

Hydrogeochemical characterization of the areas of exploitation of the CBG sites: cas of the plateaus of N'Dangara and Boundou Wandé, Sangarédi sub-prefecture, Prefecture of Boké, Republic of Guinea

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Abstract: *This work aims to analyze the quality of groundwater in the riparian areas of the bauxitic plateaus of N'Dangara and Boundou Wandé in operation by the CBG (Compagnie des Bauxites de Guinée). The geology of the study area consists mainly of sedimentary formations of the Devonian faro, Neogene and Quaternary. Three water measurement and sampling campaigns on the two plateaus were carried out with determination of piezometric measurements and physic-chemical parameters. This study showed that the general flow direction of groundwater is dispersed. The flows at Boundou Wandé are from the center of the plateau to the north and that at N'Dangara is from the center to the south and southwest. It can be seen that the direction of groundwater flow reflects overall the relief of the deposit conditioned by its geomorphological framework. It emerges from the analysis of physical and chemical parameters that well water is consumable. However, the water from wells MW15, MW16, MW17, MW18 and MW21 with a low pH (4.84 to 5.13) may present a certain nuisance for its consumption and because it can be corrosive. Analysis of the Piper diagram showed two hydrogeochemical facies (calcium and magnesium bicarbonate facies and sodium and potassium carbonate facies). However, this study strongly suggests continuous monitoring of groundwater in and around the study area in order to meet the demand for water supply to communities without compromising the ability of future generations to meet water quality requirements.*

Keywords: groundwater, Boundou Wandé, N'Dangara, Piper diagram, bauxite, hydrogeochemistry

1. Introduction

Water plays a vital role in the life of living organisms [1]. The control of water for use in the face of development requirements is an urgent necessity [2]. According to current knowledge of biology, water remains an essential substance for the balance of living beings [1]. Water remains the most immense resource on our planet. Despite its large volume, the role of this vital liquid in the human economy is all the more considerable as the increase in reserves and their rational uses deserve special attention [2]. It must be recognized that there is no branch of industry that escapes the field of water use.

According to various calculations, Africa has 9% of the world's renewable freshwater resources, or nearly 4,000 km³ of water per year. This misleading abundance masks a huge disparity in resources and serious supply difficulties for at least 25 African countries by 2025. The African continent must turn to the optimization of its groundwater resources, which are more reliable than surface water because they are less sensitive to climate variability and pollution [3]. Groundwater is the second largest reservoir of fresh water in the world. From a quantity point of view, if this volume of water is well managed, it can make it possible to smooth out the disparities between inputs and withdrawals [4].

Sangarédi, a sub-prefecture of Boké, is a mining area par excellence. It lies on the edge of the coastal zone and the highlands of Fouta Djallon. This locality is home to many companies in the country such as the Compagnie des Bauxites de Guinée (CBG) created in 1963 by an agreement between the government of the Republic of Guinea and HALCO Mining [5]. Since 1973 it has started mining bauxite in the sub-prefecture of Sangaredi. The CBG now covers 76 bauxite plateaus listed on an area of about 2931 km² [6].

As a multinational owned by HALCO 51% (ALCAN 23%, ALCOA 23% and DADCO 5%) and the Republic of Guinea 49%, it plays a key role in the national economy. Since then, it has been using explosives in operations and recently a test at the mine surface [5].

The present study covers two plateaus (N'Dangara and Boundou Wandé) which have surrounded themselves by villages (Boundou Wandé, Sinthiourou Madina, Hamdallaye and Samayabhé). They are bordered by the thiapikouré, Laafou and Pora rivers [7]. The majority of the populations of these localities consume water from springs and artisanal wells. Mining operations can impact water resources with multiple consequences on biodiversity.

According to Hadj-Said [8], studies in recent years show that even groundwater is not spared from pollution. This constitutes a major danger that threatens our environment and for which man is primarily responsible. The uncontrolled exploitation of mineral and industrial resources has a negative impact on groundwater quality.

The bauxite of our study area is exploited exclusively in the open air with the use of explosives for the felling of rocks. The use of these explosives can cause more or less significant fracturing in the rocks of the aquifer. These cracks created by explosives can alter the hydraulic conditions of aquifers,

which can affect the speed of groundwater flow. These cracks can serve as infiltration routes for pollutants generated by various mining operations (oils, explosives, hydrocarbons, etc.).

Prior to the CBG extension project, there had been no specific studies on groundwater pollution. It was only in 2015 that specific studies began with the establishment of several observation boreholes and cumulative impact control stations. And it is the perspective of assessing groundwater quality that this study is inscribed.

The general objective of this work is to analyze the quality of groundwater in the riparian areas of the bauxitic plateaus of N'Dangara and Boundou Wandé in operation by CBG. Specifically, the study will make it possible to: (1) give an overview of the study area, indicating the geographical context, and hydrogeologist; (2) Determine the direction of groundwater flow; (3) To assess the degree of groundwater contamination due to mining; (4) Determine the hydrogeochemical facies of the different water wells on the bauxite plateaus.

To better understand this work, we subdivide it into four (4) main sections which are as follows: section 2: deals with the presentation of the study area including the geographical context, and hydrogeologist; Section 3, intended for the description of the materials and methods used in this work; Section 4, devoted to the presentation and discussion of the results; and a conclusion and perspectives will close this work in Section 5.

2. Presentation of the study area

2.1. Geographical location

Sangarédi where our study area is located, is a sub-prefecture located 70 km northeast of the prefecture of Boké between 11°06'00"N and 13°46'00"W [6]. It is bounded to the north by Wendou Boorou to the east by the prefecture of Telimele, to the west by the sub-prefecture of Tanéné and to the south by the sub-prefecture of Malapouya. Its population is 81736 inhabitants [9]. The climate of Sangarédi is tropical, the average temperature is 37.3°C and an average rainfall of about 1429.8 mm per year [6].

Our study area is located in the CBG concession which covers a total area of 2931 km². In this mining concession, our study focused precisely on the bauxitic plateaus of Boundou Waadé (1111.59 ha) and N'Dangara (1491.31 ha). These plateaus are contiguous and bounded by the following geographical coordinates [7]: – 11° 02' 24" – 11° 06' 00" N – 13° 47' 05" – 13° 55' 10" W.

These bauxitic plateaus are limited by several rivers. To the north by the Thiapikouré River, to the south by the Laafou River and to the east by the Pora River. These plateaus are bordered to the west by the Sangarédi-Balandougou road. These two plateaus are separated by the Boundou Waadé River. The Boké-Sangarédi road crosses the Boundou Waadé plateau along its entire length [7].

