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Analysis of the Hydrodynamic Properties of the Fissure Aquifers of the Black Volta Catchment in Ivory Coast

Youan Ta Marc, Kouame Kouadio Armel, Akokponhoue Houngnigbo Bertrand, and Njeugeu Mbiafeu Amandine Carine

ABSTRACT

The present study aims to analyze the productivity of aquifers in the Ivorian part of the Black Volta basin. It proposed to characterize the intrinsic hydrodynamic parameters of the productivity and to know the influence of these on the productivity of the drillings. The hydraulic parameters of the catchment structures and the pumping test sheets were used to determine the hydrodynamic properties through a methodological approach integrating Cooper Jacob's empirical formulas and automated calculations using the Pumping Interpretation Assistance Tool (OUAIP). A standardized principal component analysis (ACPN) was used to analyze the correlation of the different parameters. The results obtained range over several orders of magnitude. The values of the specific flow oscillate between 0. 01 and 4.87m²/h while the transmissivity varies between 1.25E-07 and 7.34E-03 m².s^{-1}. As for the critical flow, it is between 0.869 and 26.6 m3/h. These values indicate that the aquifers generally have low specific flow rates, but fairly good transmissivity. The Normalized Principal Component Analysis (ACPN) allowed to highlight the different productivity factors of the aquifers in the region: water level variation, and hydraulic role of fractures. It also showed the influence of the depth of the drilling on productivity. These results contribute to the knowledge of the structure and hydrodynamic functioning of the aquifers of the basin basement. They show the structural links between hydrodynamics and aquifer productivity.

Keywords: ACPN, Black Volta catchment (Côte d'Ivoire), discontinuous aquifers, productivity.

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Y. T. Marc
University Research Center of Remote Sensing and Application (CURAT), Training and Research Unit of Earth Sciences and Mineral Re-sources, University Felix Houphouet-Boigny, Côte d'Ivoire.
(e-mail: youanta@gmail.com)

K. K. Armel *
Laboratory of Soil, Water and Geomaterials Sciences, Training and Research Unit of Earth, Sciences and Mineral Resources, University Felix Houphouet-Boigny, Côte d'Ivoire
(e-mail: melzocbg@gmail.com)

A. H. Bertrand
Laboratoire of Applied Hydrology, National Water Institute (INE), University of Abomey-Calavi, Benin.
(e-mail: houngnigboo@gmail.com)

N. M. A. Carine
University Research Center of Remote Sensing and Application (CURAT), Training and Research Unit of Earth Sciences and Mineral Re-sources, University Felix Houphouet-Boigny, Côte d'Ivoire.
(e-mail:
Fernand.kouame@curat-edu.org)

**** Corresponding author***

I. Introduction

The crystalline and crystallophyllous basement regions are known for their structural complexity. The associated water resources reflect this complexity: highly heterogeneous constraints to identify and characterize. It is generally accepted that they are concentrated in the upper slice of the crystalline formations (≈50 m depth), within altered formations and sub-surface fractures constituting true underground water stores often presenting the advantage of being sheltered from seasonal fluctuations and possible accidental pollution [1], [2]. This situation makes it difficult to supply drinking water in the regions concerned because the failure rate during the installation of structures and the often very low operating flows (<1 m^3/h) of these structures contribute to maintaining water stress and lead to numerous social problems in these areas accompanied by large financial losses [3], [4]. An inventory of 1,117 catchment structures built between 1973 and 2007 was compiled. 67% of the structures have low test flows, 28% of which are declared negative because they have not reached an optimum flow of 1 m^3/h. These structures are not sustainable because they are not designed to be used for the purposes of water management. The latter are not perennial, hence the cessation of operation of several of them in the short term. In such a context, knowing the intrinsic hydrodynamic properties of the reservoirs and the operating limits of the hydraulic structures located in these areas is of great importance. This study aims to analyze the hydrodynamics and productivity of aquifers for better management of water resources.

