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Study of the productivity and hydrodynamic properties of fissured aquifers in the Gagnoa region

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Abstract

Located in the central-western part of Côte d'Ivoire, the subsoil of the Gagnoa region consists of volcanic sedimentary formations and granitoids with extensive fracturing. This complex Precambrian bedrock contains most of the region's water resources. The aim of this study is to gain a better understanding of how this type of aquifer works by determining the hydrodynamic parameters of the boreholes and studying their productivity. The database consists of 154 technical data sheets on boreholes. The transmissivity and specific flow rate values vary from 3.53 x 10-6 to 1.30 x 10 m^2/s and from 0.01 to 0.471 m^2/h, respectively, ranging over 2 and 3 orders of magnitude. Nearly 20% of the structures have flow rates greater than 2.5 m^3/h, and the depth of the boreholes varies from 46 to 98 m. The PCA performed on the characteristic parameters of the boreholes and the hydrodynamic parameters show that the productivity of the boreholes is influenced by transmissivity and specific flow rate. These results could contribute to a better understanding of fractured environments.

Keywords: Ivory Coast; Gagnoa; Bedrock; Aquifers; ACPN; Transmissivity; Specific Flow Rate; Productivity

1. Introduction

Since the 20th century, waters issus have become a major concern for the entire planet. This has led to the organisation of several conferences on water, the first of which was held in Mar del Plata in 1977 [1]. In crystalline and crystallophyllian environments, water is found in two main reservoirs: on the one hand, weathered rock reservoirs, which have an essentially capacitive function, and on the other hand, deeper fissure and fault reservoirs, which have a conductive function [2]. Numerous studies [1;3;4;5] have been undertaken to improve our understanding of the different groundwater reservoirs. The Gagnoa region, located in a bedrock area, has benefited from numerous hydraulic projects, which have resulted in high failure rates (30% on average) with peaks of up to 50% (BID-2 project, 2008-2010) [3]. This situation is thought to be due to the complexity of the fractured environment.

Understanding this complexity involves studying the hydrodynamic parameters of aquifers identified in the area of interest, as recommended in the works of [3;4; 5]. It was with this idea in mind that this study entitled 'Study of the productivity and hydrodynamic properties of fissured aquifers in the Gagnoa Region' was initiated. It aims to determine the hydrodynamic parameters (T and Qsp) after correcting for the effects of quadratic head losses and their influence on aquifer productivity using the ACPN.

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2. Material and methods

2.1. Data

The analysis of the productivity and hydrodynamic properties of the region's fractured aquifers was carried out using a synthesis of 154 technical drilling reports. These technical data sheets were compiled during the BID Fromager village water supply program (2009-2010) carried out by CGC (Chinese Geological Company) under the supervision of BNETD-ARCINGENEURIE.

The data sheets contain the following information:

- The drilling report, providing technical data (thickness of weathering, total drilling depth, lithology of the various formations encountered, static level and air-lift flow rate);
- The pumping test report, which are in fact isolated drilling tests. The drawdown measurements obtained are those of the pumping well.

The tests last 4 hours of descent with a 1-hour ascent. The number of stages varies according to the air lift flow rate obtained but is generally three stages.

The geographical coordinates of these various boreholes were obtained in the field and thanks to SODECI, which made an inventory of boreholes in the Fromager region.

