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Chemical and Bacteriological Characterization of Groundwater in the City of N'Djamena

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Abstract

The city of N'Djamena, the subject of this study, is located in a semi-arid area on the alluvial plain of Lake Chad. The presence of water resources in an uncontrolled urban context increases the vulnerability of these resources to a variety forms of pollution. Stratigraphic, chemical and microbiological approaches were used to study the lithological, hydrochemical and bacteriological characteristics to determine the suitability and quality of groundwater in the city of N'Djamena. This study highlights facies variations in the superficial aquifer, influenced by climate and sediment flow. The hydrochemical characteristics of the groundwater indicate a relationship with carbonate geological formations. The chemical quality of the groundwater is within WHO drinking water standards. Bacteriological results show the remarkable presence of bacterial germs. The origin of this fecal pollution can be attributed to poor sanitation and household waste collection. Then there are the septic tanks, the conditions under which water is drawn and the structure of the borehole installations. The use of this groundwater could constitute a major health risk for the majority of N'Djamena's inhabitants, and therefore requires prior treatment before consumption.

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Keywords

N'Djamena, Quaternary, lithology, hydrogeochemistry, bacteriology, quality.

Introduction

Access to good-quality drinking water has been enshrined as a human right by the WHO and represents sustainable development goal no. 6.1. Despite this importance, access to good quality water remains a scarce resource, and global demand will increase by 55% by 2050 (OECD, 2021).

Despite this scarcity, water resources in many countries are often threatened by natural and man-made factors. The latter is reflected by the growing number of urban populations in Africa, expected to reach 1.1 billion by 2050 (UN, 2015). This evolution will be followed by intense urbanization, which in turn will generate quantitative and qualitative impacts on groundwater (Morris *et al.,* 2003).

The city of N'Djamena, like all these countries, is confronted with these realities. The population is growing at a staggering rate, having increased eightfold since 1960.

More than half of all households are not connected to the distribution networks. To make up for this shortcoming, populations have opted for alternative, informal supply methods (Temgoua *et al.,* 2009) such as sinkholes and shallow wells. However, the chemical and bacteriological characteristics of the latter are not well known, the distance between the latrine and the borehole is not always respected, and the water quality is not always assured (Temgoua *et al.,* 2009).

In addition to these observations, uncontrolled urbanization and the virtual absence of drainage systems have led to repeated flooding in the majority of neighborhoods. These waters carry faecal matter, medical waste (radioactive elements) and chemicals released by human activities (Birke *et al.,* 2010; Parslow *et al.,* 1997; Dinelli *et al.,* 2010).

These issues are the main sources of pollution and degradation of aquifer quality in the city of N'Djamena, and will have negative consequences in terms of water-borne diseases, which are the main source of mortality and morbidity among the population, especially during the rainy season (Kadjangaba, 2007).

A number of studies have been carried out in the city of N'Djamena (Hamite, 2012). The first two studies, which date back more than 20 and 12 years respectively, did not focus on the issue of pollution in the city, but rather on the functioning of the entire Chari Baguirmie aquifer. The third study investigated the factors contributing to groundwater pollution in the city. This study has been carried out since 2007, which is why it is so important, given the city's enormous demographic and industrial growth.

The aim of this study is to understand the hydrochemical and bacteriological characteristics and assess the quality of groundwater in the city of N'Djamena, with a view to preventing pollution.

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Presentation of the Study Area

Location and geomorphology

The city of N'Djamena is located in the western part of Chad (central Africa) between 12 00' and 13 00' north latitude and between 15 10' and 16 00' east longitude (Figure 1).

It is bordered to the north by the Hadjer-lamis region, to the south and east by the Chari Baguirmi region and to the west by Cameroon. It comprises 10 arrondissements and 64 districts. The city's population rose from 126483 in 1968 to 1,092,066 million in 2012 (INSEED, 2012). It is expected to exceed 2 million inhabitants by 2025. The city's morphological peculiarity lies essentially in the monotony of its flat topography (SDEA, 2003).

