

Mapping of Productive Aquifer Horizons in the Crystalline Bedrock Environment of the Bounkani Region (Northeastern Ivory Coast)

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How to cite this paper: Bouadou, R.A.M., Kouassi, K.A., Coulibaly, A., Douagui, G.A. and Gnagne, T. (2025) Mapping of Productive Aquifer Horizons in the Crystalline Bedrock Environment of the Bounkani Region (Northeastern Ivory Coast). *Open Journal of Geology*, 15, 645-658.

<https://doi.org/10.4236/ojg.2025.1510032>

Received: September 15, 2025

Accepted: October 14, 2025

Published: October 17, 2025

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Abstract

Existing drilling data was used to map the thickness of the fractured horizon beneath the alteration profile in order to optimize drilling locations in the Bounkani region. The useful fractured horizon, rich in fractures, was determined in four (4) areas, the most productive of which is estimated to be at a depth of 35 m below the base of the altered zone, with an estimated flow rate and linear flow rate of approximately 8.15 m³/h and 0.23 m³/h/m, respectively. Validation of the conceptual model allowed the method used to locate the thickness of the bedrock to be drilled to be judged relevant and satisfactory for improving drilling productivity.

Keywords

Useful Fractured Horizon, Bedrock Aquifer, Productivity, Bounkani Region, Ivory Coast

1. Introduction

Groundwater is one of the most exploited water resources by rural and urban populations in the Bounkani region. In bedrock areas, this groundwater is exploited through drilling and is contained in cracks and fractures in sound rock. Fracture aquifers developed as a result of tectonic events and various weathering phenomena affecting the surrounding rocks [1] and [2]. These constraints have led to an improvement in the hydrodynamic properties of the aquifers, hence the presence of water within these rocks at shallow depths (approximately 100 m) and the pos-

sibility of other types of resources existing at greater depths [3]. However, characterizing the geometry of these aquifers remains difficult and very often leads to unsuccessful mechanical drilling. In order to reduce the failure rate, drilling data from depths of less than 100 m have been used to identify highly fractured horizons located beneath the weathered rock and favorable for future catchment structures. To this end, the overall objective of this study is to map the depth of the bedrock to be drilled in order to optimize productivity and reduce the costs of future drilling in the Bounkani region.

2. Study Area

The Bounkani region is located in the northeastern part of Côte d'Ivoire between longitudes 2°34'51.6" and 4°20'02.4" West and latitudes 8°10'55.2" and 9°59'34.8" North. It covers an area of 22,091 km², or 6.9% of the country's total area, with a population of 427,037 [4]. However, half of its area is uninhabited and occupied by the Comoé National Park, which covers an area of 11,090 km².

In Côte d'Ivoire, it is bordered to the west by the Tchologo region, to the southwest by the Hambol region, and to the south by the Gontougo region, with which it forms the Zanzan district. However, outside Côte d'Ivoire, it borders Ghana to the east and Burkina Faso to the north (Figure 1).