II. Geological and Hydrogeological Framework

The study area (Fig. 1) is the interface of the Black Volta transboundary basin in Côte d'Ivoire. It is located between latitudes 7°78 and 9°94N and longitudes 2°49 and 3°35W and delimits a vast geographical area located in the northeast of Côte d'Ivoire. Its main river, the Black Volta (Mouhoun) River, originates in the Kong Mountains in the Dindéresso Forest Reserve, southwest of Burkina Faso. It is approximately 1,363 km long and drains a total area of 12,836 km² in Côte d'Ivoire [5]. The relief is not very rugged. The highest peak, the Bondoukou Massif, reaches an altitude of 725 m. Geologically, the basin is located in the eastern compartment of the Precambrian basement called Baoulé-Mossi (Fig. 2) of Paleo-Proterozoic age and structured by the Eburnian megacycle (2400-1600 Ma). The area is covered by a complex set of geological formations classified according to age and unevenly distributed in two domains: the Quaternary domain (Holocene) and the Birimian domain (Fig. 1).

From a hydrogeological point of view, the conceptual model accepted in the basement area [6] is the presence of a superficial film (alterites), capacitive, fed by the surface, followed by a fissured horizon (intermediate decompressed zone), with a very high permeability forming the second aquifer level [7]. The third aquifer level is located in the sound bedrock affected by tectonic fractures (faults). Levels 2 and 3 constitute the semi-captive part of this multilayered aquifer hosting a single water table [8].

III. Methodology

A. Determination of Hydrodynamic Parameters

The data sheets of 587 catchment structures built in the study area from 1973 to 2007 were analyzed. These sheets included several parameters: the locality, the nature of the work (borehole or well), its geographical coordinates (X, Y), the altitude (Z), the total depth of the work (Pt), the geological nature, the type of implantation (geophysical or geomorphological) of the borehole, the nature of the exploited aquifer (fractured basement or alterite), the static level (NS), the exploitation flow rate (Q), the depths of the water arrivals (AE) and the flow rate of the significant water arrivals. Only 273 boreholes were pump tested. These pumping tests were used to evaluate transmissivity, specific flow rate (Q/s), and critical flow rate (Qc).

The transmissivity is determined by the Cooper-Jacob graphical method based on the Theis equation. It is used when in a discontinuous water table, the transient pumping test has been performed with several constant flow rates. This method is therefore suitable for the 230 pumping test data carried out in stages on the 273 boreholes. The number of stages ranges from 2 to 3 depending on the size of the flow and the duration varies from 45 to 60 minutes. The descent lasts three or four hours and the ascent is followed by one hour of observation.

The values of transmissivity were calculated from the upwelling data in order to reduce the influence of pressure drops in the vicinity of the structure. The expression of the drawdown is then given by (1):

