Journal of Scientific Research & Reports
3(17): 2303-2322, 2014; Article no. JSRR.2014.17.005

SCIENCEDOMAIN *international*
www.sciencedomain.org

SCIENCEDOMAIN

Hydrodynamic Characterization of Fractured Aquifers in Precambrian Basement of Côte d'Ivoire: Geostatistical and Statistical Approaches

T. Lasm[1*], D. Baka[1], O. Z. De Lasme[2], M. Youan Ta[1,3], F. K. Kouamé[1,3], T. K. Yao[1], E. K. Kouadio[1], A. V. Ake[1], K. A. F. Yao[1], O. S. Akossi[1], A. Coulibaly[1] and E. A. Assoumou[1]

[1]Department of Science and Technique of Water and Environmental Engineering, Faculty of Earth Sciences and Mineral Resources, University Felix Houphouet-Boigny, Abidjan, 22 B.P. 582 Abidjan 22, Côte d'Ivoire.
[2]Department of Biology, University Peleforo Gon Couibaly of Korhogo, BP 1328 Korhogo, Côte d'Ivoire.
[3]University Research Center of Remote Sensing and Application (CURAT), University Felix Houphouet-Boigny, Abidjan, 22 B.P. 801 Abidjan 22, Côte d'Ivoire.

Authors' contributions

This work was carried out in collaboration between all authors. Author TL designed the study, wrote the first draft of the manuscript and managed the literature searches. Authors DB and OZDL designed the illustrations and improved the grammar and English language of the paper. All authors read and approved the final manuscript.

Original Research Article

Received 20th May 2014
Accepted 3rd July 2014
Published 19th July 2014

ABSTRACT

This study concerns 10 communities of Côte d'Ivoire sampled in six regions. The study aims to provide better knowledge of hydrodynamic properties of fissured aquifers from Precambrian basement of Côte d'Ivoire. Geostatistical and statistical methods are used to analyze transmissivities and specific capacities. Transmissivity and specific capacity were determined after drawdowns corrections from pumping data and using traditional and numeric methods. Indeed, the pumping test carried out in isolate drilling and drawdowns are measured in the same drilling. The results showed that these two parameters are

**Corresponding author: E-mail: theophile_lasm@yahoo.fr;*

distributed at least on 3 orders of magnitude which revealed evidence the heterogeneity of studied areas. Specific capacity mainly is low and seldom exceeds 10 m^2/h in water supply project of rural regions. The lowest values recorded in Bondoukou area with specific capacities values lower than 0.5m^2/h. There is a large dispersion of data in many areas (Oume, San Pedro, Agnibilekro, Abengourou, etc.). Indeed, transmissivity and specific capacity data are scattered (Cv> 100%). These two parameters are distributed following lognormal law. In each area, an empirical relationship was established. This relationship can be used to assess the transmissivity in the areas where this parameter is difficult to determinate. Variograms of transmissivity in these areas are structured with significantly nugget effect. Variogram of San Pedro area is the most structured with a range equals to 60 km. The weakest one is obtained at Oume (with a range equal to 7 km). Assessment of the transmissivity by krigeage of 4 studied areas (Man-Danane, Bondoukou, San Pedro and Oume) is good and significant. However, estimated values of the transmissivity present a short order of magnitude compared to experimental values. The results achieved through this study contribute to better knowledge of fissured aquifers from Precambrian basement of Côte d'Ivoire.

Keywords: Fractured aquifer; transmissivity; specific capacity; relationship; assessment; Côte d'Ivoire.

1. INTRODUCTION

Using the hammer drilling technology in crystalline metamorphic hard rocks favored development of groundwater's prospection on the basement. In this medium, groundwater flows use fracture networks. Connectivity of fracture networks is realized at the same time by longer and smaller fractures. The small fractures are generally numerous and play significant role in regional flow. A good knowledge of fractures geometry is an advantage for getting better comprehension of groundwater flows. In Côte d'Ivoire, previous hydrogeological prospections were focused on geomorphologic knowledge. Geophysical methods are used in hydrogeological prospecting when failure rate is high. Indeed, the implementation is heavy and expensive [1]. Actually, hydrogeological prospecting uses various mixed methods such as remote sensing (photo-interpretation, satellite images optical and radars) and geophysics. This approach gave good results with significant reduction of the failure rate [1].

The basement occupies 97.5% of the whole territory and the essentials of drillings for the supply of water to rural and urban populations are located on this basement. The water needs are increasing with growth of population. The coverage rate of these water needs varies from one area to another [2] and generally not satisfied. In these localities, many drillings must be carried out to satisfy these water needs. The government of Cote d'Ivoire and their national and international partners try to undertake drillings on a large scale to supply groundwater for urban and rural populations.

Currently, there are more than 19 500 drillings for exploration throughout the whole country [2,3]. Many of drillings are not useable because of mechanical failures and lack of maintenance.

The mapping of areas with high potential productivity is a guarantee to perpetuate the drillings. In Bondoukou area, [4] suggested some potential sites wherever best successful drillings can be obtained. Knowledge about hydraulic parameters allows the study of hydrodynamic behaviour of aquifers.

Transmissivity is a major hydraulic parameter which can be evaluated from pumping tests [5,6,7,8,9,10]. However, available pumping tests are often few, which do not allow analysis and assessment of the distribution of this important parameter on large areas by using classical methods [11]. Transmissivity is a highly variable parameter which often varies dramatically and exhibits large fluctuations. It is rarely feasible to obtain enough measurements to fully characterize an aquifer [12,13]. This variability in space can be explained by the fact that aquifers are often heterogeneous. The use of geostatistical techniques allows a reliable estimation of the transmissivity on the whole study domain [6,14,15].

In many regions of Côte d'Ivoire, transmissivity and specific capacity have been studied by several authors [6,14,15,2,11] and they have obtained good results. This study aims to analyze and understand the functioning of aquifers systems which will lead to cleverly manage of water resources.

This study was conducted in 6 regions of the Precambrian basement, where tectonic events led to the installation of highly developed and dense fracturing pattern in these formations [16,6,17,18]. Subsequently, this study will give opportunity to make simulation and modeling of groundwater flows.

2. STUDY AREA AND GEOLOGICAL CONTEXT

The study was conducted in 10 areas of 6 regions of Côte d'Ivoire: Man-Danane at West; San Pedro at south-west, Korhogo and Ferke at North, Agnibilekro and Abengourou at East, Bondoukou at North-east and Oume, Yamoussoukro and Katiola at Central district (Fig. 1). These regions are located on the basement part of Côte d'Ivoire and they spread on archean and paleoproterozoic areas. The study areas represent 31% of total land mass of the national territory and 32% of country basement. On geological view, this basement is dominated by crystalline and metamorphic rocks. Many tectonic events such as Leonian and Eburnean orogenies occurred on this base [19,20]. These two orogenies are the most important tectonic events occurred on archean domain. Eburnean orogeny only occured on paleoproterozoic domain. These orogenies led to develop important fracture networks [1,21,16,22,23,17]. During these last two decades, many studies have reported were realized about characterization of fracture networks on basement [16,23,17,18,24]. On hydrogeological view, we met three aquifer types in the basement. These are weathered material, fissured layers and deep faults [25,26,2,27]. The first two aquifers generally constitute a composite system [1,21,28].

