International Journal of Engineering and Applied Sciences (IJEAS)
ISSN: 2394-3661, Volume-4, Issue-11, November 2017

Hydrogeological Characterization of Hard Rock Aquifers in Tropical West Africa Based on Borehole Data: Case of Man Area (West of Ivory Coast)

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Abstract— **This study was carried out aims to characterize the fractured aquifers by highlighting the level of alteration and to establish the possible links between the boreholes parameters and aquifers productivity in the region.**

Elementary and multi-varied statistical analyses performed and permitted to correlate borehole parameters with the yields.

We noticed that the most productive depths are between 40 and 75 m and a portion of 5 to 30 m section of regolith offers the best flow rates. In addition, the majority of the borehole in the region is into the category of medium flow with high flow rates. The most productive groundwater discharge is located in the first 60 m under the base of regolith. Also, the most productive geological formations providing an excellent flow are the granites. The power of regolith positively influences the productivity of the structures, especially when these saprolite are saturated and permeable enough to release the water they contain in a fractured underlying layer.

Index Terms—**Fractured aquifer, productivity, saprolite, well depth.**

I. INTRODUCTION

The African continent, like many other parts of the world, contains extensive areas where the sole source of groundwater is from discontinuous hard-rock aquifers. Future sustainable water supplies for much of the African continent will depend on these aquifers [1]. The hard-rock aquifers that are of prime interest for water supply lie within the weathered and fissured/ fractured layers of the crystalline rock [2]. They are generally less than 100 m thick and have a medium to low productivity. Access to safe drinking water for the rural population remains among the challenges of the coming years. The main water resources are surface water and groundwater. The bacteriological and physicochemical quality of the former is often not guaranteed, and therefore requires expensive treatments that low-income communities cannot afford [3]. Côte d'Ivoire, like other non-Sahelian countries, is more and more affected by drought and faces the problem of water management. This management is a very sensitive issue that many international organizations have stressed the vital importance for this new decade [4].

It is in this context that groundwater is of great importance.

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Indeed, the researchers of the water in a crystalline environment were directed towards a better knowledge of the fractured aquifers which are supposed to be protected from the seasonal fluctuations and less exposed to the phenomena of pollution. Knowledge of the hydrogeological characteristics of these aquifers is essential in order to better organize its mobilization for the populations [5], [3], [6]. This is why the present research whose theme is " Hydrogeological Characterization of Hard -Rock Aquifers in tropical West Based on Borehole Data Africa: Case of Man area (West of Ivory Coast).

The aim is to perform hydrogeological characterization of aquifers in the Man area through the statistical analysis of borehole data from improved village hydraulic systems. Our study highlights the level of alteration to establish the possible links between parameters such as total depth, water depth, alteration thickness, borehole depth, and drilling productivity in Man area.

Many methods were used to achieve our goal.

1. A statistical study of the parameters such as borehole flow rate, alteration thickness, well depth, etc.
2. Establishment of any links between flow and borehole parameters (drilling depth, water depth, alteration thickness, well depth, etc.);
3. A study of the alteration thickness of the area.

The results of this study can be used to better guide future hydraulic campaigns in the humid tropical area.

II. PRESENTATION OF STUDY AREA

A. Geographical Features

The Man region is located in the greater Tonkpi region, one of the largest in Côte d'Ivoire, located at the extreme west in the mountain zone and bordering the republics of Guinea and Liberia.

Located 578 km from the economic capital Abidjan and 257 km from the political capital Yamoussoukro, the city of Man is located in the West of Côte d'Ivoire between 07°20 and 07°35 latitude North and 07°25 and 07°45 West longitude.

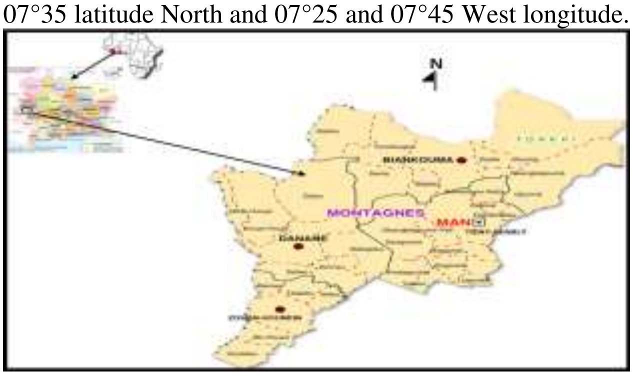

Fig. 1. Location of study area

The Man region belongs to the Guinean domain, particularly the mesophilic and mountainous sector. In that sector, there are semi-deciduous wetland dense forests, mesophilic cleared forests and mesophilic savannahs. The mountain sector consists of forest and meadow. The study area is characterized by a sub-montane climate, highly influenced by local orographic factors, because of its location at the western end of the relief of the Guinean Ridge. It is a transitional zone between sub-equatorial, tropical humid sub-Guinean and tropical climates.
Authors like Eldin [7] and Paturel et al. [8] relate this region to the transitional tropical climate or Sudanese climate. There are two distinct seasons differentiated by their rainfall regime in the absence of significant variations in temperature: the dry season and the rainy season.
The first starts in November and ends in March. During this season, the study area is affected by the effects of the continent as manifested by:

- ✓ high thermal differences;
- ✓ the permanence of the haze;
- ✓ low cloudiness and near-total precipitation in some months (December, January, and February).

