are fed on the surface by precipitation.

- The fluxes within these aquifers are continuous to discontinuous towards the alluvial systems of the rivers which form the outlets of the aquifers.
- The fluctuation of contributions to the limits is strong and the vulnerability to the drought is noted from rather to very sensitive. It is specified that the groundwater contained in the surface alteration zone of the plutono-

metamorphic rocks is very sensitive to drought (evaporation). The aquifer is exhausted by samples taken from village boreholes and large-diameter wells.

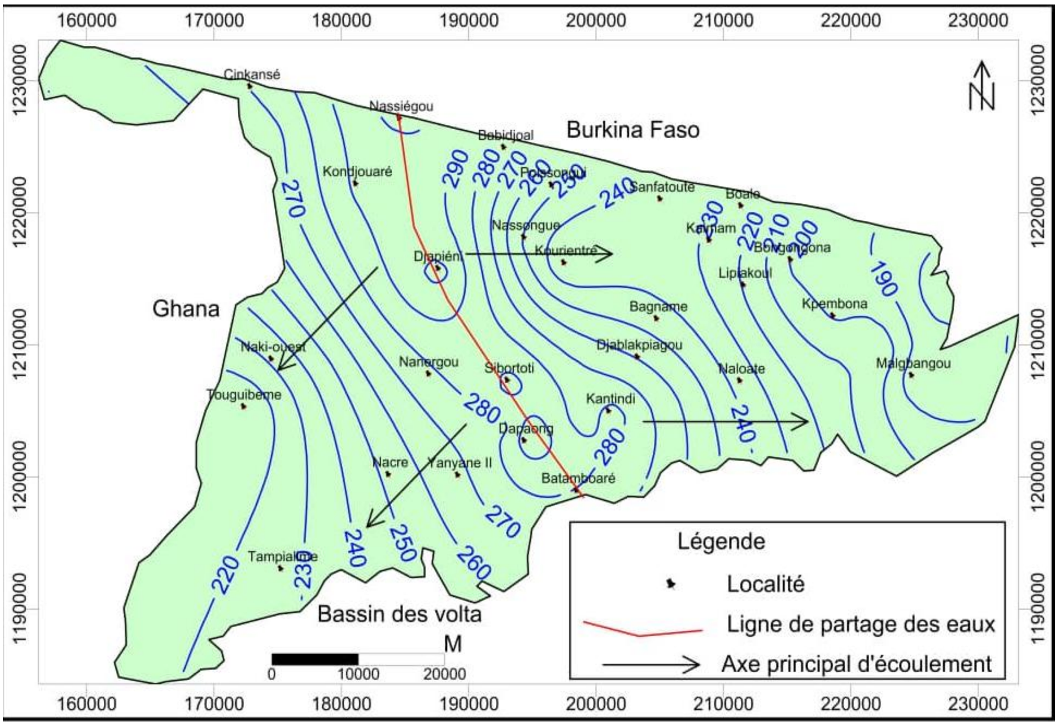

Figure 8: Piezometric map of the study area

4. Conclusion

In the Middle Birimian basement of northern region of Togo, groundwater is housed in alterites and fractures of the basement. The depth of the boreholes that captures these aquifers ranges from 30 to 100m with an average value around 50.5 m. In addition the most productive depths are between 36 and 62 m while the weathering power is between 10 and 40 m with the most productive alteration layer of 10 to 25 m. The study of hydrodynamic parameters and hydrogeological potentialities of the aquifers in the study area shows that transmissivity values obtained with the Ecopage (T1) method vary between $5.94.10^{-7}$ and $3.20.10^{-5}$m²/s with an average value of $7.85.10^{-6}$ m²/s. Those obtained with the method of Logans (T2) oscillate between $9.33.10^{-6}$ and $6.75.10^{-4}$m²/s for an average of $1.40.10^{-4}$ m²/s. The values of the various hydrodynamic parameters (transmissivity) are heterogeneous and vary according to the geological nature of the aquifers and the fracturing density of these lands. The piezometric map based on data from the September 2017 campaign measurement shows concentric isopipe curves in the west and progressively spaced east of the study area. The isopipes more or less tight to the west express a high hydraulic gradient and conversely to the East, a lower hydraulic gradient. This shows that according to Darcy's law (the hydraulic gradient is inversely proportional to Transmissivity), the East zone is more interesting in terms of productivity, and therefore more favorable for the establishment of mining structures. As for piezometry, it indicates a line of division oriented from north to south, thus reflecting the flow of the water table and the other of the line.

References

[1]. Direction Générale de l'Eau et l'Assainissement, Nov 2011. Rapport préparatoire sur le projet d'approvisionnement en eau potable et assainissement en milieu urbain et sémi-urbain dans les régions maritime et Savanes et République Togolaise.

