RESEARCH ARTICLE

HYDROGEOCHEMICAL CHARACTERISTICS OF THE QUATERNARY AQUIFER OF BONGOR AND ITS SURROUNDINGS (MAYO-KEBBI-EAST, CHAD)

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ABSTRACT

The Bongor region, located between 10°12' and 10°20' North latitude and 15°22' and 15°34' East longitude, is part of the quaternary aquifers of Chad. It has potential in water resources but knowledge of its hydrodynamic and hydrogeochemical functioning remains insufficient. Thus, this study aims to gain knowledge of the hydrogeochemistry of groundwater in the Bongor area and its surroundings. The hydrogeochemical methods adopted are based on the Piper diagram, Gibbs diagram, descriptive statistical analysis and Principal Component Analysis that can characterize these waters and understand their evolution. The piezometric map shows a direction of groundwater flow from southeast to northwest. A total of 25 samples of water points (well water, borehole water and surface water) were subjected to physicochemical analyses. The results of these analyses showed that all the waters measured have an acid pH tending towards neutrality and an average temperature of 31.6°C. The waters are generally not very mineralized, with an average conductivity of 173.71 μS/cm. The hydrogeochemical study shows an evolution from calcic and potassic bicarbonate facies to calcic and magnesian bicarbonate facies. It indicates that the groundwater is of evaporitic origin and hydrolysis of minerals from precipitation.

INTRODUCTION

Groundwater is considered, like air, as one of the essential factors of sustainable development (Herischen *et al*., 2002). Used in various fields such as industry, agropastoral and consumption, the demand for water is increasing nowadays, as an inevitable result of population growth and socio-economic development (Blinda and Thivet, 2009). Thus, the sustainability of water is based on its knowledge for an informed management. Groundwater composition is modified by the phenomenon of oxidation and precipitation of certain chemical elements that often occurs when the piezometric level drops (Temgoua *et al*., 2005). Sub-Saharan Africa is a semi-arid region where water resources are likely to change dramatically under the influence of climate fluctuations or human actions (Cudennec *et al*., 2007). These changes can affect groundwater stocks (Idder 2007), which are often significantly reduced, but also their quality (Karaoli *et al*., 2008). Although the Bongor region has significant water resources, due to its strategic location (as a crossroads), it faces enormous difficulties ranging from lack of water quality assurance to human actions (overexploitation of groundwater, agropastoral activities, overpopulation, etc.). In recent years, rice cultivation projects have been directed towards this area, from which large volumes of water are injected into the Bongor A and B basins (NEPAD, 2005). The use of fertilizers or pesticides could have an influence on the quality of these waters. Previous work done in this region, speaking of the characterization of aquifers (Rondouba, 2013)

and the work of the piezometric study of Chari-Logone (Djoret, 2000) do not provide clarity on the recharge areas of the waters of the Bongor region. Work done in the Yaere area, part of which is in Bongor, indicates that the area had high water availability in the 1950s but has experienced irregularities in recent years (Ngounou Ngatcha, 1993). As well as the work of Abderamane (2012) affirm the irregularities of rainfall in the basin regions over the last ten years. In view of these problems, it is important to have an idea of the hydrochemical process of water in order to better manage it.

MATERIALS AND METHODS

Presentation of the study site: The study area, located in southwestern Chad, is bordered to the northwest by the town of Yagoua in Cameroon. Geographically, this region is located between 10°12' and 10°20' North latitude and 15°22' and 15°34' East longitude (Figure 1). It covers an area of 939 km2. The climate is predominantly Sudano-Sahelian and is characterized by a five to six month rainy season (May-October) and a dry season (November-April). Average annual rainfall in this study area is between 700 and 800 mm with average annual temperatures of around 29°C (ANAM, 2021). The area is drained mainly by the Logone River, which sometimes meanders due to the flatness of the terrain. The geological formations (Figure 2) represented in the Bongor Basin are fluvio-lacustrine or fluvial, deposited during the transgressive or regressive phases of Lake Chad (Pias, 1968). Several formations are represented according to age and mode of deposition:

