Research Article

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Characterization of the productivity of basement aquifers at Bagoué region (North of Côte d'Ivoire)

Abstract

This study aims to characterize the productivity of basement aquifers based on a database built by pumping test and drilling report from eighteen boreholes exploited in Bagoue region of Cote d'Ivoire. By using last version of a tool to assist in pumping test interpretation suggested by the French Mining and Geological Survey, Transmissivity parameter values of confined aquifers were determined through the well-known Theis method. In the same approach, critical yield value of borehole was determined at the equivalence point of linear and quadratic pressure drop from short-term pumping test data. Geostatistical analysis and kriging of transmissivity of aquifers were realized. Then, it was elaborated few predictive equations between hydrodynamic and hydraulic parameters based on their relationship level. Comparison of aquifers productivity and boreholes hydraulic capacity ended the methodology. Transmissivity ranged from 9.10^{-7} to 4.10^{-5} $m^2.h^{-1}$ while specific yield of boreholes reached between 0.34 and 23.07 $m^3.h^{-1}$. Yields from exploited boreholes varied between 0.5 $m^3.h^{-1}$ and 12 $m^3.h^{-1}$ with an average reaching 3.44 $m^3.h^{-1}$. Critical yield varied between 2.11 and 18.8 $m^3.h^{-1}$ with an average of 6.95 $m^3.h^{-1}$. According to geostatistical analysis of Transmissivity, its spatial spreading adjusted spherical model with a range reaching 0.13 meters. Findings highlighted 44 % of aquifer areas characterized by low value of transmissivity with great value of exploited outflow. That suggests a short-term availability of drinking water for living communities. In the same way, 11.11 % of boreholes were established into aquifer areas characterized by great transmissivity and low outflow values that suggests a better supply environment with long-term groundwater availability.

Keywords: transmissivity, groundwater flow, geostatistical, borehole, Bagoué-Côte d'Ivoire

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Introduction

Water remains a safe resource searched by people for many purposes like drinking, realizing agriculture irrigation and supplying livestock. Then, water is essential to life, but access to abundant clean water is still a luxury for many people in low and middle-income countries of the world. In Africa, groundwater is the main source of drinking water into rural areas.[1] According to the country Côte d'Ivoire plan to achieve the sixth sustainable development goal, government agencies and private companies established more than one thousand boreholes equipped with human-powered pumps.[2] However, most of these boreholes are no longer in use, as either they are deteriorated or the reservoirs hosting groundwater have been overexploited. The Bagoué region, at northern part of the country (Figure 1) is not an exception of this phenomenon due that recent survey in 2020 revealed 46% of equipped hand pumps are non-functional.[3] Then, the difficulty for getting water is increasing with household far from natural water storage location. This situation is worsening with the rapid urbanization of the region and the influence of climate change negative impacts on water resources availability. In Bagoué region at 2020, the deficit of water needs reached 72% with more than 1,200 boreholes requested to cover population water needs.[3] How can we solve that problem related to groundwater accessibility in that basement area characterized by different rocks (Figure 1)? It sounds good to study the productivity of basement aquifer there to guide the sustainable management of groundwater resources already exploited and those to be exploited. Several authors (Biemi, 1992; Onétié et al., 2010)[4–6] have studied the productivity of aquifers in various regions of Côte d'Ivoire. Particularly, some of those authors proceeded by using empirical relationship between correlated intrinsic hydrodynamic parameters for estimating Transmissivity of aquifer at place where they faced lack of pumping test data.[4,7] Otherwise, some hydro geophysical studies in Ghana and Nigeria highlighted a joint inversion method to estimate aquifer hydrodynamic parameters like transmissivity or hydraulic conductivity by using theoretical relationship named Dar Zarrouk parameters derived from Ohm's law of current flow and Darcy's law for fluid flow in a medium[8,9] At volcano-sedimentary artesian plain of Pasuruan (Indonesia) the transmissivity value of artesian aquifer was computed from a free-flowing well artesian discharge data by following the transient state Houpeurt-Pouchan method when the recovery curve is interpreted as a drawdown curve with the help of either Jacob's or Theis's solution or any adapted analytical solution such as the Cooper-Jacob.[10] Nowadays, many researchers use model for estimating aquifer productivity parameters like hydraulic head and transmissivity. That option of research is fast and can be robust but, it is more critical due uncertainties around modelling results. This study focuses on characterizing the hydrodynamic properties parameters of basement aquifers. Based on the state of art about knowledge of hydrogeology of basement aquifer into studied area and its around, this study aims to characterize the productivity of basement aquifers of Bagoué region. Three specific goals are pursued for joining the global objective: i) identify the types of aquifers, 2) determine the values of hydrodynamic properties and estimate the practical extent of aquifer's transmissivity.