The average altitude varies between 290m and 305m, with slopes ranging from 1 to 2.5%. The study area's hydrographic network is dependent on the Lake Chad basin. The hydrography of this region is mainly composed of the Logone-Chari system (Figure 1) and numerous intermittent streams that are regulated by the influence of climate.

Hydroclimatic conditions

The climate is Sahelo-Sudanian, characterized by a short rainy period followed by a long dry period. The average rainfall modulus is 576.74 mm. The wettest months are July and August, with around 64% of annual rainfall. Temperatures are relatively low from December to February and very high from March to May. The city's climate is influenced by two zones of high pressure (anticyclone): the Azores anticyclone and the St. Helena anticyclone.

Geological and hydrogeological context

The geology of the study area is part of the geological history of the Lake Chad Basin. This vast (2.38 Mkm2) endoreic basin, located in an arid to semi-arid climate, is characterized by a thick detritic sedimentary deposit overlying a deep crystalline basement. The lithology is characterized by a sandy pole of pure fluvial or eolian sands and a clay pole of kaolinitic or neoformational clays (Schneider, 2001).

These formations were formed as a result of the numerous oscillations in the level of Lake Chad (transgressions and regressions) (Pias, 1970). The depth of the basement was estimated at 550 meters by BRGM (1987), based on seismic investigations. It outcrops to the northeast and southeast of the area in the form of inselbergs (Schneider, 1989).

According to Pias (1970), there are two classes of soil in the region: vertisols and hydromorphic soils. Most of these soils are sandy-clay to sandy, with occasional crusting and icy patches. These phenomena can be observed both to the south-east and north of N'Djaména, but to varying degrees. The aquifer consists of Lower Pleistocene sands, which have already been tapped to supply the city of N'Djamena. At a depth of 50-70 m, they are underlain by Upper Pliocene clays. The aquifer is to be tapped by drilling; productivity will depend on the thickness and purity of the sandy layers, as well as on the quality of the workmanship.

The level of the aquifer deepens from less than 10 m (towards the Chari) to 40 m (towards the north: Massaguet).

Materials and Methods

Data used (borehole log data)

In order to understand the structure and lithostratigraphy of the reservoir in the study area, borehole log data were used to establish correlations between facies. Knowledge of the geometry and lithology will give an idea of their role and influence on the transfer of pollutants into the water table. To achieve this correlation, a reference level was chosen, the ground surface, due to the very basic topography throughout the city and the continental context of the sedimentation environment. Two cross-sections were therefore constructed (Fig.4). According to the drilling data available to us, these sections are generally located in the eastern part of the city of N'Djamena.

Sampling and analytical methods

A high-water measurement campaign was carried out in November 2022. A total of 50 boreholes (Fig.5) were sampled throughout the city. Physical parameters (PH, EC and temperature) were measured in situ using a multi-WTW device. Samples were collected in

0.5 L polyethylene bottles for analysis of major ions, heavy metals and bacteriological analysis. Figure 5 shows all the points sampled. Ion and bacteriological analyses were carried out at the Laboratoire National d'Analyse des Eaux in N'Djamena, Chad. Na+ and K+ concentrations were determined using flame photometry, Ca2+, HCO3-, Cl- by colorimetry, Mg2+ by subtraction and NO3-, SO42-, iron by molecular spectrophotometry (DR 2800).

Samples were filtered through 0.2 µm filters prior to analysis. Analytical precision was verified by ion balance error (IBE). The IBE value is ±5%.

Bacteriological analyses were carried out to determine the microbiological quality of these waters and to pinpoint potential sources of contamination. These analyses concerned total coliforms, fecal enterococci and Escherichia coli. The method used was membrane filtration, preparation of culture media, inoculation and colony counting.

All the data were analyzed and processed to determine the structure, mineralization and use of the water in the study area.