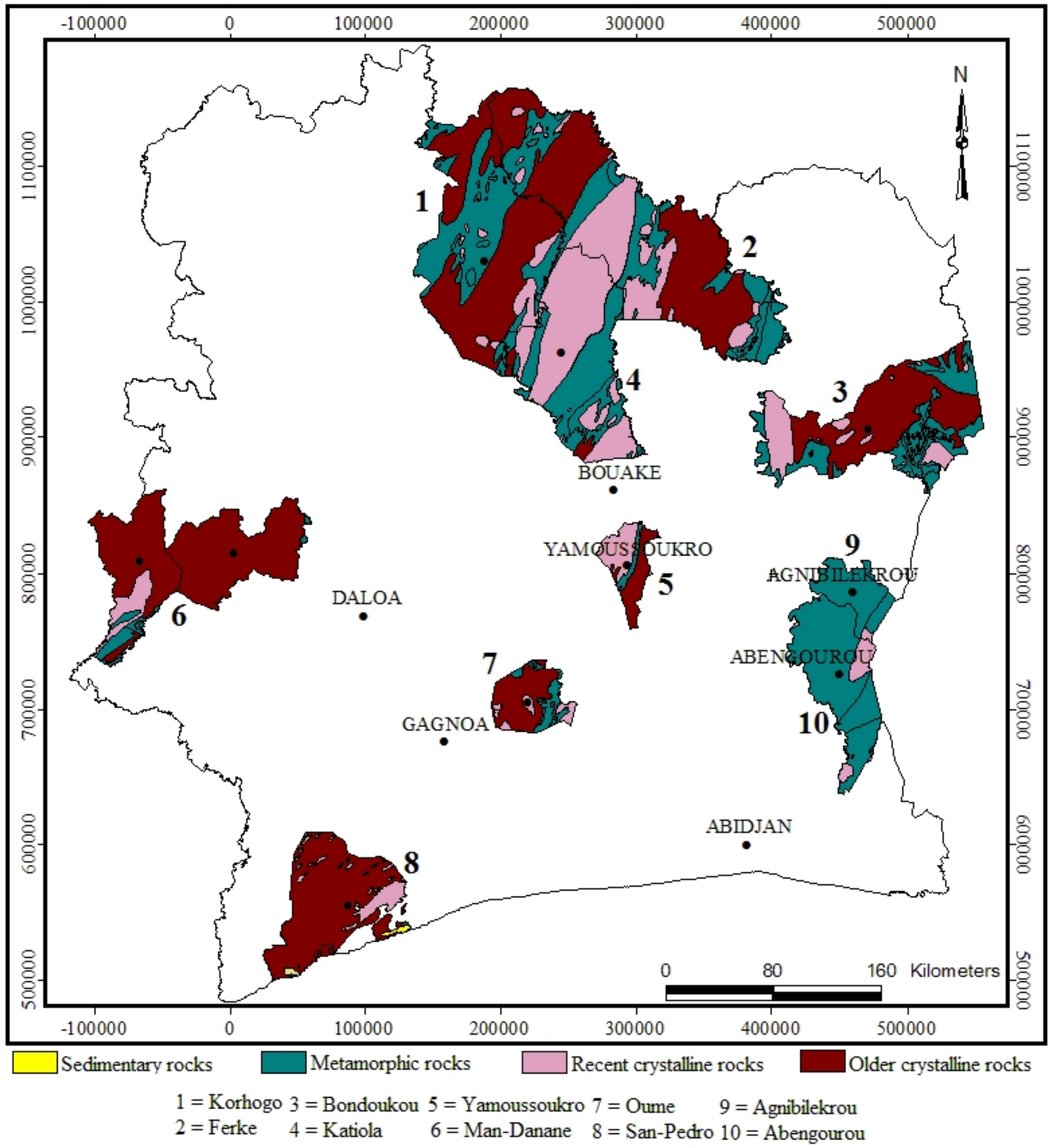

Fig. 1. Location of the study area

3. MATERIALS AND METHODS

The data came from a database of drillings technical sheet established through hydraulic programs. These drillings are unequally distributed in the whole country. This uneven distribution is explained by inaccessibility some areas. Indeed, localities with many persons and development structures are eligible for getting more water points. Drillings tap groundwater at fissured reservoirs. Pumpings generally last from 6 to 12 hours and more 24 hours respectively for short and long duration. The recovery generally lasts more than 4 hours.

In Côte d'Ivoire, except coastal sedimentary basin, there are no piezometers in basement because of economic reasons [21,29]. Available drawdowns come from pumping tests. Transmissivity has been determined from drawdown and recovery data. When drawdowns data used (measurement during pumping), drawdowns are corrected before transmissivity determination [6,30,31,32]. When discharge of pumping is very low, measures of uncertainties can be negligible and correction of drawdown data are not necessary [33,34].

Practical interest from use of drawdown data consists in the number of measurement points [31]. Indeed, numerous are measurement points exist, the precision is a better of determined parameter. Groundwater flow modeling requires the use of reliable data for getting better management and exploitation of their resources. On the whole domain (10 areas), 1 272 drillings have been studied (see Tables 1 and 2).

[30,31] used numerical model (Macro developed by Department of Hydrogeology of University Félix Houphouët-Boigny, Côte d'Ivoire by using Microsoft Excel with solver) to determine transmissivity of fissured aquifers from Agnibilekro, Korhogo and Ferke. This method consists of superimposition of experimental and theoretical drawdown curves. In the other areas, transmissivity was determined by using traditional methods such as the Theis and Cooper-Jacob approaches. Theory of these methods isnot presented here. The readers may consult available literature about this subject (see [35,36]).

The specific capacity has been evaluated at the end of the third step after 12 hours of pumping. Drawdowns were corrected for turbulent head losses before evaluation of the specific capacity [6]. Turbulent head losses were calculated by interpreting the step drawdown tests [37,35,38,6].

In Korhogo area, two studies have been performed [22,31], they were named respectively Korhogo 1 and Korhogo 2. These two authors respectively used recovery and numerical methods to determine the transmissivity.

The empirical relationship between transmissivity (T) and specific capacity (Q/s) was studied in some areas. This relationship allows to estimate the transmissivity in areas where this parameter is unknown or difficult to determine. Generally, specific capacity (Q/s) values are more numerous than those of transmissivity in environmental data bases because they are easily determined [6]. Transmissivity was estimated through empirical and geostatistical approaches. Empirical approach consists to determine a regression line between transmissivity and specific capacity in a bi-logarithmic diagram [39,40,31]. Indeed, these two parameters are distributed according lognormal law. This relation is defined by following empirical equation:

$$T = A_2 \, Q/s^{\,D} \quad (1)$$

A_2 and D correspond to coefficients of regression of power-law. This relation is significant when values of T and Q/s spread on many orders of magnitude.