[2]. Baali F. (2001). Eude hydrogéologique hydrochimique de la région karstique de Chéria N-E Algérien. Magister Univ Annaba Algerie, 100 p.

[3]. Savané I. (1997). Contribution à l'étude géologique et hydrogéologique des aquifères discontinus du socle cristallin d'Odienné (Nord-Ouest de la Côte d'Ivoire). Apport de la télédétection et d'un système

d'information hydrogéologique à référence spatiale. Thèse d'Etat, Université de Cocody, Côte d'Ivoire, 396 p.

[4]. Lasm T. (2000). Hydrogéologie des réservoirs fracturés de socle: Analyses statistiques et géostatistiques de la fracturation et des propriétés hydrauliques. Application à la région des montagnes de Côte d'Ivoire (domaine Archéen). Thèse de Doctorat de l'université de Poitiers, France, 272 p.

[5]. Soro G. (2010). Evaluation des propriétés hydrauliques des aquifères fracturés des formations cristalline et métamorphique dans la région des Lacs (centre de la Côte d'Ivoire). Estudios Geologicos [online], Vol. 66, N°2.

[6]. Soro N. (1987). "Contribution à l'étude géologique et hydrogéologique du Sud-Est de la Côte d'Ivoire," Thèse de 3è cycle Univ. Scient. Technol. et Médicale de Grenoble, France, 243 p.

[7]. Lachassagne P.; Wyns R. et Dewandel B. (2011). The fracture permeability of Hard Rock Aquifer is due neither to tectonics, nor to unloading, but to weathering processes. Terra Nova, Vol. 23, pp. 145-161.

[8]. Dewandel, B., P. Lachassagne, R. Wyns, J.C. Marechal and N. S. Krishnamurthy, 2010. A generalized 3-d geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering. Journal of hydrology, 330: 260-284.

[9]. Marechal, J.C., J.M. Vouillamoz, M.K.M. S. and D. B. (2010). Estimating aquifer thickness using pumping tests. Hydrogeology Journal 18(8): 1787-1796.

[10]. Wyns R.; Baltassat J.-M.; Lachassagne P.; Legchenko A.; Vairon J. et Mathieu F. (2004). Application of SNMR sounding for groundwater reserves mapping in weathered basement rocks (Brittany, France). Bulletin Société Géologique France, Vol. 175, N°1, pp. 21-34.

[11]. Akpataku K.V. (2018). Fonctionnement et contamination azotée du système aquifère de socle dans la Région des Plateaux du Togo: Approches géochimique, isotopique et hydrogéologique. Thèse de Doctorat, Univ de Lomé; 206p.

[12]. Assouma D. (1988). Etude par modèle mathématique de la structure et du fonctionnement d'un aquifère de socle exploité, en région tropical (Alimentation en eau potable de la ville de Dapaong-Togo). Thèse 3e cycle Université Orléans

[13]. Tchala K. (2017). Hydrogéochimie d'un aquifère de socle: cas de la formation du socle granito-gneissique à l'extrême Nord du Togo. Mémoire de Master Professionnel en Hydrologie ; Université d'Abomey-Calavi, 80p.

[14]. Baka D., Lasm T., Oga M.S, Youan-Ta M, De Lasme O, Kouakou O.S, Ettien, B F. (2011). Characterization of transmissivity in the fractured reservoirs in the Oumé area (Centre of Côte d'Ivoire)", American journal of scientific and industrial research, Vol. 2, N°2, pp. 310-322.

[15]. Kouassi A. M, Okaingni J. C, Kouakou K. E, and Biemi J. (2013). Evaluation des propriétés hydrauliques des aquifères de socle cristallin et cristallophyllien: Cas de la région du N'zi-Comoé (Centre-Est de la Côte d'Ivoire). International Journal of Innovation and Applied Studies ISSN 2028-9324 Vol. 2 No, pp. 61-71

[16]. Lalbat F. (2006). "Fonctionnement hydrodynamique de l'aquifère du Miocène du bassin de Carpentras (Vaucluse, France)," Thèse de Doctorat de l'Université d'Avignon et des pays de Vaucluse, France, 234 p.

[17]. Alassane A. (2004). Etude hydrogéologique du continental terminal et des formations de la plaine littorale dans la région de Porto-Novo (Sud du Bénin) : identification des aquifères et vulnérabilité de la nappe superficielle," Thèse de Doctorat de 3ème cycle de l'Université Cheikh Anta Diop de Dakar, Sénégal, 145 p.

[18]. Savadogo N. A. (1984). Géologie et hydrogéologie du socle cristallin de Haute-Volta. Etude régionale du bassin versant de la Sissili. *Thèse de Doctorat ès Sci. Natur., Univ. Scientif. et Médicale de Grenoble*, 340 p.