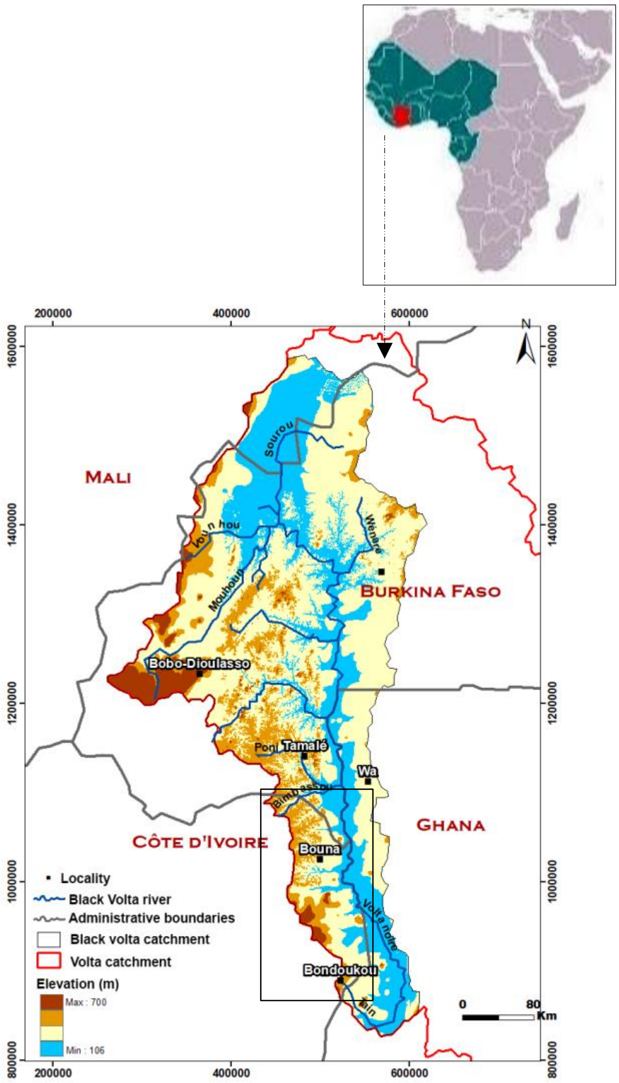

Fig. 1. Map of localization of Black Volta catchment.

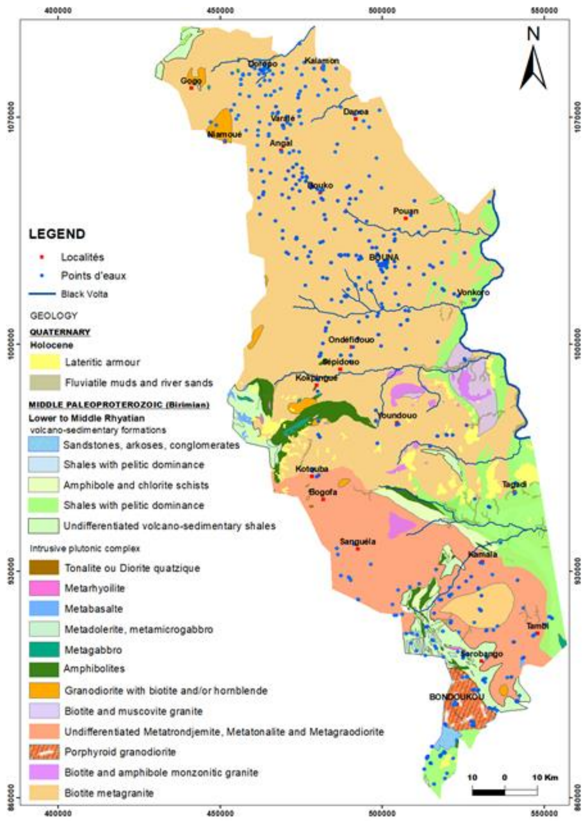

Fig. 2. Map of the different geology units of study area.

$$S(t') = 0{,}183\,\frac{Q}{T}\log\left(\frac{t_m}{t'}\right) \quad (1)$$

where
t' – the time elapsed since the pumping stopped;
tm – the corrected time defined as the time at which the drawdown would have occurred in a certain piezometer if the pumping rate had remained constant since the beginning and equal to the real rate at the final time *t* as it concerns pumping of short duration [9].

The logarithmic approximation relies on simplifying assumptions to calculate the transmissivity value (Fig. 3). The basic concepts and protocol for calculating this quantity are presented in the work of [1], [10]–[12]. Transmissivity is determined by the following (2):

$$T = 0{,}183 \times \frac{Q}{\Delta s} \quad (2)$$

where
T – transmissivity expressed in m².s-1 ;
Q – pumping rate of the first stage in m3/s ;
Δs – variation of the drawdown (m) over a logarithmic cycle of time.