2.2. Hydrogeology

Hydrogeologically, our study area has been the subject of several works. Mamedov et al. [10], in this work on the N'Dangara deposit, it is indicated that the groundwater in these plateaus can be subdivided into two:

- Diacase and interstitial waters in cracked and cavernous hard rocks (laterites and bauxites) of the upper horizon that occur only locally and preferably during the rainy season,
- Interstitial and formation waters in pseudomorphic clays of the lower horizon of altered sequences. These waters exist almost all year round and everywhere during the rainy season, they are absent only on isolated areas towards the middle or end of the dry season.

Studies by Mamedov et al. [10] indicate that during the rainy season two hydrogeological zones are individualized:

- The infiltration zone: it is the upper part (from the surface) of the altered sequences, which is composed of cracked bauxites and hard laterites with a high infiltration coefficient, which promotes the rapid infiltration of meteoric waters towards the lower clay and clay-ferruginous horizon;
- The zone of the beat of the aquifer: it is in the upper part of the horizon of clays and clay-ferruginous rocks of the altered sequence by periodically penetrating into the lower part of bauxites and laterites. During periods of intense and long-term rainfall, the upper part known as the infiltration zone is also flooded. However, from a statistical point of view, these periods of complete flooding do not last long.

Hydrogeological work by Mamedov et al. [10] reveals that the drawdown of the aquifer is due to the sudden change in rock permeability that occurs from the hard rocks of the lateritic cover to the underlying clays, which plays the role of a relatively impermeable layer. However, since the pseudomorphic clays of the altered sequence are relayed lower by sub horizontal Devonian aleuro-argillites with an even lower infiltration coefficient, the flow of groundwater on the Boundou Waadé deposit (as well as on the N'Dangara deposit) is essentially lateral.

The direction of groundwater flow reflects the relief of the deposit conditioned by its geomorphological framework. On the Boundou Wandé deposit, the underground flow is mainly to the south (towards the valley of the Boundou Wandé pond) and to the south-east (towards the valley of the Pora river) [10].

The very intense underground flow occurs above the clay-ferruginous horizon, partially touching the lower part of the bauxites and laterites of the transition horizon by moving towards the areas of the local discharge, i.e., towards the slopes and notches of the rivers. The intensity and durability of the lateral flow during heavy rains result in the formation of underground voids, or even galleries of the suffo-Karst type (with a power of 1 m to 5 m), encountered in boreholes No. 35048 (at the depth of 8.0-10.0 m), No. 35713 (at the depth of 12.0-14.0 m) No. 35815 (at the depth of 12.0-15.0 m) etc., in the southern part and

by boreholes No. 39403 (at the depth of 9.0-10.0 m), No. 39705 (at the depth of 8.0-12.0 m) etc. in the South-East part [10].

According to Mamedov et al. [10], the distribution of groundwater is partly controlled by the folds observed at the level of the rocks in place. This is clearly visible on the hydrogeological maps drawn up for the rainy season: the depth of the aquifer in relation to the surface is not always controlled by the relief.

The synclinal basin of South-East – North-West orientation, highlighted on the Boundou Waadé deposit around prospecting lines 24 – 38, during the geological survey of block three of the deposit in 1999 determines the sub-flush position of groundwater in this sector [10].

During the dry season, hydrogeological zonality presents an entirely different picture. With the end of the rains, the area of the drawdown of the water table disappears. The infiltration area gradually dries out. The level of the water table drops everywhere, and in places, the horizon of the clays loses water as it passes from the drowned state to the state of capillary humidification. In some areas it is completely dry [10].

Nevertheless, it remains true that even during the dry season, there are local areas drowned in water almost all year round and where the water table can be observed at depths very close to the surface (8.0 10.0 m), even touching the laterites of the lower transition zone. This case was found on the western flank of the deposit (around the village of Hamdallaye), where the waters descending to the side of the Parawi deposit topographically higher and still near the discharge area of the Boundou Waadé pond accumulate [10].

On the rest of the territory, during the dry season the level of the water table gradually decreases followed by the complete drying of the bauxites in December.

The slower lowering of the water table level has only been observed in the region of a synclinal basin, where the drying of the bauxitic layer ends during the month of December.

Thus, the hydrogeological conditions of the Boundou Waadé deposit are controlled by several factors such as: climate, lateral underground flow and the structural plane of the rock deposit in place [10].

The analysis of the above development on the hydrogeology of the study area shows that the level of groundwater varies according to the seasons and the porosity of the rocks crossed.

3. Materials and Methods

3.1. Choice of sampling points

Seven (7) CBG observation wells in the study area were investigated. These wells have above ground varying between 49 and 80 cm, corked to prevent the penetration of external agents (rainwater and fall of small animals). Wells are placed around operating areas, river slopes and near residential areas (see Fig. 1). Table 1 shows the distribution of sampling points.