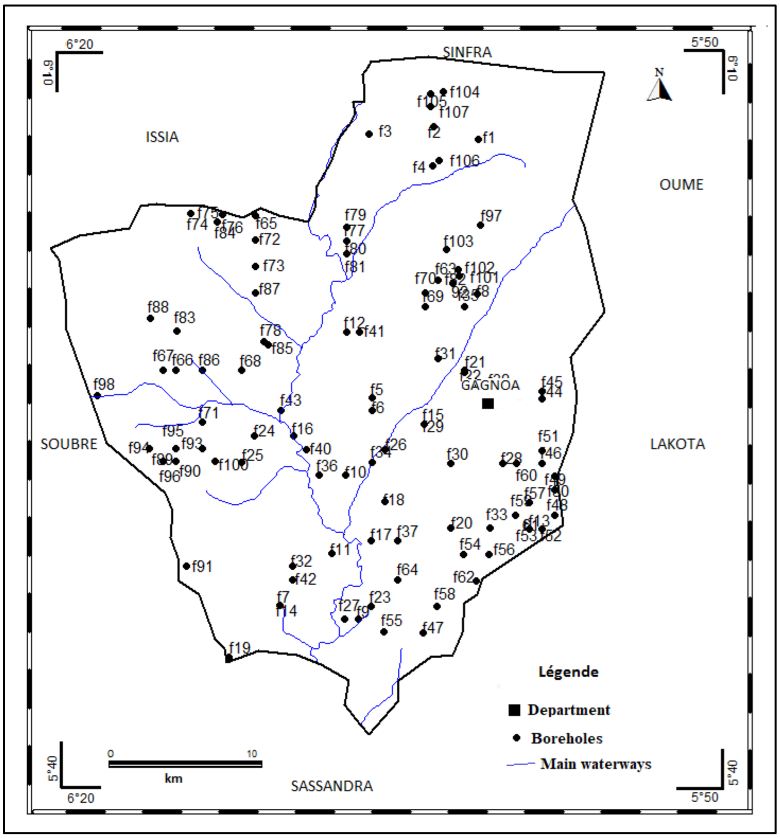

Figure 1 Location of boreholes in the study area.

2.2. Methods

2.2.1. Determination of transmissivity

The transmissivity of the fractured aquifers in the Gagnoa region was determined numerically using the calibration technique with the [6], using the corrected descent data. The descent data were used in this study because the greater the number of measurement points, the greater the accuracy of the parameter determined.

The calibration technique consists of superimposing the experimental (measured) and theoretical (calculated) curves of the drawdown by adjusting the values of the transmissivity (T) and storage coefficient (S). The theoretical drawdown is calculated using the Cooper-Jacob equation. In the absence of an observation piezometer, it is impossible to determine the value of the storage coefficient. [7] recommends that, in the absence of any rigorous determination on isolated boreholes, storage coefficient S values in the range $10^{-4} < S < 10^{-3}$ should be used for fractured reservoirs in regions with eruptive or metamorphic substrates. The transmissivity values obtained in the fractured reservoirs of the Precambrian basement of Côte d'Ivoire fall within the range $10^{-6} < T < 10^{-3}$ $m^2.s^{-1}$.

The experimental and theoretical drawdown curves will tend to either converge or diverge from each other depending on the initial values of T and S in the intervals defined above. The superimposition or calibration process can be performed manually or automatically using the Solver module in MS Office Excel.

The transmissive value that will be retained is the one for which the experimental and theoretical curves overlap. The correction of drawdowns resulting from the descent was carried out according to the approach of [8]. For more details, the reader may refer to [4].

2.2.2. Determination of specific flow rate

The specific flow rate represents the ratio between the flow rate (Q) and the drawdown (s). The flow rate (Q) used is the flow rate at the end of pumping and the final drawdown (s) of the descent. It is used to determine the efficiency of a structure [8]. It provides information on the characteristics of boreholes and on the connection between fracturing networks [9].

2.2.3. Empirical relationship between T and Q/s

To compensate for the lack of transmissivity data in certain areas, some authors have used an analytical or empirical relationship between transmissivity and specific flow rate. This relationship, based on the least squares regression method, makes it possible to reproduce a transmissive field where data is lacking. The specific flow rate (Q/s) and transmissivity (T) values are plotted on a bi-logarithmic diagram. If the resulting scatter plot aligns along a straight line, the equation of this line is determined, as well as its coefficient of determination, which reflects the quality of the fit. This relationship is often very significant when the values of T and Q/s span several orders of magnitude. A comprehensive review of the literature on the identification of such a relationship is provided by [10; 11; 12].

2.2.4. Study of the productivity of fissure aquifers

The purpose of this study is to identify the parameters that are likely to influence groundwater potential. The productivity of crystalline and metamorphic rocks was addressed. The Normalised Principal Component Analysis (ACPN) method was used to identify these parameters. This method, developed by [13], synthesises and classifies data and removes heterogeneities between the units of expression of the variables. The parameters used to perform NPA are Q (flow rate), Q/s (specific flow rate), EA (alterite thickness), Pt (total depth), T (Transmissivity).

This approach is based on establishing correlations between a set of variables using statistical analysis. PCA is used for studies involving several parameters whose interpretations are crucial to understanding certain phenomena. This method makes it possible to highlight any links that may exist between two or more variables as they evolve. Its use for this study is based on the interpretation of various factors as well as the correlation matrix obtained following data processing using STATISTICA 6.1 software.