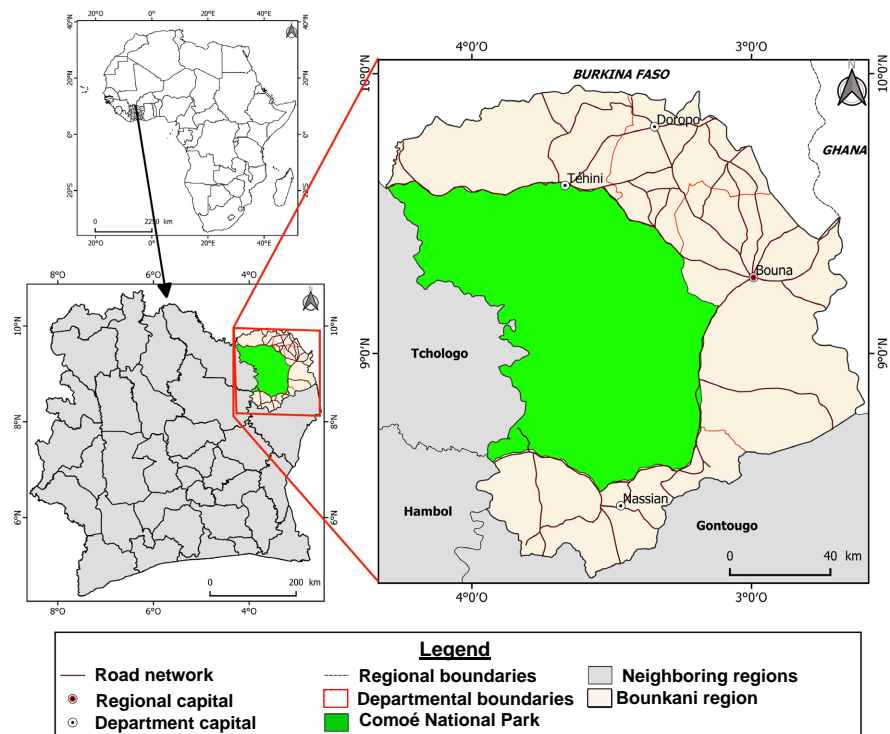


Figure 1. Geographic location of the study area.

Located in the Paleoproterozoic domain, studies [5] show that the geology is characterized by (Figure 2):

- A lower Proterozoic complex represented by orogenic plutonic rocks (heteroge-

neous biotite granitoids and generally embrachitic migmatites), concordant granitoids (akeritic granites) and discordant granitoids (calc-alkaline granites and undifferentiated granitoids, granodiorites, diorites, monzonites, and syenites).

- Birimian series composed of volcano-sedimentary formations (andesites, spilites, basalts, amphibolites, rhyolites, dacites, keratophyrs, schists, and undifferentiated rocks) and fill formations (consisting of arkosic cement conglomerates, schists, and grauwackes).

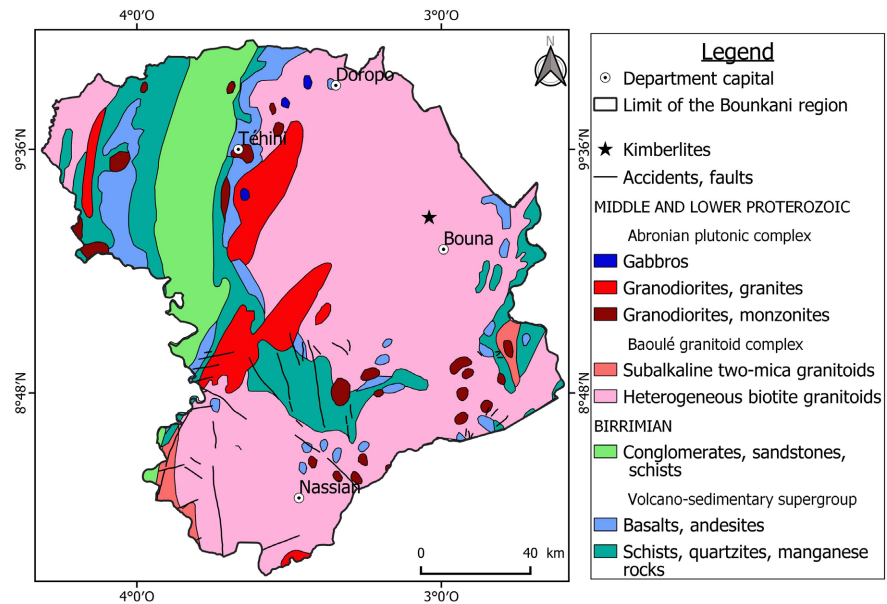


Figure 2. Geological map of the Bounkani region [5].

The hydrogeological context has shown that, starting from the ground surface to the sound rock, the lithologies of all the boreholes can be described as follows [6]:

- a layer of topsoil approximately 0.4 m thick;
- followed by approximately 30 m of clay consisting of sandy clay, lateritic clay, yellowish clay, reddish clay, and whitish clay;
- then comes clayey sand, varying in thickness from 5 to 15 m;
- granitic rocks, where fractures may or may not be present. This is the groundwater catchment area, where one (01) to five (05) water-fed fractures have been intersected by mechanical drilling (boreholes).

3. Methodology

Mapping the horizons of the subsoil rich in cracks and fractures has made it possible to locate the areas with the highest productivity for water drilling. These horizons were deduced following two linear regressions based on the following parameters: the depth of the well below the weathered zone, the flow rate of the useful fractured medium (in m^3/h), and the linear flow rate of the useful fractured

medium (in $\text{m}^3/\text{h}/\text{m}$). It should be noted that the boreholes used for the study are less than or equal to 100 m deep. Beyond this drilling limit (drilling depth greater than 100 m), there would be unnecessary over-excavation [7] [8]. This is because in Côte d'Ivoire, open and productive fractures are between 50 m and 70 m deep [9]-[11].