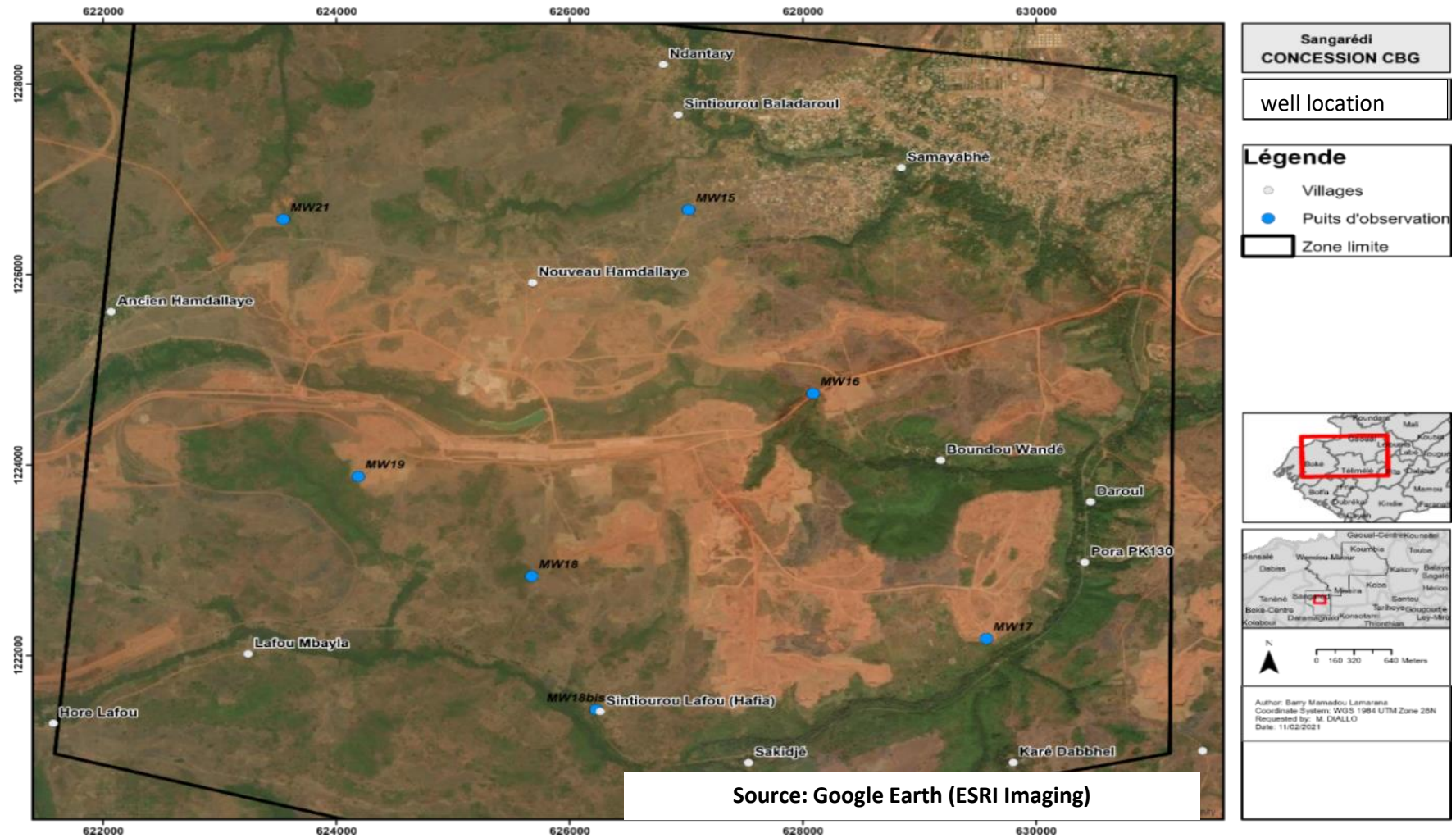


Figure 1. Location map of sampling points

Table 1. Distribution of observation wells at the level of the 2 plateaus

Plateau	Place	Well	Coordinates
Boundou Wandé	Samayabhe	MW 15	627020 E; 1226680N
	Entrée N'Dangara	MW 16	628089E; 1224754N
	Base chinoise	MW 21	628089E; 1224754N
N'Dangara	Plateau N'Dangara	MW 17	629573 E; 1222178N
	Tarissement	MW 18	625674 E; 1222834
	Sinthiourou Hafia	MW 18 bis	626229 E; 1221433N
	PCC N'Dangara	MW19	624187 E; 1223882N

3.2. Groundwater sampling procedures

Based on the procedure of the CBG monitoring service, we proceeded as follows:

For the taking of a water sample, perform steps 1 to 19 following;

For piezometric measurement, perform steps 1 to 9;

Steps:

1. Wear nitrile gloves to avoid contamination;
2. Open the well with the supplied key;
3. Measure the height of the protective tube of the ground well at the edge. (Constant value, no need to measure each time);
4. Measure the water height of the well with the depth probe and note it in the form;
5. Remove the HDPE (High Density Polyethylene) pipe present in the well, making sure not to contaminate it and deposit it on a clean surface (if the probe passes through the piezometer, no need to do this step);
6. Measure the total depth of the well;
7. If necessary, put a ball scoop at the end of the pipe;
8. Lower the end of the pipe to the base of the water column, without touching the bottom;
9. Re-establish the water height of the well;
10. Purge the well completely;
11. Wait 24 hours for the well to recharge;
12. Measure the water level with the interface probe;
13. Before taking the sample, ensure that the container(s) are in good condition;

14. When collecting, never rinse the container(s) as they may contain condoms;
15. When sampling, make sure not to contaminate the inside of the bottle or the water sampled;
16. Fill bottles up to the shoulder;
17. Put a disposable filter at the end of the pump hose and fill the metal bottle with nitric acid condom;
18. Fill the other bottles without the filter;
19. Close and lock the well.

During the fieldwork,

- (1) the water was sampled using a bailer or scoop. This is a hollow pipe used to retrieve groundwater samples from control wells [11]. The bailers are attached to a thread usually made of nylon and lowered into the water column for sampling (see Figure 2).



Figure 1. Thebailier

- (2) three piezometric measurements for each of the seven wells studied were carried out. Water levels in the wells were measured using an AGM piezometer (see Figure 3).



Figure 2. AGM piezometer

3.3. Retention of the sample

To avoid rapid alteration of water as a result of physical, chemical and biological reactions, it is advisable to store it carefully between the place of collection and analysis [12]. The samples taken were placed in plastic vials (Figure 4). To prevent their deterioration, they were placed in a glacial and then kept in the ice until the laboratory in Kamsar for chemical analysis.



Figure 3. Plastic Vial

3.4. Identification of the sample

In order to avoid errors, always identify the sample on the site using a permanent marker and write legibly. Pay attention to the cleanliness of the receptacle. Identification includes:

- The name of the company;
- The name of the sample (YYY/MM/DD-ESO-dot);
- The name of the sampler;

- The date and time;
- The parameters to be analyzed (if possible);
- The condom in the container.

3.5. Measurement and analysis equipment

The in-situ measurements were made using a Hanna HI-9829 multi-parameter probe, which measures pH, electrical conductivity, TDS (total dissolved solids) and takes temperature (Figure 5). The other metal parameters lourds, and BTEX (Benzene, Toluene, Ethilbenzene and Xylenes) were analysed respectively by ICP-MS (Inductively Coupled Plasma Mass Spectrometry) and GC-MS (Gas Chromatography–Mass Spectrometry) at the CBG Laboratory. Water levels in the observation wells were measured usingan AGM piezometer (see Figure 3).



Figure 4. Smulti parameter wave Hanna HI-9829

3.6. Data analysis

ArcGIS 10.5 software was used to develop the water flow direction map. This software offers many potentialities for the manipulation, management, analysis and editing of spatial data. The hydrogeochemical facies were determined using the Piper diagram. Also called trilinear diagram, it allows to visualize the chemical composition of water samples in hydrogeological studies. In this work the Grapher software was used to draw the Piper diagram.

