

Analysis of the Productivity of Fractured Hard-Rock Aquifers in the Central African Fold Belt Using Borehole Pumping Test: Case of Mayo Bocki Watershed, North Cameroon

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Abstract

In the Mayo Bocki watershed, the population's various water needs are met primarily by groundwater drawn from fractured bedrock aquifers. The aim of this study is to highlight the factors likely to influence hydraulic productivity and to estimate the hydraulic parameters of these fissured aquifers. To this end, the borehole data sheets and the reports on their pumping tests were consulted. The hydraulic parameters were estimated using the method developed by the Inter-African Committee for Hydraulic Studies. The investigation revealed that the flow rates in the boreholes were predominantly low. The productive depths of the bedrock are within the first 50 meters below the surface. Beyond this depth, water inflows become rare. A significant thickness of alteration overlying schist does not improve productivity, whereas in granites and gneisses, it appears to have a positive relationship with drilling rate. Schist is the most productive hydrogeological unit. The average values for the transmissivity and permeability coefficient are $2.7 \times 10^{-4} \text{ m}^2/\text{s}$ and $9.32 \times 10^{-6} \text{ m/s}$ respectively. The geological structure revealed by the litho-stratigraphic logs is similar to that proposed by the classic conceptual model in the basement area. These results will help guide any hydrogeological investigations in the study area.

Keywords

Productivity, Fractured Basement Aquifers, Borehole Pumping Test, Mayo Bocki Watershed

1. Introduction

Global freshwater use has increased six-fold in recent decades and has continued to grow at a rate of 1% per year since the 1980s [1] [2]. This situation is largely the result of the combined effects of demographic growth, industrial development and the intensification of agricultural activities [3] [4]. In fact, the freshwater available to mankind includes surface water (1%) and groundwater (30%). However, because of the great vulnerability of surface water to climate variability and pollution, groundwater has become an alternative resource of first choice for supplying drinking water to people around the world, particularly in sub-Saharan Africa [5] [6].

Groundwater is contained in aquifers, of which basement aquifers are prominent both globally (20%) and in Africa (40%) [7]. Numerous scientific studies conducted throughout the world, particularly in sub-Saharan Africa, agree that groundwater exploitation in basement zones generally poses a problem in terms of aquifer sustainability [8]-[10]. Crystalline and crystallophyll basement aquifers have localized or isolated reserves associated with fracturing corridors inherited from the region's tectonic history [11] [12]. It is also accepted that such environments potentially contain less water for the same volume than environments with significant primary porosity, such as sedimentary environments [9]. The structure of basement aquifers shows significant vertical heterogeneity as well as significant horizontal heterogeneity due to lithological variations [13]. This double heterogeneity confers an anisotropic character to these aquifers which are composite with several compartments having distinct hydraulic properties. The recent hydrogeological model for these aquifers is characterized by a superposition of three layers. These are: the upper horizon, which has a capacitive function and is made up of alterites subdivided into two sub-units, alloterites and isalerites; the fissured horizon, which mainly acts as a conductor through the fracture networks; and the lower layer, which is made up of fresh impermeable rock [11] [14].

Exploiting basement aquifers for water supply is complex because hydraulic productivity is variable spatially and even within the same geological formation [15]. This suggests that there are a number of factors that determine the hydraulic performance of fractured aquifer reservoirs. Indeed, many authors have shown that analysis of fracturing systems is a priority when drilling in fractured basement environments, as they confer the aquifer function on the geological reservoir [16] [17] [18]. While some researchers have highlighted the strong positive influence of alteration thickness on fractured reservoir productivity [15] [19], others have demonstrated through their investigations that a significant thickness of these materials seems to have an unfavourable effect on the yield of the underlying reservoir [20] [21]. In addition, the lithological nature, total depth of boreholes and water inlets, and topography are all factors that are considered when assessing productivity potential [10] [21]. This work sometimes shows major disparities depending on geographical areas and geological and hydrogeological environments. It is therefore important to take account of local realities and particularities when

looking for the best sites to locate productive boreholes.

In addition, knowledge of the hydrodynamic parameters of aquifers is essential for the rational and sustainable management of groundwater resources. They are essential for understanding the aquifer and its exploitable volumes of water. These hydraulic parameters enable us to understand how water is moved and stored underground [22]. To this end, various approaches to estimating hydrodynamic parameters, both in the field and in the laboratory, are widely presented in the scientific literature. Laboratory estimation methods, such as permeability tests and tests to determine specific yield by gravity drainage, are easy to carry out and take less time [23]. However, the values obtained from laboratory tests may not be representative of reality. On the other hand, field estimation methods have proved to be effective although expensive. These include pumping tests [24], well injection tests, geophysical measurements such as geoelectrics [25] [26], electrical sounding [27] [28], Proton Magnetic Resonance [11], Ground Penetrating Radar [29] [30], and numerical modelling [31] [32]. Of all these *in situ* methods, pumping tests are the most direct and reliable for assessing the hydraulic properties of aquifers [21] [23]. They generally give reliable results that are representative of a large area, as opposed to point observations.

In Cameroon, basement areas cover almost 86% of the total land area [20]. They contain around 27.51% of the country's total groundwater volume (55.98 km³) and supply water to a large proportion of the population [33]. This water supply is based in particular on the exploitation of fractured aquifers through drilling in the Mayo Bocki catchment, which is the subject of this study. The search for drilling sites in this hydrological unit has generally been based on the analysis of deep discontinuities that represent hydrogeological targets. However, despite the use of geophysics and sometimes remote sensing to locate fractures, around 30% of the boreholes drilled have failed due to low productivity [34]. This implies that fractures alone do not guarantee good borehole productivity. In addition to fractures, other environmental factors likely to influence the hydraulic performance of wells need to be examined. In addition, the hydrodynamic parameters, which are indices defining the aquifer's ability to recover and deliver water, are poorly understood in this study area. It is within this framework that the present work has been initiated in order to highlight the influence of geological formations and physical parameters of boreholes on the hydraulic performance of catchment works located in the fractured basement: 1) To evaluate the hydraulic parameters of these aquifers; 2) To characterize the structure of these aquifers on the basis of lithological sections of boreholes.

2. Materials and Methods

2.1. Description of Study Area

2.1.1. Location, Geomorphology and Climate

Located in the North Cameroon region, the Mayo Bocki watershed (MBWS) is divided between the Poli district in the Faro department and the Ngong and Lagdo

districts in the Bénoué department. It covers an area of 1680 km² and lies between N 8°20' - 8°55' and E 13°10' - 13°40' (**Figure 1**). The geomorphology of the study area features high plateaus and mountainous landscapes in its southern part, with altitudes varying between 515 and 1946 m. In places, these mountains form U-shaped valleys between them. On the other hand, a vast plain essentially occupies the central, south-eastern and northern parts of the basin, with altitudes of between 200 and 400 m [6]. The climate is tropical, of the Sudano-Sahelian type with a tendency to wetness, characterized by an alternating dry season (October to April) and rainy season (May to September). The inter-annual average rainfall is 1250.3 mm. The wettest months are August (330.5 mm) and September (297.5 mm), which together account for more than 60% of annual rainfall. However, December and January receive no rain at all. The inter-annual average monthly temperature is around 25.74°C. The highest values are recorded in April (33.1°C) and October (29°C), while August (24.6°C) and January (22.7°C) are the months with the lowest values. The study area is drained by a series of temporary streams whose flows converge on the Mayo Bocki, which is the main collector. The Mayo Bocki mainly originates at the foot of the mountain ranges to the south and south-west of the basin and flows in a SW-NE direction. Resulting from the junction of several tributaries, the Mayo Bocki receives the Kilbou, Dizé and Farda rivers on its left bank and the Balché and Kokra rivers on its right bank.