- Tertiary sedimentary formations corresponding to the Terminal Continental, consisting of sandy, sandstone, and kaolinite deposits. They were deposited during the first transgression of Lake Chad and form flattened sandy mounds in the northeast part of Bongor (SDEA, 2002).
- the ancient sandy-clay formations recognized at the beginning of a new pluvial (second transgression of Lake Chad) with often poorly sorted sands, are found in the marshy areas.
- The ancient fluvial formations deposited in the flooded areas following the flooding of rivers are clayey or sandy on the right bank of the Logone. They form oriented sandy mounds.
- The present fluvial formations, finely sandy-silty or silty, have an extension limited to the edges of the watercourses (bank bulges).

Hydrogeologically, the study area is part of the southern sedimentary basin of Chad called the "Chari-Logone Basin". The types of aquifers distinguished are the continuous aquifers where the generalized water table exists and the deep aquifers (Pias, 1968). The Quaternary aquifer constitutes the most remarkable hydrogeological unit and excellent aquifer reservoirs in the study area and in the entire Chadian basin (Mahamat Nour *et al.*, 2022). It is continuous from Yagoua to the outskirts of Lake Chad (Ngounou-ngatcha *et al.*, 2001).

Data: The data considered in this study are the water samples. This study was carried out on the basis of the analysis of physico-chemical parameters measured in-situ (pH, Temperature and Electrical Conductivity) and chemical parameters measured in the laboratory.
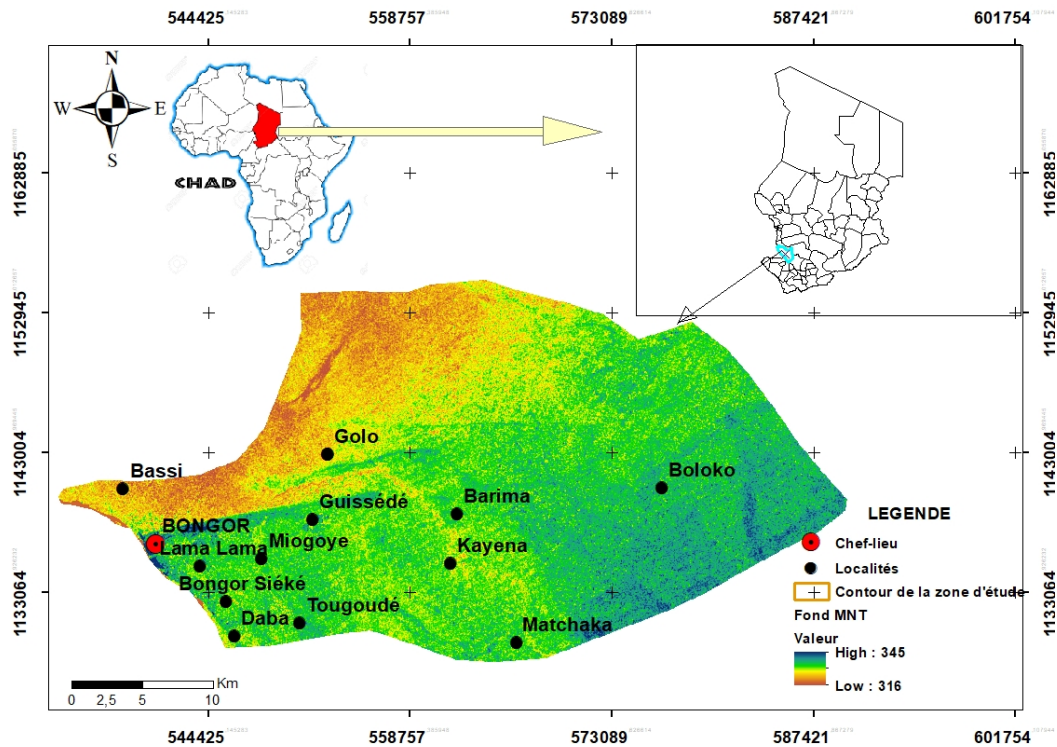