The rainy season runs from April to October inclusive. It is manifested by precipitation in the form of almost daily thunderstorms (in the evening and at night) and frequent changes of squall lines (tornadoes) giving abundant rains. The highest waterfalls occur in July to September with a peak in August. Despite the concentration of heavy rains over a few months, the wet season lasts seven months.
Fig. 2 below gives a better picture of the monthly rainfall variation at the study area level. The peaks of average rains are reached in August and September during the rainy season.

Fig. 2. Monthly rainfall evolution at Man airport station (1970-2010)

. With a hilly landscape, characterized by the presence of high peaks, the Department of Man is the mountainous region of Côte d'Ivoire. The city of Man is original by its unique set of mountains that surround it and give it a special character. This mountain range opens to the south on a vast peneplain allowing the future extension of the city. The rock masses reach more than 1,000 m in the Dan and Toura mountains. The hydrographic network of the Man region is a tributary of the Sassandra River. Indeed, the department has particularly drained the river Kô which is is affluent Sassandra river right bank.

B. Geological Context of the study Area

The study area belongs to the Kenema-Man domain, Archean formations structured during the two major orogenic cycles:
- the Leonian cycle (3500 M.a - 2900 M.a);
- the Liberian cycle (2900 M.a - 2600 Ma).

These formations include granito-gneissic complexes that cover large areas and greenstone belts containing basal to ultrabasic rocks as well as iron formations [9], [10].

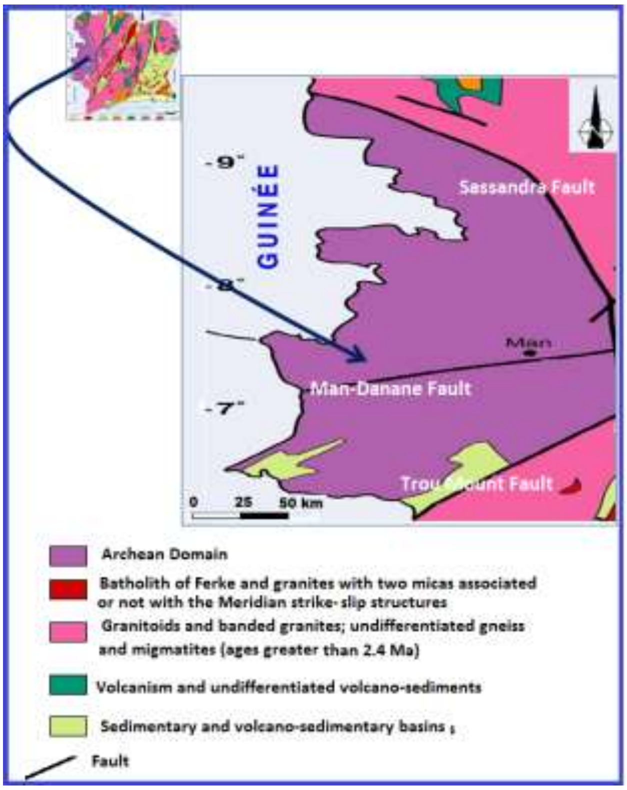

Fig. 3. Study zone geology Overview

The geological formations encountered in the Man area consist mainly of metamorphic rocks and plutonic rocks. Grouped metamorphic rocks consist of gneiss, amphibolo-pyroxenites, quartzites (with magnetites), micaschists and also migmatites. The plutonic rocks are mostly formed by a group of granites and granodiorites [11]. In addition, we have the charnockitic complex of Man characterized by all the hypersthene granitic and gabbroic rocks. Most gneisses in this region have been migrated. The formations of the zone were intensively transformed by a low to medium metamorphism and greatly folded by the Liberian tectonics. During the orogenic stage, the Liberian range was invaded by rocks of deep origin including the charnockites and norites that form the charnockitic province of Man. This province extends over most of the Man region [11].
On the structural level, according to Djro ([12], the region is formed by two mylonitic zones due to the two major accidents of the region:
- a ductile strike that is the Sassandra fault of N-S orientation;
- a fault more or less parallel to the NNE-SSW orientation that is the Danané fault. There is also isoclinal folds whose axis has a direction NNO-SSE [13].
The description of aquifer systems in the region reveals an aquifer consisting of two main zones. The first level, on the surface, consists of the saprolite (10-15 m thick), with essentially capacitive function, and the second, immediately underlying, is formed by the fractured-altered network (25-30 m d thickness) with a conductive function. The most important water inflows are located in the most superficial part of this last horizon, which is necessary to reach during the execution of the catchment structures [3],[14].