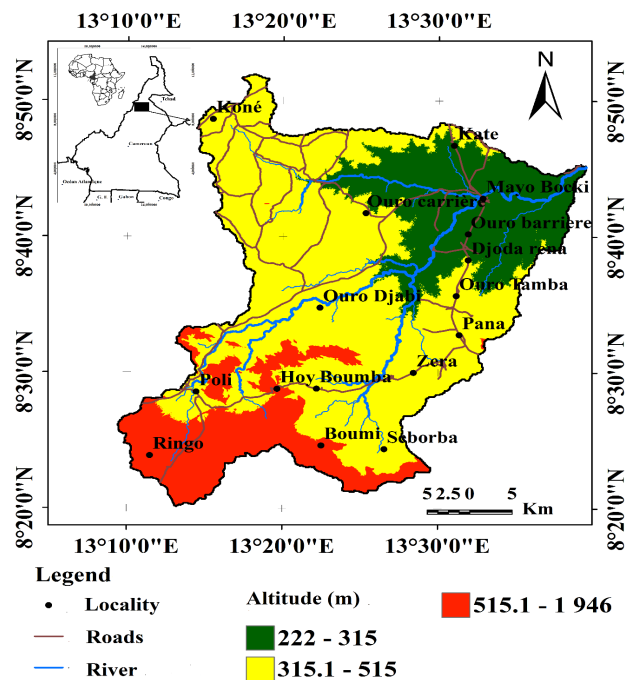


Figure 1. Location map of the study area.

2.1.2. Geology and Hydrogeology

The study area is part of the North Cameroon domain of the Pan-African Central African Chain. This domain is a vast geological unit elongated in a NNE-SSW direction, located between the Eastern Nigeria domain to the west, the Mayo-

Kebbi domain to the east of Chad and the Adamaoua-Yadé domain to the south [35]. Three (03) major geological units have been identified in the Mayo Bocki watershed, namely the Poli series, the Pan-African granitoids and the post-Pan-African formations (**Figure 2**). Schists, amphibolites and gneisses are among the lithological units formed between 830 and 665 Ma that make up the Poli series. Pan-African granitoids were formed between 540 and 630 Ma and are mainly represented in the study area by granites and gabbros [6]. The post-Pan-African formations represented are volcanic rocks (basalt, rhyolites) and sedimentary rocks (sandstone, clay, sand). In terms of mining, the presence of an unmined uranium deposit estimated at 13,125 tonnes of uranium oxide is noted in the Poli region, located to the south of the catchment area [6] [36]. From a structural point of view, a study of the lineaments using remote sensing reveals that areas of high fracture density account for around 20% of the surface area of the Mayo Bocki catchment. The major fracture directions are NE-SW (N20 - 70°E), E-W (N80 - 100°E), N-S (N0 - 20°E), while the secondary directions are NW-SE (N120 - 140°E). The NE-SW direction is related to the Cameroon Volcanic Line and regional faults, the E-W direction is associated with the Pan-African orogeny and the Sanaga fault, and the N-S and NW-SE directions are probably related to post-collision decompression phases [34].

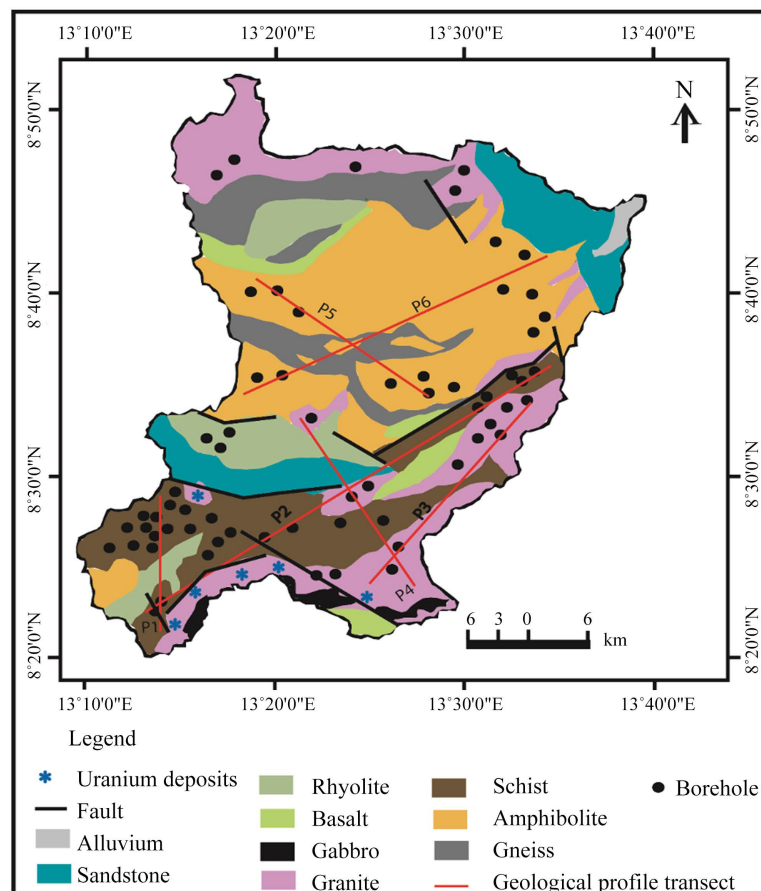


Figure 2. Geological map of the Mayo Bocki watershed.

As far as hydrogeology is concerned, the study area has groundwater deposits. These water resources are contained in the weathering aquifers and in the fractured basement aquifers. Alterite reservoirs are used more by local people for shallow, large-diameter wells. However, because of their vulnerability to pollution and exposure to seasonal fluctuations, these alterite aquifers do not always meet the needs of the population and are generally abandoned in favour of fissured aquifers. Groundwater in fractured basement aquifers of Precambrian age is tapped via deep, small-diameter wells for drinking water supply. The most common fissured aquifer reservoirs are granites, schists and gneisses [34].

2.2. Acquisition of Pumping Test Data

The hydrogeological data used in this study are derived from borehole logs and reports on pumping tests carried out between 1985 and 2024 as part of village water supply programs in the study area. These borehole records were obtained from various organizations in the northern region of Cameroon, notably MINEE, MEADEN, PNDP and FEICOM. Of the 105 borehole records initially collected across the entire catchment area, only 65 were selected and analyzed to characterize the productivity of the fractured bedrock aquifers. The selection of these 65 boreholes was based on several inclusion criteria, notably: the provision of valid, a clear description of the weathered horizons, precise indication of the total borehole depth (Pt), location of the first water inflows in the fractured horizon, a description of the lithology traversed by the borehole, and the availability of draw-down data from step-drawdown pumping tests.

The pumping tests were carried out without an observation piezometer, which means that parameters such as flow rate, the drawdown of the water level in the borehole and time were monitored only in the pumping boreholes. The duration of these pumping tests ranged from 2 to 4 hours for the drawdown phase and one hour for monitoring the recovery phase.

2.3. Statistical Analysis of Drilling Parameters

In this section, a comparative analysis of borehole flow rates was carried out in relation to the physical parameters of the boreholes (total depth, depth of water inflow, thickness of alteration mantle) and the lithological nature. The results of these analyses made it possible to specify the optimum productive depths of reservoirs, the hierarchy of geological formations in terms of productivity and the influence of the alteration mantle on the hydraulic yield of the different types of reservoir. The various parameters taken into account in this analysis were initially statistically processed using XLSTAT.2.0 software to determine the extreme values (minimum and maximum), the mean, the standard deviation (σ) and the coefficient of variation (CV). As far as CVs are concerned, the higher the value, the greater the dispersion around the mean, indicating significant variability. On the other hand, a lower CV indicates less dispersion, suggesting greater homogeneity and reliability of the data. Depending on the value of CV, the series can be char-

acterized as follows [25]: if $CV < 0.02$, the series is said to be very homogeneous, if $0.02 < CV < 0.25$, the series is said to be homogeneous, if $CV > 0.25$, the series is said to be heterogeneous. The distribution of operating flows was assessed according to the classification proposed by the Interafrican Committee for Hydraulic studies: very low flows ($0 - 1 \text{ m}^3/\text{h}$), low flows ($1 - 2.5 \text{ m}^3/\text{h}$), medium flows ($2.5 - 5 \text{ m}^3/\text{h}$) and high flows ($> 5 \text{ m}^3/\text{h}$).