Geostatistical approach is based on variogram analysis and kriging estimation. Details of these methods are developed in previous studies [41,42].

Various types of software, available on the Internet, can be used to perform geostatistics: Variowin [43], Gslib [44], Geo-Eas [45], Gstat [46]. Variowin [43] and Geo-Eas [45] have been used to perform geostatistics analysis in this study.

Transmissivity was regarded as regionalized variable, i.e. each value depends on its geographical position, and it is treated by using geostatistical methods. Variogram is defined by the following equations 2 and 3 for a given regionalised variable Z:

$$\gamma(h) = \frac{1}{2} Var\left[Z(x+h) - Z(x)\right] \tag{2}$$

$$\gamma(h) = \frac{1}{2} E\left[\left(Z\ \ (x+h) - Z\ \ (x)\right)^2\right] \tag{3}$$

Where Var [Z(x)] is the variance at point x; *h* is the vector of module (x-x'); E is the mathematical expectation.

The experimental variogram obtained here is modelled by using the exponential function given by following expression (Eq. 4):

$$\gamma(h) = C_1\left(1\ - \exp\left(\frac{-3h}{a}\right)\right) +\ C_0 \tag{4}$$

Where C_0 is the nugget effect, $C = C_0 + C_1$ is the sill, *a*is the practical range (distance at which 95% of the sill has been reached), *h* is the distance between sampling points. The nugget effect represents any small-scale data variability or possible sampling errors. The sill indicates the total variance. The range is the distance between sampling points at which the sill is reached. Beyond the range, the variance measured between the data points is independent from the respective data points and there is no longer a correlation between the points.

The estimator Z* of the variable Z at a point x_0 is given by equation 5:

$$Z_0^{\ *} = \sum_{i=1}^{N} \lambda_i Z(x_i) \tag{5}$$

where Z_0^* is a linear estimator; N is the number of values involved in the estimation; λ_i are weights.

Two major conditions such as unbiasedness and optimality condition must be checked (see [6]). The estimated errors (differences between the true values and the estimated values) should have a mean equal to zero and a minimum variance (see [6]).

They are written,

$$E\left(Z^* - Z_0\right) = 0 \tag{6}$$

$$Var\left(Z^{*} - Z_{0}\right) \text{ Minimum} \tag{7}$$

Developing Eq. (7) to satisfy these two conditions leads to a system of kriging equations written in terms of the variogram. Solving this system yields the N weights λ to be used in Eq. (5) and the kriged estimate Z^*_0 can be calculated [6]. The variance of the error of estimate (kriging variance) is given by following expressions:

$$\sigma^{2}(x_{0}) = Var\left(Z^{*} - Z_{0}\right) = \sum_{i=1}^{N} \lambda_{i}\gamma(x_{i} - x_{0}) + \mu_{0} \tag{8}$$

Where μ_0 is the Lagrange multiplier [42].

The interested readers can see more detailed presentations and calculations in [41,42,47]. Data processing was performed by using software GEO-EAS software [45].

3.1 Cross Validation Procedure

The cross validation procedure aims to validate the structural models used to perform an estimate by kriging. Its purpose is to analyse the estimation errors. In fact, the procedure eliminates a single value (Z_i) from the data set and perform a kriged estimation (Z_i*) at this location. This is repeated for all the data set. Cross validation procedure compares actual values with estimated values. If the variogram model is valid, then the following results should be verified: the average of the actual errors (AAE) should be equal zero and their variance (σ_e^2) should be a minimum; the ratio of variance of actual errors to average kriging variance (σ_e^2/σ_K^2) should be one. This procedure is described in details in [48,49,6].

In this study, transmissivity from 4 areas only were submitted to geostatistical analysis. Transmissivity was transformed before performing geostatistical analysis. These areas are located at Western (Man-Danane), North-Eastern (Bondoukou), South-western (San Pedro) and Central region (Oume). In the north-eastern area, 2 geostatistical studies were performed on the same area. They are the studies carried out by [14,11]. In accordance with good comparison requirements, these studies respectively will be called Bondoukou 1 and Bondoukou 2. At Bondoukou 1, assessment was led with 62 values of transmissivity (only on granitic rocks) and, these values were supplemented to 78 (on granitic and schist rocks) at Bondoukou 2.

4. RESULTS

4.1 Transmissivity and Specific Capacity

Transmissivity values of areas are summarized in Table 1. They vary from one area to another. About the whole studied areas, they oscillate from 1.06E-06 to 4.12E-03 m²/s, and they spread on 4 orders of magnitude. The smallest amplitude registered in North-eastern region (Bondoukou) and the highest ones registered at north (Korhogo), West (Man-Danane), East (Abengourou) and Central (Oume).The great order of magnitude demonstrates heterogeneity of areas. The average of transmissivity values oscillates from 1.18E-05 (Bondoukou 2, North-east) to 3.06E-04 m²/s (Man-Danane, west). Except the western region where transmissivity data are continuous (Cv = 40%), this parameter (transmissivity) is very scattered in the other regions, Indeed, coefficient of variation oscillates from 92 to 312%. Greatest scattering have been registered at Korhogo 1, Oume and Abengourou where coefficients of variation were high (Cv> 230%).

Specific capacity (Q/s) oscillates from 7.20E-03 (Bondoukou 2) to 13.2 m²/h (San Pedro) inside studied areas (Table 2). It also varies from one area to another and spreads on 3 and 4 magnitude orders. In the majority areas, specific capacity values are low. Indeed, more than 80% values of each area are lower than 1 m²/h. Lowest specific capacity values are determined at Bondoukou where all values of specific capacity are lower than 0.5 m²/h. According to average values of specific capacity, San Pedro and Agnibilekro areas present the highest rate.

On statistical view, distribution of transmissivity and specific capacity values are following lognormal-law.

4.2 Relationship between Transmissivity and Specific Capacity

Transmissivity and specific capacity were determined in same drillings and the relationship is an empirical type. Graphs of this relationship obtained in some areas of Côte d'Ivoire are illustrated on the Figs. 2 to 5 (Korhogo, Ferke, Katiola and San-Pedro). In all cases, data points (point cloud) are organized in straight line. Relationships remain significant when data points are numerous and drawdowns are corrected before determination of T and Q/s.

Relationships established in every study area are summarized in Table 3. In every area, coefficient of determination is superior than 0.70 (0.73 ≤ R^2 ≤ 0.99). This shows that statistical test is satisfactory and relationship obtained is significant. The slope value of these relationships (D) varies from 0.83 (Ferke) to 1.33 (Oume). Outside of Ferke and Katiola areas, slope values obtained are superior than 1. Database (T, Q/s) from Katiola, Agnibilékro and Bondoukou areas are very few. Indeed these values are less than 100. Use of these data can raise the problem of sample representativeness (Table 3).