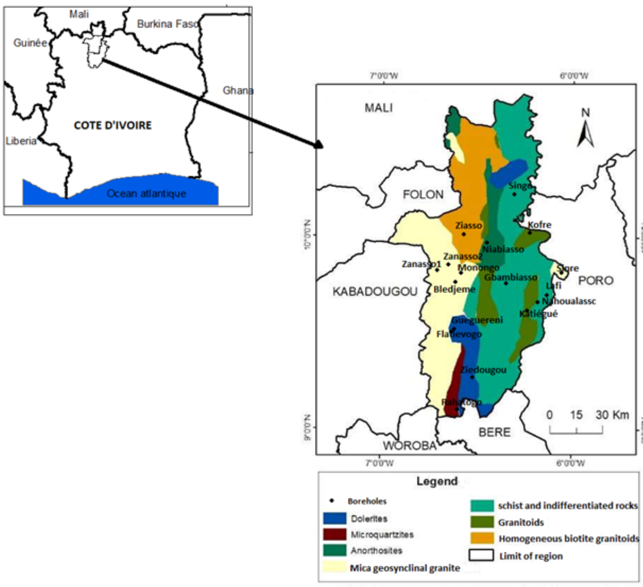

Figure 1 Geological map of Bagoue region.[3]

Materials and methods

Database

The database used for this study is essentially drilling data sheets and pumping tests on isolated boreholes. These sheets contain several pieces of information including: the flow rates pumped during the different pumping tests, the depth of borehole, the static water level, the dynamic water level values during drawdown and recovery periods, the air-lift flow rates, the geographical coordinates indicating precise localization of boreholes used. These data have been inserted into several specific software below:

I. EXCEL from Microsoft Windows 2000, for doing elementary statistical analysis.

II. OUAIP version 2: for determining automatically critical yield and transmissivity.

III. SURFER 16: for realizing geostatistical analysis and kriging of the transmissivity.

Methods

Identification of the different types of aquifers

The lithological profile of the drilling sheet of borehole allowed getting knowledge about the petrologic nature of crossed layers as the roof and the wall of the aquifer containing groundwater pumped. Then, different types of aquifers were distinguished like confined and unconfined ones. The observation of stratigraphy of crossed layers reported into drilling sheet helped to distinguish confined aquifers from those are unconfined. Confined ones are deeper than unconfined, and they are overlain by relatively impermeable rock or clay. They also sit directly on impermeable bedrock at the bottom. Some of confined aquifer are sub-horizontal fissured zones of granite. An unconfined aquifer unconfined is not overlain by impermeable material. In this study area, unconfined aquifers are not enough identified.

Determination of hydrodynamic parameters of aquifer and the critical yield of borehole

The transmissivity of the aquifers was determined by applying Theis solution method through OUAIP software where several solution methods were automatically established.[11] The user has to select the appropriate analytical solution-method after filling datasheet tables and matching aquifer conditions required by authors of solution-method like Theis.[12] Theis analytical solution method is well known and has been revised and applied by several authors of Côte d'Ivoire worked on basement aquifer hydrodynamic properties determination.[13–15,7] The resumed analytical solution-method suggested by Theis is given by equation 1 below.

$$s(t) = \frac{Q}{4\pi T} \mathrm{Ln}\left(\frac{2,25Tt}{r^2 S}\right) \quad (1)$$

With:

- S: storage coefficient, dimensionless.