2.4. Determination of Hydrodynamic Parameters of Fissured Aquifers

As part of this study, the data collected were used to estimate the specific capacity, transmissivity, and hydraulic conductivity.

2.4.1. Determination of Specific Capacity

Specific capacity (Qs) is the parameter that reflects the intrinsic productivity of the aquifer, as it expresses the aquifer's actual hydrogeological characteristics [21]. For each borehole, the specific capacity was calculated by dividing the pumping rate by the resulting drawdown over a given period. In this study, the pumping rate considered is the average of the rates obtained during short-term tests.

$$Qs = \frac{Q}{s} \quad (1)$$

where Qs : specific capacity (m^2/h), Q : average flow rate at the end of pumping (m^3/h), s : drawdown of the water table caused by pumping (m). The analysis of specific capacities was carried out according to the following classification [37]: Low specific capacities ($Qs < 0.1$), Medium specific capacities ($0.1 < Qs < 1$) and High specific capacities ($Qs > 1$).

2.4.2. Estimating Transmissivity

Understanding transmissivity is fundamental to water resource management, including determining the yield of a well or borehole, ensuring a sustainable supply and preventing problems such as overexploitation of groundwater resources [38]. It measures the ease with which a geological formation can transmit water.

In the absence of long-term pumping tests, which are generally used to determine hydrodynamic parameters, short-term tests can also be used for this purpose, provided that a plateau is reached during each cycle [8] [39]. The minimum number of stages required to obtain satisfactory results is three (3). In fact, well tests provide information about the aquifer. The total drawdown measured is the sum of two terms:

$$s = BQ + CQ^2 \quad (2)$$

BQ : linear losses from the aquifer, where B is related to the transmissivity T and time.

CQ^2 : corresponds to the quadratic losses in the well caused by turbulent flow at the strainer and the filter pack.

Several authors have used step tests to assess the hydrodynamic characteristics

of basement aquifers and have pointed out that the values of hydrodynamic parameters obtained by step pumping do not differ significantly from those obtained by conventional pumping [10] [39] [40]. This suggests that staged pumping tests yield an apparent transmissivity that is often slightly low, as the B term still includes some non-linear losses near the wellbore. In this study, transmissivity was estimated using the method for interpreting step-drawdown tests, specifically the method developed by the CIEH (Inter-African Committee for Hydraulic Studies) in collaboration with BURGEAP [37]. This method, which is specifically adapted to water wells in bedrock aquifers, is widely used in the Sahel-Sudan region of Africa. The interpretation is carried out by plotting the well's characteristic curve, *i.e.* plotting the specific yields of each stage linearly on the y-axis of a semi-logarithmic graph, and the measurement time on the x-axis (logarithmic). The resulting curve allows the slope (Δs) to be determined, which is the ratio of the difference in specific yields between two points on the line to the difference in time over a logarithmic cycle (Equation (3)).

$$\Delta s = \frac{Qs2 - Qs1}{\text{Log}t2 - \text{Log}t1} \quad (3)$$

The transmittance T (m^2/s) is thus calculated using the following Equation (4):

$$T = \frac{0.183}{3600\Delta s} \quad (4)$$

The analysis of transmissivity is based on the following CIEH classification: low class ($T < 10^{-5}$); medium class ($10^{-5} < T < 10^{-4}$); high class ($T > 10^{-4}$).

2.4.3. Definition of an Empirical Relationship between Transmissivity and Specific Capacity

According to [36] [41], transmissivity is linearly proportional to the specific storage of a well, regardless of whether the aquifer is confined or unconfined. The relationships between these two parameters are generally considered to be specific to the aquifer and the environmental context. The importance of defining these relationships lies in the fact that, when pumping test data are not available, it is possible to determine transmissivity from specific storage, which is easy to estimate [8] [41]. This relationship is best expressed using logarithms and is given by Equation (5).

$$T = A(Qs)^D \quad (5)$$

where: A and D are coefficients (constants); T : transmissivity (m^2/s); and Qs : specific capacity.

2.4.4. Determination of the Permeability Coefficient of the Fissured Layer

The permeability of the ground corresponds to the ability of a layer of ground to allow water to pass through it or to allow groundwater to flow. The coefficient of permeability (K) was deduced from the analytical method of transmissivity (Equation (6)):

$$K = \frac{T}{e} \quad (6)$$

where T : transmissivity (m^2/s), e : wet thickness (m) of the aquifer, calculated for each borehole by taking the difference between the total depth of the borehole and the depth of the static water table.

3. Results

3.1. Statistical Analysis of Borehole Parameters

3.1.1. Borehole Flow Rate

In the Mayo Bocki watershed (MBWS), the flow rates from boreholes in the fractured basement vary between 0.38 and 14.4 m^3/h , with a mean and standard deviation of 2.54 and 3.29 respectively. The coefficient of variation obtained (1.29) is greater than 0.25 and reflects a heterogeneous series and therefore a wide dispersion of flow rate values, indicating significant variability in the study area. The classification of flow rates (**Figure 3**) according to the criteria defined by Inter-African Committee for Hydraulic Studies, indicates that approximately 78.33% of the boreholes have very low and low flow rates, 11.66% of the boreholes fall into the medium flow rate class and 10% of the boreholes belong to the high flow rate class. These results show that the low-flow class predominates in the MBWS basement aquifers. However, the CIEH considers a borehole to be negative when its flow rate is less than 1 m^3/h . In this context, 30% of boreholes drilled are negative and cannot be accepted for supplying drinking water to the population. This percentage of negative boreholes (30%) also reflects the failure rate of boreholes drilled in basement aquifers in the MBWS.

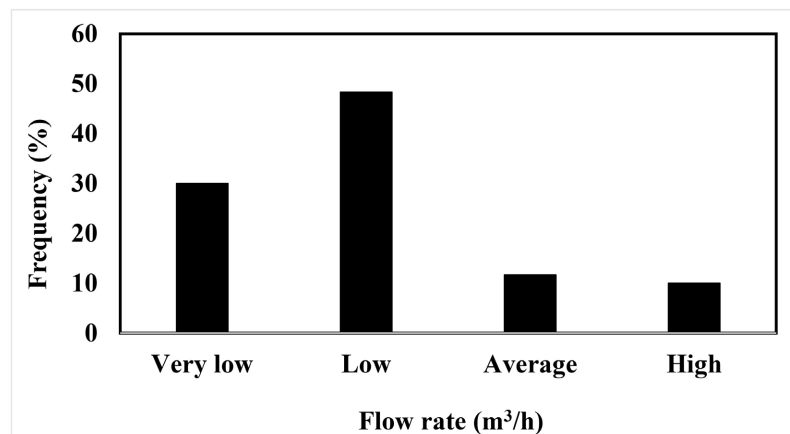


Figure 3. Classification of flow rates in the fissured bedrock of the MBWS.

The geological formations in which the MBWS boreholes are located are mainly schist, granite and gneiss. Of the 65 boreholes considered, which tap the fissured basement, 28 were drilled in schists, 19 in granites, 15 in gneisses and 03 in rhyolites. **Figure 4** shows a comparison of flow rates between the different geological units. In the schist reservoirs, around 43% of boreholes provide medium to high

flow rates, whereas in the gneiss, only 20% provide medium flow rates. The dark boreholes in the granites only recorded very low and low flow rates. In view of these results, schist reservoirs appear to be the most productive, followed by gneisses and granites in the MBWS.

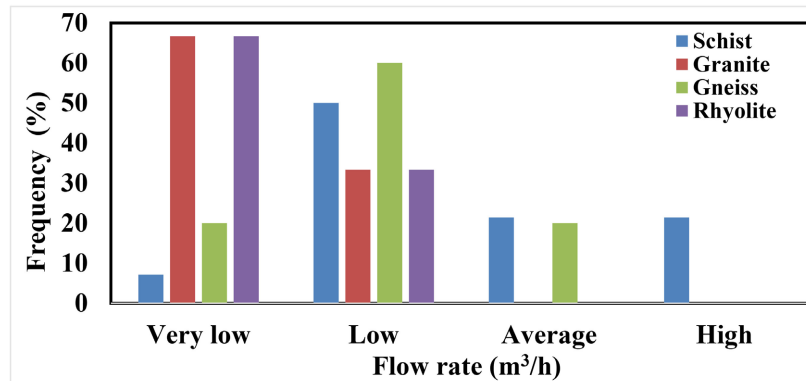


Figure 4. Borehole productivity by lithological type.