3.1. Thickness of the Fractured Horizon

The thickness of the fractured horizon (fractured-weathered horizon) is the intermediate layer between the sound substrate and the weathered material (Figure 3). It is characterized by the presence of fractures in sound rock, the density of which decreases with depth [12].

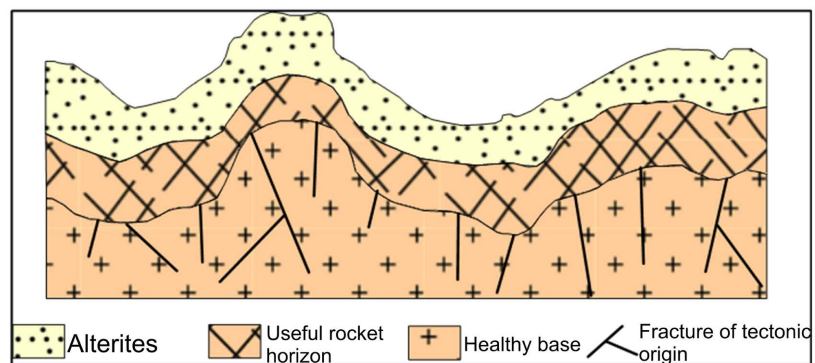


Figure 3. Illustration of the thickness of the fractured horizon.

The fractured horizon located beneath the base of the weathered zone is where most of the water inflows observed in a borehole occur. The fractured horizon can be determined by plotting the linear flow rate on an arithmetic graph as a function of the depth of the borehole beneath the weathered zone. This is an effective graphical method for identifying the thickness of the highly fractured bedrock horizon [3] and [13]. The linear flow rate represents the flow rate per meter of drilling depth below the base of the weathered rock.

3.2. Determination of Linear Flow Rate and Its Cumulative Percentage

Following the same principle of mapping the thickness of the fractured horizon, the method consisted of calculating the cumulative percentage of linear flow using the following formulas [14]:

- Expression of linear flow ($q_i(l_i)$)

$$q_i(l_i) = Q_i/l_i \quad i = 1, n \quad (1)$$

where Q_i is the instantaneous flow rate obtained at the end of drilling (m^3/h) at borehole i ; l_i is the depth of borehole i below the base of the weathered zone (m); $q_i(l_i)$ is the linear flow rate ($\text{m}^3/\text{h}/\text{m}$).

- Expression of the cumulative percentage of linear flow rate

$$P_q(L) = \sum_{l=Min}^L q_i(l) / \sum_{l=Min}^{l=Max} q_i(l) \quad (2)$$

where:

L : maximum depth (m) given for drilling below the base of the weathered rock;

$Pq(L)$: cumulative percentage of linear flow rate (%) obtained with the sample of boreholes whose depth is less than L .

It should also be noted that the cumulative percentage of the number of boreholes is also determined. This will enable us to identify the shallowest boreholes whose total linear flow rate will intersect the base of the weathered rock.

3.3. Determination of the Flow Rate and the Useful Linear Flow Rate of the Fractured Horizon

After the previous step, a graphical representation of the cumulative percentages (linear flow rate and number of boreholes) as a function of the depth of the borehole below the base of the weathered rock was plotted on an arithmetic graph (Figure 4). Analysis of this graph made it possible to deduce the linear flow rates and flow rates corresponding to the thicknesses of the bedrock read on the same graph [13].

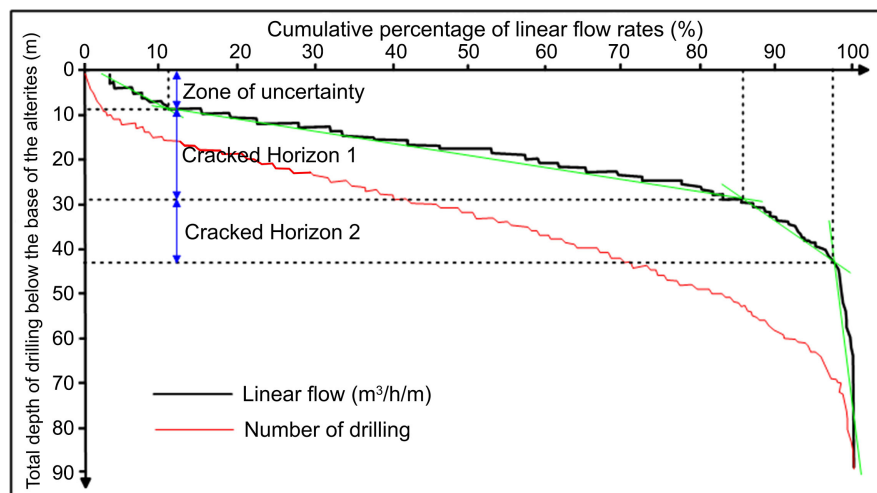


Figure 4. Cumulative percentages of linear flow rates and number of boreholes as a function of borehole depth below the base of the weathered zone.