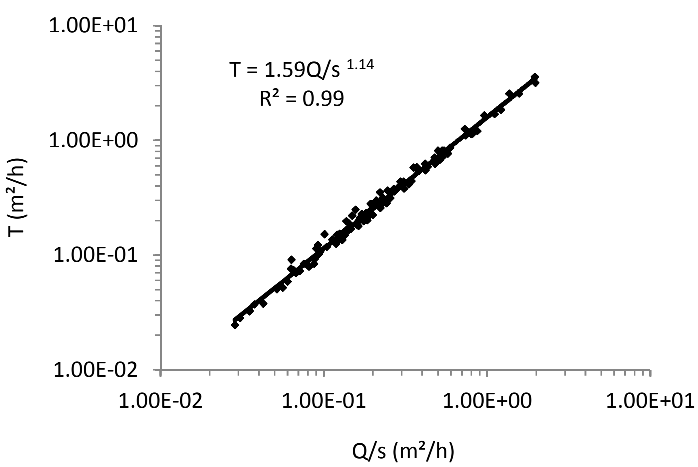

Fig. 2. Relation between T (m^2/h) and Q/s (m^2/h) on Korhogo area

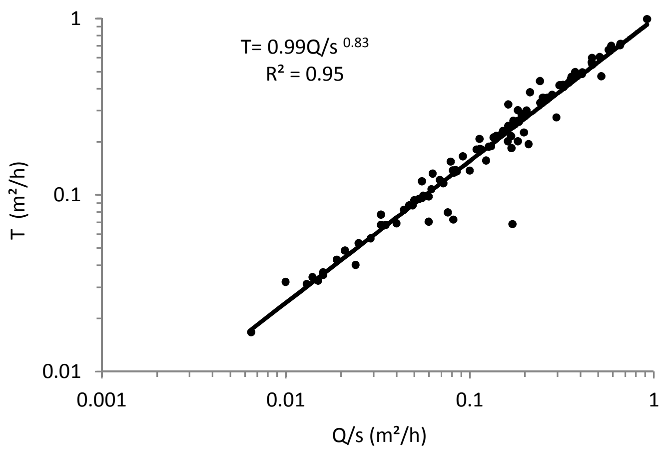

Fig. 3. Relation between T (m^2/h) and Q/s (m^2/h) on Ferke area

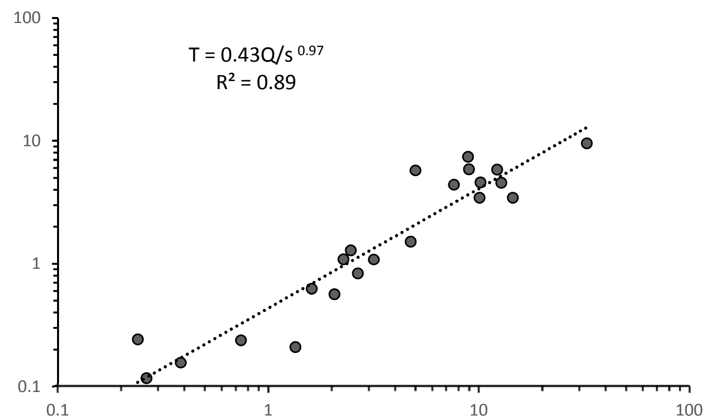

Fig. 4. Relation between T (m^2/h) and Q/s (m^2/h) on Katiola area

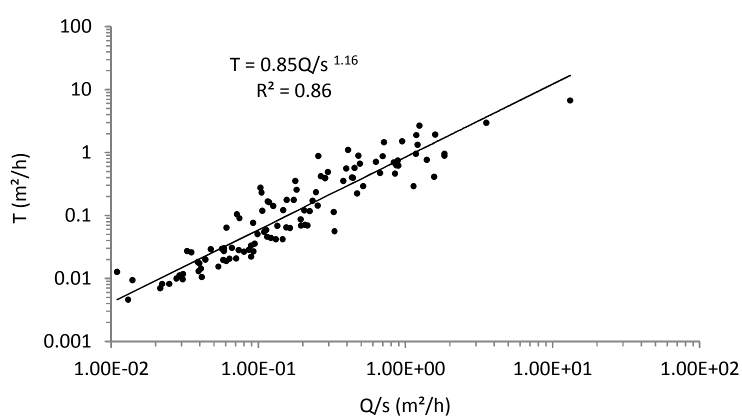

Fig. 5. Relation between T (m^2/h) and Q/s (m^2/h) on San Pedro area

Table 1. Transmissivities (m^2/h) of studied areas

Region	Area	Studied drillings	Minimum	Maximum	Average	Std dev.	Cv (%)
North	Korhogo 1	170	1.10E-06	2.42E-03	9.05E-05	2.11E-04	233.15
	Korhogo 2	121	6.09E-06	9.91E-04	1.39E-04	1.82E-04	130.94
	Ferke	130	4.62E-06	2.75E-04	9.18E-05	1.09E-04	118.74
North-East	Bondoukou 1	62	1.08E-06	5.37E-05	1.38E-05	1.84E-05	133.33
	Bondoukou 2	78	1.08E-06	5.37E-05	1.18E-05	1.09E-05	92.37
Center	Katiola	22	1.35E-06	1.10E-04	3.30E-05	3.20E-05	96.94
	Yamoussoukro	105	1.15E-06	4.48E-04	4.95E-05	8.58E-05	173.33
	Oume	142	1.08E-06	2.55E-03	1.05E-04	2.70E-04	257.14
West	Man-Danane	178	1.09E-06	2.32E-03	3.06E-04	1.23E-04	40.20
South-West	San Pedro	110	1.27E-06	8.59E-04	1.01E-04	1.62E-04	160.40
East	Abengourou	104	1.06E-06	4.12E-03	1.40E-04	4.37E-04	312.14
	Agnibilekro	50	1.91E-06	5.69E-04	8.61E-05	1.37E-04	159.12

Cv = Coefficient of variation
Std dev. = Standard deviation

Table 2. Specifics capacities (m^2/h) of studied areas

Region	Area	Studied	Minimum	Maximum	Average	Std dev.	Cv (%)
North	Korhogo 2	121	2.85E-02	1.98E+00	0.33	0.36	110.96
	Ferke	130	1.00E-02	2.56E+00	0.27	0.39	120.00
North-East	Bondoukou	78	7.20E-03	4.96E-01	0.13	0.11	82.03
Center	Katiola	22	1.00E-02	1.36E+00	0.28	0.31	111.64
	Yamoussoukro	105	8.28E-03	2.03E+00	0.19	0.26	98.42
	Oume	142	1.00E-02	2.11E+00	0.22	0.32	146.82
West	Man-Danane	178	1.00E-02	2.00E+00	0.29	0.35	123.16
South-west	San Pedro	110	1.90E-02	1.32E+01	0.47	1.32	281.85
East	Abengourou	104	1.50E-02	4.80E+00	0.34	0.66	193.29
	Agnibilekro	50	4.08E-02	2.68E+00	0.48	0.5	104.82