Results and Discussion

Litho-stratigraphic correlations

Climate and sediment flow are the main factors responsible for variations in base level and hence for the establishment of genetic sequences in such a context (Hongtao Zhu *et al.,* 2013). The results obtained show that the aquifer in the study area, in its superficial part, presents significant lateral and vertical variations in facies. Four genetic sequences were determined. All these sequences are retrograde (Fig.6 and 7.) and therefore characterize phases of successive rise in the base level. From a paleoclimatic point of view, the Quaternary is marked by alternating wet and dry periods (Schneider and Wolff, 1992).

Wet periods are characterized by fluvial deposits and lacustrine clays. This corresponds to periods of transgression (rise in base level) with the establishment of correlative retrograde sequences. Arid periods are marked by deposits of eolian sands.

Hydrochemistry

Physical parameters

The results are presented in Table 1. Temperatures measured in situ are fairly homogeneous, ranging from 27.0 to 33.5 C, with an average of 27.4 C. These values are close to the ambient air temperature in the city of N'Djamena, which averages 28.10 C. This suggests that the aquifer system is in thermal equilibrium with the atmosphere. The pH of the water ranges from 6.65 to 7.72, with an average of 7.23. These values indicate a low acidity to neutrality of the borehole water. They are most often characteristic of carbonate environments ok already removed. Electrical conductivity values (Fig.8) range from 150 to 1750 µs/cm. The very wide range of variation in conductivity explains the aquifer's highly heterogeneous distribution of mineral loads, which may be linked either to lithology or to point source pollution. High conductivities (in excess of 1000µs/cm) are located to the north of N'Djamena, while low conductivities are scattered throughout the area.

Major ions

The results for major ions are presented in Table 1 and Figure 9, and show that cations are dominated by Ca2+, with concentrations ranging from 12.72 to 122.40 mg/L and an average of 29.54. The median observed for this element is 21.60, well below the average. The median observed for this element is 21.60, well below the average. After calcium comes Na+, followed by Mg2+ and k+, with concentrations ranging respectively from 7.2 to 70 mg/l, from 1.02 to 34.02 mg/l, and from 1.0 to 6.8 mg/l.

In terms of anions, the dominant ion is bicarbonate, with concentrations ranging from 43.9 to 536.80 mg/l, with an average of 133.6 and a median of 97.6 mg/l.

Chemical facies

Only the bicarbonate facies was observed in the piper diagram of N'Djamena waters (Fig.10). Given the concentrations observed above, this is a calcic bicarbonate facies.

In shallow phreatic aquifers, recently recharged water will have a low chemical element content, as it percolates rapidly through the unsaturated zone and has not had time to acquire subsoil minerals. Recently recharged groundwater is always of the Ca-Mg-HCO3 type (CBLT/BGR 2012). The presence of this type of facies is due to groundwater recharge by the Chari River, as shown by Schneider (2001).

Microbiological parameters

Bacteriological analyses are mainly used to control drinking water, which must be free from pathogenic micro-organisms (Rodier, 2009). In the light of the bacteriological analysis carried out, over 90% of borehole water contained *Echerichia coli*, total Coliform and total aerobic flora (Fig.11). E. coli levels were high in half of the boreholes. This bacterial group necessarily results from recent contact between water and faecal matter. These organisms are the cause of numerous health problems, including gastroenteritis, dysentery, cholera and dermatitis (Siddic, 2014). This could explain the upsurge in waterborne diseases in disadvantaged areas of the city of N'Djamena, especially as these waters are consumed without any prior treatment. Mesophilic aerobic flora also present significant levels in most (98%) of the borehole waters. These colonies highlight the assessment of a water's degree of pollution, and an excess of their content in the latter is proof of very high initial contamination (Mohamed *et al.,* 2014).

In general, the presence of these bacterial colonies in the water could be explained by the poor protection of these boreholes, the use of animal waste as fertilizer and/or by faecal pollution (false septic tanks) in the vicinity of the boreholes. The pits are sometimes more than 15 m deep and come into contact with the water table. The increase in groundwater temperature at depth encourages the growth of these bacterial germs (Ousmane *et al.,* 2010).