[19]. Gnamba Franck Maxime, Oga Yeï Marie Solange, Gnangne Théophile, Lasm Théolphile, Kouakou Yao Kouman Nestor (2014). Analyse de la productivité des aquifères de fissures de socle

paléoprotérozoïque de la région de Katiola (Centre Nord de la Côte d'ivoire). European Scientific Journal February 2014 edition vol.10, No.5 ISSN: 1857 – 7881 (Print) e - ISSN 1857- 7431.

[20]. Darko, P.K., Krásny, J. (2007). Regional transmissivity distribution and groundwater potential in hard rock of Ghana. In: Krásny, J.í., Sharp-Jr, J.M. (Eds.), Groundwater in fractured rocks pp. 109-119

[21]. Krasny, J., (1993). Classification of Transmissivity Magnitude and Variation. Ground water 31, 230-236. Cheikh Anta Diop de Dakar, Sénégal, 145 p, 2004

[22]. Engalenc M. (1978). Méthodes d'études et de recherche de l'eau souterraine des roches cristallines. *Publication du Comité Inter-Africain d'Etudes Hydrauliques 1*, Ouagadougou, Burkina Faso, 250 pp.

[23]. Abdou Babaye M. S. (2012). Evaluation des ressources en eau souterraine dans le bassin de Dargol (Liptako-Niger), Thèse de Doctorat Université de Liège; 265p.

[24]. Biémi J. (1992). « Contribution à l'étude géologique, hydrogéologique et par télédétection des bassins versant subsahéliens du socle précambrien d'Afrique de l'Ouest : Hydrostructural, hydrodynamique et isotopie des aquifères discontinus de sillons et aires granitiques de la haute Marahoué (Côte d'Ivoire) », Thèse de Doct. d'Etat ès-Sciences Naturelles, Université d'Abidjan, 479p.

[25]. Koita M, (2010). 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 Montpellier II, 235p.

[26]. Faillat J.P. (1986) Hétérogénéité et effet d'échelle dans les aquifères fissurés. Approche par pompage d'essai sur station expérimentale (Afrique de l'Ouest). *Hydrogéologie, N°1*, pp. 65-76.

[27]. Maréchal J.C, Dewandel B, et Subrahmanyak K, (2004). "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, N°40, W11508, doi: 10.1029/2004WR003137.

[28]. Ahoussi K. E., Soro N., Soro G., Lasm T., Oga M. S., Zade S. (2008). Groundwater Pollution in Africans Biggest Towns: Case of the Town of Abidjan (Côte d'Ivoire). European Journal of Scientific Research, 20(2), 302-316.

[29]. Jourda J. P. R. (2005). 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, Univ. Cocody 408p.

[30]. Vouillamoz J. M. (2002). "La caractérisation des aquifères de socle du Burkina Faso par sondages RMP. Institut de Recherche pour le Développement, UR 027 GEOVAST, Burkina Faso," N°1-4.

[31]. Houmed-Gaba A. (2009). Hydrogéologie des milieux volcaniques sous climat aride. Caractérisation sur site expérimental et modélisation numérique de l'aquifère basaltique de Djibouti (corne de l'Afrique). Thèse de Doctorat de l'Université de Poitiers, France, 194 p.

[32]. Aïssata B.H. (2010). Aquifères superficiels et profonds et pollution urbaine en Afrique: cas de la communauté urbaine de Niamey (Niger), Thèse de Doctorat, Université Abdou Moumouni, Niamey," 220 p, 2010.

[33]. Traoré, A.Z., (1985). Géologie et hydrogéologie des plateaux mandingues (Mali). Région de koula-nossombougou. Thèse de 3ème cycle Université scientifique, technique et médicale de Grenoble.

[34]. Tapsoba, A.S. (1995). Contribution à l'étude géologique et hydrogéologique de la région de dabou (sud de la côte d'ivoire): Hydrochimie, isotopie et indice de vieillissement des eaux souterraines. Thèse de Doctorat 3ème cycle, Université Nationale de Côte d'Ivoire: 200

[35]. Bahir M, Carreira P, Oliveira Da Silva M. et Fernandes P. (2008). Caractérisation hydrodynamique, hydrochimique et isotopique du système aquifère de Kourimat (Bassin d'Essaouira, Maroc)," Estudios Geológicos, Vol.64, N°1, pp. 61-73.

[36]. Gnazou M. D-T. (2008) – Etude hydrodynamique, hydrogéochimique, isotopique et modélisation de l'aquifère du Paléocène du bassin sédimentaire du Togo. *Thèse de doctorat, Univ. Lomé (TOGO)*, 204 pp.