III. MATH DATASETS AND METHODOLOGY

A. Datasets and Materials

We resorted to borehole data Sheet from the project « Millennium Hydraulic and Sanitation Program » held in the region in 2011. We added the technical data sheets from drilling previously carried out in the Man area. We also used software for data processing. The data collected for each borehole are;

- ✓ the nature of the structure (borehole or well) and its geographical coordinates
- ✓ the elevation of the ground (above the sea level) at the head of the borehole;
- ✓ the total depth (TD), the thickness of the saprolite or saprolite horizon (ST), the length of fresh basement drilled (FBL);
- ✓ the piezometric level (PL) of groundwater table; the flow rate;
- ✓ lithology of the host.

We also used many software to compile data and automatically generate graphs and figures.

- ✓ Office software: Microsoft Office Pack (Word and Excel) for data entry, data processing and graph realization;
- ✓ Statisca 10.0 software for statistical calculations and corresponding graphs;
- ✓ MapInfo 10.1 for the realization of the maps.

B. Methodology

In hydrogeology, some parameters can provide sufficient information about the nature and ability of aquifers to become good groundwater reservoirs. To evaluate the aquifers productivity of the study region, we carried out a comparative analysis of the yields in relation to the physical parameters of the drillings (total depth, the thickness of saprolite, and the lithological nature of the formations.

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Acquiring drilling parameters Methods

During drilling, several pieces of information are recorded by the drilling teams in order to understand the structure and facilitate its long-term operation. Thus the drill record cards contain information such as: the air lift flow (Q), the total depth (TD), the length of the weathered zone or saprolite thickness (ST), the drilled fresh basement Length (FBL), the piezometric level (PL), the depths of instantaneous discharge (DID) etc.

Determination of statistical parameters

To better appreciate the influence of the aforementioned parameters on drilling flows, statistical analyses were carried out using Statistica software, which automates calculations of variables such as mean, maximum, minimum, variance, correlation and variation coefficient, standard deviation, correlation matrix. The interpretations of these statistical parameters made it possible to highlight the links or the absence of links between the evolution of the different parameters. Knowledge of these relationships and their interpretation will guide future drilling in the study area.

IV. RESULTS AND INTERPRETATIONS

A. Statistical analysis of the data

Drilling stastical information

The statistical parameters that characterize the 100 boreholes studied have been reported in Table 1.

Table 1. Descriptive statistics of borehole parameters

Parameters	Min	Max	Mean	SD	CV
TD(m)	41.8	96	61.99	12.26	0.198
DID(m)	9.14	87	39.3	15.39	0.391
ST(m)	3.4	37.1	15.55	8.52	0.548
FLB(m)	21	89	46.14	15.59	0.338
PL(m)	2.38	25.2	9.58	5.057	0.528
Q (m^3/h)	0.4	20	5.71	5.91	1.03

Total borehole depths range from 41.8 m to 96 m with an average of 61.99 m. These depths are often fixed by geophysical studies. But, during the execution of the drilling, they are subject to obtaining a flow rate called positive flow (about 5 m^3/h in the framework of the PHAM project) and fixed at the start of the project.

The thickness of the saprolite is between 3.40 and 37.10 m with an average of 15.55 m. Drilled basement rock thicknesses range from 21 to 89 m with an average value of 46.14 m. There are often up to four water groundwater instantaneous discharge that corresponds to the hydraulically active depths. These are the first groundwater instantaneous discharge that is the most productive. The average depth of water inflow is 39.3 m with extremes ranging from 9.14 to 87 m. The static level in the boreholes ranges from 2.38 to 25.2 m with an average of 9.58 m. The coefficients of variation for all these parameters are less than 100%. This highlights a certain homogeneity of the variables so a weak dispersion.

Borehole productivity Analyze

In Man region, the flow rate is between 0.4 and 20 m^3/h for an average of 5.16 m^3/h. It is often determined by the goals of the drilling campaign. The flow rate of the well has a coefficient of variation greater than 100%. The dispersion of this parameter explained by the coefficient of variation reflects the heterogeneity of the fissured media. The results of the yield classification according to the CIEH indicate that 34% of the boreholes fall in the class of very low (0-1 m^3/h) and low (1-2.5 m^3/h) flow rates, 21% in the class of average flow rates (2.5-5 m^3/h) and 31% in the class of strong flow rate (≥ 5 m^3/h). This shows that the majority of drilling in the region falls into the category of medium flow rates.

B. Relations between the flow rate (Q) and catchment structure

Table 2 shows a lack of significant relationship between the different parameters taken individually with the flow rate. This results in low correlation coefficient values. Nevertheless, in the following we will show that trends can be released under certain conditions when we observe the scatter plots.