Cv = Coefficient of variation
Std dev. = Standard deviation

Table 3. Empirical relationship between T and Q/s (m^2/h)

Region	Area	Method	Q/s	R^2	A2	D	Data pairs
North	Korhogo	Théis	Corrected	0.99	1.59	1.14	121
	Ferke	Théis	Corrected	0.95	0.99	0.83	130
North-East	Bondoukou	Cooper Jacob	Uncorrected	0.86	0.38	1.06	78
Center	Katiola	Cooper Jacob	Uncorrected	0.89	0.43	0.97	22
	Yamoussoukro	Jacob	Uncorrected	0.82	0.94	1.19	105
	Oume	Cooper Jacob	Uncorrected	0.73	1.61	1.34	142
West	Man-Danane	Theis	Corrected	0.88	0.89	1.30	178
South-West	San Pedro	Cooper Jacob	Uncorrected	0.86	0.85	1.16	110
East	Abengourou	Cooper Jacob	Uncorrected	0.73	1.17	1.20	104
	Agnibilekro	Cooper Jacob	Uncorrected	0.98	2.44	1.10	50

4.3 Geostatistical Analysis

All variograms are structured with more or less significant nugget effect. Variogram of transmissivity from San Pedro area is characterized with two sills which indicate two elementary structures. Modeling equations from these variograms are given by expressions (9 to 13) below:

Boudoukou1 $$\gamma(h) = 0.156 + 0.063 \times \left[1 - exp\left(\frac{-3h}{10}\right)\right] \quad (9)$$

Boudoukou 2 $$\gamma(h) = 0.12 + 0.072 \times \left[1 - exp\left(\frac{-3h}{12}\right)\right] \quad (10)$$

Man-Danane $$\gamma(h) = 0.024 + 0.039 \times \left[1 - exp\left(\frac{-3h}{10.8}\right)\right] \quad (11)$$

San Pedro $$\gamma(h) = 0.399 + 0.239 \times \left[1 - exp\left(\frac{-3h}{15}\right)\right] + 0{,}082 \times \left[1 - exp\left(\frac{-3h}{60}\right)\right] \quad (12)$$

Oume $$\gamma(h) = 0.318 + 0.234 \times \left[1 - exp\left(\frac{-3h}{7}\right)\right] \quad (13)$$

Range varies from 7 to 60 km in studied areas and nugget effect value corresponds 38 to 71% of total dispersion. Variograms of transmissivity are not the same according to geological contexts.

Results of cross validation procedure are reported in Table 4. These results show that cross validation procedure is satisfied. Indeed, average errors and ratio of variance (error variance/average estimation variance) are respectively close to 0 and 1. Estimated values of transmissivity obtained after back-transform operation spread on 2 and 3 magnitude orders (Table 4). One can note a first feature common to the four assessments: the amplitude of the estimated values of T is reduced compared to that of the actual values of T. The observed T values span 4 orders of magnitude while the estimated values span only 3 or 2 orders of magnitude. This might be due to the fact that T values are not continues (extreme values are much less numerous than values close to the arithmetic mean) and to the smoothing effect of kriging (or cokriging).

Bondoukou 2 estimate is better than Bondoukou 1 according to cross validation results (Table 4). Indeed, kriging reconstitute high and low values of T. These estimated values are comparable with observed values. Highest kriging standard deviation values correspond to bad assessment of transmissivity. About studied areas, more than 95% of estimated kriging standard deviation values are low. This result testifies good assessment of transmissivity and can be considered as satisfactory.

Table 4. Estimated transmissivities by using kriging approach on areas

Region	Area	Minimum	Maximum	Average	AAE	σ_e^2/σ_k^2
North-East	Bondoukou 1	4.01E-06	1.72E-05	9.18E-06	-0.03	0.92
North-East	Bondoukou 2	3.86E-06	1.84E-05	8.42E-06	0.005	1.10
Center	Oume	1.26E-05	2.41E-04	5.10E-05	0.060	1.00
West	Man-Danane	7.81E-06	1.30E-04	4.22E-05	0.006	1.10
South-West	San Pedro	1.29E-05	1.06E-04	3.89E-05	0.062	0.98

AAE = average of the actual errors, σ_e^2 = variance of the actual errors, σ_k^2 = average kriging variance

5. DISCUSSION

5.1 Statistical Analysis

Specific capacity is an intrinsic parameter of aquifer that gives more information about drillings productivity [50,51,39,52,53]. Thus, it is necessary to know specific capacity before starting advanced studies such as groundwater flow in fracture networks [21]. Majority specific capacity of aquifers from studied areas are low as others basement regions of the country [1,21,29]. This similarity of results can explain by many reasons [1,39,40,52]: i) lack of complete studies before carrying out of drillings; ii) drillings procedure, iii) project goals, iv) regime variation, v) filling of fractures, boundary impermeable effect, etc. The most important reason is the quality of study during prospecting stage. Indeed, in rural areas drillings carried out following geomorphologic knowledge [1,21]. Remote sensing and geophysics studies are made when failure rate is high [1,21,32]. According [1,54], specific capacity values give information about drilling operations somewhere. In rural areas, Q/s values seldom exceed 1 m^2/h and never reach 3 m^2/h [1]. Contrarily, water supply operations in urban areas showed that more than 50% drillings delivered Q/s superior than 1 m^2/h and sometimes reached 10 m^2/h.

Transmissivity values obtained in this study are comparable to those determined generally at other basement areas of Africa and particularly in West Africa [21,14,32,15,2]. Transmissivity depends on many factors such as geomorphology, hydrogeology and structural characteristics of studied aquifer, also lithology, density and fractures geometry [34,55]. Inside Precambrian basement of Côte d'Ivoire, transmissivity depends on geometry more than density of fractures. Transmissivity and specific capacity are not clustered in preferential areas and that the high values of T or Q/s are not grouped together. We can meet low and high values everywhere. These high values are distributed over the whole studies areas. It can also be noted that the high values of T correspond to those of Q/s. These two parameters are lognormally distributed in each of the studied areas.

High values of transmissivity are met at Man-Danane, San Pedro, Korhogo and Abengourou areas. These values of transmissivity represent reliable characteristics of aquifers from Cote d'Ivoire basement [21,6].

Transmissivity and specific capacity distributions following log-normal law are well recognized in the literature [56,57,58,59,21,38,22,6,14,15,2]. However, [60] pointed out that transmissivity can be distributed by power-law.

5.2 Empirical Estimation of Transmissivity

Empirical relationship between transmissivity and specific capacity from aquifers varies through basement. In Cote d'Ivoire, this relationship in many studies is variable. Coefficient of determination A2 and slope values D varies respectively from 0.4 (Katiola) to 2.44 (Agnibilekro) and from 0.83 (Ferke) to 1.33 (Oume). This approach generally is used when available transmissivity data are not enough to make estimation with geostatistical methods [6,34,2]. Indeed, specific capacity (Q/s) is easy to measure and these values are numerous than transmissivity ones [6].