- T: transmissivity (m²/s);

- Q: pumping rate (m3/s);

- t: time elapsed since the beginning of pumping, (s);

- r: distance from the piezometer to the axis of the well (m);

- s: drawdown (m).

The specific yield delivered by each aquifer is calculated by following the ratio of the constant pumped air-lift flow and the measured drawdown during long-term pumping test operation.

$$\mathbf{Q_{sp}} = \frac{\mathbf{Q}}{\mathbf{s}} \quad (2)$$

With:

- Q: pumped air-lift flow;

- s: drawdown observed into borehole (m).

The value of the critical flow rate was determined automatically by identifying the analytical matching point from characteristic curve of drawdown where linear and quadratic pressure loss got the same value during short duration pumping tests. The OUAIP software automatically determines that equivalent point and the given critical yield of borehole that must not exceeded by users.

Estimation of practical range of aquifer productivity

The regional estimation of aquifer productivity involved performing a geostatistical analysis of transmissivity due that this parameter gives the real potentiality of aquifer for delivering groundwater. The geostatistical analysis begins with elementary statistical analysis followed by drawing of variogram which is the main tool of geostatistical issues. This variogram was adjusted to a statistical experimental model (spherical, exponential, etc.) in order to highlight the spatial structuring of the natural phenomenon studied. The application of geostatistics is conditioned by two hypotheses:

I. Stationarity or continuity hypothesis that means the existence of a function of regionalized variable with constant variance and fixed average.

II. Intrinsic or homogeneous hypothesis (minimum variance and depending on the distance) of the regionalized variable.

The kriging method is applied after getting an adjusted theoretical model to experimental spreading of regionalized variable function. Then, the spatial interpolation of productivity parameter is obtained with its error associated. Kriging is the best method of spatial interpolation of geological local regionalized phenomenon due it estimates the values of a variable by considering a technique for minimizing the error estimation.[14]

Results

Distribution of aquifers nature and type identified

The distribution of aquifer nature and types from the dataset used are summarized in Table 1 & 2. According to those tables, 55% of aquifers are weathering aquifers, 38% are fissured layers and only 7% are deep fractured aquifers. More than half (61%) of aquifers is confined.

Table 1 Distribution nature of aquifers

Nature of aquifers	Number	Percentage
Weathered materials	10	55.54
Fissured layer	6	38.88
Deep fractured	2	5.58
Total	18	100

Table 2 Distribution of types of aquifers

Types of aquifers	Number	Percentage (%)
unconfined aquifer	7	38.88
confined aquifer	11	61.12
Total	18	100

Hydraulic characteristics of boreholes

Elementary statistics of hydraulic characteristic of boreholes are summarized into Table 3. The total depths of the boreholes vary between 40 and 65 m while static levels of groundwater inside them vary from 17 to 55m. Their critical yield that must not be exceeded varies between 2.11 and 18.8 $m^3.h^{-1}$. The yield delivered by exploited boreholes varies between 0.5 and 12 $m^3.h^{-1}$.

Table 3 Hydraulic characteristics of boreholes

Borehole's location	Bedrock	Critical yield ($m^3.h^{-1}$)	Drilled depth (m)	Exploited yield ($m^3.h^{-1}$)	Water table (m)
SINGO	Schist	9.83	65	6	55
BLEDJEMENE	Granite	0.86	50	0.6	28
KOFFRE	Granite	6,7	60	2.7	43
ZIASSO	Granite	2.74	45	1.3	28
ZANASSO 2	Granite	9.42	50	3.6	34
ZANASSO 1	Granite	1.85	50	1.2	19
NIAMBIASSO	Granit	18.8	40	12	26
GAMBIASSO	Schist	4.38	50	4	43
MONONGO	Granit	5.26	45	3.35	23
KODJAGA	Granit	6.9	45	6.2	21
PAHATOGO	Granodiorit	3.02	45	1.8	17
ZIEDOUGOU	Granit	1.02	60	0.7	30
SINRE	Gneiss	0.69	44	0.5	32
LAFI	Schist	5.84	60	3.6	36
KATIEGUE	Granit	14.82	50	9	38
NAHOUALASSO	Granit	2.27	50	1.45	40
FLATIEVOGO	Granit	2.02	50	1.3	23
GUEGUERINI	Gneiss	10.2	45	6.5	24