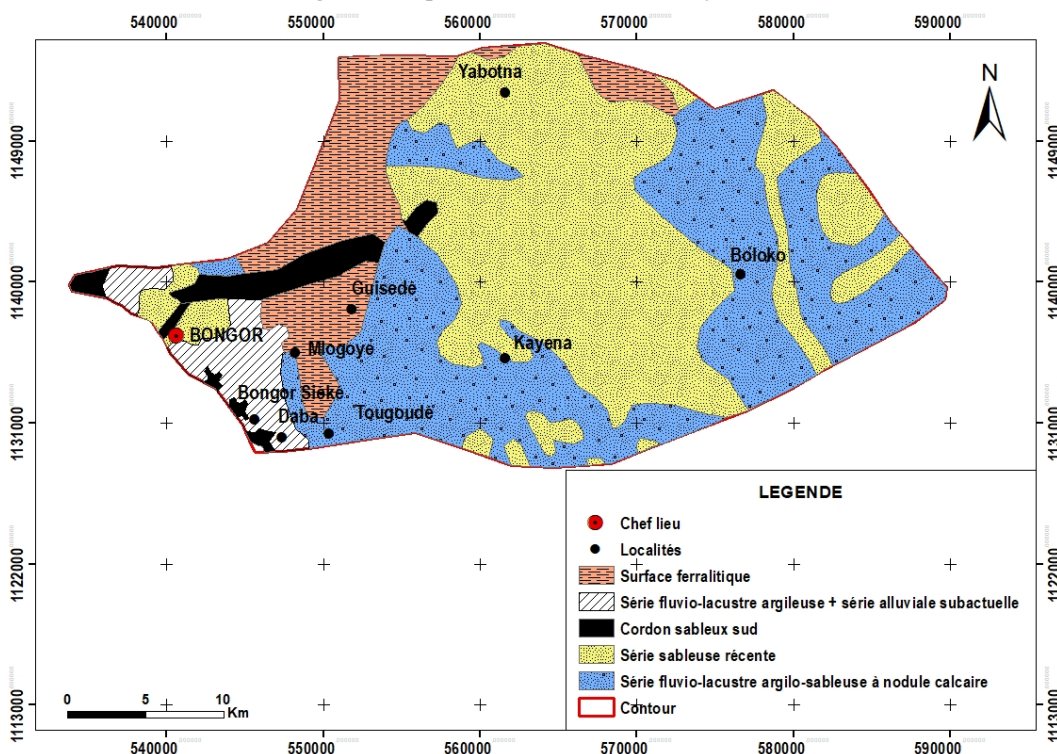**Figure 1. Map of the location of the study area**

Figure 2. Geological sketch of the study area (after Pias, 1970, modified)

The chemical analyses concern turbidity, total hardness, concentration of nitrates, sulfates, phosphates, chlorides, bicarbonates, calcium, magnesium, potassium and sodium, present in the water. The water sampling mission was conducted during the low water period in April 2021. Water samples were collected for analysis from surface water, well water and water from human powered boreholes. A total of 25 water samples were taken, 4 from boreholes, 20 from wells and one from the Logone River. In the case of the borehole water samples, we first eliminated the stagnant water in the pipes by pumping at a maximum flow rate for 3 minutes before proceeding with the sampling. At the National Water Laboratory of the Ministry of Hydraulics and Water in N'Djamena, where our chemical analyses were performed, different methods were adopted for the determination of chemical elements. Sodium and potassium were determined by the flame photometer, the complexometric method was used for calcium, magnesium and total hardness. Nitrates, sulfates and phosphates were determined by the Spectrophotometer, titration for bicarbonates and carbonates. The indicator potassium chromate titrated with silver nitrate is used for chlorides.