Equations written for each region of the country are significant when data spread at least on 2 magnitude orders [6,2]. Coefficient of determination (R^2) is superior than 0.70 which indicates that statistical test is significant [61,2].

In this relationship, high values of transmissivity and specific capacity are associated. This implication shows the pertinence of empirical relationship determined at least on two logarithmic cycles. [6] used this approach to complete database at Man-Danane area. These authors used available database to make two geostatistical estimation of transmissivity and compared them. Some of these relations appear more significant than others because of drawdowns corrections and number of data pair (T, Q/s) considered. It concerned Man-Danane, Ferke and Korhogo areas. Indeed, many studies [30,31,32] carried out in Côte d'Ivoire respectively at Agnibilékrou (Eastern part), Korhogo and Ferke (Northern part) respectively showed that empirical relationship can include uncertainties due to well losses when drawdowns are not corrected. Don't forget that pumpings are carried out in isolated drilling and drawdowns measurements have been realized in the same drillings. Inside of the drilling, water level is disturbed at filters and creates turbulent head losses [62,63,21,38,6,3,30,31,32,2]. [33,34] indicate that drawdowns correction will not be necessary if water discharge is very low. When drawdowns are corrected, transmissivity and permeability values estimated are significant than those that came from raw drawdowns [57,38,30,31,32]. When sample are very few, relationship is not-significant. This relationship can be improved after supplementing data. [6,11] supplemented data respectively at Man-Danane and Bondoukou areas for geostatistical assessment and they obtained significant results. Many authors [64,65,66,67] studied the representativeness of sampling. For statistical analysis, [64,65] suggest to use at least 30 samples while [66, 67] suggest 100. Relationship between transmissivity and specific capacity has been studied at many parts of the world by different authors [57,68,39,40,38,69,34,55]. Two last authors realized a compilation and critical synthesis of some empirical relations. Similar studies were made in Côte d'Ivoire about aquifers from basement areas [21,6,2,30,31,32,27]. Empirical relation varies here following geology context such as archean or paleoproterozoic domains. According to some authors [39,69,6,34,55], relationship also depends on many parameters such as drillings depth, pumping time, imperfect well and method of hydrodynamic parameters determination (T and Q/s). This relationship characterizes an area and it is not possible to interchange empirical relationship from one area to another if hydrogeology contexts is not similar [32,2]. These relationships can be used to determine transmissivity values in areas where this parameter is absent or not easily determined by using classical methods [21,6,2].

5.3 Geostatistical Assessment of Transmissivity

All variograms show nugget effect which represents any small-scale data variability or possible sampling (measurement and/or location) errors [70,6]. According with these authors, it is not possible to distinguish on a variogram the part of small-scale data variability and sampling errors.

With regard to all studied areas, transmissivity range oscillates from 7 km at Oume to 60 km at San Pedro. Variogram of tranmissivity of San Pedro is complex with two successive sills (a_1 = km 15 and a_2 = 60 km) those represent 2 elementary variograms. These ranges are superior than the average range about national scale which is equal to 10 km. This absence of similarity about variogram structuring is due to intensity of tectonic event, fracture networks organization and their connectivity [17,11,2]. This interpretation is in accordance with statistical studies carried out on fractures networks in Côte d'Ivoire by several authors

[21,22,17,26,27,71,72]. These authors showed that fractures networks reached different developing stages, according to their geological history. Transmissivity assessment by kriging method is significant and satisfactory. Indeed, cross-validation procedure is satisfied. Lowest and highest values of transmissivity were reconstituted on different areas. That is indicating robustness of kriging method. Kriging standard deviation permitted to appreciate quality of estimation. Sometimes, in geostatistical assessment smoothing effect can reduces data amplitude [73,6,14,2]. This effect explains the reduction orders of magnitude from 3 to 2 about estimated values. [6,2] explain this reduction by predominance of values close to the arithmetic mean in data. Indeed, in the database used, extreme values are less numerous than values close to the arithmetic mean. Sectors where data are few, assessment is not better than the area where data are numerous. The estimates values obtained in these areas are significant and coherent. These estimates can be used for modeling and simulation of groundwater flows.

6. CONCLUSION

Hydrodynamic parameters are determined in many areas of Côte d'Ivoire. These parameters spread on more than two orders of magnitude that are putting in evidence heterogeneity of studied areas. Empirical relationships determined with transmissivity and specific capacities are significant. These relationships are very reliable when drawdowns are corrected. They are not transposable from one area to another because their typical characteristics. Variogram of transmissivity is structured with nugget effect on the study areas. This nugget effect represents 38 to 71% of total dispersion. However, the spatial spread of this variable is not same according to regions. The greatest structuring of variogram is observed at San Pedro area with maximal range reached (a = 60 km) and the smallest one at Oume area where range reached (a = 7 km). Estimated transmissivity values are significant and agreed with observed values. The geostatistical approach proved useful to provide a reliable estimation of the transmissivity of fractured aquifer of these areas.

Transmissivity and specific capacity are well known in Precambrian basement of Côte d'Ivoire through studies carried out. Available results allow to undertake groundwater modeling and groundwater flow in these areas.

ACKNOWLEDGEMENTS

The authors would like to gratefully thank the anonymous reviewers for their comments and suggestions which helped to improve an earlier version of this paper, and the Department of Water and Forest and Economic Infrastructures of Côte d'Ivoire for the data used in this study.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Faillat JP. Heterogeneity and scale in aquifers cracked effect. Approach by pumping test experimental station (West Africa). Hydrogeology. 1986;1:65-76.