3.1.2. Optimum Productive Depth

The total depths (Pt) of the boreholes drilled in the fissured basement vary between 24 and 75 m, with a mean of 38.68 m and a standard deviation of 10.45, giving a coefficient of variation of 0.27. This coefficient of variation is high (>25%) and shows that the depth series in the fissured basement is heterogeneous and dispersed around the mean. **Figure 5** shows the distribution of flow rates as a function of the total depth of boreholes drilled in the fractured basement. Analysis of this graph reveals that the best flow rates (>2.5 m³/h) are obtained at depths of between 25 and 50 m.

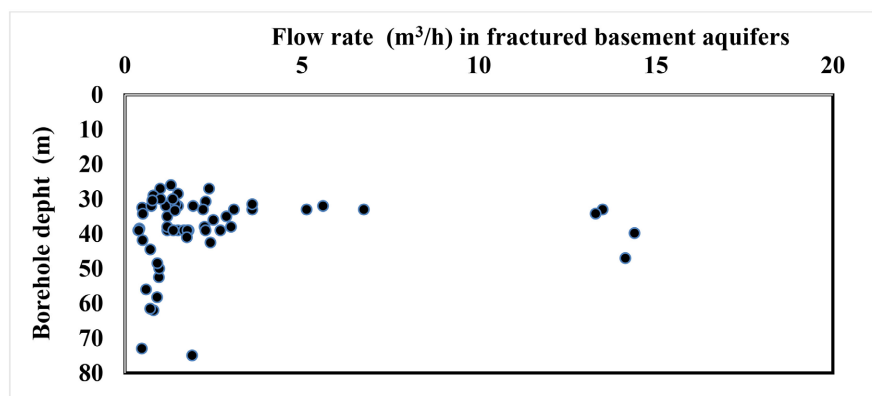


Figure 5. Relationship between flow rate and total depth of boreholes in the MBWS bedrock.

In the MBWS boreholes, there are often up to 4 water inlets (AE), corresponding to hydraulically active depths. These depths vary overall between 2.75 and 60 m, with an average of 27.4 m. The first and second inlets are the most abundant in the geological units. The intervals 2.75 - 17.9 m, 8.5 - 60 m, 14.25 - 35.3 m and

31.5 - 41.04 m correspond respectively to the ranges of variation from the first to the fourth inflow in the boreholes. **Figure 6** shows the frequency of AEs as a function of depth class in the various aquifer reservoirs. This figure shows that around 80% of water inflows are located in the first 20 meters in schists and gneisses, while in granites, 73% of AEs are located in the first 30 meters, with a predominance between 20 and 30 m depth.

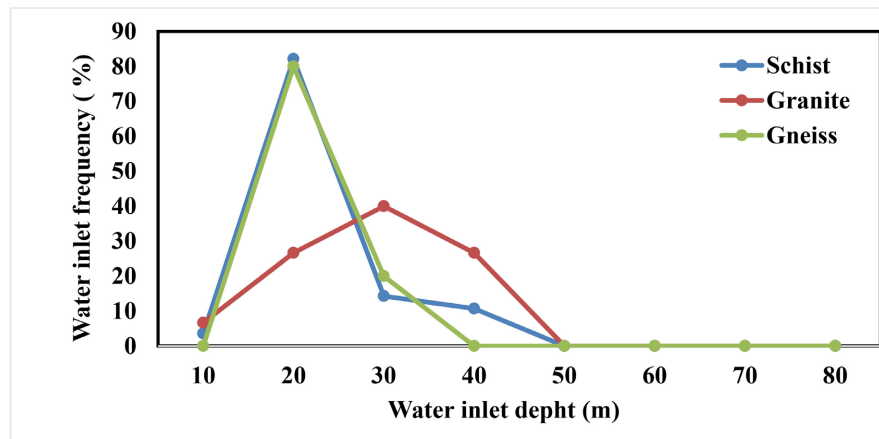
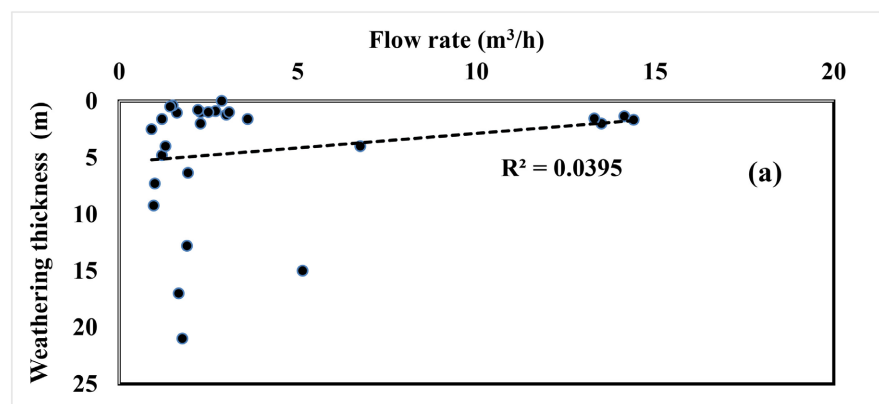


Figure 6. Relationship between water inlet and drilling depths.

3.1.3. Relationship between Alteration Thickness and Flow Rate

The thickness of alteration overlying the fractured basement horizon in the MBWS ranges from 0 to 21 m, with an average of 5.12 m, a standard deviation of 3.9 m and a coefficient of variation of 0.76. The greatest thicknesses are found in the granitic and gneissic reservoirs, with a maximum of 14 m and an average of 5.97 m. The most frequent weathering thicknesses are in the 1 to 2 m range, with a percentage of 21%. **Figure 7** shows that in schist formations, medium and high flow rates ($>2.5 \text{ m}^3/\text{h}$) are observed in 99% of cases in boreholes with an alteration thickness of between 0 and 5 m. Beyond this depth, borehole flow rates fall into the very low and low classes (**Figure 7(a)**). However, in granites and gneisses, the thickness of the alteration appears to have a positive relationship with the drilling rate (**Figure 7(b)**, **Figure 7(c)**).