ACPN provides community circles, projections of statistical units in factorial plans and numerous tables, two of which enabled analysis and interpretation. These are the correlation matrix table and the eigenvalues table. The correlation matrix gives the correlation coefficients between the different variables, two by two. The correlation is said to be strong when this coefficient is greater than 0.7. If this value is positive, the phenomena influencing these parameters are the same; when it is negative, these phenomena are opposite and evolve in opposite directions.

The table of factor eigenvalues, percentages and cumulative variances allows us to determine the number of factors needed to interpret the phenomena, based on the cumulative percentage of variances expressed. In terms of factorial designs, variables are only representative when they are close to the extremes of these factors.

3. Results

3.1. Study of the hydrodynamic parameters of aquifers

3.1.1. Transmissivity

The calculated transmissivities range from 3.53 10-6 to 1.65 10^{-4} with a geometric mean of 2.69 10^{-5} $m^2.s^{-1}$. They span two orders of magnitude, highlighting the heterogeneity of the environment. These transmissivities were studied on the two main types of geological formations encountered in the study area. The results are shown in Table 1. From a statistical point of view, the transmissivity values obtained for these two formations are comparable. However, the transmissivities on volcanic-sedimentary rocks are less dispersed than those on granitoids.

Table 1 Different transmissivity values for the two main types of geological formations

T ($m^2.s^{-1}$)						
	Total	**Min**	**Max**	**Geometric Mean**	**Standard Deviation**	**CV**
Volcano-sedimentary Formation	20	4.85 10^{-6}	9.83 10^{-5}	2.76 10^{-5}	2.23 10^{-5}	120
Granitoid	90	3.53 10^{-6}	1.65 10^{-4}	2.66 10^{-5}	3.13 10^{-5}	90

According to the classification proposed by [9], the transmissivities obtained for each formation were subdivided into three classes (low, medium, and high) representing 10%, 90%, and 0% on volcano-sedimentary rocks, compared to 8.89%, 85.55%, and 5.56% on granitoids (Table 2). More than 80% of the boreholes have transmissivities greater than 10^{-5} m^2/s in both formations. These boreholes are characterized by very good hydrodynamic properties.

Table 2 Classification of transmissivity on the two main types of geological formations

Transmissivity class	**Volcano-sedimentary**		**Granitoids**	
		%		%
Lower Class ≤ 10^{-6}	2	10	8	8.89
Middle Class (10^{-5}- 10^{-4})	18	90	77	85.55
Strong Class≥ 10^{-4}	0	0	5	5.56
TOTAL	20	100	90	100

3.1.2. Specific flow rate

The specific flow rate values (Q/s) determined after correction for drawdown range from 1 10^{-2} to 4.71 $10^{-1}$$m^2.h^{-1}$, with an average of 1.09 10^{-1}m. These values span two orders of magnitude.

3.1.3. Relationship between transmissivity and specific flow rate

The relationship between transmissivity and specific flow rate was investigated in a bi-logarithmic diagram for raw and arithmetic values. This figure illustrates this relationship. The different points align along a straight line, highlighting a clear correlation between these two parameters. The linear regression line (least squares) was used to determine the equation of the line with a coefficient of determination of 0.90. The value of this coefficient indicates that the test is satisfactory. This relationship is expressed as (1):

$$T = 0{,}0003Q/s^{0{,}8975} \qquad \text{...........(1)}$$

T and Q/s are expressed in m^2/s.

When T and Q/s are expressed in m^2/h, the equation becomes (equation 2):