The thicknesses of the base were determined by identifying different slopes observed on the graph. The intersection of the segments of the different slopes is read on the axis of total drilling depths below the base of the weathered rock.

The linear flow rate (flow rate of the useful fractured medium relative to the thickness of the useful fractured horizon) and the flow rate of the useful fractured medium are calculated as follows:

- Average linear flow rate or linear flow rate of the useful fractured horizon

$$q_M(L) = \sum_{l=Min}^L q_i(l) / j(L) \quad (3)$$

where:

$q_M(L)$: average linear flow rate ($m^3/h/m$) calculated for the depth range L (m) located below the elevation using the slope method; $j(L)$: corresponding num-

ber of boreholes.

- Flow rate of the useful fractured horizon

$$Q_M(L) = q_M(L) \times L \quad (4)$$

where:

$Q_M(L)$: flow rate of the useful fractured horizon, the product of the previous parameter and the thickness defined by the slope method.

3.4. Conceptual Model and Validation of Different Useful Aquifer Horizons

After estimating the various useful depths and their corresponding flow rates, a conceptual model was developed. This model highlighted the layout of the various thicknesses of the useful horizons determined beneath the base of the weathered rock using the slope method.

Validation consisted of verifying the reliability of the method used to map the thicknesses of useful fractured horizons and their productivity. Logs and technical drilling equipment were used to validate the model. Surfer 11 software was used to implement the conceptual model and validate it.

4. Results

4.1. Relationship between Linear Flow Rate and Drilling Depth below the Base of the Weathered Zone

Figure 5 shows the vertical distribution of the linear flow rate for 414 boreholes drilled in the study area. The linear flow rates range from 3.4×10^{-3} to $4.33 \text{ m}^3/\text{h}/\text{m}$, with an average of $0.19 \text{ m}^3/\text{h}/\text{m}$. The depths of the boreholes below the base of the weathered rock range from 2 to 90.5 m, with an average of 26.83 m. The linear flow rate decreases gradually with the depth of the boreholes below the base of the weathered rock. In addition, we also note that the best linear flow rates are observed around the first 50 meters below the base of the weathered rock.

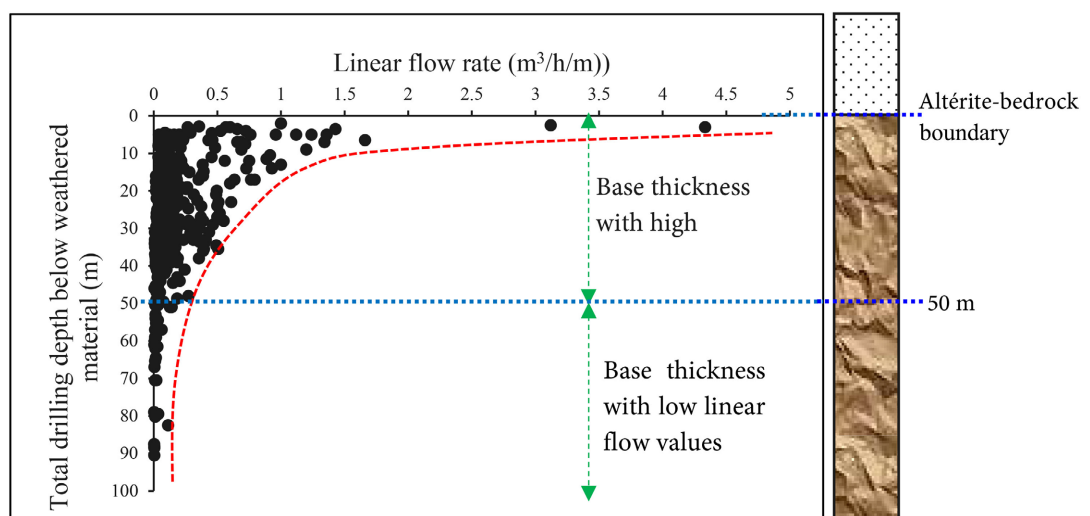


Figure 5. Distribution of linear flow rate as a function of drilling depth below the base of the weathered rock.

