Journal of Water Resource and Protection, 2019, 11, 728-739
http://www.scirp.org/journal/jwarp
ISSN Online: 1945-3108
ISSN Print: 1945-3094

Borehole Productivity Controlling Factors in Crystalline Bedrock Aquifer of Gkêkê Region, Center of Côte d'Ivoire

Boris Kouassi Kouame[1], Aristide Gountôh Douagui[1*], Innocent Kouassi Kouame[1], Eugène Wonnan Yeo[2], Issiaka Savane[1]

[1]Unité de Formation et de Recherches des Sciences et Gestion de l'Environnement, Université Nangui Abrogoua, Laboratoire Géosciences et Environnement, Abidjan, Côte d'Ivoire
[2]Ministère de l'Hydraulique, Direction de l'alimentation en eau potable, Côte d'Ivoire
Email: boriskouame2siokro@gmail.com, *douaguiaristide@yahoo.fr, innocent_kouassi@yahoo.fr, eugenewyn@gmail.com, savanei@hotmail.com

How to cite this paper: Kouame, B.K., Douagui, A.G., Kouame, I.K., Yeo, E.W. and Savane, I. (2019) Borehole Productivity Controlling Factors in Crystalline Bedrock Aquifer of Gkêkê Region, Center of Côte d'Ivoire. *Journal of Water Resource and Protection*, **11**, 728-739.
https://doi.org/10.4236/jwarp.2019.116043

Received: April 11, 2019
Accepted: June 18, 2019
Published: June 21, 2019

Abstract

The presence of both weathered rocks and fractured crystalline bedrock aquifers makes Hydrogeology in Gbêkê region of Côte d'Ivoire. Access to water in this region is not easy. This study focuses on the influence of borehole depth, weathering thickness and electrical resistivity of the geological structures on borehole productivity that exploit the crystalline aquifer system. Bivariate analysis was used to determine the relationships between these factors and specific capacity for measuring borehole productivity. The values ranged from 0.0088 to 2.20 $m^3 \cdot h^{-1} \cdot m^{-1}$. The analysis shows that there is no correlation between productivity and weathering thickness. However, weathering depths between 15 and 35 m provide the highest specific capacity values ($Qs \geq 1$ $m^3 \cdot h^{-1} \cdot m^{-1}$). For hydrogeological discontinuities interest, boreholes located in KH, QH and H anomaly curve types were the most productive. As productivity diminishes with depth, a deeper borehole can be more productive if it reaches a geological structure that is favorable for groundwater flow. Those hydrogeological parameters are extremely important in borehole productivity in Gbêkê region.

Keywords

Crystalline Rocks, Groundwater Occurrence, Specific Capacity, Gbêkê Region, Côte d'Ivoire

1. Introduction

Groundwater is a vital water source of supply for drinking, agricultural and industrial uses. Though there are other sources of water such as streams, rivers, lakes and ponds, none is as hygienic as groundwater because groundwater has excellent natural microbiological and generally adequate chemical qualities for the majority of its uses [1]. Because of their accessibility for disposal of various types of waste, surface waters are the most susceptible and vulnerable water bodies to contamination. Contaminant levels have then to be reduced by proper treatments and materials [2] [3] [4] [5]. Moreover, surface water resources shrink due to the excessive use and seasonal changes. Therefore, groundwater resources and the wise management of these resources are crucial for sustainable development in areas that need the reliable sources of urban and rural water supply.

The development of crystalline bedrock aquifers as a reliable source of water supply is complicated, and groundwater occurrence is spatially highly variable [6]. Studies of the behavior of groundwater in crystalline rocks are shown that the factors that actually influence the productivity of boreholes in these formations have not been well established, or that these vary according to the particular characteristics of the area [7]. Despite this fact, several authors show that the depth of the boreholes, the lithotypes, the geological structures, the topographic setting and weathering thickness are among the most investigated factors considered as determinant of borehole productivity [8] [9] [10] [11] [12]. These factors all play a significant role in the occurrence of groundwater because they control the development of fracture and fault zones and the presence of higher porosity material [6].

Gbêkê region in Côte d'Ivoire is located in an environment of crystalline rocks and is densely populated [13]. Pressure on environment and on water resources is still tremendous. The quantity and quality of groundwater which is the main source of drinking water in rural and urban zones are threatened. Several campaigns for supplying water through drilling, have registered a significant failure rate. However, few hydrogeological studies have been conducted in the region. Thus, there is a need to provide more insight into the hydrogeological characterization of crystalline formations in these regions.

This study analyzes the influence of three factors which potentially interfere in the productivity of the boreholes that exploit the crystalline aquifer systems in Gkêkê region: borehole depth, weathering thickness and electrical resistivity of the geological structures.

