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Hydrodynamic, hydrochemical and isotopic characterization of the waters of the quaternary aquifer of Bahr-El-Ghazal, north central Chad.

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Abstract

Located in the middle of the Sahel, the study area is an integral part of the Bahr-El-Ghazal region. It is crossed by a fossil valley, which has a geological history similar to that of rivers that disappeared under the influence of climate change where evaporation phenomena were intense. From the hydrogeological point of view, the free water table of this region is housed in sedimentary geological formations of different natures. It passes from the sand tablecloth to that of the fluviolacustrine clays. In some cases, the latter confer particularly bad chemical qualities to the water, even though groundwater is the main source of drinking water for the local population. For this reason, a study aimed at understanding the different mechanisms that govern the chemical functioning of the aquifer of the Bahar-El-Ghazal region has been carried out.

It is with this in mind that a piezometric study is being carried out in the first instance. This reveals the presence of some hydrodynamic anomalies. Thus, a shallow depth of the body of water is observed in the Harr and in the sandy formations of the extreme West. However, underground flows oriented from these two zones towards the central part characterize a deepening of the water level. Subsequently, a hydro-chemical study was undertaken. As regards the chemical facies, they also show an evolutionary character. They pass from calcium and magnesian bicarbonate facies to chloride or sodium and potassium sulphate facies in the piezometric depression. The values of the isotopic composition of the studied groundwater vary from -4.86 to 4.04‰ and -35.60 to 14.50‰ and **δ**2H respectively.

Keywords: Groundwater; Piezometric; Hydrochemistry; Isotopy; Bahr-El-Ghazal

1. Introduction

The Lake Chad basin, due to its geographical location in an arid and semi-arid zone, suffers from repeated droughts linked to rainfall deficits and resulting in the reduction of surface water bodies and groundwater resources (Lemoalle et al., 2012, Mahamat et al., 2017).

The Sahel and in particular Bahr El Ghazel shows a quasi-absence of permanent surface water resources due primarily to climate change in the increasing decrease of rainfall regime, high evaporation and the establishment of sand dunes (Bader et al., 2011; Lemoalle et al., 2012 and Bouchez et al., 2016).

In this sector of the Sahel, groundwater exploitation remains the only way to achieve drinking water satisfaction and occupies a primordial place in agro-pastoral activities (Bouchez et al., 2016).

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In recent decades, the Bahr El Gazel region has experienced strong population growth (260865 hbts, according to RGPH, 2009 with a growth rate of 2.6%) and a massive sedentarization of nomads in villages and urban centers. The movement of people and their animals as well as their activities could have an impact on available water resources and the infrastructure of installed hydraulic works. These changes could also have an impact on the degradation of groundwater quality.

Effective qualitative and quantitative management of groundwater resources requires a good understanding of the functioning of the reservoir being used, particularly in arid or semi-arid zones where the drop in rainfall weighs on the recharge of the water table. This would contribute to sustainable management.

The previous study by Schneider and Wolf, 1992, shows that the continuous groundwater of Bahr El Gazel is recharged in the central and western parts. There is also salt water in places where it is highly mineralized (Bouchez 2015).

The process of water mineralization over the whole area, the direction of groundwater flow and its relationship with the surface waters are very little known.

This work is part of the hydrogeological investigation studies in Bahr-El-Ghazal, which contains 260,866 inhabitants living in a Sahelian context over an area of 50432 Km^2 (INSEED, 2009). It is home to more than a third of Chad's nomadic population (9th EDF Program, 2011). These nomadic populations represent 38% of the population of the study area and their way of life is based on a combination of transhumant livestock farming and occasional millet cultivation.

This paper is an example of the application of classical geochemical methods for hydrogeological investigation in a semi-arid context in order to shed light on environmental and social development problems.

Using classical tools, we will determine recharge and discharge zones, characterize the chemical facies of surface groundwater, understand water mineralization processes and establish water-rock interactions.

2. Material and methods

2.1. Study area and climate

The study area is located in central-western Chad (Fig. 1), bounded approximately by latitudes 13° N and 14° N and longitudes 16° E and 17° E and is located on either side of the 15th parallel. It covers an area of 16,564 km2 . Having a slightly uneven relief, the region is characterized by two (2) different geomorphological landscapes. These are the sandy plateaus which occupy the eastern and extreme western part of the study area where the highest altitudes (314 m) are found. The fossil valley crossing these two dune systems is the most depressed area within which the lowest altitude (281m) is measured.