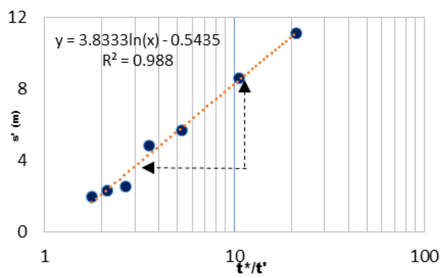

Fig. 3. Graphical determination of transmissivity (Cooper-Jacob).

The specific flow rate (Q/s) is the pumped flow rate (Q) related to the drawdown (s). Since specific flow rates in the basement decrease very rapidly with depth [13], only the specific flow rates calculated on the third stage at the boreholes were considered as recommended by [1]. It is assumed that boreholes with a Specific flow (Q/s) greater than or equal to 1 m²/s is good productivity [1].

As for the critical flow, it is the yield not to be exceeded during operation at the risk of accelerating the deterioration of the structure and the poor quality of the water withdrawn. The value of the critical flow rate can be determined graphically by identifying on the characteristic curve the equivalence point between linear and quadratic pressure drops during short pumping tests. The OUAIP software automatically calculates the value of the flow at this equivalence point.

B. Analysis of the Productivity of Fissure Aquifers

To analyze the productivity of the fractured aquifers in the study area, a normalized principal component analysis (ACPN) was used for eight hydrodynamic and hydraulic parameters.

It allowed us to assess the correlations between the studied parameters in order to know the intrinsic influence of these parameters on the productivity of the aquifers.

This method synthesizes and classifies the data and removes the heterogeneities between the expression units of the variables.

The input data were therefore normalized according to (3).

$$z = \frac{x-\mu}{\sigma} \quad (3)$$

where
z – the normalized value;
x – the data.
μ and σ – the mean and standard deviation of the data, respectively.

STATISTICA 9.1 software was used for the application of ACPS. The analysis included a total of 130 samples with 08 parameters: total depth (Pt), basement depth (Ps), weathering thickness (EA), inflow 1 (AE1), transmissivity (T), static level (NS), operating flow (Q), critical flow (Qc), and specific flow (Q/s). Based on the correlations revealed by the multivariate analysis, empirical relationships were established between the variables in pairs in order to approach the hydraulic properties of the reservoirs indirectly. Indeed, a sometimes very good correlation allows to estimate one or the other of the variables when it is missing.

IV. Results

A. Descriptive Statistical Analysis

The main characteristics of the hydrodynamic and hydraulic parameters of the aquifers in the Black Volta catchment are recorded in Table I. The values range over several orders of magnitude.

The hydrodynamic parameters T, Q/s, Q and Qc have quite high coefficients of variation implying a strong dispersion around the mean. This reflects the heterogeneity of the environment studied. The distribution of T and Q/s values according to the classes defined [14] (Fig. 4) shows that 58% of T values are located in the middle to high classes against 78% of Q/s values. It is inferred that the aquifers are characterized by fairly good hydraulic properties. The basement occurs at an average depth of 24.08 m throughout the area with a water table located at about 8 m in the alterites communicating with the fractured basement through a network of fractures [15].

TABLE I: Descriptive Statistics of Hydrodynamic Parameters

	Effectif	Mean	Minimun	Maximun	Standard deviation	CV (%)
T ($m^2.s^{-1}$)	199	2.04E-04	1.25E-07	7.34E-03	7.57E-04	1.55E-05
Q/s ($m^2.s^{-1}$)	199	0.58	0.01	4.87	0.85	147.96
Qc ($m^3.h^{-1}$)	80	6.18	0.869	26.6	6.48	95.25
NS (m)	288	7.95	0.4	29.6	4.62	58.1
Pt (m)	288	62.16	18.3	97	15.62	25.12
Ps (m)	288	24.08	1.5	57.4	12.43	51.63
AE (m)	288	38.39	9.9	254	1.12	49.54
Q ($m^3.h^{-1}$)	288	3.71	0.2	18	3.8	102.59