$$T = 0{,}0001 Q/s^{0{,}8975} \quad \text{..........(2)}$$

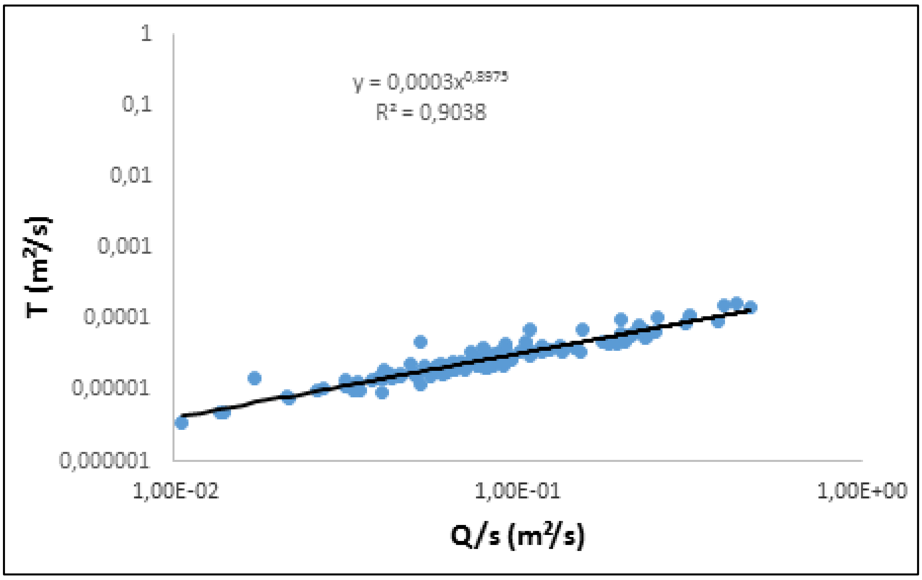

Figure 2 Relationship between transmissivity and specific flow rate

3.1.4. Hydraulic parameters

A basic statistical analysis of various drilling parameters shows that 83% of the boreholes have a depth of between 50 and 80 m. This shows that in the region, most hydraulic structures are drilled to great depths. The majority of structures, 79.6%, have significant alteration thicknesses and 20.4% are semi-deep. Structures in the study area have high alteration thicknesses (> 25 m). Less than 20% of flow rates are considered moderate to high. This low rate, which characterizes village water supply programs, is thought to be due to a lack of in-depth studies during the drilling process.

3.2. Characterization of borehole productivity using PCA

A standardized principal component analysis (PCA) was carried out to highlight the relationships between the various borehole productivity parameters.

3.2.1. Correlation matrix analysis

The correlation matrix analysis highlights several correlations between the parameters taken into account (Table 3), particularly between T and Q/s. There is a correlation between Q and Q/s, and between T and Q.

Table 3 Correlation matrix of productivity parameters

	EA	**T**	**Q/S**	**Q**	**Pf**
EA	1	-0.357	-0.318	-0.203	0.376
T		1	0.956	0.667	-0.293
Q/S			1	0.684	-0.346
Q				1	-0.189
Pf					1

3.2.2. Percentage of variance expressed by the factors expressed

Factors F1, F2 and F3 express 57.59%, 21.21% and 12.52% of the variance expressed, respectively (Table 4). These three factors alone account for more than 70% (91.33% of the total variance) and are more than sufficient to conduct the analysis. The factorial plans F1×F2 and F1×F3 will constitute the projection plans for the scatter plot.

Table 4 Eigenvalues, percentages of variance expressed and cumulative variance

	Eigenvalue	% Variance expressed	% Cumul Variance expressed
Factor 1	2.87	57.59	57.59
Factor 2	1.06	21.21	78.81
Factor 3	0.62	12.52	91.33

3.2.3. Spatial analysis of variables

-Factorial plan F1×F2

Analysis of the community circle of the F1×F2 factorial plan shows that factor F1 is defined by parameters Q, Q/s and T in its negative part and, to a lesser extent, by EA and Pf in its positive part (Figure 3). EA alteration and bedrock thickness constitute the drilled depth. As a result, factor 2 represents the thicknesses of the horizons crossed during drilling to reach an aquifer.