The study area is also affected by a subarid climate. Precipitation is very irregular and is influenced by the movements of the Intertropical Front (ITF) which are in turn governed by two major centers of action: (i) the Harmatan, a hot and dry wind blowing from the high pressure of the Sahara, and (ii) the monsoon, a cool and humid wind coming from the Atlantic. Climatic data from the Moussoro station located in the center of the study area indicate an average annual rainfall of 314 mm with a peak in August. The temperature varies between 35°C and 41°C with an average of 38°C/year. The warmest months are December and January, while the highest values are observed in April and May. Evaporation (Piche method) is very intense in the months of March and April where it reaches its maximum values (208 and 203 mm respectively). It decreases with the monsoon season and reaches its minimum value in August (80 mm). It rises again with the advance of Harmattan before reaching its second minimum in January (151 mm).

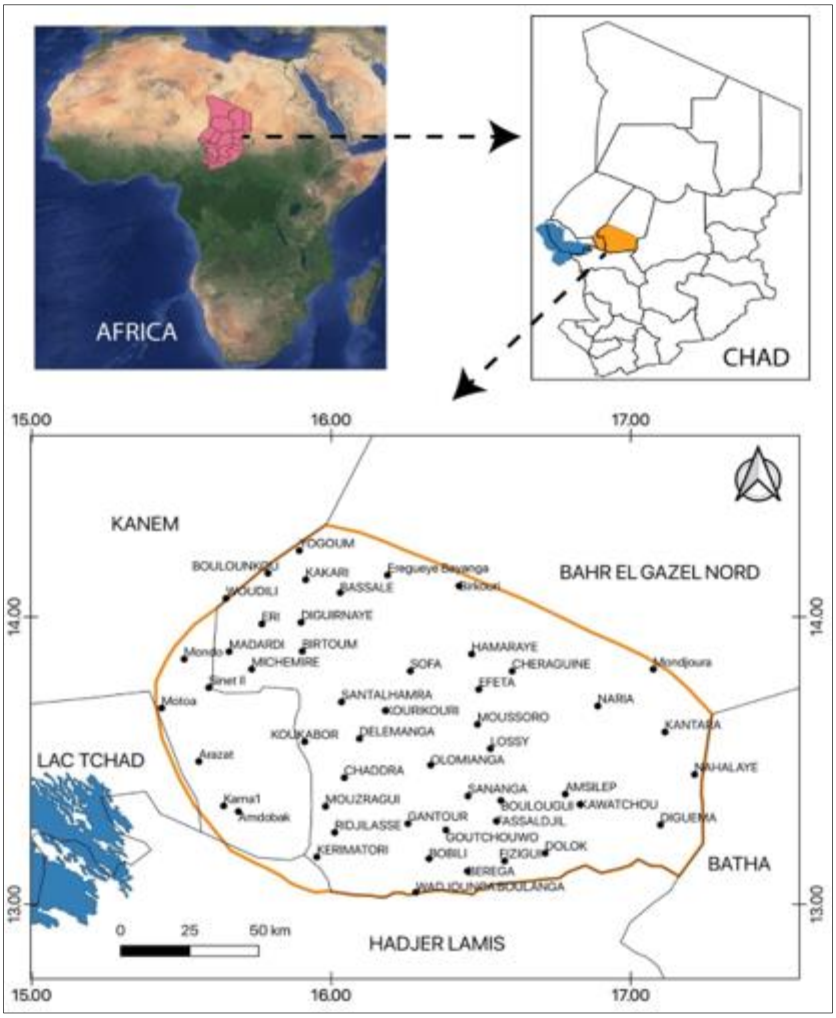

Figure 1 Location map of the quaternary aquifer around Bahr El Gazel

2.2. Geologic and Hydrogeologic settings

The geology of Chad was known thanks to the research conducted by BRGM and ORSTOM in the context of petroleum and hydrogeological research from 1943 to 1964.

The geology of the study area includes : (i) the Quaternary formations immediately underlie the Base Complex. This results in deposits evolving between a sandy pole (pure sands, fluvial or aeolian sands) and a clay pole (kaolinite clays) from the Cretaceous to the Quaternary (Louis, 1970, Schneider and Wolf, 1992, Moussa 2010). (ii) The Cenozoic or Continental Terminal (CT) corresponds to fluvial and lacustrine sandstone and clayey lacustrine sediments with numerous intercalations of ferruginous horizons and levels of ferruginous oolites and cuirasses (Servent, 1973, Schneider J.L. & Wolf J.P., 1992, Durand, 1993; Moussa, 2010).