Data processing: For the processing of our analytical results, the descriptive analysis of the data based on the determination of the minimum and maximum values and the average allowed us to compare our values to other works. For the hydrochemical method, we used the Piper Diagram software to determine the different chemical facies of the groundwater of the Bongor aquifer and their interpretation. By means of the Gibbs diagram, the accuracy of the source of mineralization of the water is identified. Finally, Principal Component Analysis (PCA) was used to perform a multidimensional descriptive analysis to establish a correlation between chemical variables.

RESULTS

Physico-chemical parameters of groundwater: The results of the physico-chemical parameters are summarized in the table in Appendix 1. These values are particularly variable from one to another. They concern the following parameters: pH, temperature, total dissolved solids and conductivity. In order to facilitate understanding, the statistical analysis of these results are shown in Table 1.

of 5.88. Well and borehole water temperatures range from 25.8°C to 34.8°C. The average groundwater temperature is 31.6°C. TDS values observed in the area range from 74.97 ppm and 208.3 ppm in wells and 59.37 ppm and 823.3 ppm in boreholes with an average of 279.18 (ppm). The majority of the waters in the study area have very low TDS levels.

Chemical parameters of water: The chemical elements of the water found include the following major cations and anions: calcium, magnesium, potassium, sodium, bicarbonate, sulfate, nitrate, and chloride (Table 2). In the boreholes, calcium levels vary from 13.2 mg/l to 125.6 mg/l, magnesium from 0.9 mg/l to 10.7 mg/l, potassium from 1.4 mg/l to 56 mg/l and sodium from 8 mg/l to 25 mg/l. At the level of the wells, the proportions are as follows: from 4.1 mg/l to 36.8 mg/l for calcium, from 0.2 to 24.3 mg/l for magnesium; 0.4 to 16 mg/l for potassium and finally sodium has levels that range from 3 to 66 mg/l. Bicarbonate levels in the boreholes range from 45.9 to 219.6 mg/l. Sulphates vary from 0 to 56 mg/l. Nitrate concentrations range from 4 to 10 mg/l and chlorides from 15 to 40 mg/l. In the wells, the following values are recorded: from 14.6 mg/l to 268.4 mg/l for bicarbonates, from 0 to 62 mg/l for sulphates; 2 to 15mg/l for nitrates and finally chlorides have levels that vary from 1.1 to 35mg/l.

Hydrochemical classification of waters: The analytical results of the water samples reported in the Piper diagram (Figure 3), show two facies, namely: the calcic and magnesian bicarbonate facies and the sodium and potassium bicarbonate facies.

Assumptions of water mineralization

Gibbs diagram: To try to explain the source of mineralization of our waters, the Gibbs diagram (figure 4) and the Principal Component Analysis (figure 6) and table 5 allowed us to identify the mechanisms of geochemical evolution and their origin.

Distribution of chemical elements: The distribution of chemical elements in the wells and boreholes are shown in Figure 5.

Principal Component Analysis (PCA): Principal component analysis (PCA) is one of the most widely used statistical methods today to solve some of the hydrochemical problems that govern the overall mineralization of groundwater (Kadjangaba *et al.*, 2018).

Tableau 1. Descriptive statistics of physical data

	Actifs	pH	T (°C)	TDS (ppm)	CE (µS)	Puits
Min	20	8,33	31,7	74,97	37,51	
Max	20	9,52	32,4	208,3	103,7	
Moy	20	8,887	32,12	148,26	74,17	
Ecart-type	20	0,45	0,27	58,58	29,28	
Min	4	7,53	25,8	59,37	29,8	Forage
Max	4	12,19	34,8	823,3	854,6	
Moy	4	9,40	31,24	410,10	273,33	
Ecart-type	4	0,93	1,11	220,64	164,29	
Moy	1	5,88	32	59,37	29,8	Logone