2. Materials and Methods

2.1. Study Area

The study area is Gbêkê region, located in the center of Côte d'Ivoire. It covers the area between longitudes 4˚24' and 5˚43'N and latitudes 7˚12' and 8˚12'W (**Figure 1**). The population is estimated at 1,200,000 inhabitants. This area is under the influence of the wet tropical climate with two distinct seasons: a long dry season (November-March) and a long rainy season (April-October). The

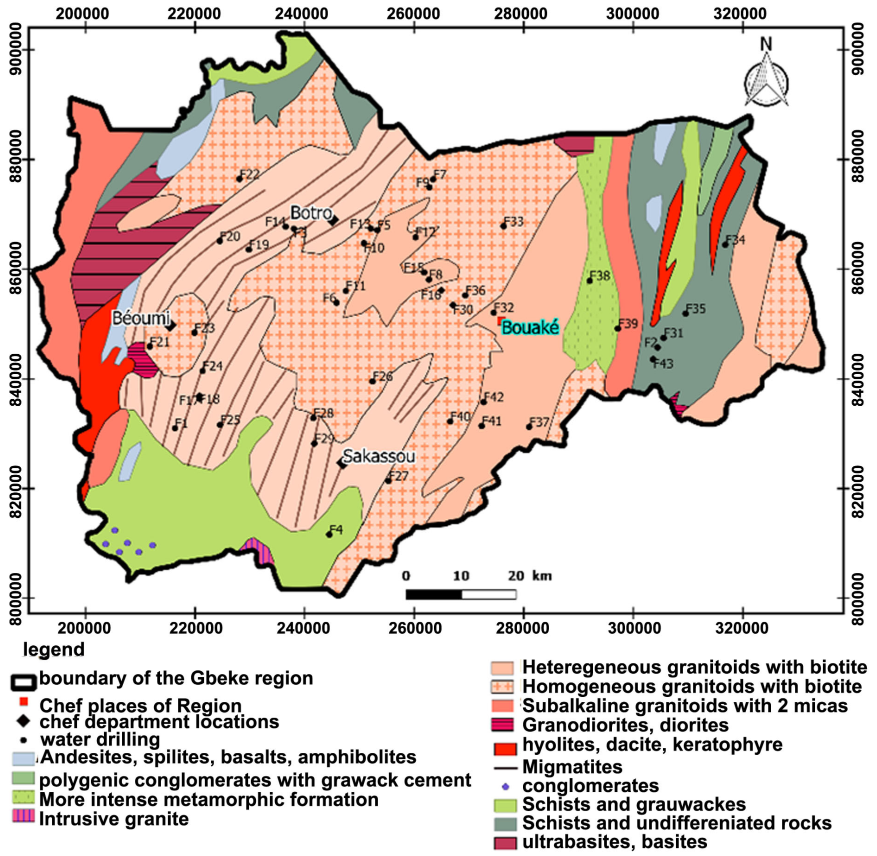

Figure 1. Geological map of the study area showing borehole location.

study area covers 9136 km^2. The geological bedrock consists of the volcano-sedimentary and the granitoids, which are essentially constituted by granites (**Figure 1**). On the one hand, the volcano-sedimentary includes meta-sediments mostly constituted of sandstone and schists intruded by several generations of granitoids. On the other hand, the volcano-sedimentary is covered by metavulcanites which consist of amphibolites, meta-andesite, rhyolites, meta-basaltes, metagabbro and metadolerite.

Two aquifers exist in the study area for the groundwater extraction. The most important aquifers are the fractured aquifers of crystalline and schist rocks. Their permeability is conditioned by the presence of discontinuities such as faults and joints and, in some cases, by lithlogic contacts [14]. Over the fractured rocks, the weathered layer may constitute a porous aquifer.

2.2. Data Collection

The dataset for the study consisted of 43 boreholes from the rural and urban water supply programs in Gbêkê region (**Figure 1**). The parameters taken into account are borehole yield Q (m^3·h^{-1}), borehole depth (m), weathering depth (m), resistivity data of the geological structures and specific capacity Qs (m^3·h^{-1}·m^{-1}). The borehole yield is the air lift flow measured at the end of the drilling by blowing air under pressure at the bottom of the borehole and providing a good estimate of the aquifer's transmissivity. The specific capacity is defined as the ratio between the outflow from a borehole (Q) and the drawdown (s).