4. Results and Discussions

4.1. Groundwater flow direction

The measurement of the water level of the water in the well is the main operation of the inventory of the groundwater resource in a given land. It copes with the highest level of water in natural equilibrium in control wells [13].

Figure 6 shows the map of the direction of water flow in the study area. The analysis in Figure 6 shows that the general direction of water flow is dispersed. The flows at Boundou Wandé are from the center of the plateau to the north and that at N'Dangara is from the center to the south and southwest. It can be seen that the direction of groundwater flow reflects on the whole the relief of the deposit conditioned by its geomorphological framework.

According to the surveys (measurements) carried out during the study period on the seven water points, the depth of the water in relation to the ground varies from 13 to 21 meters as observed in Figures 7 to 9. Groundwater thicknesses range from 1.09 m (MW18 well) to 17.39 m (MW15 well). This low thickness at the MW18 well is due to its positioning (peak level) in relation to the recharge zone. As indicated in Trépanier's work [14], hydraulic gradients are well correlated with the topography of the terrain.

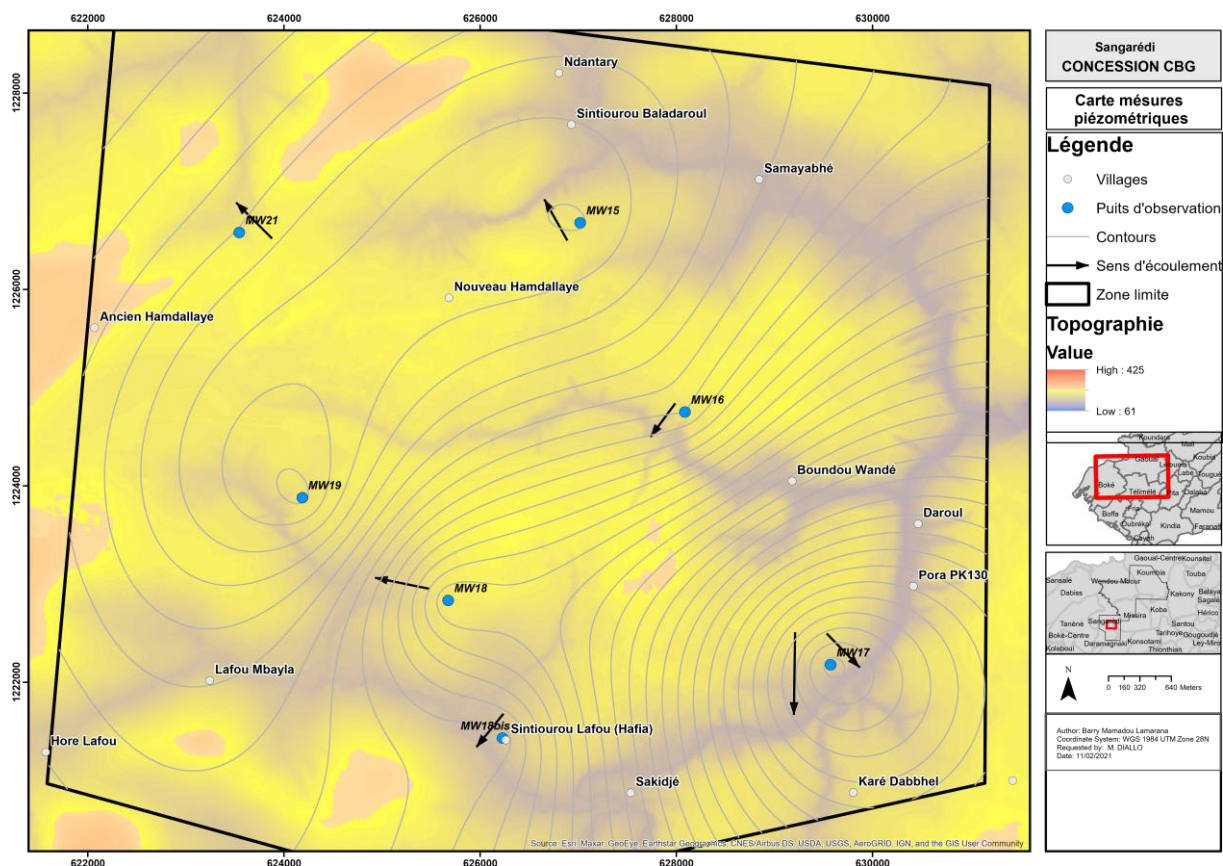


Figure 5. Study Area Water Flow Direction Map

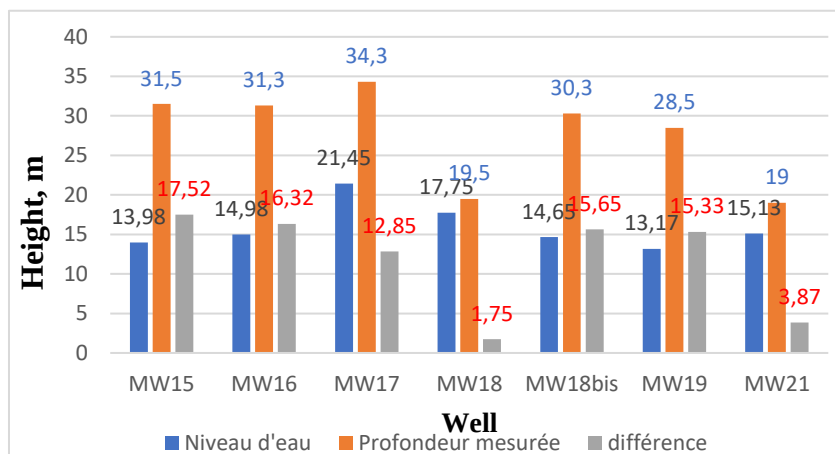


Figure 6. Measured February 21, 2020

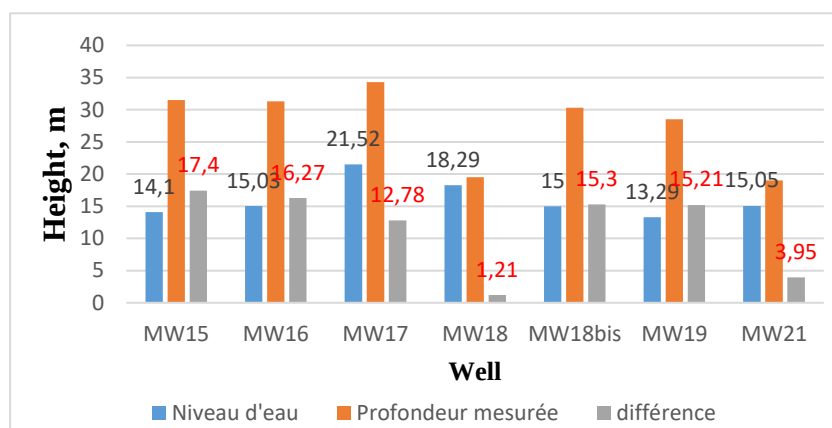


Figure 7. Measured March 03, 2020

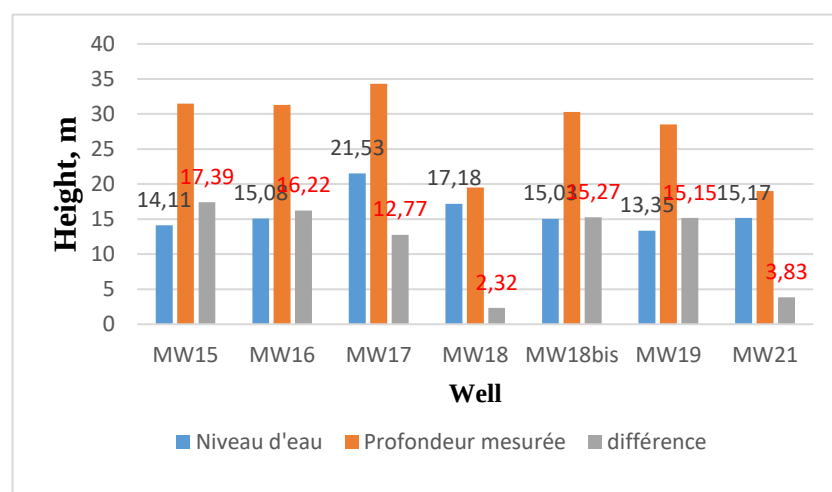


Figure 8. Measured March 18, 2020