The free Bahr-El-Ghazal aquifer circulates in the Upper Pleistocene formations (UNDP/UN, 2002). The Upper Pleistocene Ogoli wind sands are quartzose and well classified as a result of intense wind action. This results in good permeability, which translates into high to very high productivity for the structures. This water table has a depth that varies from 35 to 90 metres (Leblanc, 2002). Thus, it is variable according to topography and outcrops in inter-dune hollows (Schneider and Wolff, 1992).

The region as a whole lies between two (2) piezometric domes of the water table, in the aeolian formations in the middle of which is the fossil valley of Bahr-El-Ghazel, which constitutes a piezometric depression (Schneider, 1989) :

- One in the Chitati corresponding to a piezometric dome located west of Mao ;
- The second crosses the Harr in a west-east direction.

On the other hand, the lower Pleistocene formations are characterized by a clear lithological heterogeneity linked to fluvivioleacustrine conditions (Moji series) where a predominantly clayey series with gypsum inclusions is individualized (Schneider, 1989). The water table of this series is known thanks to its waters characterised on the one hand by their high concentrations of dry residue (between 4 and 6 g/l), and on the other hand, by their sodium sulphate facies (Schneider and Wolff, 1992).

2.3. Data Collection

Static or dynamic levels were measured using a piezometric probe. A total of 50 water points were measured. The physico-chemical parameters (45 samples) such as electrical conductivity (EC), water temperature of each sample were measured in situ using a WAGTECH conductivity meter. As for the pH measurement of the water, it was done using a pH paper in the form of paper strips with a colored label.

Forty-five water samples for chemical analysis, of which twenty-two for isotopic analysis, were collected in 0.5 liter polyethylene bottles that were thoroughly washed and rinsed with distilled water. These samples are kept in a cool place until their analysis.

2.4. Analysis of chemical and isotopic data

The analyses in major ions were carried out at the Laboratory of Water and Environment of Farcha (LABEEN) located within the Faculty of Exact and Applied Sciences (FSEA) in N'Djamena-Chad. All samples were filtered using 0.2 µm filters prior to analysis. The major ions analyzed are : Na+,K+, Ca2+,Mg2+,Cl-, HCO3-, SO42-, and NO3- by generation photometer HACH 7100.

An ion balance within ±5% was observed for all the points investigated except for 4 samples with ion balances greater than 10%.

Water samples were analyzed for d2 H using a fully automated chromium reduction system at 800 C (H/Device, ThermoFinnigan) directly coupled to the dual inlet system of a Thermo Finnigan Delta XP isotope ratio mass spectrometer. Water samples were analyzed for d18O using an automated equilibration unit (Gasbench 2, Thermo Finnigan) in continuous flow mode. All samples were measured at least in duplicates and the reported value is the mean value.

3. Results

3.1. Dynamic level

3.1.1. Piezometric levels

The static or dynamic level of the sampled structures varies from 2 m to 20 m (Table 1). The lowest water depth is observed at Chaddra (2.36 m) while the highest is at Dolok and Safi (20 m).

3.1.2. Piezometric map

The piezometric map in Figure 2 allowed us to highlight the existence of piezometric domes and troughs. The most accentuated dome is located in the elongated Harr dunes following the East-West direction and in the village of Sananga and Kantara with piezometric levels of 298 and 294 m respectively. This illustrates that the piezometric surface shows a watershed in the Harr aeolian formations. On the other hand, the most pronounced piezometric depression, whose water level is encountered at a height of 268 m, follows the fossil valley of Bahr-El-Ghazal and is located at Bir Kouri, coinciding with the fossil valley. In the extreme south of the study area, a deepening of the water level is observed, which would be the northern limit of the great piezometric trough of Chari Baguirmi.