We also used resistivity data from fourty three horizontal profiling and vertical electrical sounding using the Schlumberger array. The electrical resistivity methods are used as described by [12] and [15]. These methods consist in setting a direct current in the soil using electrodes A and B and measuring the potential difference between the two other electrodes M and N, including between A and B. The electrical profiling is the preliminary method to any geoelectric study and is the basis for the activation of other electrical implementations. In this study, the electrical profiling was used to monitor the lateral continuity of layers for a given position, and enabled to confirm the effectiveness or not of conductive anomalies [16]. The electrical profiling was conducted according to the Schlumberger mechanism with the following geometric features: $AB = 300$ m, $MN = 20$ m with a 10 m measurement step. Vertical electrical sounding (VES) is performed at the location where the conductive anomaly was detected. That is to quantify the thickness and the resistivity of both the saprolitic and the stratiform fractured layers. The apparent resistivity (ρ_a) values obtained from the survey are estimated as follows [12]:

$$\rho_a = \pi \frac{\left[(AB/2)^2 - (MN/2)^2 \right]}{MN} \frac{\Delta V}{I} \tag{1}$$

where ρ_a is the apparent resistivity, ΔV and I are the potential difference measured between the potential electrodes (volts) and the applied current strength (milliampere), respectively. AB represents the distance between the current electrodes (meters), MN is the distance between the potential electrodes (meters).

The apparent resistivity values obtained from the survey are plotted against the half electrode spacing on a log-log plot. The initial interpretation of VES data is made using curve matching techniques utilizing master curves [17] and the corresponding auxiliary curves [18] from which the resistivity values and thicknesses of the layers are obtained. Further, interpretation of sounding data is made using IPI2W in software.

2.3. Data Analysis

Bivariate analysis was used to determine the relationships between the productivity of boreholes considered as specific capacity values and the depth of drilling and the thickness of alteration as described by [19]. Correlation studies were carried out using the Spearman correlation test. It is a nonparametric technique for measuring the statistical dependence between two variables. The method assesses how well the relationship between two variables can be described using a monotonic function. The advantages of this test are that variables do not need to follow a normal distribution, the method is not very sensitive to outliers, and it is used for data collected on ordinal, interval or ratio scales. In addition to the correlation coefficient (r), standard hypothesis testing was conducted. They tested the null hypothesis that the ranks of one variable do not covary with ranks of the other variable. A significance level (p-value) of 0.05 was used throughout the study. Bivariate analyses were conducted within semi-log space with specific capacity on a logarithmic scale and hydrogeological parameters on an arithmetic scale.

Moreover, the Kruskal-Wallis test was performed to compare specific capacity values between the resistivity sounding curve types in studied cities. The Kruskal-Wallis test is a nonparametric test for comparing more than two independent groups. It assesses a null hypothesis that the data sets originate from the same population. If p-value is below 0.05, then, there is a statistically significant difference between the groups.

3. Results and Discussion

3.1. Borehole and Hydrogeological Characteristics

Specific capacity values ranged from 0.0088 to 2.20 $m^3 \cdot h^{-1} \cdot m^{-1}$ (**Table 1**). The study area was generally characterized by deeper boreholes that the depth varied from 40 to 117.55 m (**Table 1**). Eight resistivity sounding curve types were delineated namely H curve types for 16 stations (37.21%), KH curve types for 11 stations (25.58%), A curve types for 4 stations (9.30%), QH curve types for 4 stations (9.30%), KHKH curve types for 4 stations (9.30%), KHA curve types for 2 stations (4.65%), QHK curve types for 1 station (2.33%) and HKH curve types for 1 station (2.33%) (**Table 2**). H and A curve types are the three layers earth models. QH and KH curve types are the four layers earth models. QHK, KHA and HKH curve types are the five layers earth models while KHKH curve types are the six layers earth model.

3.2. Borehole Depth

Figure 2 shows specific capacity evolution with borehole depth. Borehole productivity had a low and negative correlation ($r = -0.30$; $p < 0.05$) with borehole depths. A low trend of decreasing borehole productivity with increasing depth is noticeable. The influence of the depth boreholes productivity from this study is consistent with [7]. These authors found that in the Jundiaí River Catchment, a tendency of decreasing well productivity with increasing depth exists, but the correlation coefficient among the variables was considerably low. For [9], the

Table 1. Summary of borehole characteristics in the study area.

Parameter	Qs ($m^3 \cdot h^{-1} \cdot m^{-1}$)	Borehole depth (m)	Weathering depth (m)
N	43	43	43
Minimum	0.009	40.000	3.31
maximum	4.090	117.55	51.75
Mean	0.243	65.66	22.84
SD	0.418	17.28	9.74

Table 2. Summary of VES interpretation results.