In Figure 10, we observe that the variation in the level of groundwater on the N'Dangara and Boundou Wandé plateaus gradually decreases compared to the progress of the dry season.

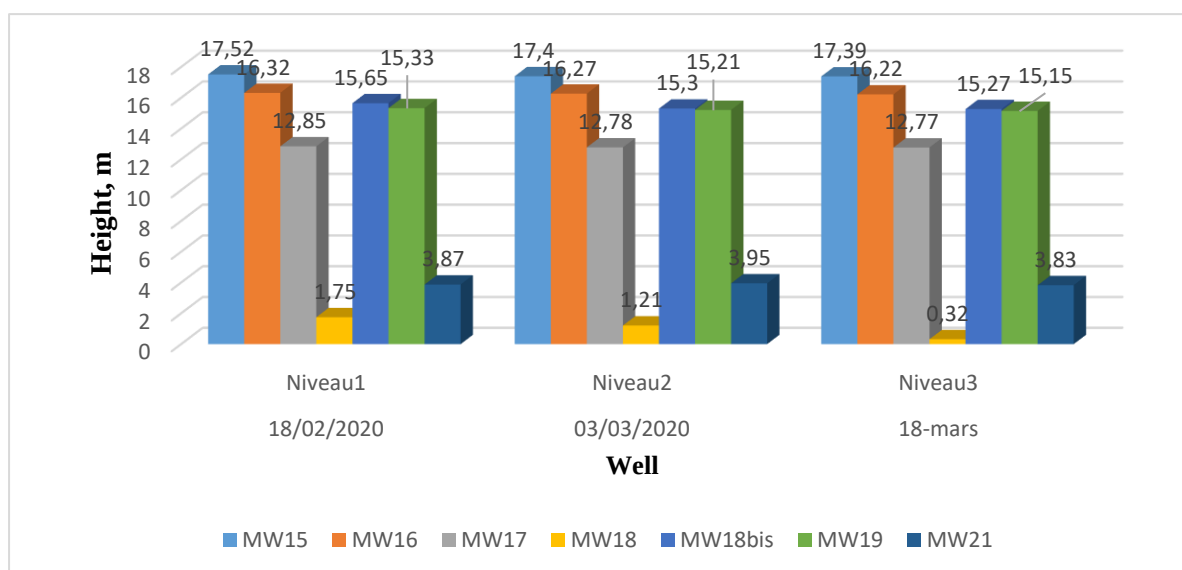


Figure 9. Comission of campaign measures

4.2. Physical parameters

The following physical parameters (pH, temperature and electrical conductivity) were determined and compared to WHO drinking water quality standards.

4.2.1. Temperature

The groundwater temperature measured on March 18, 2020 over the entire study area ranged from 29.5°C in the MW16 well in Boundou Wandé to 34.6°C in the MW18bis well in N'Dangara, Figure 11. This variation can be assumed to be normal in the context of Sangarédi where the temperature varies from 27°C to 40°C in March. In other words, the temperature of groundwater is related to the ambient temperature. The work of Derwich et al. [15] and Akil et al. [16] respectively showed that groundwater temperature is a function of the ambient temperature of the study area.

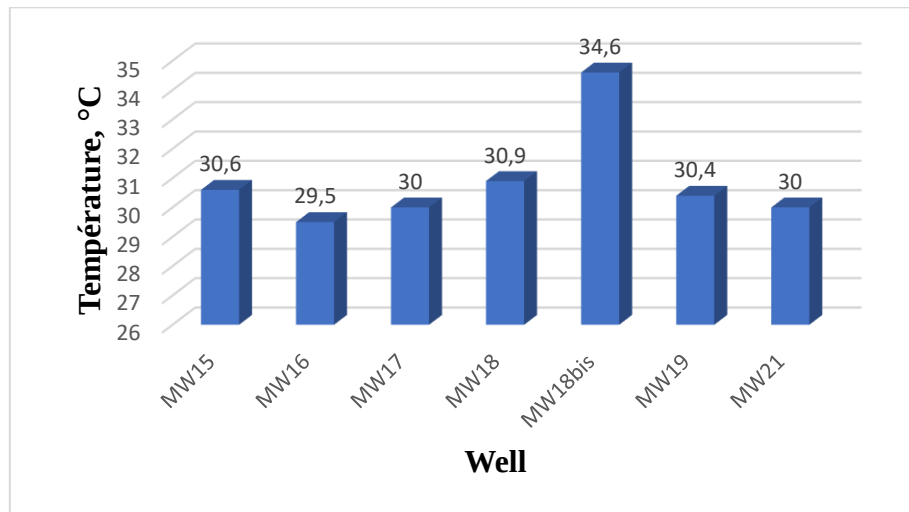


Figure 10. Variation in the temperature of groundwater in the Boundou Wandé and N'Dangara

4.2.2. Hydrogen potential (water pH)

The pH of the water provides information on its acidity and alkalinity. Usually, pH values are between 6.5 and 8.5 in natural waters [17] and between 6.5 - 9.5 according to the WHO. The pH of groundwater in the study area varies between 4.84 and 6.49 (see Figures 12), an average of 5.39. Indicated in the work of [18], the acidity of the waters does not affect its consumption by the population but it can be corrosive.