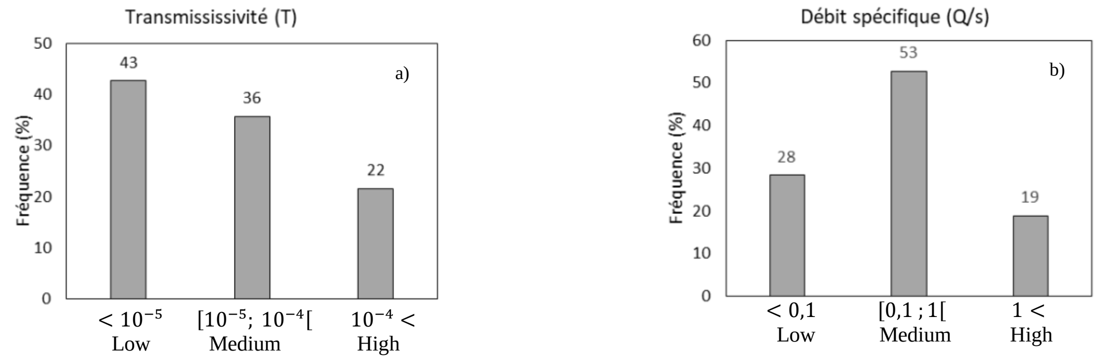

Fig. 4. Frequency of distribution of transmissivity values (a) and specific flow (b)

B. Correlations of Hydraulic and Hydrodynamic Parameters

The ACPN highlighted, through the correlation matrix, the level of correlation that exists between the different parameters evaluated (Table II).

The most relevant correlations are those between the variables T and Q/s (0.98), between T and Qc (0.87), and Q/s and Qc (0.85). The relationship between transmissivity, specific flow rate, and critical flow rate is related to the geometry and yield of fracture aquifers. There is also a significant correlation between Pt and AE1 (0.70). This relationship highlights the water capacity of deep fractures. From these correlations, a predictive relationship in the form of a math equation is established between T and Q/s. Thus, T and Q/s are fitted according to a power-type regression equation with a correlation coefficient equal to 0.98 and an estimated characteristic exponent of 1.52 (Fig. 5). The relationship is given by (3):

$$T = 0.0002 \times Q/s^{1.52} \tag{3}$$

C. Correlations of Hydraulic and Hydrodynamic Parameters

The ACPN highlighted, through the correlation matrix, the level of correlation that exists between the different parameters evaluated (Table II).

D. Analysis in the Space of the ACPN Variables

The main factors influencing the hydrogeological functioning of the studied aquifers are 3, and they represent 76.15 % of the total variance expressed (Table III and Fig. 6). Saturations are presented in Table IV.

1) Factorial plane F1-F2.

In the F1-F2 plane structure (Fig. 7), factor 1 is correlated with parameters such as T, Qsp, Qc, and Q. These parameters are intrinsic to the productivity of fracture aquifers. Indeed, transmissivity (T) and specific flow rate (Q/s) reflect the hydrodynamic potential of aquifers, i.e., the capacity of the aquifer system to allow water to flow through it and provide acceptable flow rates. The exploitation flow rate (Q) and the critical flow rate (Qc) remain linked to this productivity. Factor 2 is defined by the variables Pt, Ps, NS and Ps. It could express the influence of the depth of the structures in the basement on the water levels. In other words, this correlation reflects the variation of the water level according to the depth of the drilled basement.