VES n°	LOCALITES	Layer thickness (m)					Layer resistivity (Ω·m)						Curve type
		H1	H2	H3	H4	H5	$\rho 1$	$\rho 2$	$\rho 3$	$\rho 4$	$\rho 5$	$\rho 6$	
1	Amani kaha	4.31	8.06				343	13.5	21,049				H
2	N'doukouassikro	1.5	11.5	23.2			58.5	395	62.4	1316			KH
3	Takrakogodian	2.84	36.2				164	62	11,013				H
4	Allakro	2.21	31.5				319	127	2945				H
5	Pliyebouessou	3.22	2.74	11.6			226	809	28.4	17115			KH
6	Ahougnanou	1.68	2.1	24.1			78.4	13.2	41.2				H
7	Yobouekro	2.46	8.67	18.2			73.5	424	24.6	8310			KH
8	Kodoubo	3.5	21.8				432	2342	11,423				A
9	Kouassioussoukro	1.5	11	23.2			325	411	75	31103			KH
10	Adiebonou	0.6	10.2				58.4	35.1	1128				H
11	Gbangaoupri	0.34	0.45	1.32	2.66	16	34.5	181	26.2	2143	79.1	41481	KHKH
12	Konankro	0.28	1.44	6.33			1573	226	29	1215			QH
13	Koumanbo	2.13	4.61				50.4	13.8	1005				H
14	TakraMangouakro	1.84	4.82	25.1			651	215	45.6	9229			QH
15	Télébopri	0.6	1.56				124	12	28,900				H
16	YébouekroLangaman	0.46	0.70	1.29	3.1	15.6	446	826	99	2785	205	6700	KHKH
17	Gouarebo	3.5	21.8				432	2342	11,423				A
18	Djamalazué	9.26	8.31				140	138	920				H
19	Ahokokro	2.6	1.4				186	19.6	1014				H
20	Aloukrou-Yakro	0.87	6.65	17.8	7.04		389	177	124	47,639	2154		QHK
21	Konsou	2.01	22				1356	90.6	8721				H
22	Kouakoubakakro	0.56	0.64	7.61	41.3		1692	197	2472	282	13308		HKH
23	Safoue Dan	0.8	12	26.2			1478	1478	92	8338			QH
24	Tiendebo	0.6	2.6	2.8	5.9	38.64	244	309.5	108.2	240	6298		KHA
25	ZedeNdrebo	1.62	39.7				373	115	15,649				H
26	Allouboti	0.5	0.8	3.63	8.7	18.4	1180	7721	328	1504	388	9608	KHKH
27	Kanangokpanigokro	0.6	1.25	3.54			2110	9235	17.8	1635			KH
28	LongbonN'gattakro	0.26	4.26	5.7	15.4		261	818	39.7	2226			KH
29	NgbedjoAdjoblessou	0.35	1.05	2.32			86.1	999	66.6	3325			KH
30	Ahougnanou	2.89	5.2				163	58.6	60,089				H
31	Sokouamekro	3.33	8.37	19.4			218	1883	14.7	25,326			KH
32	Garekan	1.6	2.7				315	401	14,104				A
33	Kouameassekro	12.3	15.7				199	37.6	3933				H
34	Sabaribougou	1.5	34				98.1	85	2382				H
35	Takikro	12.4	23.2				46.8	20.7	17,610				H
36	Allokokro	1.6	2.1	10.1			508	13,343	284	2293			KH

Continued

37	Amoinkanoukro	0.7	1.38	3.14			31.1	1143	24.3	24,376			KH
38	Assengoukpi	4.72					42.3	1503					A
39	Badiokouamekro	1.42	1	1.81	5.37		285	804	99.5	627	19,142		KHA
40	Kanouan	1.35	4.5	6.56			1222	718	29	475			QH
41	Komabo	2.31	3.8				50.1	11.4	21,382				H
42	Logbakro	0.3	0.6	1	2.2	9	67	482	51.3	702	39.1	723	KHKH
43	Pindikro	1.2	11	23.2			325	411	75	31,103			KH

[a]Vertical electrical sounding.