Tableau 2. Statistics of chemical analysis

	Numbers amples	Turb. (NTU)	CaCO3 (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	K^+ (mg/l)	Na^+ (mg/l)	HCO_3^- (mg/l)	SO_4^- (mg/l)	NO_3^- (mg/l)	Cl^- (mg/l)	type of waterworks
Min	20	6,38	37,6	13,2	0,9	1,4	8,00	45,9	0,0	4,0	14,8	
Max	20	6,98	108	25,6	10,7	56	25	219,6	56	10	40	
Moy	20	6,64	57,2	17,1	4,675	15,47	14,75	110,8	15,3	7,5	24,2	Wells
STD	20	0,195	25,4	4,25	3,675	20,26	5,125	64,9	20,4	1,75	9,25	
Min	4	6,11	14	4,7	0,2	0,4	3,0	17,1	0,0	2,0	1,1	
Max	4	6,99	220	48	24,3	16	66	268,4	62	15	53	
Moy	4	6,612	78,85	19,88	7,075	3,44	23	96,60	11,5	7,6	22	Drilling
STD	4	0,222	47,35	9,2735	6,115	2,312	11,2	57,835	12,4	2,62	9,5	
Moy	1	1,0	12	4,1	0,4	0,6	6,0	14,6	0,0	7,0	5,0	Logone

Based on the results obtained, it can be observed that the pH values of the waters measured in the area are generally not very variable. They range from 6.38 to 6.98 with an average of 6.64 in the boreholes; 6.11 to 6.99 in the wells with an average of 6.58. Surface waters have a pH

The correlation matrix is a table that visualizes the set of correlation coefficients between variables at the intersection of rows and corresponding columns using the XLSTAT 2022 correlation tool in

Excel. The analysis of Table 3 reveals the following observations between the items:

- Satisfactory correlation: Ca and CaCO3, Na and CaCO3, Ca, Mg; HCO3 and Ca, Mg; Na and Mg; Cl and HCO3 ;
- Less satisfactory correlation : Ca and pH; HCO3 and pH, CaCO3,Na; SO4 and CaCO3, Ca, Mg, HCO3; Cl and pH, Ca, Mg, Na, SO4, As well as the elements : CaCO3 and pH, TDS, Ca and TDS, Mg and TDS, Na and TDS; SO4 and pH, CaCO3, K and Na.
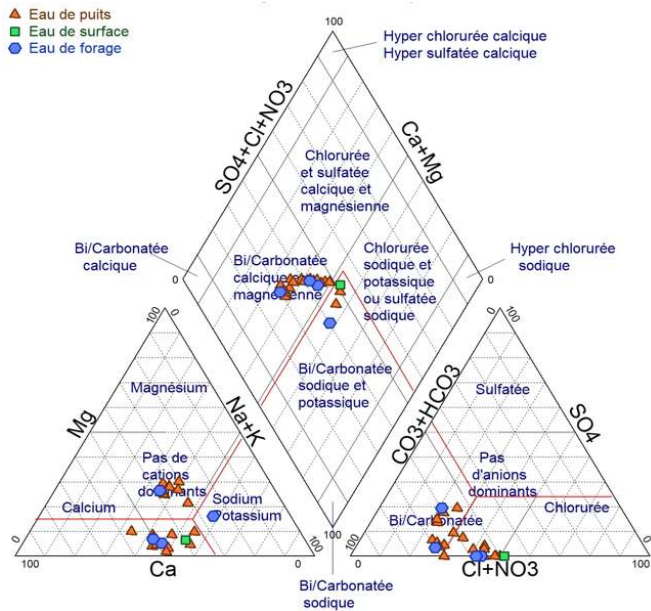

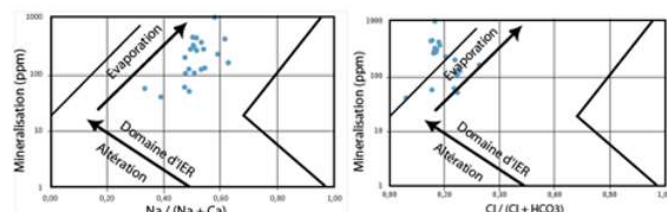**Figure 3. Piper diagram showing hydrogeochemical facies**