TABLE II: Correlation Matrix of the Parameters

Variables	T	Qsp	NS	Pt	Ps	AE1	Q	Qc
T	1							
Qsp	0,988	1						
NS (m)	-0,199	0,182	1					
Pt (m)	0,134	0,135	0,173	1				
Ps (m)	0,124	0,100	0,212	0,121	1			
AE1(m)	-0,079	-0,076	0,326	0,700	0,107	1		
Q ($m^3.h^{-1}$)	0,351	0,409	0,026	-0,235	-0,036	-0,011	1	
Qc ($m^3.h^{-1}$)	0,868	0,854	-0,271	0,167	0,058	-0,117	0,142	1

TABLE III: Eigenvalues Expressed and Cumulative Variances Correlation Matrix of the Parameters

	F1	F2	F3
proper value	3,043	1,919	1,129
variability (%)	38,039	23,989	14,115
% cumulative	38,039	62,028	76,143

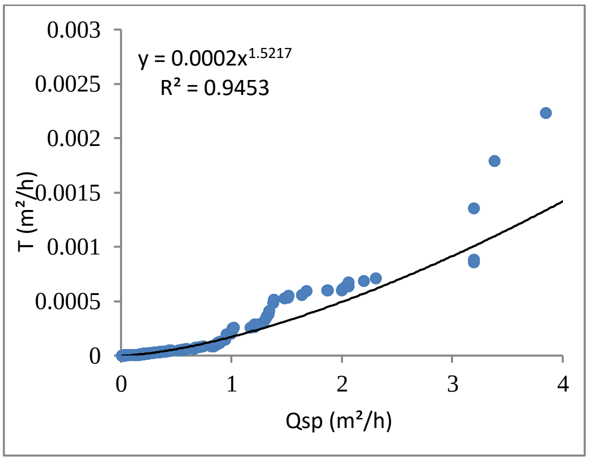

Fig. 5. Relationship between transmissivity and specific flow.

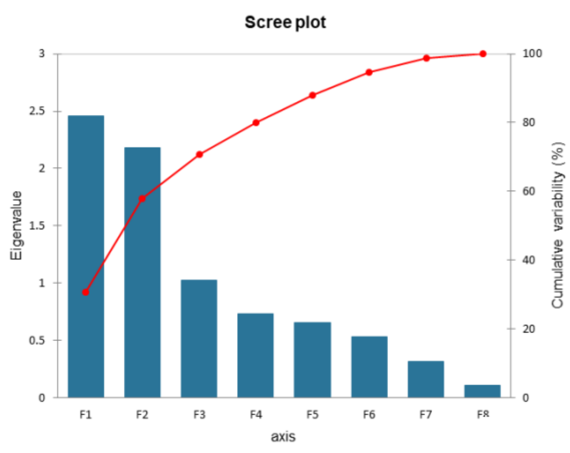

Fig. 6. Factor saturation.

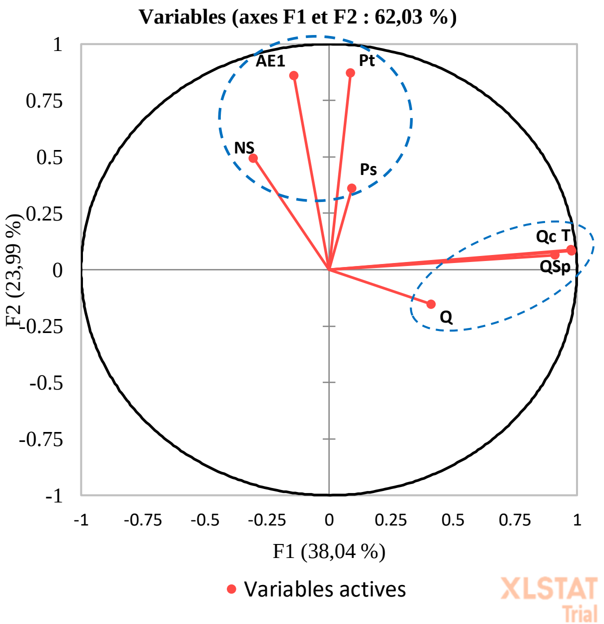

Fig. 7. Projection of variables in the F1-F2 factorial plane.