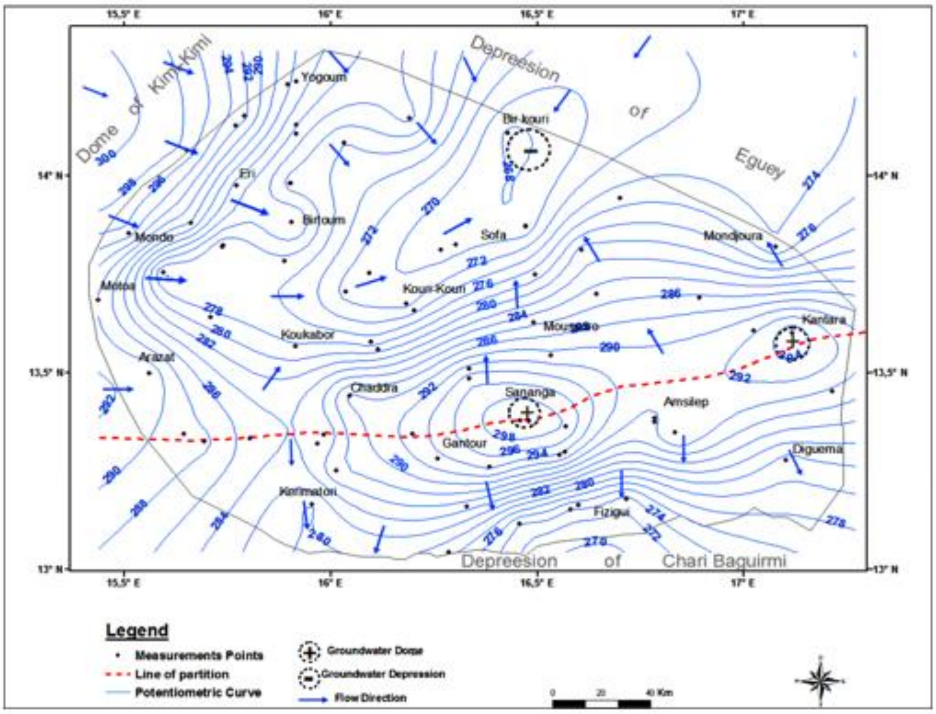

Figure 2 Piezometric map of the Bahr El Gazel Zone

3.2. Physico-chemical parameters

Table 1 presents physico-chemical parameters of the waters. The pH values range from 5.97 to 8.36 with an average of 7.32, indicating that the waters are generally weakly acidic to neutral. Water temperatures range from 28 to 32 °C with an average of 30 °C. Electrical conductivity is very heterogeneous and ranges from 119 to 4355 µS/cm.

	Paramètres physico-chimiques des eaux			
	Minimum	**Maximum**	**Moyenne**	**Ecart-type**
Ph	5.97	8.36	7.47	0.43
Conductivité (µs/Cm)	119	4355	1243	1232,97
TDS (mg/L)	96	3903	831,54	842,31
Température °C	27,6	32,2	30.48	1.86
Ca^{2+} (mg /L)	8	219,32	56,59	51,62
Mg^{2+} (mg /L)	1,43	57,8	13,72	14,96
K^{+} (mg /L)	1,3	77,8	24,25	19,47
Na^{+} (mg /L)	5	726	167,26	221
HCO_3^- (mg /L)	28	922	319,92	292,71
SO_4^{2-} (mg /L)	1	1232	246,37	349,79
NO_3^- (mg /L)	0,04	119	25,46	32,36
Cl^- (mg /L)	0,82	299	33,19	69,94

3.3. Chemical Elements

3.3.1. Order of abundance

The dominant cation is sodium with an average concentration of 167 mg/L, followed by calcium with a concentration of 57 mg/L, potassium and magnesium with average concentrations of 24 mg/L and 14 mg/L respectively. The bicarbonate ion is largely dominant with an average concentration of 320 mg/L, followed by SO_4^{2-} which has an average concentration of 246 mg/L, Cl^- (33 mg/L) and NO_3^- (25 mg/L).

3.3.2. Chemical facies

In order to distinguish groups of water with different chemistries and mineralization within this aquifer, the piper diagram was used (Fig.3). This diagram shows that 34% sodium and potassium bicarbonate, 30% of the samples have calcium and magnesium bicarbonate facies, 21% sodium and potassium chloride or sodium sulfate and 15% calcium and magnesium chloride and sulfate facies.