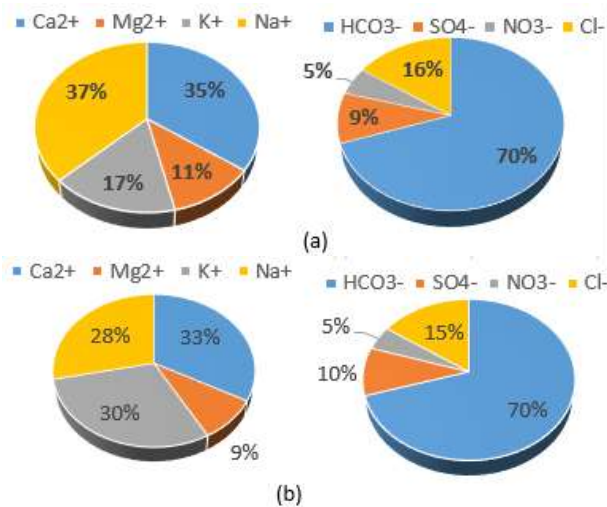**Figure 4. Gibbs diagram of groundwater**

Figure 5. Spatial distribution of cations and anions in wells (a) and boreholes (b)

Based on the factor analysis of the XLSTAT 2022 software, the different chemical constituents of the waters were highlighted. The

eigenvalues (7.46; 1.87), percentage variance (53.29; 13.38) and cumulative percentage variance of the factors (53.29; 66.68) are given in Table 4. The projection of the variables on the axes (Figure 6) also allows us to identify the correlations between the elements.
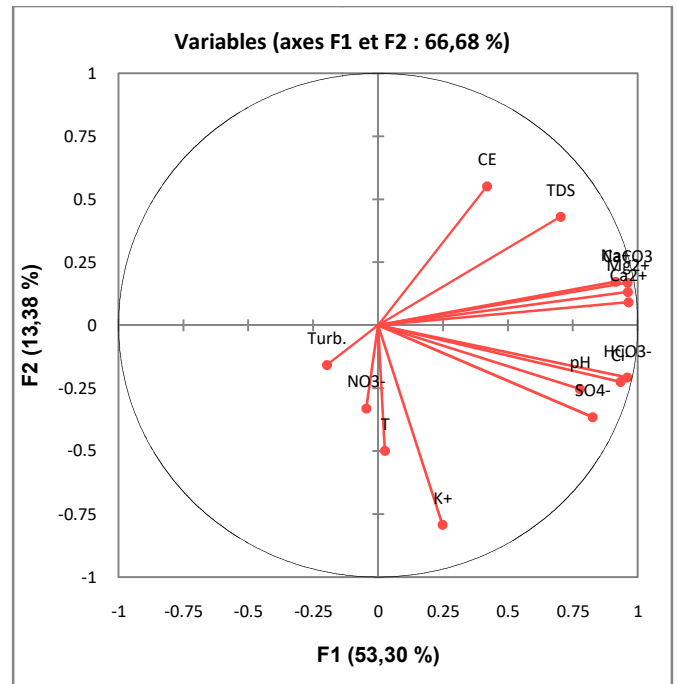

Figure 6. Projection of the variables in the correlation circle

The contribution of the different variables in defining the main factors is given in Table 4. Each factor is defined by a number of essential variables in the highlighting of the mechanism of mineralization of water. The first factor F1 (which represents 53.296% of the total variance) groups together electrical conductivity, Calcium, Chlorides, Sulphates, Sodium and Alkalinity. This factor appears as an axis of overall water mineralization. The five chemical elements that define the F1 factor, present more or less significant correlations between them (figure 6). Thus, there is a good correlation between alkalinity and calcium, and a more moderate correlation with sulfates, sodium and chlorides. This factor includes most of the chemical elements of natural origin. The F2 factor (13.38%) includes NO3-, K+ and turbidity ions. In our context, the presence of nitrates in the water is due to anthropic pollution. This corroborates with the results of Djoret and Travi, (2001), Stadler *et al*, (2008), Foster *et al*, (2011), Minda, (2016).