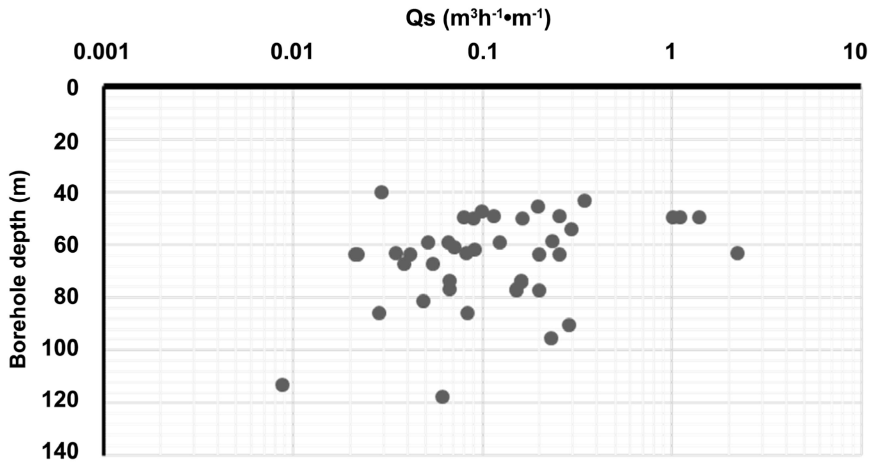

Figure 2. Graph showing the correlation between specific capacity and borehole depth.

reduction of the borehole productivity is due to the closure of discontinuities by lithostatic pressure to lower the density and connectivity of fractures with depth. However, in this study it is remarkable that aligned points, indicating boreholes of identical depth (50, 60 and 80 m for instance) often present distinctly specific capacity values. In agreement with [7], this leads to the thinking that borehole depth is defined according to contractual issues, user's necessity and construction profits, which sometimes prevail over possible productivity gains by increasing the depth. Thus, it was not possible to define a best-yielding depth interval. Although productivity tends to diminish with depth, a deeper borehole can be more productive if it reaches in subsurface a geological structure that is favorable to groundwater flow. Some authors [8] have defined the best depth interval or the maximum depth that a well must reach in order to obtain satisfactory productivity in crystalline rocks. They have shown that, because of the closure of discontinuities by lithostatic pressure in depth, the deeper the well, the lower the productivity.

3.3. Weathering Influence

Figure 3 shows the productivity of boreholes from the weathering depth. There was no correlation between the depth of weathering and the specific capacity (r

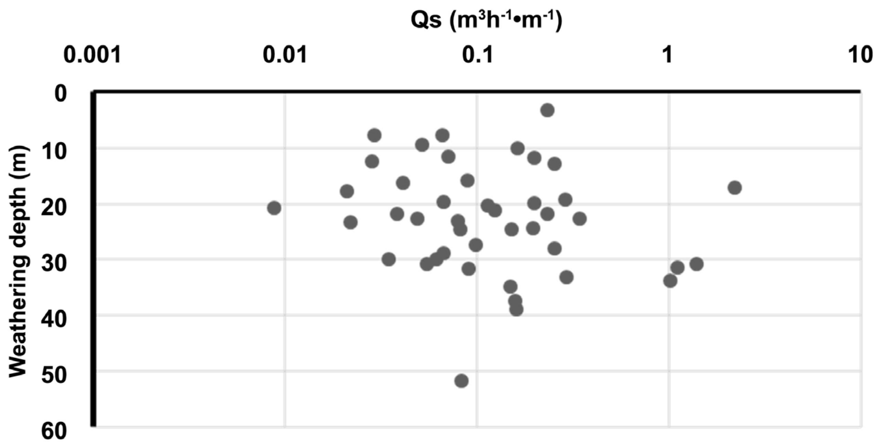

Figure 3. Graph showing the correlation between specific capacity and weathering depth.

= 0.23; $p < 0.05$). From this study, neither the nature of the regolith, nor the rock in which it was formed has been taken into account. As a result, in agreement with [20] and [11], a correlation between specific capacity and weathering depth can be verified or identified, as highlighted by the experimental data. Some authors have shown that the productivity of boreholes increases with weathering depth in the crystalline rocks [21]. In this study, we note that high specific capacity values (≥1 $m^3 \cdot h^{-1} \cdot m^{-1}$) were concentrated where the weathered layer was 15 - 35 m thick. Similar results were obtained by [20] and [22] in Côte d'Ivoire, and [11] in Cameroon. These authors observed generally medium and high yield between 5 and 45 m of regolith thickness.