4.2. Identify the Headings

The parameters sought were determined using the slope method. This method made it possible to identify different horizon thicknesses, including their corresponding flow rates and linear flow rates. These classes of fissured horizon thickness were defined by the presence of slopes observed on the curve of cumulative percentages of linear flow rates as a function of drilling depth below the base of the weathered rock (Figure 6). It revealed the existence of four (4) distinct zones:

- Zone 1 is between 0 and 7 m. It corresponds to the part of uncertainty in the interpretation of the altitude of the base of the weathered rock during drilling. It has a linear flow rate of $0.61 \text{ m}^3/\text{h}/\text{m}$ and a flow rate of $4.27 \text{ m}^3/\text{h}$.
- Zone 2 varies from 7 to 35 m. It has a thickness of 28 m. A linear flow rate of approximately $0.17 \text{ m}^3/\text{h}/\text{m}$ and a flow rate of $4.68 \text{ m}^3/\text{h}$ were recorded.
- Zone 3 is between 35 and 51 m. It has a thickness of 16 m, a linear flow rate of $0.09 \text{ m}^3/\text{h}/\text{m}$ and a flow rate of $1.37 \text{ m}^3/\text{h}$.
- Zone 4 corresponds to a thickness greater than 51 m below the base of the weathered rock. The limited drilling data available does not allow us to determine whether the linear flow rate is constant or decreasing.

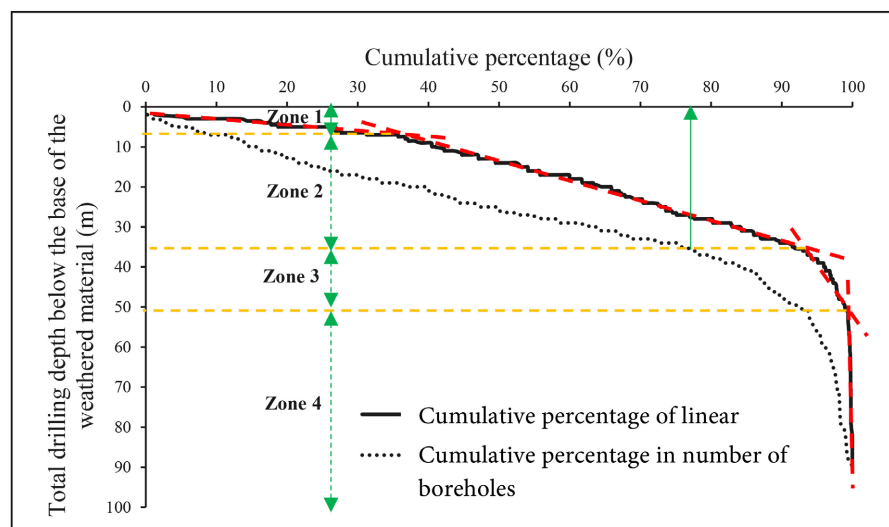


Figure 6. Cumulative percentages of linear flow rates and number of boreholes as a function of borehole depth below the base of the weathered zone.

The results of the slope method indicate that the desired thickness of the fractured horizon is the sum of the first two zones. Consequently, the thickness of the fractured horizon is 35 m below the weathered rock, with a linear flow rate of $0.23 \text{ m}^3/\text{h}/\text{m}$ and a flow rate of $8.15 \text{ m}^3/\text{h}$. Furthermore, this thickness corresponds to 76% of shallower boreholes that pass through the weathered rock.

4.3. Conceptual Model of Fractured Horizon Thicknesses

In order to characterize useful and productive fissured horizons, the synthesis of the results of the slope method made it possible to obtain a three-dimensional

(3D) conceptual hydrogeological model. Under the weathered rock, the conceptual models identify four (4) fractured horizons based on fracture density. Starting from the base of the weathered rock at the bedrock, we have:

- Area of uncertainty in the interpretation of the weathered rock-granite interface

This is the point of contact between the alteration zones and the granite massif. In our case, it represents an area of uncertainty in determining the depth of the alteration zone wall or the roof of the healthy bedrock. **Figure 7(a)** revealed that the alteration zone-granite interface is observable in the south at depths of 250 m above sea level in Téhini, 290 m above sea level in Trikonko, 400 m above sea level in Garankodouo, and in the east at around 330 m above sea level between the towns of Yolankora and Doropo. The depth of the alteration-granite interface can also be identified at an altitude of around 340 m north of Tchamino and at an altitude of 220 m west of Téhini (**Figure 7(b)**). The gradient method has shown that this zone is productive, with an estimated flow rate of 4.27 m³/h for a thickness of 7 m.