In accordance with the above-mentioned standards, the water from the wells in the study area has acidic pH. Indeed, the MW15, MW16, MW17, MW18 and MW21 wells located respectively on the Boundou Wandé plateau and southeast of N'Dangara, have the lowest pH, between 4.84 and 5.13 (see Figure 12).

This may be due to the presence of quartz sandstones in the area. Wells MW18bis and MW19, located south and west of N'Dangara, respectively, have relatively high pH values between 6.25 and 6.49. The relatively high pH would be due to the low presence of sandstones in N'Dangara. The acidity of groundwater according to Ahoussi et al. [19] is one of the characteristic features of groundwater. Indeed, in tropical areas, this acidity would come mainly from the decomposition of plant organic matter, with the production of CO₂ in the first layers of the soil [20]. As indicated in the work of Nouayti et al. [21], the acidity of groundwater is generally due to the nature of the land crossed.

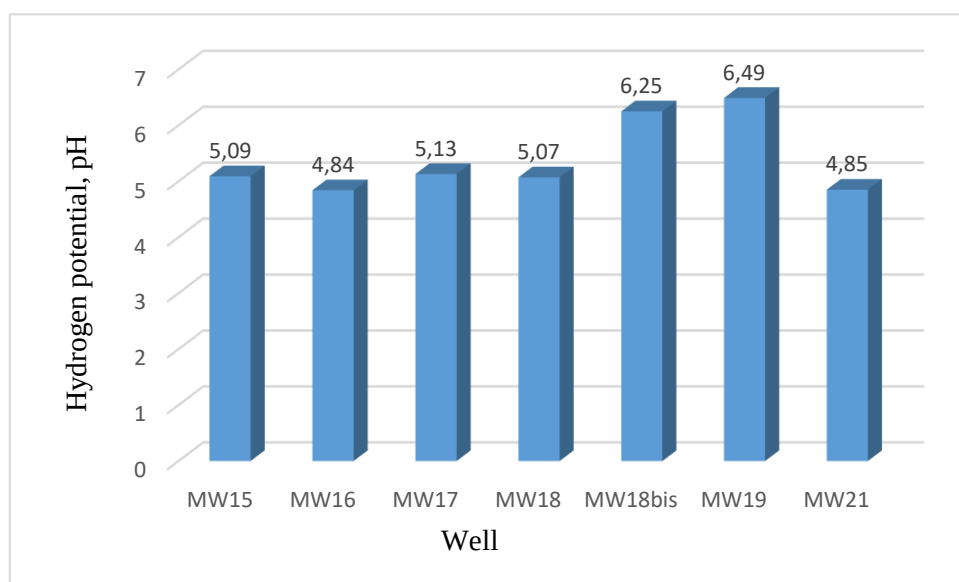


Figure 12. Change in pH in the waters of the study area

4.2.3. Electrical conductivity

Electrical conductivity is used to assess the number of salts dissolved in water and gives an assessment of its mineralization [22]. A high conductivity testifies to a very large number of dissolved salts. Electrical conductivity depends on charges of endogenous and exogenous organic matter, generating salts after decomposition and mineralization [22].

The electrical conductivities of the water of the seven wells range from 0.02 to 0.17 mS/cm (Figure 13). The value of the electrical conductivity of the various control wells is below the WHO standard for the quality of drinking water (2.5 mS/cm). The waters of the bauxitic plateaus of Boundou Wandé and N'Dangara are of very good quality with maximum conductivity of 170 μ S/cm.

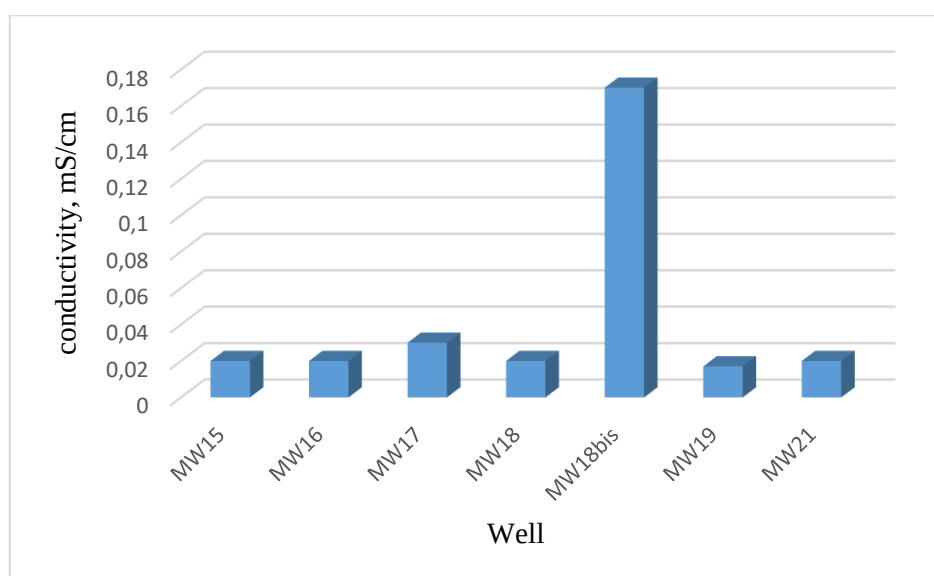


Figure 13. Electrical conductivity

4.3. Chemical parameters

4.3.1. Dissolved metals

The chemical analysis of metals is given in Table 2. For the qualification of these results, they were compared to WHO standards in its review of guidelines for drinking water quality. The calcium magnesium and manganese contents are the highest and vary respectively between: Ca (610 to 12000 µg/l), Al (15 to 31 µg/l), Mg (290 and 6400 µg/l) and Mn (11 and 230 µg/l). The heavy metal chemical composition As, Cd, Cr, Co, Cu, Hg, Ni, Pb, Se and Zn of the seven wells remains below the reported detection limit (Table 2). The standard for Al allowed in drinking water is 0.2 mg/l, or 200 µg/l as shown in Table 2. In this sense, we can say that the presence of Al in the water of the various control wells is significantly lower than the maximum value of the standard. This leads to the conclusion that the waters of the area are drinkable. From the same perspective, all dissolved metals have a value below the WHO reference standard (Table 2).