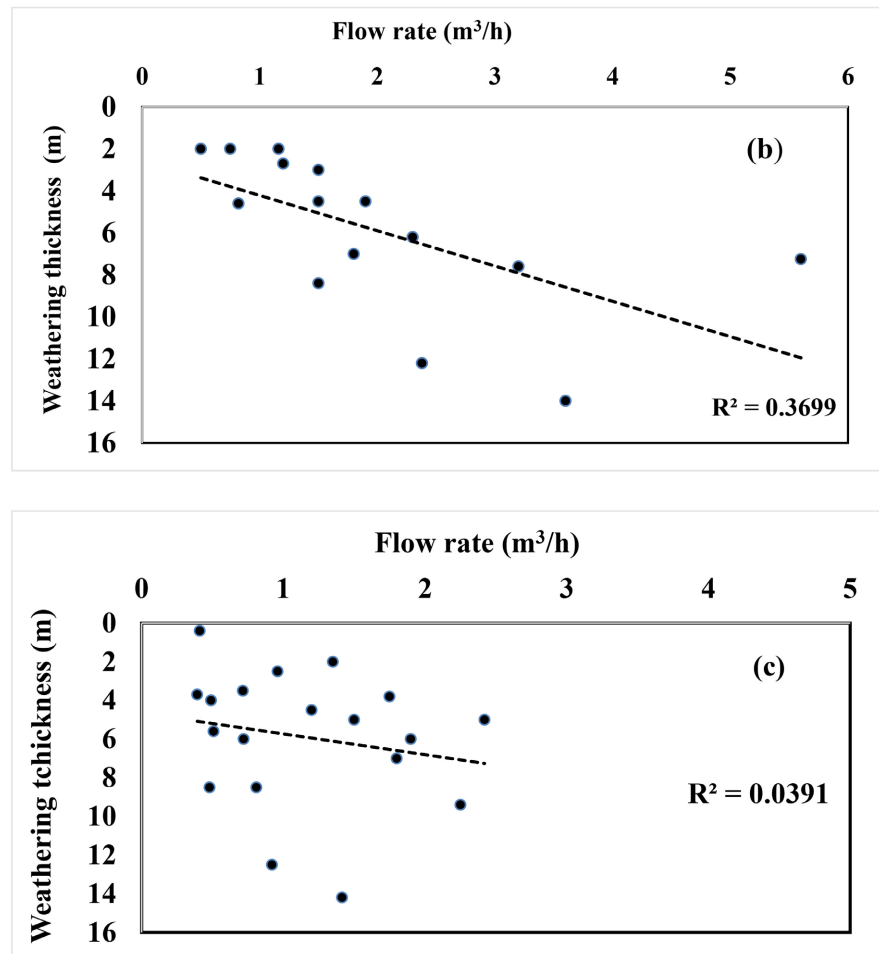


Figure 7. Relationship between weathering thickness and flow rates in schist (a), gneiss (b) and granite (c).

3.2. Characteristics of Hydraulic Parameters

3.2.1. Specific Capacity (Q_s)

Table 1 presents the statistical results for the hydraulic parameters of the fractured bedrock aquifers in the study area. The range of specific capacity values across all geological formations extends from 0.005 to 8.6 m²/h, with a mean value of 1.26 m²/h, a standard deviation of 1.9 and a coefficient of variation of 1.2. The highest value is recorded in the schist, whilst the lowest is observed in the granitic formations. Indeed, low ($Q_s < 0.1$ m²/h), medium ($0.1 < Q_s < 1$ m²/h) and high ($Q_s > 1$ m²/h) specific capacities are represented by 34.7%, 48% and 17.3% respectively, in accordance with the CIEH classification.

3.2.2. Transmissivity (T)

Transmissivity values range from 6.07×10^{-6} to 2.8×10^{-3} m²/s, with an average of 2.7×10^{-4} m²/s. The standard deviation is 5.9×10^{-4} and the coefficient of variation is 1.2. The standard deviation is $5.9 \cdot 10^{-4}$ and the coefficient of variation is 1.2 (**Table 1**). The different classes of low, medium and high transmissivity cover 28.57%, 64.3% and 7.1% of the hydraulic structures respectively. In fact, around 93% of

the boreholes in the MBWS record low to medium transmittances, which shows that the basement aquifers in the MBWS have a weak conductive function. It should also be noted that transmittance varies according to the petrographic nature of the reservoirs. The transmissivities of schists, granites, gneisses and rhyolites range from 6.07×10^{-6} to 2.8×10^{-3} m²/s, 1.7×10^{-6} to 3.6×10^{-4} m²/s, 2.8×10^{-6} to 8.4×10^{-4} m²/s and 1.16×10^{-6} to 1.73×10^{-5} m²/s respectively (Tables 2-4). Analysis of Figure 8 shows that the highest transmissivities are observed in the schists formations and almost 72% of the water points have average transmissivities. The decreasing order of productivity of geological formations in relation to transmissivity is as follows: schist > gneiss > granite > rhyolite.

In the MBWS, the empirical relationship between the two parameters is given by the equation: $T = 2.73 (Q/s)^{0.998}$, with $R^2 = 0.78$ (Figure 9).

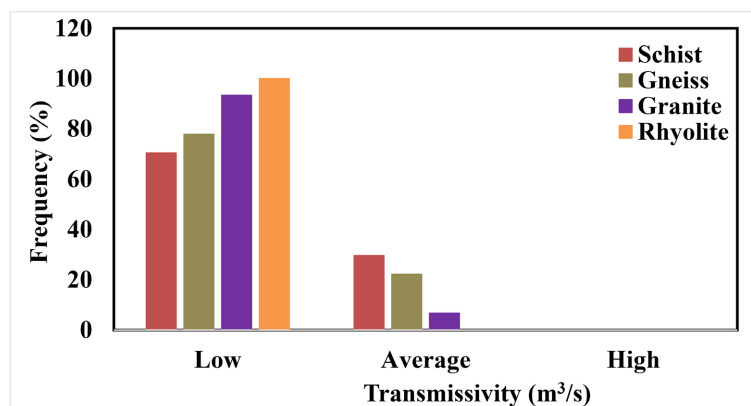


Figure 8. Classification of the transmissivity of aquifers.

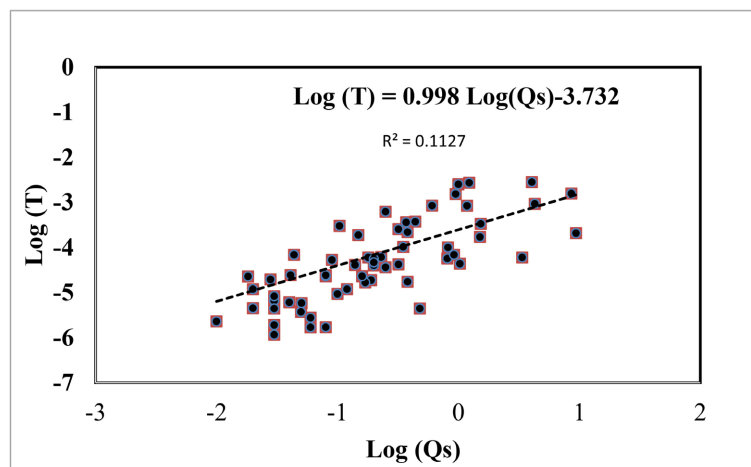


Figure 9. Relationship between transmissivity and specific capacity.

3.2.3. Hydraulic Permeability Coefficient (K)

The values of the coefficient of permeability obtained in this study for all the formations fluctuate between 1.09×10^{-8} and 1.2×10^{-4} m/s, giving an average of 9.32×10^{-6} , a standard deviation of 1.25×10^{-5} and a coefficient of variation of 1.34. Depending on the petrographic nature of the rocks, the permeability's are as fol-

lows: 8.7×10^{-8} to 1.08×10^{-4} m/s, with an average of 1.59×10^{-5} m/s in schist; 3.5×10^{-8} to 1.18×10^{-5} m/s, with an average of 1.14×10^{-6} m/s in granitic formations and 1.2×10^{-7} to 3.4×10^{-5} m/s, with an average of 6.7×10^{-6} m/s in gneissic formations (**Tables 2-4**).

Table 1. Physical and hydraulic parameters of fractured basement formations.

	Pt	EA	1AE	2AE	3AE	4AE	Q	Qs	T	K
	(m)	(m)	(m)	(m)	(m)	(m)	(m ³ /h)	(m ² /h)	(m ² /s)	(m/s)
Min	26	0	2.75	8.5	14.25	31.5	0.38	0.032	6.07×10^{-6}	8.69×10^{-8}
Max	75	21	48	60	35.29	41.04	14.4	8.6	2.8×10^{-3}	1.08×10^{-4}
Avg	38.6	6.55	17.87	29.56	26.41	35.6	2.54	1.25	4.7×10^{-4}	1.6×10^{-5}
σ	7.21	6.2	7.68	9.99	7.12	4.26	3.29	1.9	5.9×10^{-4}	1.99×10^{-5}
CV	0.19	0.95	0.43	0.34	0.27	0.12	1.29	1.2	1.2	1.25

Min= minimum, Max = maximum, Avg = mean, σ = standard deviation, CV = coefficient of variation, Pt = total depth, EA = weathering thickness, 1AE= first water inflow, Q = flow rate, Qs= specific capacity, T = transmissivity, K= hydraulic permeability coefficient.

Table 2. Physical and hydraulic parameters in schists formations.