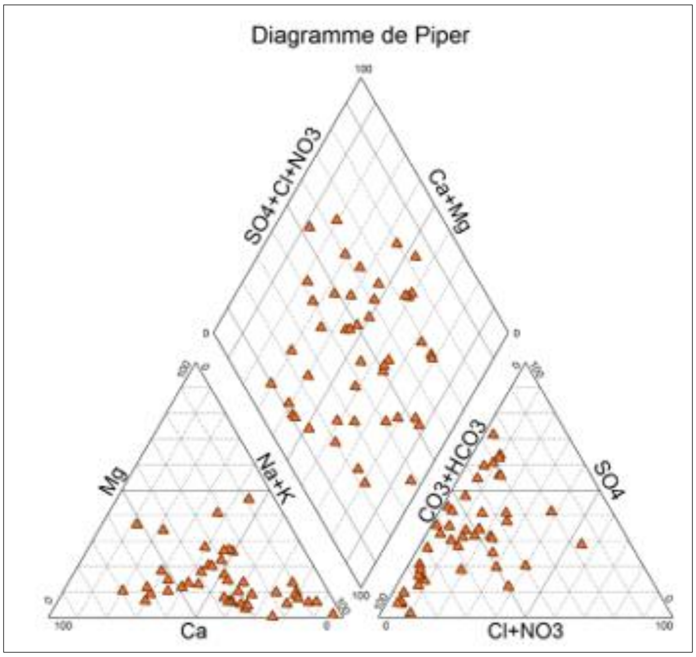

Figure 3 Chemical facies of the quaternary aquifer waters of the Bahar El Gazal zone

3.4. Isotopic composition of water in δ18O and δ2H

The values of the isotopic composition of the studied groundwater vary from -4.86 to 4.04‰ and -35.60 to 14.50‰ and **δ**2H respectively.

The analysis of these data (Figure 4) allowed us to categorize the water into three groups:

- group A: impoverished waters that have values close to the weighted average of rainfall in N'Djamena (**δ**18O=-3.78‰ and **δ**2H=-19.87‰) in the Sahel.
- group B: poorly enriched waters with values close to 0‰ in **δ**18O and **δ**2H.
- group C: water enriched on average in **δ**18O= 4‰ and **δ**2H=-14‰.

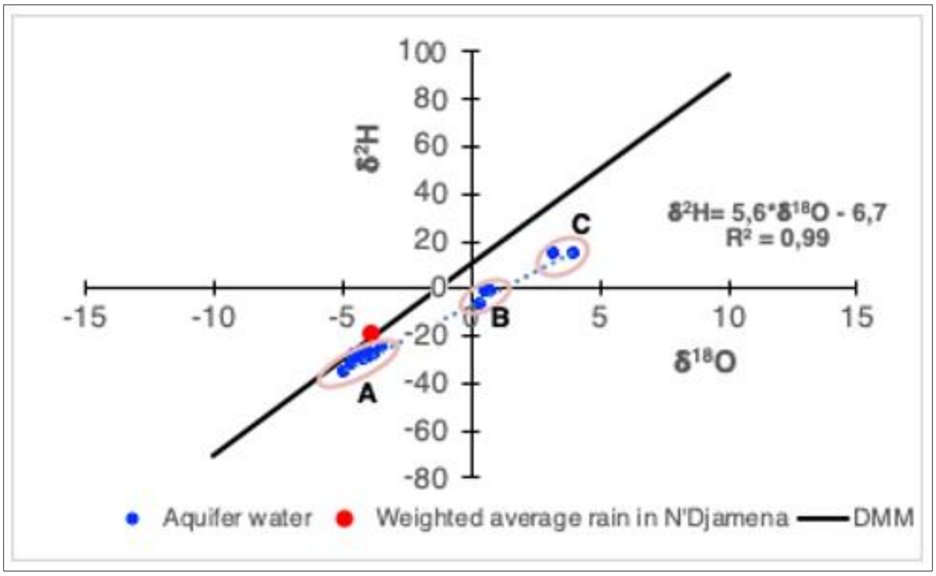

Figure 4 Isotopic composition in **δ**^{2}H and **δ**^{18}O of the waters of the Quaternary aquifer of Bahr El Gazel

4. Results and discussion

4.1. Origin of groundwater

4.1.1. Evaporation line and system input signal

There is a good correlation of the isotopic composition of the waters (between **δ**2H and **δ**18O with R2= 0.99). These waters show a small slope (5.6) compared to the slope (8) of the global meteoric waters. They are located on an evaporation line (**δ**2H= 5.6***δ**18O - 6.7).

The intersection between the line drawn by these waters and the MMD gives the input signal of the waters. They are located around -7‰ in **δ**18O and -40‰ in **δ**2H. These values are poorer than the weighted average rainfall values in N'Djamena (1960-2015) (Mahamat Nour, 2019).