3.4. Electrical Resistivity Anomalies

Figure 4 shows the distribution of Qs values from the resistivity sounding curve types. Qs values varied from 0.009 to 1.017 $m^3 \cdot h^{-1} \cdot m^{-1}$ in H curve types and from 20.7 to 24,376 in A curve types. The resistivities of H curve types ranged from 11.4 to 60,089 Ω·m (**Table 2**). The geoelectrical layers here are generally interpreted as a three subsurface layers that are topsoil-lateritic layer, weathered-fractured layer and the fresh basement or bedrock [13]. The topsoil-lateritic layer is composed of clayey sand and sand. Its thickness ranged between 0.60 and 9.26 m (**Table 2**). The weathered-fractured layer constitutes the main aquifer unit. It had a thickness ranging between 1.40 and 39.7 m. In the hard rock identified at the H curve types, the resistivity values were often low. It was the case at Yebouekro ($\rho 3$ = 24.6 Ω·m), Ahougnaou ($\rho 3$ = 41.2 Ω·m) and TakraMangouakro ($\rho 3$ = 45.6 Ω·m) (**Table 2**). These zones with low resistivity could be the fractured formations, vein zones or faults. The resistivity values ranged from 20.7 to 24,376 Ω·m in A curves. In agreement with to [23]., the A curve types give a best-fitted three-layered model with resistivity values of topsoil ranging from 1.6 to 4.72 m. The topsoil could be mostly composed of sand with low resistivity values. The second layer could be the weathered basement with resistivity and thickness values varying between 401 and 2342 Ω·m, and 2.7

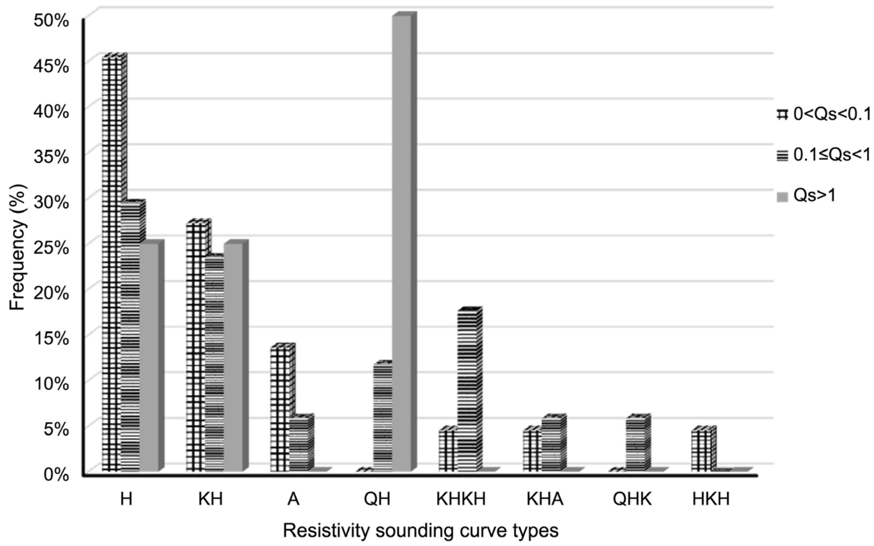

Figure 4. Frequency of specific capacity (Qs: $m^3 \cdot h^{-1} \cdot m^{-1}$) from boreholes located in different resistivity sounding curve types of the study area.

- 21.8 m respectively. The third layer could be presumably fresh basement whose resistivity values reached 14,104 Ω·m.

The KH curve types gave resistivity values ranging from 14.7 to 31,103 Ω·m. The geoelectrical layer could be interpreted as a four subsurface layered that is topsoil, alluvial deposits, granitic sand and hard rock.

QH curve types gave a four-layered model. The near-surface layer has variable resistivity values ranging from about 651 to 1573 Ω·m. The difference in the resistivity values is due to the variation in grain size [23]. The thickness of the top soil layer varies was very thin. It was estimated as less than 2 m. The third layer could be a water saturated sand horizon with a low resistivity ranging between 29 and 92 Ω·m. The thickness was less than 27 m. The fourth layer with high resistivity (475 - 9229 Ω·m) was associated to bedrock.

The five layers HKH, QHK and KHA curve types were observed at Kouakoubakakro (VES 22), Alloukrouyakro (VES 20), Tiendeho (VES 24) and Badiokouamekro (VES 39). The first has a resistivity range between 197 and 13,308 Ω·m. The resistivity values of the second and the third ranged from 124 to 47,639 Ω·m and from 99.5 to 19142 Ω·m. These layers could be interpreted as topsoil/sand/clay or clayey sand/sand or clayed sand/hard rock or altered bedrock.

Spatial differences of Qs values were clearly found. The highest values of Qs were recorded in KH, QH and H curve types, while their low levels were found in QHK and HKH curve types. The results of the distribution of Qs values following the resistivity sounding curve types are consistent to the Kruskal-Wallis test (**Table 3**). The test result indicated a significant difference (p = 0.001) between Qs values following the resistivity sounding curve types. The sounding anomalies of K, QH and H types may reflect the discontinuities and geological structures effectiveness such as vein zones, fractures, faults and geological contacts for the fractured aquifer permeability in the crystalline bedrock. However, in

Table 3. Comparison of specific capacity values between the resistivity sounding curve types of the study area using Kruskal-Wallis test.