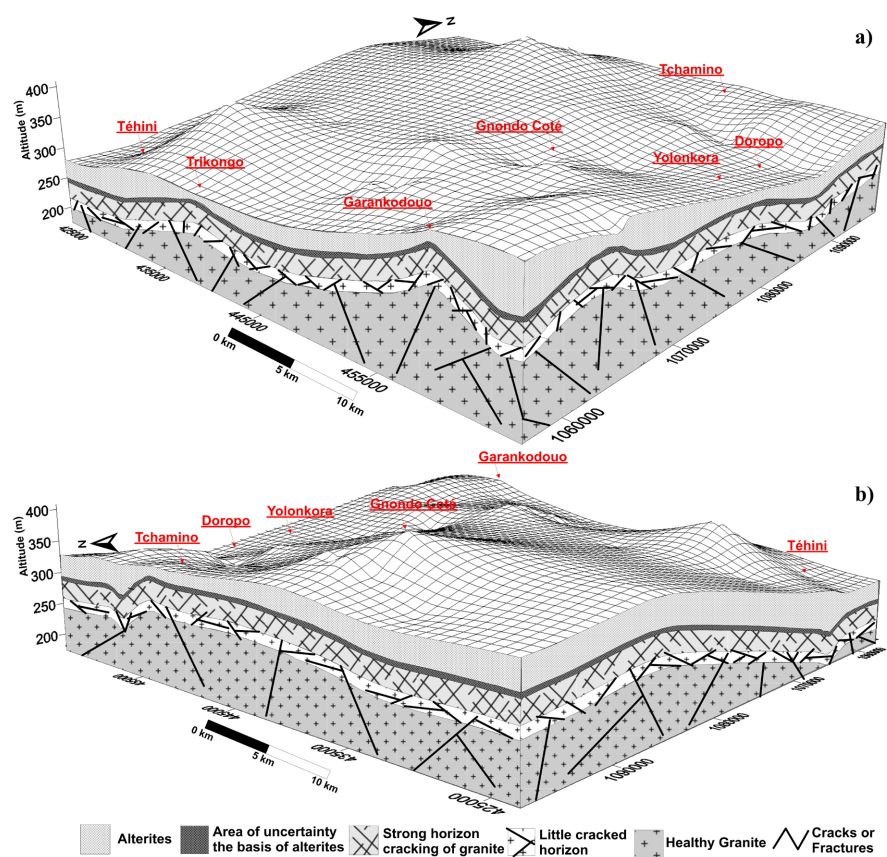


Figure 7. Conceptual model of productive fractured horizons in the Doropo-Téhini section.

- Horizon of intense fracturing

This horizon is located below the zone of uncertainty. The conceptual model

showed that its roof is located to the south at altitudes of 240 m in Téhini, 280 m in Trikongo, 390 m in Garankodouo, and to the east, it is around 310 m between the towns of Yolonkora and Doropo (**Figure 7(a)**). The roof of this horizon is also located at 200 m west of Téhini and 330 m north of Tchamino (**Figure 7(b)**).

– Slightly fissured horizon

This is the lower part of the highly fissured horizon. It is therefore the extension of the highly fissured horizons at depth. The 3D model showed that in the east, the roof of this horizon is at a depth of about 270 m between the localities of Yolonkora and Doropo, and in the south, it is at an altitude of 220 m in Téhini, 250 m in Trikongo, and 350 m in Garankodouo (**Figure 7(a)**). To the north, the roof is at an altitude of 275 m in Tchamino and 200 m west of Téhini (**Figure 7(b)**).

– Sound granite substrate

It is characterized by a very slightly fractured granite substrate. These fractures are the result of tectonic phenomena that have affected the sound rock. The lack of drilling data at this depth prevents us from determining whether the flow rate is constant or decreasing. In other words, we cannot reliably estimate the productivity of this horizon.

After analyzing the 3D conceptual model, drilling productivity is calculated as the cumulative estimated flow rates of the various horizons identified using the slope method. To verify the performance of the catchment structures, validation is performed by comparing the drilling logs with the conceptual model.