This leads us to believe that these waters could be recharged at a period that is wetter than the present one. Or an exceptional and rainier year could be the source of this recharge.

4.1.2. Recharge and discharge zones

The analysis of the piezometric map and the data on the isotopic composition of the water (**δ**18O and **δ**2H) allowed us to conclude that the peripheral zone is considered as the water recharge zone. These zones are the North-West dunes (Kimi Kimi domes) and the Sanaga and Kantara domes. All the waters converge towards the Eguey depression at Bir Kouri where more evaporated waters in isotopic composition can be observed at **δ**18O and **δ**2H. The domes of Sanaga and Kantara also constitute a watershed between the great depression of Chari Baguirmi and the depression of the Bahr El Gazel valley (Egey depression).

The Bir Kouri depression (Egey) coincides with the fossil valley. This piezometric depression is thought to be the consequence of intense evaporation of the free Quaternary water table (Abderamane, 2012).

Moreover, the waters of group A are located at the edge of the study area in the Kimi Kimi dunes and at the Sanaga dome (Fig. 2). These domes are assumed to be potential recharge zones of the Quaternary aquifer. Group C waters are centrally located in the Bahr El Gazel valley. This area is considered a water accumulation zone. These enriched waters could be attributed to evaporative effects from the recharge zone to depressions. The waters of group B are intermediate between the 2 previous water groups.

4.2. Water Mineralization

Groundwater concentrations in the study area are highly variable from point to point. This shows that we are in an area with a locally highly variable and heterogeneous lithology. This lithological heterogeneity is responsible for various chemical processes. Depending on the flow path and residence time, water can interact with the aquifer matrix. Consequently, it can become enriched and/or depleted in specific ions.

The increase in elemental concentrations in water could have two origins: either evaporation, or dissolution of rocks, or both.

The high concentration and the shallow depth of some water points leads us to believe that this increase in concentration could be due to evaporation effects.

We used linear correlations between the elements to identify rocks that could be the origin of water mineralization.

The figure below shows that the diagrams Na vs K; Ca vs Mg; Ca vs SO4; Ca vs HCO3, Mg vs Na and Mg vs SO4 are not or only weakly correlated. This shows that the alkalis le (Na and K) and the alkaline earths (Ca and Mg) do not evolve in the same way. On the other hand Na vs HCO3 shows a good correlation with R2= 0.72; Na vs Cl and Mg vs HCO3- also show quite good correlations.

The good positive relationship observed between sodium and bicarbonates could be attributed to the dissolution of evaporites (sodium hydrogen carbonates or natron), reported in the study area, during the course of water flow or during its stay in aquifer formations (Pias, 1970). The correlation between Na and Cl suggests that on the one hand the dissolution of NaCl and on the other hand their origin could be attributed to meteorite waters (rainwater). As well as the dissolution of carbonates at the occurrence of dolomite which could be at the origin of the presence of Mg and HCO3-