2. De Lasme O, Lasm T, Oga M-S, Youan Ta M, Baka D, Ettien FB, Kouakou S, Onetié OZ, Yao TK. Analysis of hydrodynamic properties of fractured aquifers in the region of San Pedro (South-western Côte d'Ivoire). Estudios Geológicos. 2012;68(2):217-232.
3. Soro G, Soro N, Ahoussi KE, Lasm T, Kouamé FK, Soro TD, Biémi J. Evaluation of the hydraulic properties of fractured aquifers of crystalline and metamorphic formations in the Lake District (central Côte d'Ivoire). Estudios Geologicos. 2010;66(2):227-242.
4. Youan Ta M, Lasm T, Jourda JP, Saley M B, Miessan GA, Kouamé K, Biémi J. Mapping groundwater in fractured medium by MCA. If Bondoukou (Ivory Coast). Journal of Geomatics. 2011;21(1):43-71.
5. Mace RE, Smyth RC, Xu L, Liang J. Transmissivity, Hydraulic conductivity and storativity of the Carrizo-Wilcox aquifer in Texas: bureau of economic geology. The University of Texas at Austin, submitted to the Texas Water Development Board. 1999;76.
6. Razack M, Lasm T. Geostatistical estimation of the transmissivity in a highly fractured metamorphic and crystalline aquifer (Man-Danane Region, Western Ivory Coast). Journal of Hydrology. 2006;325:164-178.
7. Gupta CP. On analysis of step drawdown test data. Ground Water. 1989;27(6):874-880.
8. Kawecki MW. Recovery analysis from pumping tests with stepped discharge. Ground Water. 1993;31(4):585-592.
9. Kawecki MW. Meaningful interpretation of step-drawdown test. Ground Water. 1995a;33(1):23-32.
10. Helweg OJ. A general solution to the step-draw-down test. Ground Water. 1994;32(3):363-365.
11. Lasm T, Youan Ta M, Baka D, De Lasme OZ, Oga MS, Jourda P, Biémi J. Improvement of aquifer transmissivity assessment in crystalline and metamorphic fractured hard rocks in Bondoukou area, north-eastern Côte d'Ivoire. American Journal of Scientific and Industrial Research. 2012;3(5):315-330.
12. Painter SL, Woodbury AD, Jiang Y. Transmissivity estimation for highly heterogeneous aquifers: comparison of three methods applied to the Edwards aquifer, Texas, USA. Hydrogeology Journal. 2007;15:315-331.
13. Boucher M, Favreau G, Vouillamoz JM, Nazoumou Y, Legchenko A. Estimating specific yield and transmissivity with magnetic resonance sounding in an unconfined sandstone aquifer (Niger). Hydrogeology Journal. 2009;17:1805-1815.
14. Lasm T, Youan Ta M, Razack M. Geostatistical analysis of the transmissivity in fissured reservoirs of Bondoukou region (northeast, Côte d'Ivoire). In the IAH Selected papers book series titled: Applied groundwater studies in Africa, SegunAdelana, Alan MacDonald, Tamiru Alemayehu & Callist Tindimugaya (editors). Publisher: Taylor & Francis. The Netherlands. 2008;473-485.
15. Baka D, Lasm T, Oga M-S, Youan Ta M, De Lasme O, Kouakou SO, Ettien FB. Characterization of transmissivity in the fractured reservoirs in the Oumé area (Centre of Côte d'Ivoire). American Journal of Scientific and Industrial Research. 2011;2(2):310-322.
16. Lasm T, Razack M. Scaling laws in the fracturing of crystalline hard rocks and into the water system partner. Minutes Paris Academy of Sciences, Earth Science and Planetary. 2001;333:225-232.

17. Youan Ta M, Lasm T, Jourda JPR, Kouamé KF, Razack M. Mapping of geological features in satellite images Landsat-7 ETM + and analysis of fracture networks of the Precambrian basement of the Bondoukou region (North-eastern Côte d'Ivoire). Remote Sensing. 2008;8(2):119-135.
18. Kouamé KF, Lasm T, De Dreuzy JR, Akaffou AG, Bour O, Davy P. Contribution hydrogeological model of a stochastic discrete fractures in the study of fractured aquifers of Archean basement of Touba (north-western Côte d'Ivoire). Journal of Water Science. 2010;22(5):617-632.
19. Camil J. Petrology, chronology of Archean granulite and associated ensembles in the region of Man Ivory Coast training). Implications for the geological history of the West African craton Thesis of doctorate in Natural Sciences, University of Abidjan, Ivory Coast. 1984;306.
20. Djro SC. Tectono-metamorphic evolution of Archean granulite gneiss sector Biankouma. Thesis State Doctorate in Natural Sciences, University of Cocody, Côte d'Ivoire. 1998;171.
21. Lasm T. Hydrogeology of fractured reservoirs pedestal: Statistical and geostatistical fracturing and hydraulic properties analyzes. Thesis single thesis, University of Poitiers (France). 2000;233.
22. Jourda JPR. Methodology of application of remote sensing and geographic information systems to study fractured aquifers of West Africa. Concept of spatial hydrotechnique: case tests Ivory Coast areas. Thesis of doctorate in Natural Sciences. University of Cocody (Abidjan, Ivory Coast). 2005;403.
23. Jourda JP, Saley MB, Djagoua EV, Kouamé KJ, Biémi J, Razack M. Using Landsat ETM + data and GIS for assessing groundwater potential in the Precambrian fractured medium in the region of Korhogo (north of Côte d'Ivoire): MCA approach and test validation. Remote Sensing. 2006;5(4):339-357.
24. Koudou A, Lasm T, Kouamé KF, Youan Ta M, Assoma TV, Biémi J. Contribution Terra Aster images to the attention of fractured aquifers in the region Duekoué (western Côte d'Ivoire). Photo-interpretation European Journal of Applied Remote Sensing. 2013;4:48-79.
25. Lachassagne P, Wyns R, Dewandel B. The fracture permeability of hard rock aquifer is due neither to tectonics, nor to unloading, but to weathering processes. Terra Nova. 2011;23:145-161.
26. Baka D. Geometry, and hydrodynamic modeling of fractured reservoirs of Proterozoic basement of the Oumé region (center-west of Côte d'Ivoire). PhD thesis, University Felix Houphouet Boigny. 2012;249.
27. De Lasme OZ. Contribution to a better understanding of fractured aquifers of the Precambrian basement; case of the San Pedro (South-western Côte d'Ivoire). PhD thesis, University Félix Houphouët-Boigny. 2013;176.
28. Dewandel B, Lachassagne P, Wyns R, Marechal JC, Krishnamurthy NS. A generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering. Journal of Hydrology. 2006;330(1-2):260-284.
29. Lasm T, Kouamé KF, Oga M-S, Jourda JPR, Soro N, Kouadio BH. Study of productivity of fractured reservoirs basement areas. If the Archean core Man-Danané (western Côte d'Ivoire). Ivorian Journal of Science and Technology. 2004;5:97-115.