Hydrodynamic properties of aquifers

Transmissivity values resulting Theis analytical solution vary from 9.10^{-7} to 4.10^{-5} $m^2.h^{-1}$ with an average reached 7.10^{-6} $m^2.h^{-1}$. About the intrinsic specific yield can be delivered by aquifers; it varies between 0.34 and 23.07 with an average of 4.34 $m^2.h^{-1}$. These results are resumed into Table 4 below. Those two parameters can be relied.

Table 4 Hydrodynamic properties values of aquifers at borehole's location

Borehole's location	Transmissivity ($m^2.h^{-1}$)	Specific yield ($m^2.h^{-1}$)
Singo	1.05E-05	5.06
Bledjemene	7.45E-07	0.38
Koffre	4.35E-06	2.14
Ziasso	6.65E-07	0.34
Zanasso 2	1.24E-05	6
Zanasso 1	9.82E-06	4.76
Niambiasso	1.07E-05	5.17
Gambiasso	9.06E-07	0.46
Monongo	7.60E-06	3.7
Kodjaga	2.63E-05	12.5
Pahatogo	9.06E-07	0.46
Ziedougou	8.46E-07	0.43
Sinre	5.23E-06	2.564
Lafi	3.56E-06	1.76
Katiegue	1.61E-06	0.81
Nahoualasso	1.34E-05	23.07
Flatievogo	4.22E-06	2.08
Gueguerini	1.24E-05	6

Predictive relationship about productivity parameters and water needs

The empirical relationship of Transmissivity (T) and Specific yield (Qsp) is given by the following equation:

T ($m^2.h^{-1}$) = $2.10^{-6} \times$ Qsp1.02 ($m^2.h^{-1}$), while critical yield (Qcr) and exploited yield (Qexp) values of boreholes can be determined through the equation below: Qexp($m^3.h^{-1}$) = 0.0816 + 0.6017×Qcr($m^3.h^{-1}$) at studied area. The spatial distribution of transmissivity with exploited borehole yield delivered and the water needs in 2020 year are separately highlighted on two maps of the region (Figure 2). A comparison of these maps reveals that exploited yield of many boreholes is not aligned with the hydrodynamic potentiality of aquifer. Most of water supply infrastructures like boreholes deliverance were aligned with local human being water needs. Then. around 44 % aquifer areas characterized by low value of transmissivity with high value of exploited yield. That suggests a short-term availability of drinking water for supplying human communities. In the same way. around 11 % of boreholes were established into aquifer areas characterized by high transmissivity with low values of exploited yield. That kind of aquifer exploitation allows to predict a better supply environment with long-term groundwater availability. Even if urgent water needs ordered borehole establishment somewhere, that fact contributes to a poor management of groundwater resources when aquifer hydrodynamic potentialities are ignored or overlooked in the process. Therefore. the objective of sustainable development cannot be achieved.

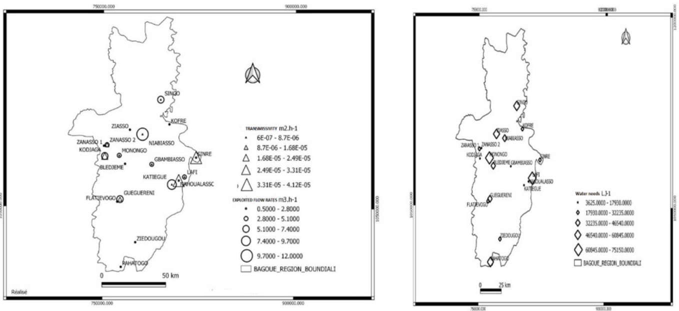

Figure 2 Distribution map of transmissivity. exploited boreholes yield and water needs at Bagoue region.