DISCUSSIONS

The pH values of groundwater in the study area measured are mostly acidic to neutral. In the shallow aquifers, the values range from 6.38 to 6.98 with an average of 6.64; while in the deep aquifers, they range from 6.11 to 6.99 with an average of 6.58. In general, the waters have an average pH of 6.55. This shows the acidity of the waters in the majority. The acidity of the water is thus linked to the dissociation of carbonic acid from atmospheric CO2 solubilized in water, and to that of humic and fulvic acids released during the degradation of soil organic matter (Ndembo, 2009). There is little variation in pH values in aquifers. For slightly acidic to neutral pH values. These variations would be due to the nature of the geological formations (sands) crossed. Acidic groundwater with a medium pH, are characteristic of sandstone aquifers and purely siliceous sands (Bakalowicz, 1979). The high pH values, are observed in the water points ECHF1BON, ECH4BON, ECH6BON, ECH7BON and ECH15BON could be explained by the statement of Fréderic (2000) and Schuster *et al*., (2016) that the increase in pH would be due to a progression of the water facies from calcic bicarbonate to sodium bicarbonate.

Tableau 3. Correlation matrix of chemicalelements

	pH	T	CE	TDS	CaCO3	Ca2+	Mg2+	K+	Na+	HCO3-	SO4-	NO3-	Cl-
pH	1,00												
T	0,30	1,00											
CE	0,35	-0,19	1,00										
TDS	0,39	-0,14	0,53	1,00									
CaCO3	0,69	-0,01	0,40	0,69	1,00								
Ca2+	0,72	0,04	0,38	0,65	0,99	1,00							
Mg2+	0,68	-0,03	0,39	0,69	0,98	0,95	1,00						
K+	0,37	0,12	-0,18	-0,11	0,02	0,08	0,09	1,00					
Na+	0,59	-0,03	0,36	0,68	0,95	0,94	0,92	-0,06	1,00				
HCO3-	0,77	0,06	0,28	0,56	0,89	0,90	0,91	0,46	0,80	1,00			
SO4-	0,65	0,02	0,18	0,48	0,68	0,71	0,71	0,58	0,69	0,87	1,00		
NO3-	-0,08	0,08	-0,14	-0,05	-0,09	-0,05	-0,12	0,08	0,11	-0,07	0,14	1,00	
Cl-	0,71	0,09	0,21	0,52	0,86	0,88	0,87	0,42	0,84	0,95	0,82	0,01	1,00

Tableau 4. Matrix of the weight of different ions in groundwater

	F1	F2
pH	0,77	-0,25
T	0,02	-0,49
CE	0,41	0,55
TDS	0,70	0,43
Turb.	-0,19	-0,15
CaCO3	0,96	0,16
Ca2+	0,96	0,09
Mg2+	0,96	0,13
K+	0,24	-0,79
Na+	0,91	0,17
HCO3-	0,95	-0,20
SO4-	0,82	-0,36
NO3-	-0,04	-0,33
Cl-	0,93	-0,22
Valeur propre	7,46	1,87
Variabilité (%)	53,29	13,38
% cumulé	53,29	66,68

Well water temperatures in the area generally range from 25.8°C to 34.8°C with an average of 31.6°C. Temperature is an essential element that varies according to air temperature, seasons, geological nature and depth of water level in relation to the ground surface. They govern exothermic physicochemical reactions such as oxidation and reduction (Loukman *et al*., 2017). Based on the table in Appendix 1, conductivity values range from 29.28 µS/cm to 854.6 µS/cm with an average of 173.71 µS/cm for both aquifer types. The majority of the waters in the study area have low conductivity values. They are a very low in mineralization. This could testify the presence of formations containing low soluble rocks (sandy); because the sandy aquifer formations provide very low mineralized waters, therefore with low electrical conductivity (Moukandi, 2012). As for the measured values of total dissolved solids, they are in the range of 74.97 ppm and 208.3 ppm in the wells and 59.37 ppm and 823.3 ppm in the boreholes (Appendix 1). The average is about 279.18 ppm. These very low values obtained are characteristic of the sandy nature of the aquifer.