	Pt (m)	EA (m)	AE (m)	Q (m ³ /h)	Qs (m ² /h)	T (m ² /s)	K (m/s)
Min	26	0	10	0.91	0.0049	6.07×10^{-6}	1.09×10^{-8}
Max	75	21	43.5	14.4	8.6	2.8×10^{-3}	1.08×10^{-4}
Avg	37.6	4.41	20.74	3.93	0.714	2.7×10^{-4}	9.32×10^{-6}
σ	6.37	4.15	6.98	3.12	0.83	3.7×10^{-4}	1.25×10^{-5}
CV	0.17	0.94	0.43	0.79	1.17	1.38	1.34

Table 3. Physical and hydraulic parameters in granite formations.

	Pt (m)	EA (m)	AE (m)	Q (m ³ /h)	Qs (m ² /h)	T (m ² /s)	K (m/s)
Min	30	0.4	2.75	0.39	0.0049	1.69×10^{-6}	3.5×10^{-8}
Max	73	14.2	60	2.42	0.37	3.6×10^{-4}	1.18×10^{-5}
Avg	44.7	5.97	25.85	3.93	1.04	3.5×10^{-5}	1.14×10^{-6}
σ	9.84	3.10	9.21	3.12	0.53	5.01×10^{-5}	1.64×10^{-6}
CV	0.22	0.52	0.36	0.79	0.51	1.43	1.44

Table 4. Physical and hydraulic parameters in gneiss formations.

	Pt (m)	EA (m)	AE (m)	Q (m ³ /h)	Qs (m ² /h)	T (m ² /s)	K (m/s)
Min	27	2	7.97	0.5	0.019	1.16×10^{-6}	1.09×10^{-8}
Max	48.8	14	36.72	5.6	0.38	1.73×10^{-5}	5.0×10^{-7}
Avg	33.4	5.8	19.12	1.97	0.14	9.23×10^{-6}	1.7×10^{-7}
σ	3.73	3.73	6.62	1.13	0.16	8.07×10^{-6}	2.1×10^{-7}
CV	0.11	0.64	0.35	0.57	1.11	0.88	1.21

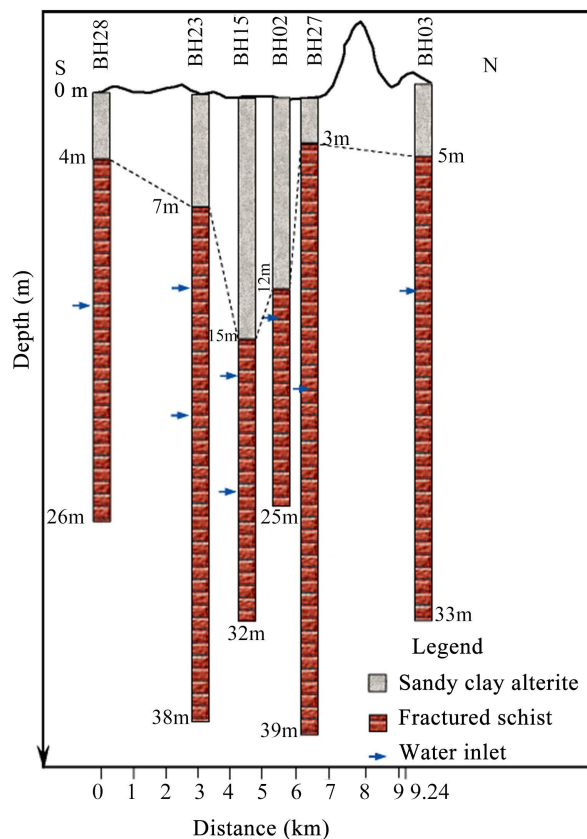
3.3. Structure of Aquifer Reservoirs in the Study Area

The geological profiles highlighted in the schists, granites and gneisses show a vertical structure from top to bottom as follows:

The upper horizon (saprolite), which is dominated mainly by clayey-sandy alterites (alloterites), sometimes surmounted locally by lateritic cuirasses. In the granitic and gneissic reservoirs, the arena (isalerite) levels are surmounted by alloterites, whereas in the schists they disappear in favour of the alloterite layer (**Figure 10**). Analysis of the various profiles shows that this upper horizon constitutes the first level of the groundwater reservoir and varies in thickness, even within the same type of geological formation. Unlike the ridges, the greatest thicknesses of this upper horizon are found in the valleys. This can be justified by the fact that the valleys are the preferred areas for the accumulation of materials removed by erosion from the slopes and summits. In addition, the shallow slope of the valleys means that the water can remain for longer, favouring meteoric alteration.

- The medial horizon underlies the alteration layer. It consists of consolidated rocks affected by cracks or fractures. This horizon appears in these profiles from 3 m in the schists, 4 m in the granites and 2.3 m in the gneisses. It is in this horizon that water inflows were recorded during drilling (**Figures 10-12**).

- The lower horizon consists of sound rock. Of all the profiles carried out, only profile 2 (transect P2) shows local evidence of sound schist at depths of 39 m and 75 m (**Figure 10**).



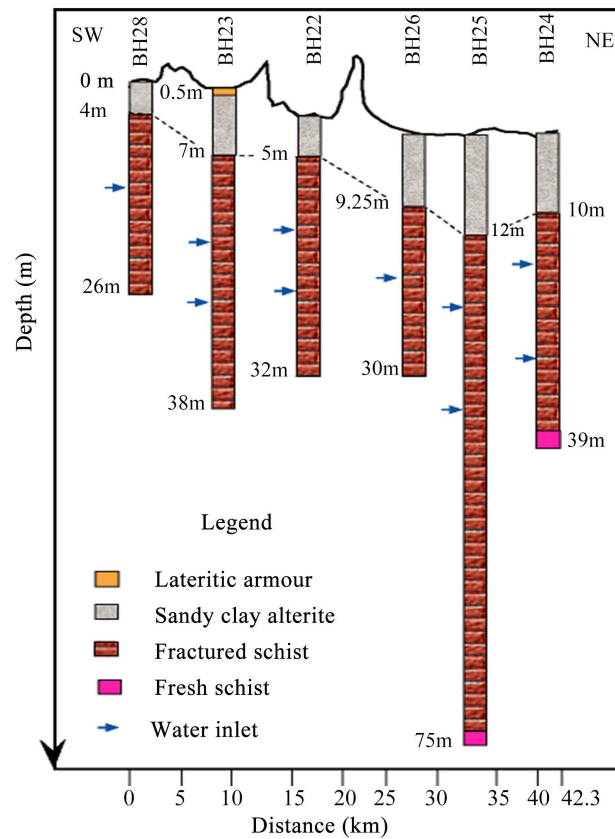
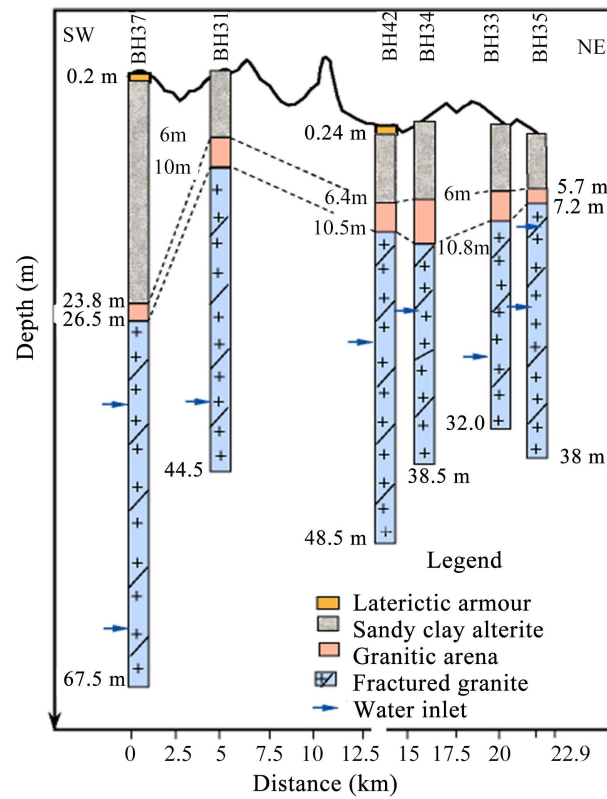


Figure 10. Transects P1 (S-N) and P2 (SW-NE) in the MBWS schist formations.