Variogram and kriging of transmissivity

According to statistical data arrangement conditions before applying geostatistical analysis. the transformed values of transmissivity were performed for getting spatial structuration named variogram of transmissivity (Figure 3). The parameters derived from the variogram study are: nugget effect (0.005). bearing (0.334 m) and range (0.136 m). That experimental variogram fitted spherical model whose equation is written below (equation 3):

$$\tilde{\mathbf{a}} = 0.05 + 0.33\left(\frac{3}{2}\frac{\mathbf{h}}{0,13} - \frac{1}{2}\frac{\mathbf{h}^3}{0,13^3}\right) \quad (3)$$

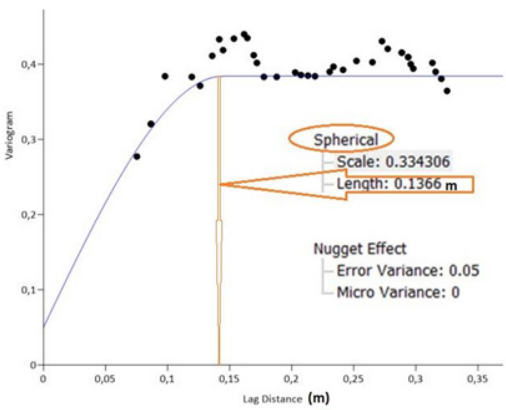

Figure 3 Variogram of transmissivity transformed values.

That equation helps to estimate value of transmissivity at one point into studied area depending on lag distance between two experimental data. It indicates that the practical spatial range of transmissivity phenomenon must not exceed 0.13 meters. That information helps for getting better management of groundwater exploitation through borehole establishment into Bagoue region.

The variogram of transmissivity has given a regionalized variable with unfolds in the space like a structured manner. That good spatial structuring made it possible to consider its estimation by kriging over the entire study area (Figure 4). This map distinguishes two main zones (red and blue) with different levels of transmissivity. Sub-areas characterized by high value of transmissivity can be localized at the west and east parts of the Bagoue region. At those places. there are not enough boreholes characterized exclusively by low values of exploited flow rate or yield. Even if exploited borehole's yield is not high. the transmissivity of aquifer is the highest ones. Contrary. sub-areas characterized by low values of transmissivity can localized at the center and south parts of the studied area where we can also remark some high value yield of exploited boreholes. That confirmed former analysis based on comparison of water needs. exploited borehole yield and aquifer transmissivity.

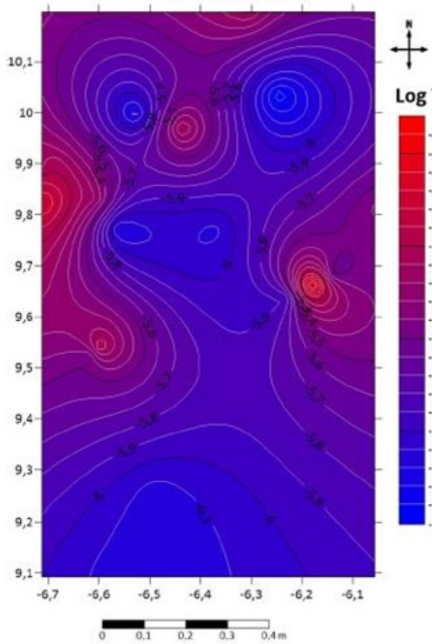

Figure 4 Kriging map of transformed transmissivity values.