Table 2. Correlation coefficient of the borehole parameters

Couple of parameters	Correlation coefficient
Flow Rate- Total Depth	0.125
Flow Rate –Instantaneous Discharge Depth	-0.129
Flow Rate –weathering Thickness	-0.303
Flow Rate – Drilled Fresh basement Thickness	-0.063
Flow Rate –Piezometric Level	-0.157

Relation between borehole depth and flow rate

The figure above shows the relationship between borehole depth and air lift flow rate.

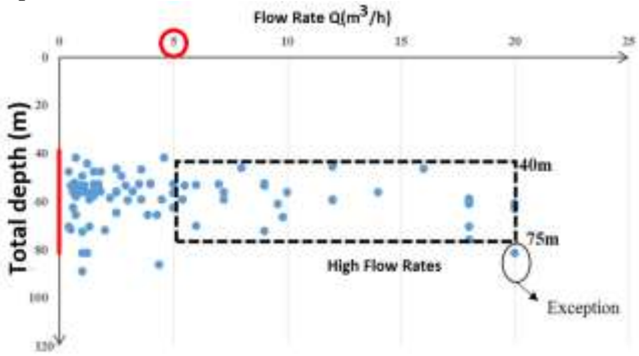

Fig. 4. Total depth according flow rate (Q)

There is no particular trend on this graph. For the majority of the drillings the total depth is between 40 and 80 m. In this section we find both high flow rates and low flow rates. It can be noted that the highest flow rates (> 5m^3/h) do not correspond to the highest depths, most of these flow rates are between 40 and 75 m. It should be pointed out, however, that all borehole depths greater than 85 m have a flow rate of less than 5 m^3/h.

Exceptionally, a borehole with a flow rate of 20 m^3/h is obtained at 81.5 m depth. In general, the maximum depth drilled during hydraulic programs is set at the beginning of the project and a flow deemed positive. If this positive flow rate is reached, the drilling process is stopped immediately without considering the possibility of finding more consistent flow rates ahead. In the opposite case some drilling process are extended in search of the prescribed flow rate. This explains why the deepest boreholes were caused by the lack of yield in the first meters.

Relationship between saprolite thickness and flow rate

The analysis of the graph above indicates an influence of the thicknesses of saprolite on the yields of the structure. Indeed, in the region of Man, strong and very strong flow rates are provided by thicknesses of saprolite ranging from 5 to 30 m. In addition, a significant thickness of saprolite can become a factor of productivity in the recharge of fissured aquifers provided that they have a good permeability (shown in Fig. 5). If not, they tend to oppose the recharge of the underlying fractures.

The distribution of the points on this graph has about the same structure as on the graph of the alteration thickness as a function of yield.

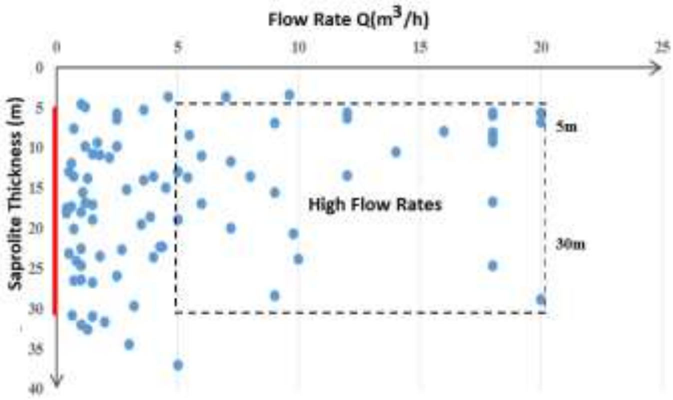

Fig. 5. Saprolite thickness and flow rate

Relationship between the length of groundwater instantaneous discharge and borehole yield

The distribution of the points on this graph has about the same structure as on the graph of the alteration thickness *vs* flow rates. There is no particular tendency, the depth of groundwater instantaneous discharge for the maximum of borehole between 10 m and 60 m. We have more or less important groundwater discharge at all depths.

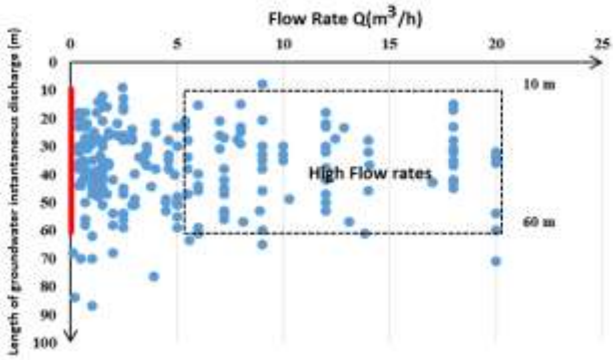

Fig. 6. Length of groundwater instantaneous discharge and borehole yield

Relationship between the length fresh basement drilled and flow rate

Considering this time not the depth of groundwater instantaneous discharge from the ground but the depth of groundwater discharge into the rock (fractured/fissured) as illustrated by the graph of Fig. 7, the following observation can be done: almost all flows above 5 m^3/h are obtained between 20 and 60 m. This tend to confirm the result stated previously; from a certain depth the fractures are less dense and begin to seal. This depth would be about 60 m under weathering in the Man area.