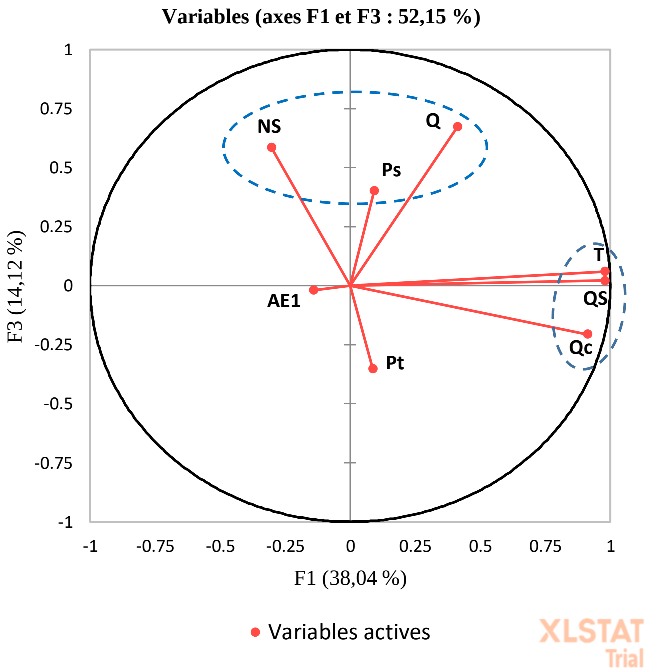

Fig. 8. Projection of variables in the F1-F2 factorial plane.

TABLE IV: Factors Coordinates of The Variables According To The Factors F1, F2, and F3

	F1	F2	F3
T	0,978	0,088	0,022
Qsp	0,979	0,084	0,059
NS	-0,304	0,494	0,587
Pt	0,087	0,873	-0,353
Ps	0,092	0,360	0,401
AE1	-0,142	0,861	-0,020
Q	0,413	-0,153	0,673
Qc	0,911	0,064	-0,207

2) *Factorial plane F1-F3*

In this plane, factor 1 is almost always defined by the same variables, T, Q/s, Qc. It characterizes the productivity of the aquifer (Fig. 8). The central position of AE (at the origin of the circle) shows that the information contained in this variable is not accessible to the F1 factor or the F3 factor.

The F3 factor is determined by the variables Ps, Q, and NS. The correlation between these parameters expresses the hydraulic role of the fractured bedrock in the aquifer system, i.e., the contribution of the fractures in feeding the water table and providing significant flows. The F3 factor thus reflects the hydraulic role of the fractures in the aquifer system. The Pt variable occupies an opposite position to the variables in this group. The recharge of the water table would decrease when the total depth increases.

V. Discussion

Several studies [3], [10], [16], [19] on the productivity of catchment works have been conducted to assess the real potentialities of fissure aquifers.

These works have defined the range of average values to obtain satisfactory productivity at crystalline rocks. However, it should be noted that these indicators are influenced by several factors mainly economic [3], [20].

In this study, the productivity of fractured reservoirs was analyzed from the statistical description of the intrinsic hydrodynamic parameters of fractured aquifers (transmissivity, specific flow rate, critical flow rate).

The study of the correlations between the latter and the hydraulic parameters (total depth, depth of the basement, thickness of alteration, water inflow, static level, and exploitation flow rate) allowed to know the influence of the hydrodynamic parameters on the productivity of the drillings.

The values of the specific flow vary between 0.01 and 4.87 m²/h with an average of 0.58 m²/h and a standard deviation of 0.85 m²/h. The aquifers of the Black Volta basin are not very productive since the majority of the boreholes, 81%, have a specific flow rate less than or equal to 1 m²/h. These results are in line with those of [3] in the Haut Marahoué region, [4] in the Odienné region, [1] in the Man region and [10] in the Bondoukou department belonging to the basin studied. The values of transmissivity vary between 1.25E-07 and 7.34E-03 $m^2.s^{-1}$ with an average of 2.04E-04. The dispersion of values around the latter is estimated at 7.57E-04 $m^2.s^{-1}$. These values fit perfectly within the range of transmissivity values obtained on the Ivorian basement and in West Africa in general.