Discussion

Many of basement aquifers identified at Bagoué region is confined. It is the same proportion at neighbor's area like Korhogo and Ferkéssedougou too.[7] Little works evidenced such classification of basement aquifers in Cote d'Ivoire. The flow rates of boreholes exploited varied between 0.5 and 12 $m^3.h^{-1}$ with an average reaching 3.44 $m^3.h^{-1}$. These flows are suitable for supplying groundwater at rural areas of Cote d'Ivoire. Indeed. values observed at Bagoue region are like ones observed by different authors at other basement locations of the country.[16,17] Those authors indicated that a flow rate of 1 $m^3.h^{-1}$ is sufficient for supplying potable water in rural areas. Most of them focused on productivity characterization by evidencing factors of the productivity of aquifers and the kind of bedrock which is the most productive according to hydrodynamic properties and yields values delivered. At the center of Côte d'Ivoire, shales aquifers deliver great flow rates values (Biemi, 1992; Soro 2010) At other areas like Bagoue in the North and Bondoukou at the east part of the country[18] with San Pedro at south-western[5] granit delivered great values of groundwater yield. According to findings of different authors the productivity of hard-rock aquifer can be due to weathering processes[19] or position of schistosity plan of schist bedrocks (Biemi, 1992) or density of subsurface rock fracturation.

The range of transmissivity of aquifers values at Bagoué area included into the largest one found by authors working at neighbor area like Korhogo and Ferkessedougou where transmissivity ranged between $4.62.10^{-6}$ and $6.38.10^{-4}$ $m^2.s^{-1}$.[20,7] The same order of magnitude as the range of transmissivity values can be explained by the same nature of basement rocks not modified. In plus, those authors often used local empirical relations to estimate transmissivity when the pumping test data are not available to compute transmissivity through analytic solutions. In Canada, Sandra et al.[21] successfully investigated whether a reliable estimate of transmissivity can be obtained using historical records of specific capacity data in granular and fractured-rock aquifers. Indeed, Razack and Huntley[22] held that empirical relations are better than the theoretical relations for heterogeneous alluvial aquifer. Nevertheless, the analytic solutions typically used to predict transmissivity from specific capacity in alluvial aquifers do not agree well with the measured transmissivities in fractured-rock aquifers. Transmissivities derived using the vertical fracture model of Gringarten and Witherspoon[23] however, correlate very well with the observed specific capacities.[22]

Several authors[24,25,14,18,26] have conducted spatial interpolation of hydrodynamic parameters. using geostatistical methods. Some of them like Lasm[14] and Razack[24] advocated using the transformed values of transmissivity to perform the analysis because presenting a better structuring than the raw values. Thus. the geostatistical analysis of logT in the Bagoué indicates that this parameter behaves unambiguously as a regionalized variable. The value of the range is less important than that determined in various regions of Côte d'Ivoire. Indeed. the geostatistical analysis of transmissivity has been deployed at Man-Danané region. with the range a = 10.8 km.[24] and at Bondoukou with the range a = 10.08 km.[25] The regional pratical range of transmissivity in Bagoué region is less important because the data used is concentrated in a small area of the study area. The areas of high transmissivity values determined on the kriging map of transformed transmissivity values coincide with the study sub-areas where there are many data available by referring to the transmissivity and water requirements map. As one move further away from these areas. the estimates become worse and worse.[26,27] Kriging map of transmissivity of Bagoue region is less classified due small amount of data and the discontinuous nature of basement aquifers area studied.[28,29]

Conclusion

The objective of this study is to characterize the productivity of basement aquifers in the Bagoué region of Cote d'Ivoire. The free software OUAIP is used to help into interpretation data from pumping tests and drilling reports. The findings indicated that groundwater can be accessed at depths greater than 30 meters through drilling. Most of the groundwater environments were found to be confined aquifers or weathered materials. with calculated transmissivity values ranging from 9.10^{-7} to 4.10^{-5} $m^2.h^{-1}$ and specific flow rates between 0.34 and 23.07 $m^2.h^{-1}$. Geostatistical analysis showed that the logarithm of transmissivity behaves as a regionalized variable function. with a practical range of 0.13m. Spatial interpolation through kriging of transmissivity revealed potentially productive groundwater zones in the western and eastern parts of the Bagoue region. These significant findings suggest new indicators for sustainable groundwater management in the region.

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Conflicts of interest

On behalf of all authors. the corresponding author states that the abstract of that paper was presented at IAH-Conference held Paris in 2022 May 6-9 but there is no conflict of interest on that entire article.

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