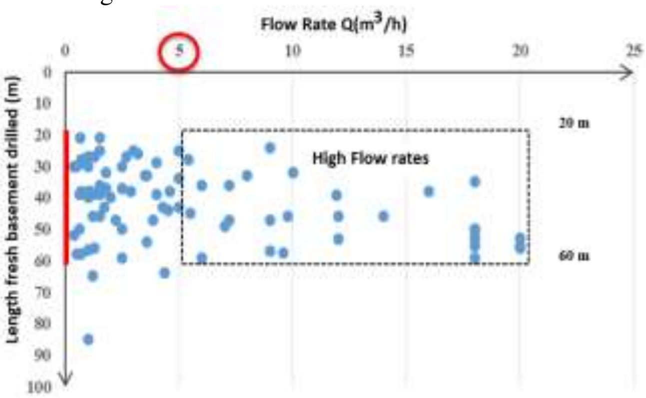

Fig. 7. Length fresh basement drilled *vs.* flow rate

C. Comparison between flow rate and rock nature

Drilling flow rate depends to a large extent on the geometry of the fracture system and the petrographic nature of the host rock. In the Man region, the geological formations encountered are granites, diorites, quartzite and gneisses. Thus, an analysis allowing to appreciate the relation which could link the productivity of the drillings to the petrographic nature of the rocks was carried out. It is illustrated in Fig. 8.

The graph analysis shows that granites appear to be the most productive geological formations in the region. In fact, 86% of the borehole on granite has flow rates between 2.5 and 5 m^3/h against 14% for diorites and gneisses and 89.6% have rates greater than 5 m^3/h against 10.3 % in quartzites, gneisses, and rhyolites. This gives a proportion of over 47.8% of drilling in granites with high flow rates. However, 34% of the borehole g in the granites has a flow rate lower than 2,5m^3/h. It should be noted that in the Tonkpi region, the most productive geological formations (which provide a high flow rate) are the granites.

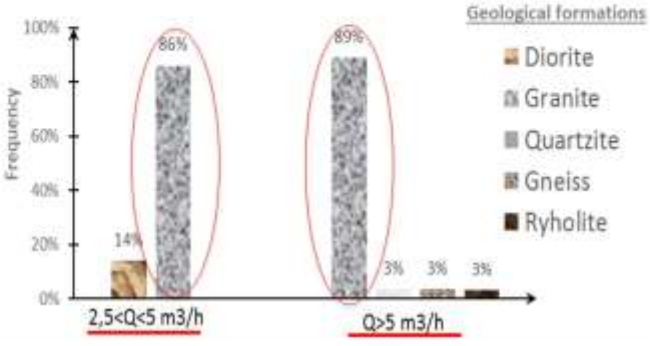

Figure 8. Borehole productivity *vs.* geological formations

D. Correlation matrix of Borehole Parameters

The analysis of the correlation matrix shows that there is no significant correlation between the various boreholes parameters in general. Nevertheless, compared to the other coefficients of the matrix, there would be a weak correlation between the sparolite thickness (ST) and the flow rate (-0.303). This correlation would mean that a large (> 45 m) saprolite layer causes low flow rate in granitic formations. This confirms a conclusion stated above; from a certain thickness of saprolite (30 m), the chances of encountering significant yields diminish.

Table 3. Correlation matrix of variables

Variables	TD	DID	ST	FBD	PL	Q
TD	1	0,09	-0,09	0,43	0,25	0,12
DID		1	-0,08	0,16	0,05	-0,13
ST			1	0,44	0,33	**-0,30**
FBD				1	0,12	-0,06
PL					1	-0,16
Q						1

E. . Weathering profile of Man Area

Description

In the region of Man, the Weathering thickness varies between 3.4 and 37.10 m with an average of 15.55 m. The Weathering consists on average of fresh rock towards the surface, sandy clay with an average thickness of 5.32 m, clay with an average thickness of 9.08 m, clay sand (7. 15 m as average thickness) and sand with an average thickness of 3.64 m. The profile is shown in Fig. 9 below.