	Vertical electrical sounding curve types							
	KH	QH	H	KHKH	A	KHA	QHK	HKH
KH		0.002	0.980	0.980	0.980	0.990	0.980	0.002
QH		0.000	0.239	0.000	0.000	0.000	0.011	0.000
H				0.341	0.980	0.980	0.990	0.130
KHKH					0.332	0.980	0.990	0.000
A						0.980	0.990	0.134
KHA							0.990	0.005
QHK								0.000

agreement with [7], the location close to these stuctures does not indicate that a borehole built there should be highly productive. It is necessary to locate the boreholes at a favorable position with the structural dipping with a depth that can reach the geological structure in the subsurface. Furthermore, the direction of the structure should be favorable to opening via tectonical stresses.

4. Conclusions

The main parameter used in this study to measure borehole productivity was the specific capacity which was grouped from the drilling depths, weathering depth and electrical resistivity anomalies. It was not possible to define a best-yielding depth interval as borehole depth was mainly defined by the driller's and user's needs. Although productivity decreased with depth, a deeper borehole could be more productive if it reached a geological structure in subsurface that was favorable to groundwater flow. The most productive boreholes were obtained from weathering thicknesses between 15 and 35 m despite the lack of correlation between the specific capacity and the alteration thicknesses. Boreholes located in KH, QH and H anomaly curve types were more productive than in the other curve types.

This study can be used as a work reference for future groundwater development programs. For prospective studies, additional data should be collected and be used to analyze the hydrogeological importance of each parameter on groundwater occurrence in Gbêkê region.

Acknowledgements

We would like to extend our sincere thanks to the research department "Société Ingénierie Géologique et Travaux" for providing us with the borehole dataset used for this study. Thanks are also given to the reviewers and editors whose comments on the manuscript are greatly appreciated.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Okafor, P. and Mamah, L. (2012) Integration of Geophysical Techniques for Groundwater Potential Investigation in Katsina-Ala, Benue State, Nigeria. *The Pacific Journal of Science and Technology*, **13**, 463-474.

[2] Singh, K.P., Malik, A., Mohan, D., Sinha, S. and Singh, V.K. (2005) Chemometric Data Analysis of Pollutants in Wastewater: A Case Study. *Analytica Chimica Acta*, **532**, 15-25. https://doi.org/10.1016/j.aca.2004.10.043

[3] Mastropietro, T.F., Drioli, E., Candamano, S. and Poerio, T. (2016) Crystallization and Assembling of FAU Nanozeolites on Porous Ceramic Supports for Zeolite Membrane Synthesis. *Microporous and Mesoporous Materials*, **228**, 141-146. https://doi.org/10.1016/j.micromeso.2016.03.037

[4] Frontera, P., Candamano, S., Macario, A., Crea, F., Scarpino, L.A. and Antonucci, P.L. (2013) Ferrieritezeolitic Thin-Layer on Cordierite Honeycomb Support by Clear Solutions. *Materials Letters*, **104**, 72-75. https://doi.org/10.1016/j.matlet.2013.03.138

[5] Candamano, S., Sgambitterra, E., Lamuta, C., Pagnotta, L., Chakraborty, S. and Crea, F. (2019) Graphene Nanoplatelets in Geopolymeric Systems: A New Dimension of Nanocomposites. *Materials Letters*, **236**, 550-553. https://doi.org/10.1016/j.matlet.2018.11.022

[6] Holland, M. and Witthüser, K.T. (2011) Evaluation of Geologic and Geomorphologic Influences on Borehole Productivity in Crystalline Bedrock Aquifers of Limpopo Province, South Africa. *Hydrogeology Journal*, **19**, 1065-1083. https://doi.org/10.1007/s10040-011-0730-5

[7] Neves, M.A. and Morales, N. (2007) Well Productivity Controlling Factors in Crystalline Terrains of Southeastern Brazil. *Hydrogeology Journal*, **15**, 471-482. https://doi.org/10.1007/s10040-006-0112-6

[8] Davis, S.N. and Turk, L.J. (1964) Optimum Depth of Wells in Crystalline Rocks. *Ground Water*, **22**, 6-11. https://doi.org/10.1111/j.1745-6584.1964.tb01750.x

[9] Banks, D. (1992) Optimal Orientation of Water-Supply Boreholes in Fractured Aquifers. *Ground Water*, **30**, 895-900. https://doi.org/10.1111/j.1745-6584.1992.tb01572.x