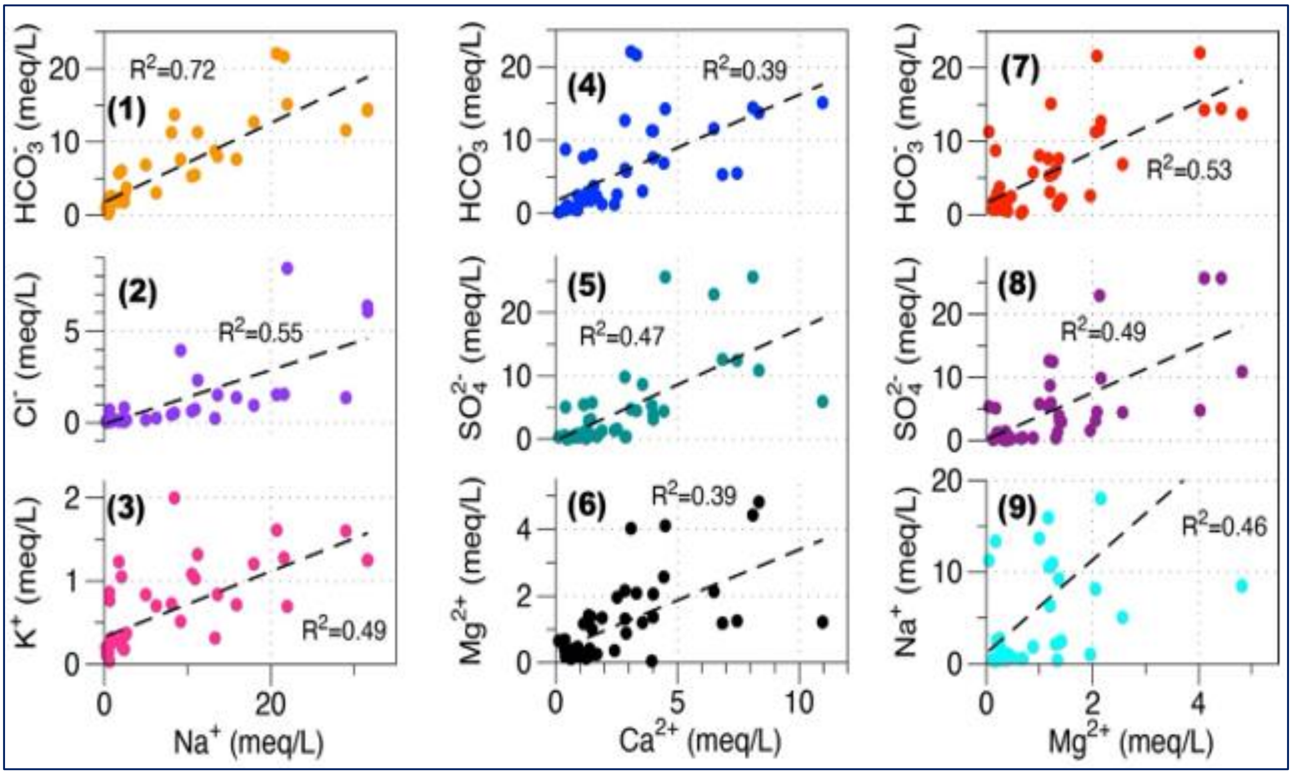

Figure 5 Correlation diagram between the different chemical elements

The presence of sulphates in the waters is attributed to the gypsium reported in clays from the wet periods of the Quaternary (Schneider, 1989), although we have not observed a perfect correlation between Ca and SO_4^{2-}.

The groundwater analysed seems to be affected by anthropogenic activities as shown by the NO3- concentrations with samples with values that greatly exceed the limit established by the WHO (10 mg/l). Far from the influence of nitrogen fertilizers due to the virtual absence of irrigated crops, the high nitrate concentrations in the wells indicate anthropogenic pollution. The most likely explanation for this contamination may be due to traditional methods of drawing water, which means that a significant part of the water flowing around the well, mixed with the excrement of livestock during watering, could be transported by the drawing rope or other means to the bottom of the well, thus locally contaminating the water table (Abderamane, 2012).

5. Conclusion

Groundwater is the only resource for the Bahr El Gazel region for both drinking water supply and livestock watering.

The Quaternary is characterized by a dominance of sandy to sandy-clay formations. Like all of Chad's northern regions, the Bahr El Gazel region is also subject to the advance of the desert. The present study has made it possible to characterize the Quaternary aquifer from both hydrodynamic and hydrogeochemical points of view. The piezometric map shows the existence of piezometric domes and troughs (Harr and Kimi-Kimi). The most accentuated dome is located in the elongated Harr dunes following the East-West direction. This illustrates that the piezometric surface shows a watershed in the Harr aeolian formations. On the other hand, the most pronounced piezometric depression, whose water level is encountered at a height of 268 m, follows the fossil valley of Bahr-El-Ghazal. On the hydrochemical level, the results of the physico-chemical analyses made it possible to determine the different chemical facies of the waters, their interaction and their quality. Thus, anthropogenic activities have had an impact on the quality of the waters as shown by the NO3- concentrations with samples having a value that largely exceeds the limit established by the WHO (10 mg/l). Far from the influence of nitrogen fertilizers due to the virtual absence of irrigated crops, the high nitrate concentrations in the wells indicate anthropogenic pollution.

In order to understand the functioning of the Bahr el Gazel aquifer system, the isotopic study carried out has shown the variation of O18 and δ2H contents in the different zones (Kimi-Kimi and Eguey piezometric domes). The oxygen-18/deuterium relationship $\boldsymbol{\delta}2H = 5.6*\boldsymbol{\delta}18O - 6.7$ reflects a continental regime of precipitation with evaporation which suggests an evaporation recovery, also confirmed by the important presence of sand layers in the unsaturated zone.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

No potential conflict of interest was reported by the authors.

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