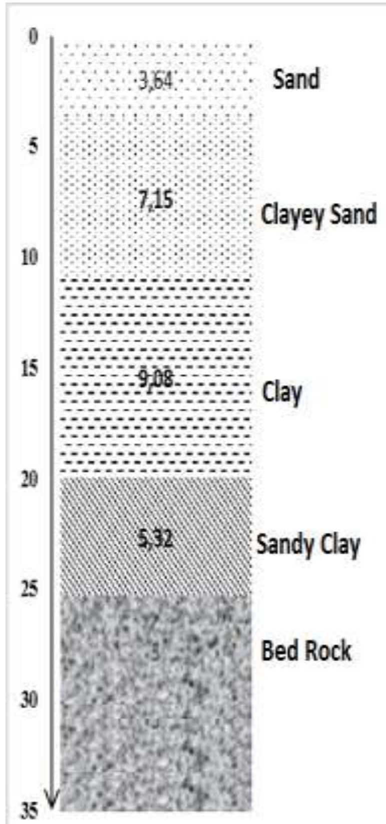

Fig. 9 Mean Weathering Profile of Man region

Weathering according lithology

Table 4 describes different rocks forming the alteration profile above each geological formation (sound rock). The analysis of the table reveals that the geological formations present in the study area have almost the same alteration profiles above. In the study area, the probability of obtaining a high yield in the gneisses is reduced compared to other formations. This tends to confirm the low flow rates obtained in the gneisses and the important flow rates obtained in granites and quartzites.

For example, 20 m^3/h in granites with a saprolite thickness of 28.82 m and 18 m^3/h in quartzites with a saprolite thickness of 16.76 m. we have said before that a layer of important saprolite can become a factor in the recharge of fissured aquifers provided that it has a good permeability. We note that the geological formation with the greatest thickness of alteration is diorite. The diorite top layer is the clay that is impervious, so it tends to oppose the groundwater recharge of fractures or fissures of diorite despite the extensive layer of saprolite. This could explain the low flow rates is seen in diorites.

In the gneisses, we find a small thickness of weathering, in addition, the layer of saprolite present at the top of the gneiss is the clay also. From what precedes it is evident that one obtains a weak flow rate.

Table 4. Description of the weathering according to the underlying formation

Fresh basement:	*weathering profile composition*	*Mean thickness (m)*	*Mean thickness above fresh basement (m)*
Granite	- Sandy clay	2.62	18.49
	- Clay	7 .58	
	- Clayey sand	5.79	
	- Sand	2.5	
Diorite	- Clay	17.08	33.3
	- Clayey sand	11.06	
	- Sable	5.19	
Gneiss	- Clay	2.1	7.69
	- Clayey sand	2.89	
	- Sable	2.7	
Quartzite	- Sandy clay	8.03	31.23
	- Clay	9.56	
	- Clayey sand	9.47	
	- Sand	4.17	

The depth of a structure does not guarantee a high flow rate. Also from 85 m depth or 60 m under saprolite, the chances of encountering high yields are reduced. Significant groundwater instantaneous discharges are observed in the first 60 meters of fissured rock. The power of the alterations positively influences the productivity of the structures, only the alterations must be saturated and permeable enough to release the water they contain in a fissured underlying layer.

V. DISCUSSION OF RESULTS

In fissured-rock reservoirs, in addition to the densities and orientation of fractures, the productivity of structures can also be related to certain parameters such as borehole depth and the thickness of saprolite [16]. Regarding depth, there is a depth beyond which the chances of finding an aquifer are decreasing, especially within the weathered basement rock [15]. Thus, several studies [5], [16], [3], [15] have thus defined the optimal depth to be achieved during drilling to obtain satisfactory productivity in crystalline rocks.

This is to avoid unnecessary drilling added value which are very often seen during drilling campaigns in West Africa. These added values from drilling do not improve the productivity of the structures [18], but rather have financial implications for the budget allocated to projects. In the Tonkpi area, regardless of the nature of the rock, the majority of the boreholes have depths that rarely exceed the depth limits of drilling proposed in previous work (80 m on granites, and 100 m on the other rocks).

The greatest depths observed in the region would be related to the fact that has not obtained the desired yield, one continued the drilling. In fact, negative or low-productivity drilling is drilled deeper in the hope of reaching a minimum exploitable flow [19]. Authors such as N'go *et al*. [20], argue that the possibility of obtaining productive drilling is real at a deep distance. In the Tonkpi region, the most productive depths are between 40 and 75 m.

This result is consistent with the scientific studies carried out in Côte d'Ivoire setting the lower limit of open fractures at 50-70 m depth ([3], [21]; [20],[22] and that of reference [23], which highlighted the most productive depth range in the Katiola region (30-75 m).

Several studies have also shown the importance of saprolite horizons in the water supply of fracture networks [24], [2], [25]. The average value of granite is much higher than those proposed by reference [26] which is 15 to 20 m. This result is in accordance with our (18.49 m average thickness of saprolite on granites). The statistical examination carried out on the data shows that the portion of the saprolite offering large flow rates is generally between 5 and 30 m and that beyond 40 m, no interesting yield is observed. This result agrees with the results of other work done in Côte d'Ivoire [27], [19] in Burkina Faso [28], and in Togo [29].

The most productive groundwater discharge is located in the first 60 meters. These results are consistent with earlier studies on the basement [30], [31], [32], [3], [24]. The flow rate of these water groundwater instantaneous discharge being determined by counting the number of productive fractures encountered during the execution of a borehole [15], it can be concluded that this section (10 to 60 m) is the area of many open and productive fractures.