4.4. Validation of the Conceptual Model

The total depths of the boreholes range from 262.25 m above sea level at Yolonkora to 321.9 m above sea level at Garankodouo (**Figure 8**). In the bedrock region, most of the water inflows identified in the boreholes are observed beneath the weathered layers. Given the depths of the roof and wall of the fractured horizon, the Garankodouo, Yolonkora (**Figure 8(a)**) and Tchamino (**Figure 8(b)**) boreholes intersect these down to the sound bedrock. The Trikongo borehole, however, only intersects the first two horizons without reaching the slightly fractured horizon (**Figure 8(a)**). All water inflows from the boreholes are observed in the strongly and slightly fractured horizons of the model. This confirms the presence of fractured horizons at these depths in our study area.

However, the flow rates of some boreholes do not match those estimated using the slope method. These are the locations of Garankodouo, Yolonkora, and Tchamino. They obtained flow rates of 1.5 m³/h, 2.05 m³/h, and 1 m³/h, respectively. These low flow rates could be due to a lack of interconnections between fractures or the presence of dry fractures. These flow rates are well below 8.15 m³/h, which is the threshold flow rate for a borehole located in the useful fractured horizon. In contrast, the Trikongo and Gnondo Coté boreholes recorded flow rates of 12 m³/h and 9.9 m³/h, respectively. These are in line with the flow rates estimated using the slope method because the boreholes in these locations obtained 5 and 4 water inflows, respectively (**Figure 8(b)**). Unlike the latter boreholes, the Yolonkora lo-

cality benefited from a low-flow catchment structure ($2.05 \text{ m}^3/\text{h}$) with five water inflows. This low flow rate can be explained by the fact that the borehole probably intersected one or more wet fractures, suggesting that water is being collected from them.

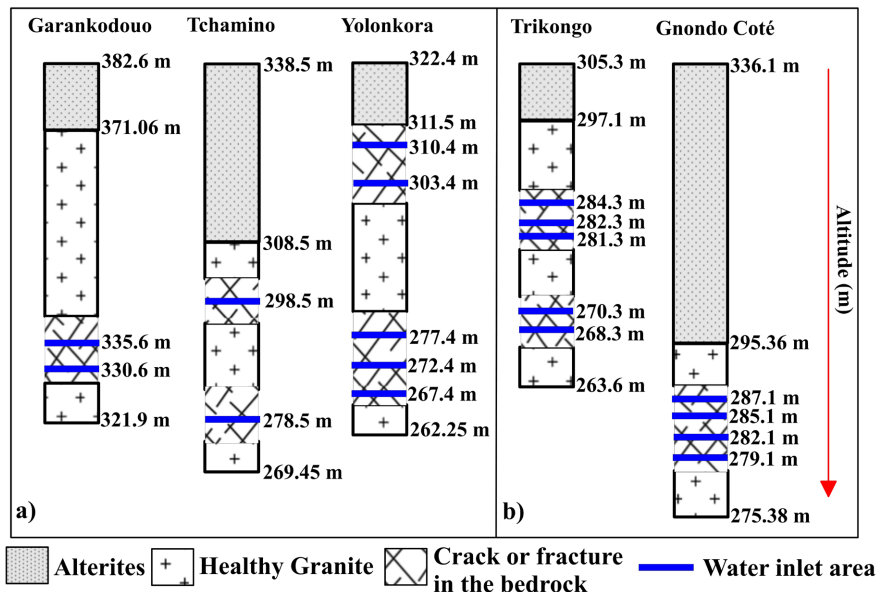


Figure 8. Log of boreholes with flow rates: (a) less than $8.15 \text{ m}^3/\text{h}$ and (b) greater than $8.15 \text{ m}^3/\text{h}$.

5. Discussion

One of the factors contributing to the success of water drilling productivity is knowledge of the thickness of the fractured horizon beneath the weathered rock. Correlating the linear flow rates and total depths of 414 boreholes located beneath the weathered rock has facilitated the mapping of the geometry of the fractured and fissured aquifers in the study area. Analysis of this relationship revealed a decrease in linear flow rates with increasing depth. This decrease in linear flow rates with depth was observed in the work of [12] [15] and [16], who conducted their research in the Jurassic granites of South Korea, the bedrock of Burkina Faso, and the Brittany region, respectively. The decrease in linear flow rates with depth can be explained by the fact that the number of cracks in the rocks decreases as depth increases. The slope method revealed four (4) fissured horizons whose productivity decreases with depth. Thus, the best flow rate and linear flow rate were obtained around the first 35 meters below the weathered layers. This corroborates the work of [12] and [17], which showed that the fractured horizon below the weathered layers represents the environment with the best permeability of the subsoil, hence the best instantaneous flow rates. Furthermore, in Côte d'Ivoire, previous work by [18] and [19], carried out respectively in the regions of Bongouanou (eastern Côte d'Ivoire) and Niellé (northern Côte d'Ivoire), showed that the underlying fractured horizons are only permeable for the first 30 meters. This thickness of the fissured horizon is very similar to that in our study area. With the