Note that 56% of the boreholes have transmissivities higher than 1.1E-5 m²/s. They are therefore, characterized by very good hydraulic properties. We find transmissivity values in the same order of magnitude as the gross transmissivity values observed by [21] in Korhogo, [26] in Ferkéssedougou, [22] in Bongouanou and [23] in several localities of northern Côte d'Ivoire (Ganaoni, M'bengue, Tongon, Nielle, Ferke and Tafire).

This study integrates an important parameter that very often conditions the exploitation of a hydraulic structure because it allows a rational use of the latter. It is about the critical flows. The critical flows are not to be exceeded during the operation of the wells to avoid the deterioration of the structure. It allows to guarantee the durability of the pump to be installed and especially to avoid the exhaustion of the aquifer solicited.

Apart from the work of [23], this parameter is absent from most previous work, especially in the Ivorian Precambrian basement. Its relationship with other parameters is even less discussed. In the Black Volta basin in Côte d'Ivoire, Critical flows vary between 0.869 and 26.6 m^3/h. This work has therefore the merit of highlighting this parameter which allows to appreciate the level of precaution to be established during the operation of the hydraulic structure.

The relationship between hydrodynamic parameters has been addressed by several works in Côte d'Ivoire [1], [10], [18], and [24]. According to these authors, such a relationship amounts to an indirect approach to the hydraulic properties of reservoirs two by two. The correlations sometimes very good have led some authors like [21], [23], [25], and [26] to establish mathematical equations of correlation of these parameters and even use them for some of the relationship that links these parameters to determine at the level of a few boreholes, for example, transmissivity when there is only the specific flow. In this study, several parameters were correlated, and a multivariate analysis was used, namely Normalized Principal Component Analysis (ACPN). The ACPN is an extremely powerful tool for synthesizing information, very useful when there is a large amount of quantitative data to process and interpret. In this study, it was used to describe the correlations between the different parameters studied and therefore to deduce the factors that preferentially influence this productivity. The results showed that on the one hand, transmissivity, specific flow, and critical flow have a positive influence on aquifer productivity. This could be attributed to the fracture density often observed in this part of the territory. On the other hand, this study revealed that the variation of the groundwater level in the aquifers is closely related to the total depth drilled, the static level and the water inflow. Finally, the hydraulic capacity of the fractures is more clearly shown by the depth of the bedrock than by the depth of the bedrock drilled. This means that the drilled depth must necessarily be greater than the depth of the basement or must reach the basement to have good flows and acceptable water levels.

VI. Conclusion

The relationships between the different hydrodynamic and hydraulic parameters have contributed to a better identification of the factors influencing the productivity and exploitation of groundwater resources. In the Black Volta basin in Côte d'Ivoire, the analysis of intrinsic hydrodynamic parameters revealed that the aquifers are moderately productive (81% of Q/s <1 m^2/h) but have a fairly good transmissivity with 58% of the values belonging to the medium to high class.

The average critical flow rate of the area not to be exceeded to maintain a good performance of the works is estimated at 6.18 $m^3.h^{-1}$.

The Normalized Principal Component Analysis (NPA) has allowed us to highlight the different factors of productivity of the aquifers in the region. This is closely related to the depth of the works in the basement. As the depth of drilling increases, productivity decreases, which is related to the reduction in the number of fissures and/or the progressive closure of these. The water capacity of the fractures is highlighted in this study.

These different results bring necessary elements for the understanding of the functioning of fractured aquifers. The consideration of all these factors is essential for the positioning of large flow boreholes. The results of this study allow us to identify the perspectives of this work. Thus, it seems necessary to:

- develop a hydrogeological model to simulate the underground flows and the exchanges of aquifer-river flows (black volta),
- to better manage this transboundary water resource.

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Conflict of Interest

Authors declare that they do not have any conflict of interest.

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