In the case of Man, if beyond 85 m if a significant flow rate is not obtained, it is not necessary to continue the drilling. Indeed, from a certain depth, the fractures become less dense and some close or become clogged thus reducing the chances of encountering large yields [33].

VI. CONCLUSION

This study work held in Man and Biankouma departments aims to contribute in the orientation of future building up groundwater catchment facility. It was mainly to highlight the level of weathering in the region, to establish the possible links between the various parameters and the borehole productivity.

The technical data of previous and recent drilling operations have made it possible to have a dataset. This one has been treated with software and elementary and multivariate statistical programs.

The statistical analysis of the parameters allowed us to affirm that in the region of Man the drilling depth varies from 41.8 m to 96 m with an average of 61.99 m. The most productive depths are between 40 and 75 m. The thickness of the saprolites is between 3.4 and 37.10 m with an average of 15.55 m. The 5 to 30 m section of saprolite offers the best flow rates (> 5 m3/). The underlying formations encountered are granites, diorites, gneisses, quartzites, and rhyolites.

The most dominant and productive are the granites. 92% of the boreholes studied were made in granites. However, they also offer low flow rates. The drilling flow rate is between 0.4 and 20 m3/h for an average of 5.16 m3/h. The average weathering profile consists of fresh rock to the surface of sandy clay, clay, clay sand and sand with respective average thicknesses of 5.32 m, 9.08 m, 7.15 m and 3 m, 64 m. Average thicknesses of saprolite in granites, diorites, quartzites, and gneisses are respectively 18.49 m, 33.3 m, 7.69 m and 31.23 m.

These results provide guidance for future village groundwater campaigns, drilling depths and saprolite thicknesses with satisfactory yields in the region.

REFERENCES

[1] Courtois N., Lachassagne P., Wyns R., Blanchin R., Bougaïre F.D., Some, S. and Tapsoba A. (2010). Large-Scale Mapping of Hard-Rock Aquifer Properties Applied to Burkina Faso. Groundwater. Vol. 48, N°2 pp. 269–283.

[2] Dewandel, B., Lachassagne, P., Wyns, R., Maréchal, J., & Krishnamurthy, N. (2006). A generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering. Journal of Hydrology (330), pp. 260-284. http://www.sciencedirect.com/science/article

[3] Biemi J. (1992). Contribution à l'étude géologique hydrogéologique et par télédétection des bassins versants subsahariens du socle précambrien d'Afrique de l'ouest: hydrostructurale, hydrodynamique, hydrochimie et isotopique des aquifères discontinus de sillons et aires granitiques de la haute Marahoué (Côte d'Ivoire). Thèse de Doctorat d'État, Université d'Abidjan, 480 p.

[4] Savane Issiaka, Coulibaly Kapo Martin, Gioan Pierre (2001). Variabilité climatique et ressources en eaux souterraines dans la région semi-montagneuse de Man. Sècheresse. 12, numéro 4, pp. 231-7.

[5] Savadogo A. (1984). Géologie et hydrogéologie du socle cristallin de Haute-Volta. Étude régionale du bassin versant de la Sissili. Thèse d'État Université Scientifique et médicale de Grenoble 350 p.

[6] Maréchal, J-C., Dewandel, B., Subrahmanyam, K. (2007) Characterization of fracture properties in hard rock aquifer system. In: Thangarajan M, 2007, Groundwater – Resource evaluation, Augmentation, Contamination, Restoration, Modeling and Management, Springer, 362 pp.156-188.View at google Scholar

[7] Eldin M. (1971). Le climat. Mém. ORSTOM N°50, pp. 77-108.

[8] Paturel JE, Servat E, Kouame B, Boyer JF. (1995) Manifestation de la sécheresse en Afrique de l'Ouest non-sahélienne: cas de la Côte d'Ivoire, du Togo et du Benin. Bull Sécheresse, Vol. 6: pp.95-102.

[9] Tagini B. (1971). Esquisse structurale de la Côte d'Ivoire. Essai de géotectonique régionale. Thèse Université Lausanne. Soc. Dév. Min. Côte d'Ivoire (SODEMI), 302 p.

[10] Yacé I. (2002). Initiation à la géologie. L'exemple de la Côte d'Ivoire et de l'Afrique de l'Ouest. Éditions CEDA (Abidjan), Côte d'Ivoire, 183 p.

[11] Camil J. (1984). Pétrographie chronologique des ensembles granulitiques archéens et formations associées de la région de Man (Côte d'Ivoire). Implications pour l'histoire géologique du craton Ouest africain. Thèse Doctorat d'État, Université de Côte d'Ivoire, 306 p.

[12] Djro SC. (1998). Évolutions tectono-métamorphiques des gneiss granulitiques archéens du secteur de Biankouma-Touba (Nord-Ouest Côte d'Ivoire). Thèse d'État, université de Cocody

[13] Koné, M., Y. Vialette, P.Tempier, S. Lemoine et J. Camil. (1996). "Transpression post archéenne dans l'ouest de la Côte d'Ivoire (craton Ouest africain", Africa Geosci. Review, 3(3/4), 1996, pp. 407-411.