useful fractured horizon being 35 m below the weathered layers, 76% of shallower boreholes cross the base of the weathered layers with a flow rate of 8.15 m³/h. Consequently, to optimize boreholes, it is essential to locate them within 35 m below the base of the weathered layers. According to [20]-[22], bedrock aquifers owe their permeability to the stratified fissured horizon, where the density of fissures decreases with depth. According to [13], the useful fractured horizon corresponds to a thick layer of subsoil rich in fractures, resulting from the weathering of sound rock, which provides the best productivity in terms of instantaneous flow rate. In addition, these fractures generally constitute the preferred pathways for groundwater flow in sound rock [23] and [24]. The slope method also made it possible to establish a conceptual model that identified four horizons located beneath the weathered zones, whose useful flow rate decreases with depth. Consequently, all boreholes crossing the four zones must have a productivity that is a function of the cumulative flow rates of the water inflows from these zones, if and only if the boreholes intersect hydraulically active fractures. In validating the conceptual model, it was found that the flows of the boreholes in Garankodouo, Tchamino, and Yolonkora, which reached the sound bedrock, did not match the flow values estimated using the slope method. This is due to the fact that these boreholes intersected fissures, some of which were dry (barren fissures) or were not interconnected. It should also be added that these boreholes are located in areas of weakly fissured bedrock that is heavily clogged by the overlying altered formations. The same observations were made by [25] in the departments of Sikensi and Tiassalé (southern Côte d'Ivoire) and by [26] in the Gbêkê region (central Côte d'Ivoire). These authors assert that even if the fracture is identified using geophysical methods, it may correspond to a sterile fracture or a mineralized fracture with a very low water content. This assertion is confirmed by the Yolonkora borehole, which had five (5) water inflows resulting in a low flow rate of 2.05 m³/h. However, the Trikongou and Gnondo Coté drillings recorded flow rates of 12 m³/h and 9.9 m³/h, respectively. These are in line with the cumulative values of the flow rates estimated using the slope method. These flow rates even exceeded those expected. This high productivity means that the boreholes in Trikongou and Gnondo Coté were drilled in bedrock areas with a dense network of water-saturated fractures. In addition, boreholes with high flow rates have numerous water inflows. This is consistent with the results of work carried out by [3] in the bedrock area of the Loire-Atlantique department. The author explains that the overall flow rate of a borehole does not depend on whether it intersects a fracture with exceptional properties, but is in fact a function of the number of fractures intersected, given that all fractures have a similar order of magnitude permeability and are likely to have a similar origin.

6. Conclusions

Our study reveals regional knowledge of the geometry and productivity of useful fissured horizons representing bedrock aquifers. This study highlights four (04) aquifer horizons located beneath the base of the weathered rock, meaning that

their flow rates decrease with depth. Of the different zones listed, the first 35 meters below the base of the weathered rock are the most productive and correspond to 76% of shallower boreholes that pass through the base of the weathered rock.

The conceptual model derived from the results of the slope method made it possible to highlight the roof and wall of each fractured horizon. This model was validated with drilling log data, which confirmed the presence of different fractured horizons based on the position of their water inflows. This study is of major interest for groundwater resource management in bedrock environments. Indeed, mapping the thicknesses of fractured horizons using existing drilling data can be combined with aquifer reconnaissance methods (geophysical methods, remote sensing, geomorphology and mechanical survey or drilling) to optimize the location of water wells in bedrock environments.

Given the complexity of the subsoil in the Bounkani region, mapping the useful fractured horizon has made it possible to define a threshold (35 m) for the depth of the bedrock that must be applied when locating future boreholes in order to achieve long-term productivity (flow rate greater than or equal to 8.15 m³/h) for groundwater collection structures.

Acknowledgements

This research was supported by the Hydrogeology and geophysics Research Group of the Geosciences and Environment Laboratory at Nangui Abrogoua University in Abidjan, Ivory Coast. The constructive and valuable comments of the anonymous readers and the Editor-in-Chief of the Journal are greatly appreciated.

Conflicts of Interest

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

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