In conclusion, the Quaternary water table of the city of N'Djamena harbors high densities of indicators of fecal contamination, and these results are similar to those found in the M'nassra water table in Morocco.

Water quality

Assessment of water quality for domestic use based on physico-chemical data

The physico-chemical results were compared with the WHO standard, 2017, to determine the suitability of N'Djamena city water for domestic use. It shows that, with the exception of Mg and HCO3, all other parameters are below the recommended standard. In order to further assess water quality, the Drinking Water Quality Index (DWQI) was used. It has been used by several authors in many parts of the world (Tian *et al.,* 2019). DWQI was calculated for each sample using ten (10) parameters: EC, pH and concentrations of Ca2+, Mg2+, Na+, K+, HCO3-, Cl-, SO42-, NO3- in water and the 2017 WHO drinking water quality standard with the aim of determining the suitability of water samples for consumption in the study area. Each water quality parameter was assigned a specific weight (wi) ranging from 1 to 5 (Table 1) according to its relative importance on water quality (Al-Mashagbah 2015). The highest weight of 5 was assigned to parameters that have the greatest effects on drinking water quality (NO3), and a minimum of 1 was assigned to parameters (K) that are considered non-harmful (Srinivasamoorthy *et al.,* 2014; Vasanthavigar *et al.,* 2010). Other parameters were weighted between 1 and 5 according to their importance in overall drinking water quality (Ketata-Rokbani *et al.,* 2011). In addition, to determine the DWQI, we first calculated the relative weight (Wi) of each parameter according to equation (1):

$$Wi = \frac{wi}{\sum_{i=n}^{n} wi} \quad \ldots(1)$$

Where wi is the weight assigned to each parameter, n is the number of parameters and Wi is the relative weight. The values of the assigned weight (wi) and the calculated relative weight (Wi) are shown in Table 2.

The parameter quality scale is then calculated using equation (2):

$$qi = \frac{Ci \times 100}{Si} \quad \ldots(2)$$

Where Ci and Si are respectively the concentration of the chemical parameter (mg/l) in the water sample and the corresponding WHO standard limit.

Finally, the water quality sub-index SI was obtained by multiplying the quality score by the Wi of each parameter (Eq. 3), the integrated WQI was obtained by summing all the sub-indices (Eq. 4)

$$SI = Wi \times qi \quad \ldots(3)$$

$$DWQI = \sum_{i=1}^{n} SI \quad \ldots(4)$$

The result (Tab.3) obtained shows that 92% of the samples are of excellent quality for domestic use.

Water quality for irrigation

Various criteria were used to assess the suitability of water for irrigation in the city of N'Djamena. The criteria and results are presented in Table 4.

The results show that water is 92% acceptable according to the CE criterion, 100% acceptable according to SAR, CR, KR, MAR and 94% and 80% respectively for PI and RSC.

The irrigation water quality index developed by Mireille was used, taking into account numerous criteria. In addition to CE, Na, HCO3 and CL data, ranges of irrigation water quality parameters (qi, wi) were used to calculate the irrigation water quality index (IWQI) at each point of the N'Djamena city water table (Tab.5). They are defined according to the impact of each element on irrigation water quality.

The results obtained (Tab.6) show that, on the basis of this index, 69% of N'Djamena city water is moderately restricted, 28% is severely restricted and 4% is severely restricted.

Origin of mineralization

The binary relationship was established between Ca and Mg, HCO3 and Ca and finally HCO3 and Ca+Mg on the straight line 1:1 and 2:3 and 2.5:1 (Fig.12). This relationship shows an alignment on the 2:3 line for calcite and 1:1 for dolomite. This result is in line with that of the piper diagram previously presented. Similar results were found by Ben *et al.,* (2014).