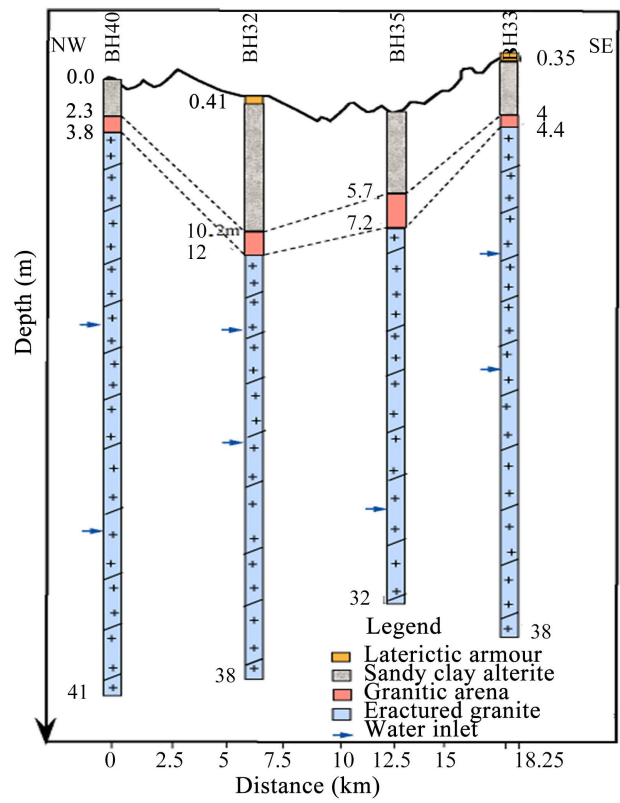
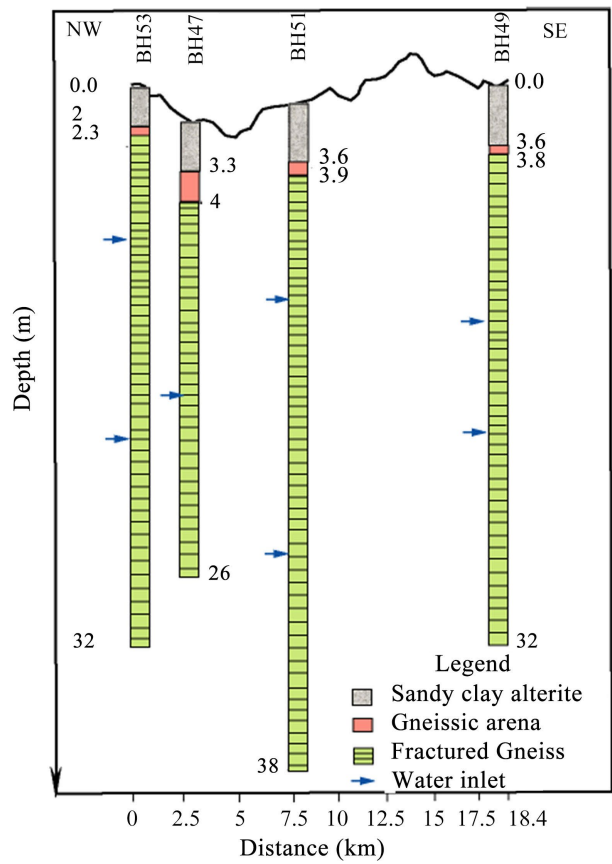


Figure 11. Transect P3 (SW-NE) and P4 (SW- NE) in the granite formations of the MBWS.



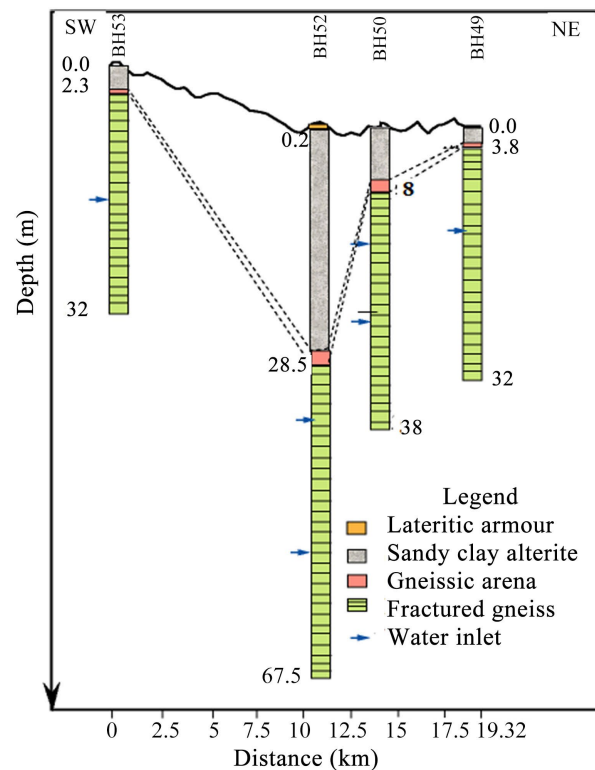


Figure 12. Transects P5 (NW-SE) and P6 (NE-SW) in the gneiss formations of the MBWS.

4. Discussion

4.1. Well Yield

The well yield is a parameter that reflects the productivity of a given hydraulic structure or aquifer. In the fractured bedrock of the study area, well yields range from 0.38 to 14.4 m³/h, with an average of 2.54 m³/h. This range of well yield values is similar to that reported by [42] for formations of the same type in Ngaoundéré (2.8 - 5.14 m³/h). It is lower than the values recorded in the granito-gneiss formations of the Ndé department (1.5 - 10.5 m³/h) in western Cameroon [43]. However, these values are higher than those recorded in the bedrock of the Far North region of Cameroon (0.04 - 4 m³/h) by [10]. The classification of well yields in the study area reveals that 70% exceed 1 m³/h. This finding is consistent with that reported by several authors in the bedrock zone of Côte d'Ivoire [8] [9], who indicate that 80% of yields exceed 1 m³/h and would be sufficient for the supply of drinking water to rural areas.

4.2. Factors Influencing Well Productivity

4.2.1. Influence of Lithology on Productivity

Statistical analyses of well production rates and lithological types have shown that schist reservoirs appear to be the most productive, followed by gneiss and granite in the MBWS. This ranking of geological units in terms of productivity has also been observed on the Cameroonian basement [10] [15] and in Côte d'Ivoire [8] [9]. The high productivity of shales can be explained by the fact that, in addition

to tectonic influences, the foliated and rectified structures of schists give them the advantage of being more permeable than other formations.

4.2.2. The Influence of Borehole Depth on Productivity

In addition to the orientation and density of fractures. Other parameters such as depth and the thickness of the weathered zone influence the productivity of fractured aquifers [39]. With regard to depth, several authors [11] [13] estimate that, depending on the geological and hydrogeological environment, there is a depth beyond which the chances of finding an aquifer horizon diminish, particularly within fractured basement formations. This is due to the decrease in the frequency and disappearance of permeable fractures. Thus, statistical analysis of the relationship between well yields and well depth in the MBWS shows that medium to high well yields ($>2.5 \text{ m}^3/\text{h}$) are obtained between 25 and 50 meters.

This observation is similar to that made by [39] in the Lakes region of Côte d'Ivoire, where it was noted that the top 60 meters of the bedrock are productive. If we adhere to the minimum flow rate set by the CIEH for declaring a borehole successful ($>1 \text{ m}^3/\text{h}$) in supplying rural populations, depths between 25 and 75 meters are those offering relatively acceptable productivity. Beyond a depth of 75 meters, flow rates decrease sharply ($<1 \text{ m}^3/\text{h}$). In order to avoid unnecessary over-drilling, *i.e.* drilling that yields no improvement in productivity [8] and [10] have respectively proposed depths of between 55 and 75 m as the maximum depths not to be exceeded when drilling in the bedrock zone of the Far North of Cameroon and in Côte d'Ivoire. However, the values found in this study fall within the range of values proposed by these previous authors.