Table 2. Mvices dissolved in groundwater (sample analysis results)

METALS ICP-MS	Units	Well							Norm from WHO	LDR
		MW15	MW16	MW1 7	MW1 8	MW1 8 bis	MW1 9	MW2 1		
Aluminium (Al)	µg/l	<10	<10	28	22	31	27	15	200	10
Silver (Ag)	µg/l	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	-	0.10
Arsenic (As)	µg/l	<0.30	<0.30	<0.30	<0.30	<0.30	<0.30	<0.30	10	0.30
Barium (Ba)	µg/l	6.3	9.8	2.1	3.3	3.2	18	7.0	300	2.0
Cadmium (Cd)	µg/l	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	3	0.20
Calcium (Ca)	µg/l	1800	4100	890	860	660	12000	610	75000	300
Chromium (Cr)	µg/l	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	50	0.50
Cobalt (Co)	µg/l	0.57	<0.50	<0.50	<0.50	0.69	<0.50	<0.50		0.50

Copper (Cu)	µg/l	<0.50	<0.50	0.60	<0.50	0.60	<0.50	<0.50	2000	0.50
Tin (Sn)	µg/l	<1.0	<1.0	3.3	3.5	3.6	3.6	<1.0		1.0
Magnesium (mg)	µg/l	1600	3400	650	400	290	6400	340	50000	100
Manganese (Mn)	µg/l	230	190	23	22	14	100	11	500	0.40
Molybdenum (MB)	µg/l	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	70	0.50
Mercury (Hg)	µg/l	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	1	0.10
Nickel (Ni)	µg/l	1.4	4.5	2.0	<1.0	1.5	<1.0	<1.0	20	1.0
Lead (Pb)	µg/l	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	10	0.10
Selenium (Se)	µg/l	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	10	1.0
Zinc (Zn)	µg/l	8.6	<5.0	<5.0	<5.0	22	<5.0	8.8	3000	5.0

4.3.2. BTEX

The benzene, toluene, ethylbenzene and xylene composition (BTEX) of the waters of the seven (7) wells is given in Table 3. These values are well below WHO standards. The BTEX values in the waters of all control wells are almost all below the reported detection limit values (Table 3). So, we can say that these elements do not have a major influence on the potability of the water of these two plateaus as indicated in the work of Bellenfant et al. [23].

Table 3. Les BTEX per GC/MS (groundwater)

Parameter	Units	Well								LDR
		MW15	MW16	MW17	MW18	MW18 BIS	MW19	MW21	WHO Standards	
Benzene	µg/l	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	10	0.20
Toluene	µg/l	0.12	<0.10	<1.0	<1.0	<1.0	<1.0	<0.10	700	0.10
Ethylbenzene	µg/l	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	300	0.10
Xylenes	µg/l	<0.40	0.98	<0.40	<0.40	<0.40	<0.40	<0.40	500	0.40

4.3.3. Conventional parameters

Dissolved organic matter (MOD) refers to a complex and heterogeneous set of organic macromolecules formed by the degradation of animal or plant biological material of terrestrial or aquatic origin [24]. In Table 4, the value of dissolved organic matter is well below the WHO standard. This indicates that these waters are not toxic for consumption and do not harm human health.

Table 4. Conventional parameters (groundwater)

Parameter	Units	Well							WHO Standards	LDR
		MW15	MW16	MW17	MW18	MW18 BIS	MW19	MW21		
Dissolved organic carbon	mg/L	0.34	0.30	<0.20	<0.20	0.24	0.33	0.29	25	0.20
Total alkalinity (caCO ₃) pH 4.5	mg/L	13	52	6.9	11	4.7	76	5.3	-	1.0
Chlorides (Cl)	mg/L	0.64	0.68	0.22	1.0	0.41	0.42	1.2	250	0.050
Sulphates (SO ₄)	mg/L	<0.50	1.4	<0.50	0.70	<0.50	1.3	<0.50	250	0.50
Total dissolved solids	mg/L	<10	37	35	24	35	160	<10	600	10

According to Nouayti et al. [21], chlorides are important inorganic anions contained in varying concentrations in natural waters, usually in the form of sodium chloride (NaCl) and potassium chloride (KCl). Looking at Figure 14, it can be seen that the ions are more concentrated in the north-west and south-west parts where the concentrations are greater than or equal to 1 mg/l. Despite this, chloride levels are well below the WHO standard (see Table 4).

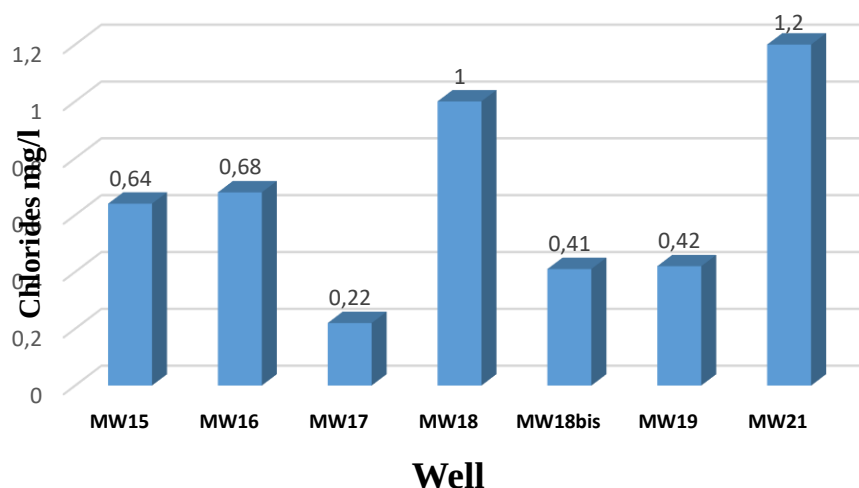


Figure 14. Chloride variation

The assessment of groundwater quality is carried out by studying the pollution parameters, then by interpreting the overall quality on the basis of a simplified grid (Table 5) comprising two parameters indicative of physico-chemical pollution [21], these parameters are:

- Electrical conductivity, which provides information on the mineralogical quality of water;
- Chloride ions that provide information on the mineralogical quality of water.