Table.1 Descriptive statistics

Statistic	pH	CE	Ca	Mg	Na	K	HCO3	Cl	SO4	NO3
Nbr. of observations	51	51	51	51	51	51	51	51	51	51
Minimum	6,65	150,00	12,72	1,02	7,20	1,00	43,92	7,80	1,00	0,11
Maximum	7,72	1750,00	122,40	34,02	70,00	6,80	536,80	60,00	55,00	23,00
1st Quartile	7,11	341,00	18,40	5,27	14,35	1,60	89,06	12,50	6,00	0,95
Median	7,25	441,00	21,60	6,85	19,00	2,00	97,60	15,00	8,00	2,90
3rd Quartile	7,34	566,00	23,24	9,48	22,50	2,50	115,41	18,50	14,50	4,35
Mean	7,23	503,43	29,54	8,41	22,00	2,29	133,35	18,11	12,07	4,53
WHO, 2017	6,5-8,5	750,00	75,00	30,00	200,00	100,00	200,00	250,00	250,00	50,00

Table.2 Weights (wi) and relative weights (Wi) of physicochemical parameters and drinking water quality standards (WHO, 2017).

	Unit	WHO (2017)	Weight (wi)	Relative weight(Wi)
pH		6,5-8,5	4	**0,14**
EC	µs/cm	1000	4	**0,14**
Ca	mg/l	75	2	**0,07**
Mg	mg/l	50	2	**0,07**
Na	mg/l	200	3	**0,10**
K	mg/l	12	1	**0,03**
HCO_3	mg/l	500	3	**0,10**
Cl	mg/l	250	2	**0,07**
SO_4	mg/l	250	3	**0,10**
NO_3	mg/l	50	5	**0,17**
			∑wi=29	**∑Wi=1,00**

Table.3 N'Djamena water quality index results

Domaine DWQI	Class	% Total results	
< 50	Excellent	47	**92%**
50-100	Good	4	**8%**
100-200	Poor		**0%**
200-300	Very poor		**0%**
>300	**Unsuitable**		**0%**

Table.4 Results of different criteria to assess the suitability of groundwater for agriculture.

Paramètres de qualité de l'eau d'irrigation	Catégorie	Références	Surface (n=4)	% (65 échantillons)
EC (µS cm-1)	Excellent <750 Acceptable (750-2000) Douteux >2000	Wilcox, 1955	47 4	92,2% 7,8%
√	Excellent <10 Acceptable (10 -18) Douteux (18 - 26)	Richards, 1954	51	100%
	Acceptable (<1) Douteux (>1)	Ryzner, 1944	51	100%
	Excellent (<40) Acceptable (40-60) Douteux (>60)	Wilcox, 1955	3 48	6% 94%
	Acceptable (<1)	Kelly,	51	100%

Table. 5 Ranges of Irrigation Water Quality Parameters (qi, wi) used to calculate Irrigation Water Quality Index (IWQI) in each point of groundwater N'Djamena city.

Irrigation Water Quality Parameters	Range of q_i	$q_i$max	$q_i$amp
	85-100	100	15
qi	60-85	85	25
	35-60	70	25
	0-35	55	35
	Parameters		w_i
Weights (w_i) for each	Electrical Condutivity (EC)		0.211
parameter considered	Sodium (Na^+)		0.204
with Sw_i = 1	Bicarbonate (HCO_3^-)		0.202
	Chloride (Cl^-)		0.194
	Sodium Adsorption Ration (SAR)		0.189
IWQI	Water restriction		Code
85-100	No restriction		NR
85-70	Low restriction		LR
70-55	Moderate restriction		MR
55-40	High restriction		HR
0-40	Severe restriction		SR

Table.6 IWQI results in N'djamena waters.