[10] Lachassagne, P., Wyns, R. and Berard, P. (2001) Exploitation of High Yields in Hard-Rock Aquifers: Downscaling Methodology Combining GIS and Multicriteria Analysis to Delineate Field Prospecting Zones. *Ground Water*, **39**, 568-581. https://doi.org/10.1111/j.1745-6584.2001.tb02345.x

[11] AnabaOnana, A.B., NdamNgoupayou, J.R. and MvondoOndoa, J. (2017) Analysis of Crystalline Bedrock Aquifer Productivity: Case of Central Region in Cameroon. *Groundwater for Sustainable Development*, **5**, 66-74. https://doi.org/10.1016/j.gsd.2017.05.003

[12] Naziya, J. and Singh, N.P. (2018) Identification of Fracture Zones for Groundwater Exploration Using Very Low Frequency Electromagnetic (VLF-EM) and Electrical Resistivity (ER) Methods in Hard Rock Area of Sangod Block, Kota District, Rajasthan, India. *Groundwater for Sustainable Development*, **7**, 195-203. https://doi.org/10.1016/j.gsd.2018.05.003

[13] Douagui, G.A., Kouassi, K.A., Kouamé, K.B. and Kouadio, A.K.S. (2018) Using Geophysical Anomalies for Locating Rural Groundwater Supplies in Crystalline Basement Environments of Gbêkê Region, Center of Côte d'Ivoire. *Environmental and Water Sciences, Public Health & Territorial Intelligence*, **2**, 69-82.

[14] Neves, M.A. (2005) Integrated Analysis Applied to Groundwater Exploration in the Jundiaí River Catchments, São Paulo State, Southeastern Brazil. PhD Thesis, Universidade Estadual Paulista, Rio Claro. (In Portuguese)

[15] Massing, O., Adoum, I., Abderamane, H. and Dingamnodji, N. (2017) Role of Remote Sensing and Geophysics to Determine Potential Sites for Boreholes in the Crystalline Basement of the Wadifira Region: Case Study of Iriba. *Asian Journal of Science and Technology*, **8**, 7073-7082.

[16] Bakkali, S. and Jaâfar Bouyalaoui, J. (2005) Contribution of the Geoelectrical Prospection Applied to the Data of the Hydraulic Resources of the Anergui People (Tafraoute, Moroccan Antiatlas). *e-Gnosis*, **3**, 1-12. http://www.e-gnosis.udg.mx/vol3/art5

[17] Koefoed, O. (1979) Geosounding Principles, 1: Resistivity Sounding Measurements. Elsevier, Amsterdam.

[18] Orellana, E. and Mooney, H.M. (1966) Master Tables and Curves for Vertical Electrical Sounding over Layered Structures. InercienciaCostanilla de Los Angeles, Los Angeles, 125 p.

[19] Mayer, J.M., Allen D.M., Gibson, H.D. and Mackie, D.C. (2014) Application of Statistical Approaches to Analyze Geological, Geotechnical and Hydrogeological Data at a Fractured-Rock Mine Site in Northern Canada. *Hydrogeology Journal*, **22**, 1707-1723. https://doi.org/10.1007/s10040-014-1140-2

[20] N'Go, Y.A., Goné, D.L., Savane, I. and Gobé, M.M. (2005) Potentialitésen eau souterraines des aquifèresd'Agboville (Sud-ouest de la côte d'Ivoire): Caractérisation hydroclimatique et physique. *Afrique Science*, **1**, 127-144. https://doi.org/10.4314/afsci.v1i1.35401

[21] Kouassi, A.M., Coulibaly, D., Koffi, Y.B. and Biémi, J. (2013) Application of Geophysical Methods to the Study of the Productivity of Water Drillings in Crystalline Aquifers: Case of the Toumodi Region (Central Côte d'Ivoire). *International Journal of Innovation and Applied Studies*, **2**, 324-334. http://www.issr-journals.org/ijias

[22] Youanta, M., Lasm, T., Jourda, J.P.R., Kouamé, K.F. and Razack, M. (2008) Cartographie des accidents géologiques par imageriesatellitaire landsat-7 ETM+ et analyse des réseaux defractures du socleprécambrien de la région de Bondoukou (nord-est de la côte d'Ivoire). *Revue Télédétection*, **8**, 119-135.

[23] JanvierDomra Kana, J.D., Djongyang, N., Raïdandi, D., Philippe NjandjockNouck, P.N., Nouayou, R. and Tabod, T.C. (2015) OumarouSanda Geophysical Investigation of Low Enthalpy Geothermal Potential and Ground Water, Reservoirs in the Sudano-Sahelian Region of Cameroon. *Journal of African Earth Sciences*, **110**, 81-91. https://doi.org/10.1016/j.jafrearsci.2015.06.007