All the waters of the study area are generally of good quality, this quality status is due to:

- At mineralization, with a maximum recorded value of 170 $\mu\text{S}/\text{cm}$ (very good quality);
- Chloride contents 12 mg/l (very good quality).

Table 5. Simplified grid for the assessment of overall groundwater quality [21]

Appreciation	Parameters	
	Electrical conductivity ($\mu\text{S}/\text{cm}$)	Chlorides (mg/l)
Excellent	<400	<200
Good	400-1300	200-300
Average	1300-2700	300-750
Bad	2700-3000	750-1000
Very bad	>3000	>1000

4.4. Hydrogeochemical facies

Analysis of the chemical results (cation and major anion) by the hydrochemical method that uses the triangular Piper diagram shows that groundwater has different facies [25]. Figure 15 shows the hydrogeochemical facies of the waters of the seven wells on the Piper diagram. The Piper diagram is an indispensable diagram for the determination of hydrogeochemical facies of groundwater [26]. It shows the relative concentration of the different ions from the individual water samples [27]. After calculating the relative concentrations in (meq%), these values were projected onto the Piper diagram. The analysis of the Piper diagram shows that the groundwater of the N'Dangara and Boundou Wandé plateaus is essentially divided into two large hydrogeochemical facies. The waters of the MW18bis, MW19 and MW21 wells are bicarbonate, calcium and magnesium with 42.86%, while the MW15, MW16, MW17 and MW18 wells are carbonate, sodium and potassium facies with 57.14%. The reporting of the results of the analyses of the waters of the aquifers on the triangular piper diagram (Figure 15), highlights the impact of the lithological facies on the quality of the waters and also makes it possible to estimate the percentages of the chemical elements and their classification [28]. Bicarbonates can intervene during the recharge period of the aquifers [29]. Bicarbonates are produced following the contribution of CO_2 by infiltration which, by hydrolysis reaction, allows on the one hand the formation of HCO_3^- and on the other hand the increase in pH assuming an evolution in a closed environment [30].

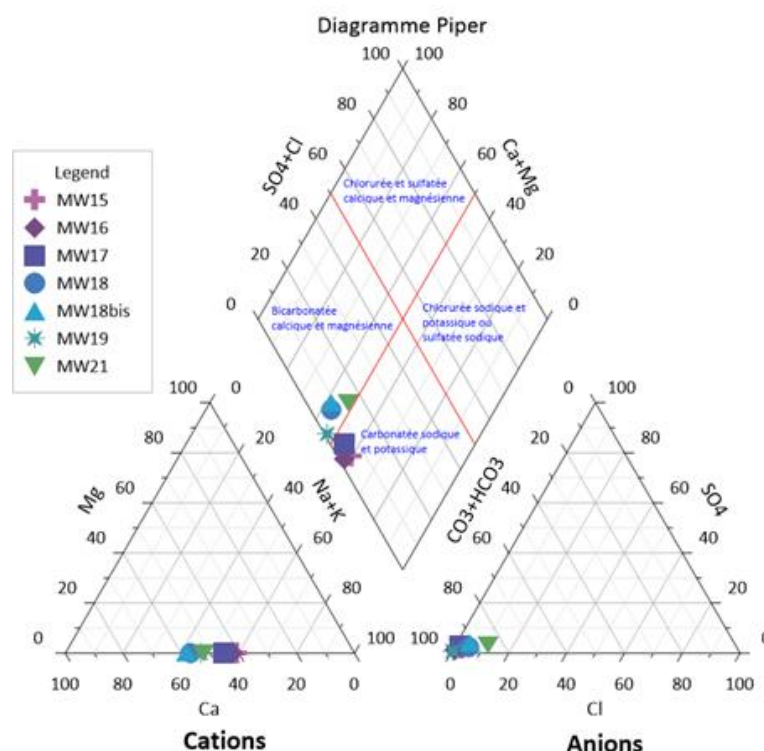


Figure 15. Hydrogeochemical facies of the wells of the N'Dangara and Boundou Wandé plateaus

5. Conclusion and outlook

The objective of this work is to analyze the quality of drinking water in the riparian areas of the bauxitic plateaus of N'Dangara and Boundou Wandé in operation by CBG. The geology of the study area consists mainly of sedimentary formations of the Devonian, Neogene and Quaternary. Hydrogeologically, the study area has been the subject of several works. These studies reveal that the behavior of the aquifer is due to the sudden change in rock permeability that occurs from the hard rocks of the lateritic cover to the underlying clays, which plays the role of a relatively impermeable layer. During the study period we carried out three water measurement and sampling campaigns on the two plateaus. Analysis of the groundwater flow direction map shows that the general flow direction of groundwater is dispersed. The flows at Boundou Wandé are from the center of the plateau to the north and that at N'Dangara is from the center to the south and southwest. It can be seen that the direction of groundwater flow reflects overall the relief of the deposit conditioned by its geomorphological framework. Analysis of the physical parameters showed that the temperature varies between 29.5 and 34.6°C, the very low electrical conductivity, all values of which are less than 0.2 mS/cm and the pH of all the wells on the N'Dangara and Boundou Wandé plateaus below the WHO normal value.

The results of chemical analysis showed that the heavy metal composition as well as the BTEX are below WHO standards. Analysis of the Piper diagram showed two hydrogeochemical facies (calcium and magnesium bicarbonate facies and sodium and potassium carbonate facies).

It emerges from the analysis of physical and chemical parameters that well water is consumable. However, the water from wells MW15, MW16, MW17, MW18 and MW21 with a low pH (4.84 to 5.13) could present a certain nuisance for its consumption and because it can be corrosive.

From our point of view, it is fair to say that no work ever covers the entire research that the researchers planned to cover when they started the project. The same applies to this research. The hydrochemical characterization of groundwater is generally based on the availability of a large amount of physico-chemical data.

The main limitation of this study is due to a lack of hydrogeochemical data over a long period of time. The conclusions of this study would therefore require further study confirming or refuting assumptions related to water quality, and the direction of groundwater flow. However, the knowledge generated, as well as the data and methodological approaches of this study, will be a guideline for future research.

For a detailed analysis of water quality in the study area, monitoring and analysis should be performed over a longer period of time. The minimum duration of such monitoring should be one year in order to obtain a set of data or trends that confirm the reliability of the research. The installation of additional observation wells to monitor groundwater quality and flow direction would also make the data obtained more consistent.

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