30. Kouakou OS, T Lasm, D Baka, MS Oga, M Youana, OZ De Lasme, N Soro. Determination of the effect of pressure drop on the outcome of transmissivity test drilling in remote pumping. Application to the Agnibilékrou region (eastern Côte d'Ivoire), 5th Congress AAWG Bassam, Abidjan, Côte d'Ivoire; 2010.
31. Onétié OZ, Lasm T, Baka D, Fossou NMR, Kouakou SO, Youan TM, De Lasme OMSO, Soro N. Influence of quadratic losses accrued on transmissivity and specific yield determined on isolated drilling: the case of the region of Korhogo in northern Ivory Coast). Ivorian Journal of Science and Technology. 2010;16:261-283.
32. T Lasm, O De Lasme, M-SY Oga, M Youan Ta, D Baka, F Kouame, TK Yao. Hydrochemical characterization of fractured aquifers in the region of San Pedro (South-western Côte d'Ivoire). International Journal of Biological and Chemical Sciences. 2011;5(2):642-662.
33. Fransson A. Characterization of fracture geometry using specific capacities: Numerical and experimental study of a fracture replica. Bulletin of Engineering Geology and the Environment. 2001;60:139-144.
34. Srivastav SK, Lubczynski MW, Biyani AK. Upscaling of transmissivity, derived from specific capacity: A hydrogeomorphological approach applied to the Doon Valley aquifer system in India. Hydrogeology Journal. 2007;15:1251-1264.
35. Kruseman GP, De Ridder NA. Analysis and evaluation of pumping test data. International Institute for Land Reclamation and Improvement. Wageningen, The Netherland. 2nd ed. (completely revised). 1991;377.
36. Banton O, Bangoy LM. Hydrogeology: Environmental multiscience groundwater. Presses de l'Université du Québec. 1997;460.
37. Driscoll FG. Groundwater and Wells. Reynolds Guyar Design Publisher Austin, Minnesota. 1986;1089.
38. Jalludin M, Razack M. Assessment of hydraulic properties of sedimentary and volcanic aquifer systems under arid conditions in the Republic of Djibouti (Horn of Africa). Hydrogeology Journal. 2004;12:159-170.
39. Mace RE. Determination of transmissivity from specific capacity test in a karst aquifer. Ground Water. 1997;35(5):738-742
40. Mace RE. Estimating Transmissivity Using Specific-Capacity Data. Bureau of Economic Geology. The University of Texas at Austin. 2000;70.
41. Journel AG, Huijbregts CJ. Mining geostatistics. Academic Press. 1978;600.
42. Isaak EH, Srivastava MR. An introduction to applied geostatistics. Oxford University Press, New York. 1989;561.
43. Pannatier Y. VARIOWIN: Software for Spatial Data Analysis in 2D. Springer, New York; 1996.
44. Deutsch CV, Journel AG. GSLIB. Geostatistical Software Library and User's Guide. Oxford University Press, Oxford; 1992.
45. Englund E, Sparks A. GEO-EAS, Geostatistical environmental assessment software. US Environmental Protec Ag. 1991;600/8-91/008:186.
46. Pebesma EJ, Wesseling CG. GSTAT, a program for geostatistical modelling, prediction and simulation. Computer Geoscience. 1998;24:17-31.
47. Kitanidis PK. Introduction to Geostatistics, Application in Hydrogeology. Cambridge University Press, Cambridge; 2000.
48. Clark I. The art of cross validation in geostatistical applications. Proceedings of the 19th International APCOM Symposium, Pennsylvania. State University. 1986;211-220.

49. Gascuel-Odoux C, Bovin P, Walter C. Elements of geostatistical. In: Des processus pédologiques. Ed Actes. 1994;217-247.
50. Bertachini AC. Study of the hydrogeologic characteristics of crystalline terrain under humid climate in Jundiai Region, Sao-Paulo State. PhD Thesis. University of Sao-Paulo (Brazil); 1987.
51. Chilton PJ, Foster SSD. Hydrological characterization and water-supply potential of basement aquifers in tropical Africa. Hydrogeology Journal. 1995;3:36-49.
52. Tam VT, De Smedt F, Batelaan O, Dassargues A. Study on the relationship between lineaments and borehole specific capacity in a fractured and kartstifiel limestone area in Vietnam. Hydrogeology Journal. 2004;12:662-673.
53. Won JH, Kim JW, Koh G-Wet Lee JY. Evaluation of hydrogeological characteristics in Jejuisland, Korea. Geosciences Journal. 2005;9(1):33-46.
54. Biémi J. Contribution to the geological survey, hydrogeological and remote sensing of the Sahelian sub-watersheds of the Precambrian basement of West Africa: hydrostructurale, hydrodynamics, water chemistry and isotopic discontinuous aquifers furrows and granitic areas of high Marahoué (Coast Ivory). Ph.D thesis in Natural Sciences. Université de Cocody. Abidjan (Côte d'Ivoire). 1992;493.
55. Rotzoll K, El-Kadi AI. Estimating hydraulic conductivity from specific capacity for Hawaï aquifers, USA. Hydrogeology Journal. 2008;16:969-979.
56. Thiery D. Statistical analysis of the conditions of successful drilling activity in region cracked foundation. Application au Togo. Bulletin B.R.G.M., SGN 674 EAU. 1981;81:81.
57. Razack M, Huntley D. Assessing transmissivity from specific capacity in a large and heterogeneous alluvial aquifer. Ground Water. 1991;29:856-861.
58. Bracq P, Delay F. Transmissivity and morphological features in chalk aquifer: a geostatistical approach of their relationship. Journal of Hydrology. 1997;191:139-160.
59. Fabbri P. Transmissivity in the geothermal Euganean Basin: A geostatistical analysis. Ground Water. 1997;35(5):881-887.
60. Gustafsson G, Fransson A. The use of Pareto distribution for fracture transmissivity assessment. Hydrogeology Journal. 2005;14:15-20.
61. Bodin J, Razack M. Image analysis applied to the automatic processing of fields fractures. Geometric properties and scaling laws. Bulletin de la Société Géologique de France. 1999;170(4):579-593.
62. Detay M. The drilling of water: Production, maintenance, rehabilitation. Editions Masson, Paris. 1993;379.
63. De Marsily G. Hydrogeology: Understanding and estimating groundwater flow and contaminant transport. Ecole des Mines de Paris. 1994;242.
64. Wickman FE. Repose period patterns of volcanoes: volcanic eruptions regarded as random phenomena. Arkivfor Mineralogi och Geologi. 1966;(4-4):292-302.
65. Spiegel MR. Theory and applications of statistics. Série Schaum, 17ème tirage. 1991;358.
66. Liebovitch L, Toth T. A fast algorithm to determine fractal dimension by box counting. Physics Letters, Serie A. 1989;141:386-390.
67. Dubois J, Pambrun C. Studies of the distribution of inversions of the terrestrial magnetic field 165 between the current and Ma. Compte Rendu Académie des Sciences, Série II, Paris. 1990;311:643-650.
68. Huntley D, Nommensen R, Steffey D. The use of specific capacity to assess transmissivity in fractured rock aquifer.Ground Water. 1992;30(3):396-402.

69. Hamm S-Y, Cheong J-Y, Jang S, Jung C-Y, Kim B-S. Relationship between transmissivity and specific capacity in the volcanic aquifers of Jeju Island, Korea. Journal of Hydrology. 2005;310:111-121.
70. Massoud H. Modeling techniques by petite fracturation geostatistics. Document B.R.G.M. 1988;155:197.
71. Gnamba FM. Contribution of water chemistry, and hydrodynamics to the knowledge of reservoir cracks Paleoproterozoic basement of the region Katiola (north-central Côte d'Ivoire). Thèse de doctorat, Université Félix Houphouët-Boigny. 2014;209.
72. Lasm T, Youan Ta M, Baka D, De Lasme O, Jourda JP, Kouamé FK, Yao TK, Kouadio E, Yao FA. Fractures networks organization on Precambrian basement of Côte d'Ivoire: statistical and geostatistical approaches. International Journal of Emerging Technology and Advanced Engineering. 2014;4(1):335-344.
73. Razack M. Application of numerical and statistical methods to the identification of carbonate reservoirs cracked in hydrogeology. PhD in Natural Sciences. Université Languedoc (France). 1984;394.

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history.php?iid=594&id=22&aid=5389