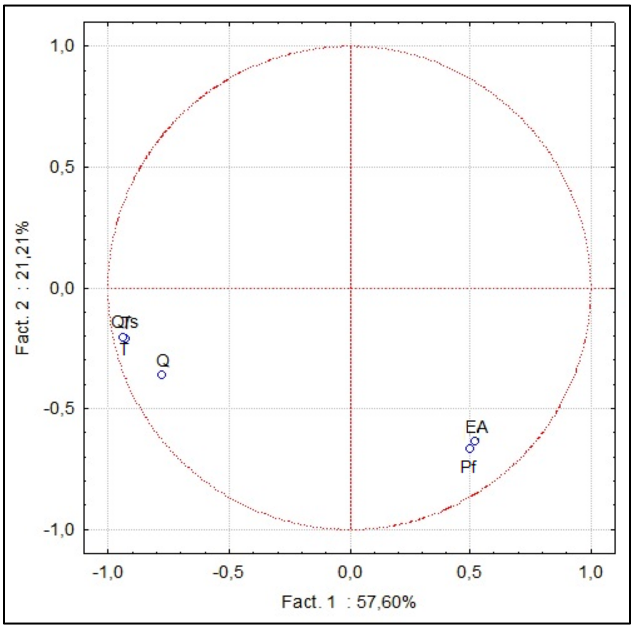

Figure 3 Community circle of the F1×F2 factorial design in the variable space

Factorial plan F1×F3

In this design, Q, Q/s and T remain linked (Figure 4). They still define factor 1. The EA and Pt parameters occupy opposite positions and are halfway from the F3 end. These parameters could potentially provide information on this factor despite its low variance (10.73%). This factor favors the opposite evolution of weather thickness and total rock drilling depth. Weather thickness influences drilling productivity. Indeed, a high thickness of alteration or a low thickness does not guarantee a high flow rate. Also, the probability of recording a good yield decreases with increasing drilled depths. Thus, factor 3 represents the probability of obtaining good productivity from the structures.

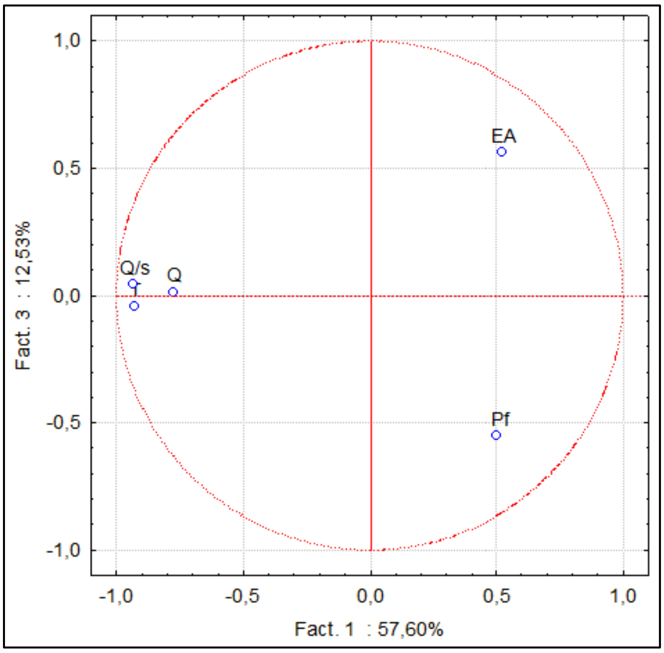

Figure 4 Community circle of the F1×F3 factorial plan in the variable space.

4. Discussion

In the Gagnoa region, transmissivity values range over two orders of magnitude. This interval is similar to that found in the bedrock zone in Côte d'Ivoire [1;9; 14;15]. Several authors [3;12;16] have studied the empirical relationship between T and Q/s, two important parameters. [17] compiled the various empirical relationships obtained in different environments. The transmissivity values obtained for the two major geological units show that they have similar productivity. However, in terms of flow rate, there appears to be a slight advantage for the volcano-sedimentary formations, with an average flow rate of 2.5 m^3/h. This result is thought to be due to a vertical adjustment of the schistosity planes, the presence of quartz and pegmatite veins in the intra-cratonic furrow deposits, and the presence of dolomitic and calco-dolomitic intercalations in the schistose banks [3;18;19;20]. A study of the productivity of boreholes in the Gagnoa region using the ACPN method shows that it is influenced by parameters such as transmissivity and specific flow rate. In addition to equipment, other non-quantifiable parameters, such as the petrographic nature of the bedrock, geomorphology, the strategy for installing structures, and the expertise of the driller [21;22], customs, traditions and, very often, the moods of local personalities have an impact on the productivity of hydraulic structures [18].

5. Conclusion

The hydrodynamic parameters (specific flow rates and transmissivity) vary from 0.01 to 0.471 m^2/h and from 3.53 10-6 to 1.3 10-4 m^2/h, respectively. In the Gagnoa region, the depth of boreholes varies from 46 to 98 m. The thickness of weathered rock is mostly 'deep' at 76% (25 to 75 m). Nearly 20% of the structures have flow rates greater than 2.5 m^3/h. Specific flow rates are low, ranging from 0.01 to 0.471 m^2/h. Transmissivity varies from 3.53 10-6 to 1.3 10-4 m^2/h, i.e. over three orders of magnitude. The study of productivity parameters for the two major lithological units in the study area showed that these two units have equivalent productivity. The PCA performed on the characteristic parameters of the boreholes and the hydrodynamic parameters show that the productivity of the boreholes is influenced by transmissivity and specific flow rate. The hydrodynamic properties and productivity of these complex aquifers were studied. This provides a better understanding of how these aquifers function and enables optimal management of their resources.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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