The mechanisms of hydrochemical evolution are governed by three essential parameters: atmospheric precipitation, hydrolysis by rock weathering, and evaporative concentration (Gibbs, 1970). Based on the Gibbs diagram (Figure 4), two main chemical facies emerged from the Piper diagram: (1) the calcium bicarbonate facies and (2) the sodium bicarbonate facies observed in the diagram. The hydrogeochemical study shows an increase in calcium, potassium, sodium, magnesium and bicarbonate ions. The first facies would indicate the presence of mineralization by water-rock interaction. This confirms the hypothesis of the low contribution of precipitation in the recharge of these aquifers. The high contents of calcium and sodium in the piper diagram would testify by the complex base exchanges that take place between these two ions within the clayey materials; while the excess of potassium compared to sodium would be explained by the high contents of potassium of the pre-existing rocks that have placed the sediments. This rationale also corroborates the assertion by Njonfang *et al*. of the calc-alkaline composition with a hyperpotassic tendency of the rocks of the Pan-African Range of Cameroon.

Excess bicarbonate ions may result from the alteration of certain minerals (feldspars, calcite...) or from the combination of atmospheric or soil carbon dioxide with water molecules during rainfall (Njueya, 2012). Thus, groundwater in the study area would be controlled by a combination of evaporation and mineral dissolution. Alternatively, the water points that came out of the diagram could be explained by other complex hydrogeochemical factors of shallow aquifers. This also corroborates with the study by Yao *et al*, (2020). The spatial distribution of ions (Figure 5) show that most groundwater samples are rich in calcium in the cation group. The order of abundance is: Ca2+ > Na+ > K+ > Mg2+ in well water and an order of: Ca2+ > K+ > Na+ > Mg2+ in boreholes. In the order of anion abundance, the bicarbonate ion is the dominant one for all groundwater. This order is as follows: HCO3- > Cl- > SO42- > NO3-. According to the Principal Component Analysis, Table 4 and Figure 6 and show the F1 and F2 axis at more than 66.68% the mineralization pole of the water. The clustering of the elements in pole shows a different evolutionary process than the others. The mineralizations would come from evaporitic origin. This confirms the assertions of Bahir *et al*, (2008) that chlorides are well correlated with sodium. The weak positive correlations probably reflect the heterogeneity of the sources and processes of mineralization acquisition (Ngouala, 2020).

CONCLUSION

This work focused on the evaluation of the hydrogeochemical characteristics of the waters of the quaternary aquifer of Bongor and its surroundings allowed to know the hydrogeochemical characteristics of the study area. Hydrogeochemically, the hydrochemical mechanisms evolve from sodium and potassium bicarbonate facies to calcium and magnesium bicarbonate facies. Groundwater is mostly weakly mineralized. The mineralization of well water is linked to bicarbonate ions, while deep groundwater has a weak mineralization dominated by calcium and sodium ions. The

analysis of major ions (cations and anions) has allowed us to understand the mineralization process of the waters. The mineralization would come from the dissolution-precipitation of the aquifer rock, evaporites and base exchange. Through factor analysis and correlation matrix, the results suggest the same processes listed above reflecting the mineralization of waters in our study area. That is, hydrolysis of silicates, cation exchange between water and clay minerals, and evaporation are the main actors. This work has contributed to characterize the aquifer from the hydrogeological and hydrogeochemical point of view.

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