Statistical analysis of the data shows that the most productive water inflows are located within the first 30 meters. This is consistent with findings from numerous regions in bedrock aquifers, notably in India [11], Côte d'Ivoire [9] and Burkina Faso [22]. However, beyond a depth of 50 m. water inflows become very rare in the fractured bedrock horizon, which means that it is open. Hydraulically active fractures tend to close with depth. Nevertheless, these fractures may be sealed by clay particles overlying the fractured horizons.

4.2.3. The Influence of Weathering Thickness on the Productivity of the Fractured Bedrock Aquifer

The importance of weathering thickness in the water supply to fracture networks has been demonstrated in numerous studies [11] [13]. Indeed, according to these researchers, a significant weathering thickness above the underlying layer promotes good productivity. This observation appears to apply only to granitic and gneissic formations in the MBWS. In schist aquifers, by contrast, the highest flow rates are found where there is a thin weathering layer (0 - 5 m). This is likely due to the clayey nature of the weathered materials derived from the weathering of the schist, which severely limit infiltration potential by sealing the fissures and fractures. Thus, it should be noted as in [20], that a thick layer of weathered material can only become a factor in the recharge of fractured aquifers if these aquifers

have good permeability. Otherwise, they would act as a hydraulic barrier and prevent the recharge of the underlying fractures.

4.3. Hydraulic Parameters of Fractured Aquifers

4.3.1. Specific Capacity

83% of boreholes in the study area have a low specific yield ($<1 \text{ m}^3/\text{h}/\text{m}$). These results are in stark contrast to those reported by [38] in the Yaoundé bedrock, where 82% of hydraulic structures exhibit specific yields greater than $1 \text{ m}^3/\text{h}$. In the granitic and schistose reservoirs of the N'zi Iffou and Moronou regions of Côte d'Ivoire [22] recorded values ranging from 0.02 to $4.09 \text{ m}^3/\text{h}$, with 76% of these boreholes exhibiting good productivity.

4.3.2. Transmissivity of Fractured Aquifers

The various transmissivity values obtained fall within the range of transmissivity values (10^{-8} to $10^{-4} \text{ m}^2/\text{s}$) encountered in the African basement in general [44]. In the Far North of Cameroon, [10] obtained lower transmissivity values (3.0×10^{-7} to $7.8 \times 10^{-4} \text{ m}^2/\text{s}$) than in the study area. In western Cameroon, and more specifically in the Ndé Department, the estimated values of basement transmissivity range from 10^{-6} to $10^{-4} \text{ m}^2/\text{s}$ [43]. In the Yaoundé bedrock, [15] [38] and [45] obtained values ranging from 6.54×10^{-7} to 1.6×10^{-4} , 3.5×10^{-6} to 4.7×10^{-4} , 1.16×10^{-6} to 1.51×10^{-3} and 4.83×10^{-7} to $4.7 \times 10^{-4} \text{ m}^2/\text{s}$, respectively. These transmittances are of the same order of magnitude as those determined in the MBWS. They are low compared with those found by [46] in Italy (3.10^{-5} to 10^{-3}) and [47] in granites in Japan (10^{-5} to 3.8×10^{-3}). The spatial heterogeneity of transmissivity would be linked not only to the variation in lithological facies encountered in the MBWS basement zone, but also to the quantitative and qualitative variation in fracturing.

4.3.3. Correlation between Transmissivity and Specific Capacity

Many authors have established the relationship between transmissivity and specific capacity in order to determine the transmissivity for certain boreholes where only the specific capacity is known. This relationship can therefore be used to estimate either variable when the other is missing [8] [39] [41]. In the MBWS, the empirical relationship between the two parameters is expressed by the equation: $T = 2.73 (Q/s)^{0.998}$, with $R^2 = 0.78$ (Figure 9). This relationship indicates that high transmissivity values are associated with high specific capacities. The value of the correlation coefficient means that at least 78% of the transmissivity values in the study area are related to specific capacities. The relationship obtained differs from that obtained in other regions around the world. For example, in the Yaoundé basement aquifers, [38] obtained $T = 0.0158 (Q/s)^{1.01}$, with $R^2 = 0.64$. Similarly, [41] found $T = 0.63 (Q/s)^{1.3}$, with $R^2 = 0.72$ in certain basement aquifers in Côte d'Ivoire. In Ghana, [48] obtained a correlation $T = 0.769 (Q/s)^{1.075}$, with $R^2 = 0.83$ in basement aquifers. Similarly, in Canada, [46] and [49] respectively obtained and $T = 1.3858 (Q/s)^{1.0765}$, with $R^2 = 0.86$ and $T = 4.48 (Q/s)^{1.15}$, with $R^2 = 0.66$.

These various results lead to the conclusion that the relationship between transmissivity and specific capacity cannot be generalized, as it varies depending on the hydrogeological context and is therefore specific to the study site, as noted by [8]. According to [41], the significant differences noted between geological environments can also be attributed to the methodology implemented, in particular the type and duration of test pumping.

4.3.4. Permeability Coefficient of the Saturated Zone in Fissured Aquifers

In Africa in general and in India, [11] estimated the permeability coefficient of fissured aquifers to be between 10^{-6} and 10^{-4} m/s. The values obtained in this study fall well within the range proposed by these authors. The highest transmissivities and permeabilities are found in schists formations. These results are similar to those obtained by [8] in the Bongouanou region, confirming the high productivity of schists compared to other geological formations (gneiss, granite, rhyolite).

4.4. Conceptual Hydrogeological Model of Bedrock Aquifers

In the hydrogeological sense, the geological structure presented by the various transects shows a bilayer aquifer with an alterite layer and a fissured layer. This structure is similar to that proposed by the classic conceptual model for basement zones [14]. These observations are in line with those described for Sahelian climates [11] [39] [44]. At the scale of the basin, the layers are not stratiform. The weathering materials are thin at ridge level and thick at valley level. This configuration is consistent with that observed in a Sahelian climate by [39] in Burkina Faso [50] and in a humid tropical climate by [20] in Yaoundé, [9] make the opposite observation in Côte d'Ivoire (humid tropical climate). According to them, the thickening of the weathering profile is observed more at ridge level and a thinning at valley level. These differences are thought to be linked to tectonic and morphogenetic armouring processes, the anisotropy of the hydrodynamic properties of geological formations and the action of water in wet and dry climates [11] [14] [39].

5. Conclusion

The aim of this study was to assess the hydrodynamic parameters and factors likely to influence the productivity of fractured aquifers in the Mayo Bocki catchment. The results of this investigation show that the flow rates of the boreholes encountered are predominantly low (78%). The productive depths of the basement are within the first 50 meters below the ground surface. Beyond this depth, water inflows become rare. A significant thickness of alteration overlying schist does not always improve productivity, due to the clayey nature of the alterites resulting from the alteration of the schist, which severely limits the possibilities of infiltration. However, in the granites and gneisses, the thickness of the alterites appears to have a positive relationship with the drilling rate. The most productive geological units appear in the following descending order: schist > gneiss > gran-

ite > rhyolite. As regards hydraulic parameters, low, medium and high specific capacities account for 34.7%, 48% and 17.3% respectively. Transmissivity values range from 1.16×10^{-6} to 2.8×10^{-3} m²/s, with an average of 2.7×10^{-4} m²/s. Approximately 93% of the boreholes in the study area record low to medium transmissivities, reflecting the poor conductive function of fractured basement aquifers. The hydraulic permeability coefficient values obtained for all the fractured basement formations fluctuate between $1.09.10^{-8}$ and 1.2×10^{-4} m/s, giving an average of 9.32×10^{-6} m/s. Overall, the geological structure revealed by the lithostratigraphic logs is similar to that proposed by the classic conceptual model for the basement area.

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Conflicts of Interest

The authors declare that they have no conflict of interest in relation to this article.

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