[14] Kouame K.F (1997). Contribution à l'étude géologique et hydrogéologique des aquifères discontinus de montagne à l'ouest de la Côte d'Ivoire: cas du secteur Biankouma-Man. Apports de la télédétection et d'un Système d'information géographique. Mémoire de DEA des sciences de la Terre. Université de Coccody Abidjan Côte d'Ivoire.

[15] Kouadio K. E.; Soro N. and Savane I. (2010). Strategy for borehole depth optimization in hard rock aquifers (Denguele region, northwestern Ivory Coast). Journal of Water Science, Vol. 23, N°1, pp. 1-15.

[16] Durand V. (2001). : Recherche des relations entre la structure des aquifères de socle et leur fonctionnement hydrogéologique à partir d'un signal. Traitement à deux échelles différentes de bassins versants. Mémoire DEA, Ecole des mines de Paris et école nationale du génie rural, des eaux et forêts, 50p

[17] Banks D. (1992). Estimation of apparent transmissivity from capacity testing of boreholes in bedrock aquifers. Applied Hydrogeology, Vol. 4, pp. 5-19. ISSN1435-0157 https://doi.org/10.1007/PL00021539

[18] Gombert P. (1997). Variabilité spatiale de la productivité aquifère du socle sahélien en hydraulique rurale. Hard Rock Hydrosystems, IAHS Publ., Vol. 241, pp. 113-122.

[19] Gassita S., Gageonnet M., Solages S. (1987). Synthèse des résultats du premier programme d'hydraulique rurale exécutée en République du Gabon. Hydrogéologie, n°2, pp. 113-126.

[20] N'Go Y. A., Gone D. L., Savane I. et Goble M. M. (2005). Potentialités en eaux souterraines des aquifers d'Agboville (sud ouest de la Côte d'Ivoire): Caractérisation hydroclimatique et physique. Afrique SCIENCE 01 (1).pp 127-144.

[21] 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.

[22] Youan Ta M. (2008). Contribution de la télédétection et des systèmes d'informations géographiques à la prospection hydrogéologique du socle précambrien d'Afrique de l'Ouest: cas de la région de Bondoukou (Nord-Est de la Cote d'Ivoire). Thèse de Doctorat de l'Université de Cocody-Abidjan, Côte d'Ivoire, 237p.

[23] Gnamba F. M., Oga M-S., Gnangne T., Lasm T., Biémi J., Kouakou Y. et Kouman N. (2014). Analyse de la productivité des aquifères de fissures du socle paléoprotérozoïque de la région de Katiola (centre-nord de la Côte d'Ivoire) European Scientific Journal, Vol.10, N°5, pp.79-98 http://www.eujournal.org/index.php/esj/article/view/2713

[24] Wyns R., Baltassat J.-M., Lachassagne P., Legchenko A., Vairon J. and Mathieu F. (2004). Application of proton magnetic resonance sounding to groundwater reserve mapping in weathered basement rocks (Brittany France). Bull. Soc.géol. fr. N°1. pp. 21-34. https://doi.org/10.2113/175.1.21

[25] Lachassagne P.; Wyns R. and 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.

[26] Engalenc, M. (1978). Méthodes d'étude et de recherche de l'eau souterraine des roches cristallines de l'Afrique de l'Ouest. Comité interafricain d'études hydrauliques, Série hydrogéologie, vol.1, 318 p. vol. 2, 193 p.

[27] Berger J., Camerlo J., Fahy J.C. et Haubert M. (1981). Étude des ressources en eau souterraines dans une région de socle cristallin: la « Boucle du Cacao» en Côte d'Ivoire. Bull. BRGM, série 2, section III, n°4, pp. 335-338.

[28] Compaoré, G. (1997). Estimation of the rock alteration specific storage experimental site at Sanon (Burkina Faso): granite-gneiss bebrock in sudano-sahelian climate. Université d'Avignon et des Pays de Vaucluse. PhD Thesis, 178p.

[29] Assouma D. (1988). Étude 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, 183p.

[30] Camerlo J. et Fahy J. C. (1981). Premiers résultats obtenus en Côte d'Ivoire dans les recherches d'eau axées sur les fractures secondaires des roches grenues du socle. Bull. BRGM., Sér. II, Sect. III, n°4, pp. 289-291.

[31] Faillat J. P. (1986a). 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.

[32] CEFIGRE (1990). L'hydrogéologie de l'Afrique de l'Ouest. Synthèse des connaissances du socle cristallin cristallophyllien et sédimentaire ancien. Collection Maîtrise de l'eau 2ème édit., 147p.

[33] Lachassagne, P. et Wyns, R. (2005). Aquifères de socle: nouveaux concepts, Application à la prospection et la gestion de la ressource en eau. Géosciences (2), pp. 32-37.

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