Parameters Irrigation Water Quality	Water quality category	Samples	% (51 Samples)
IWQI	NR		
	LR		
	MR	35	**69%**
	HR	14	**27%**
	SR	**2**	**4%**

Figure.1 Location of the study area

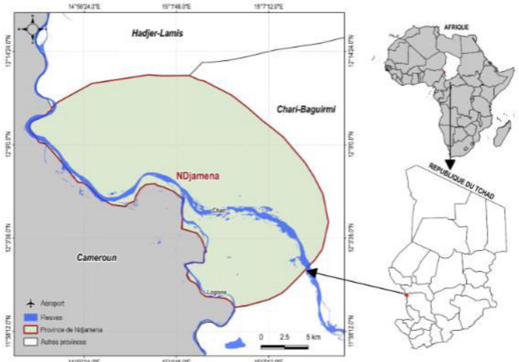


Figure.2 Average monthly rainfall in Ndjamena (1987-2021)

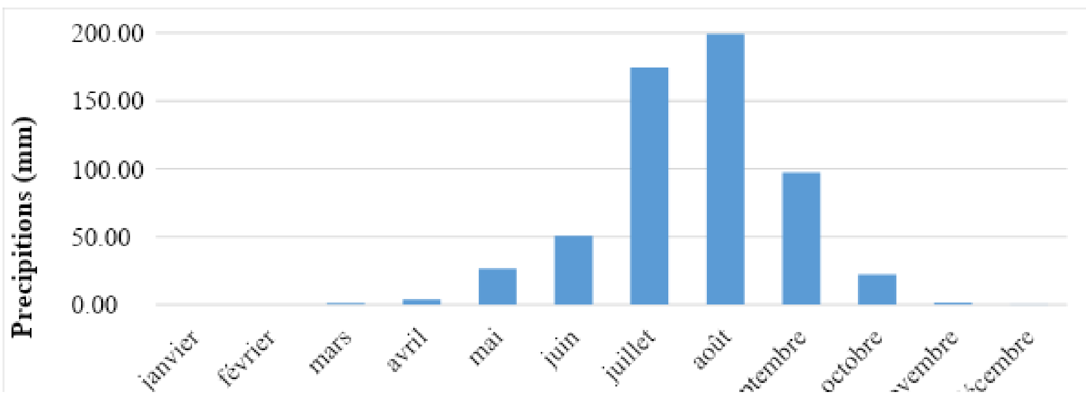


Figure.3 N-NW and S- geological section of the study area (Source: schematic section of Lake Chad - Goré by Schneider and Wolf, 1992 modified and simplified by Mahamat Nour (2019).

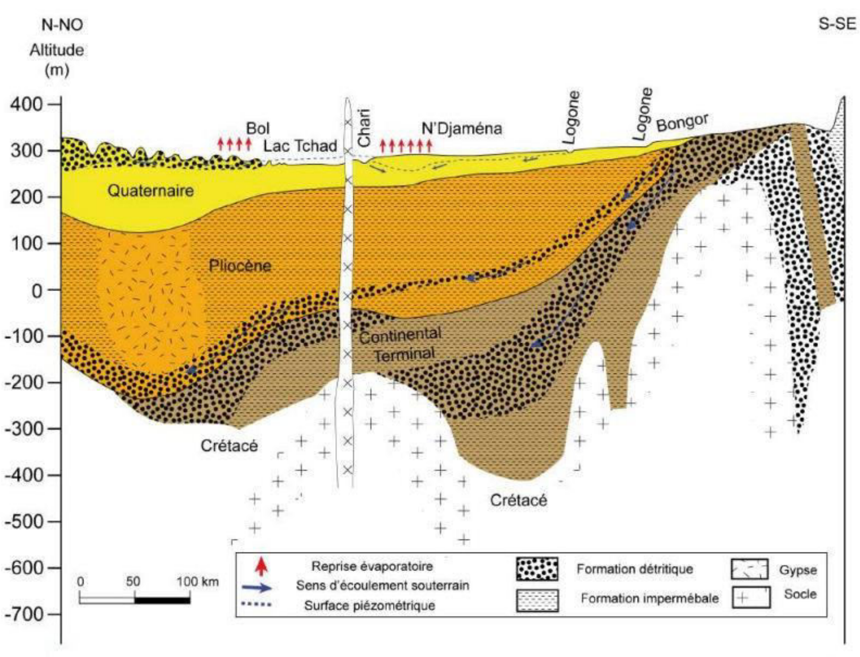


Figure.4 Profile location map

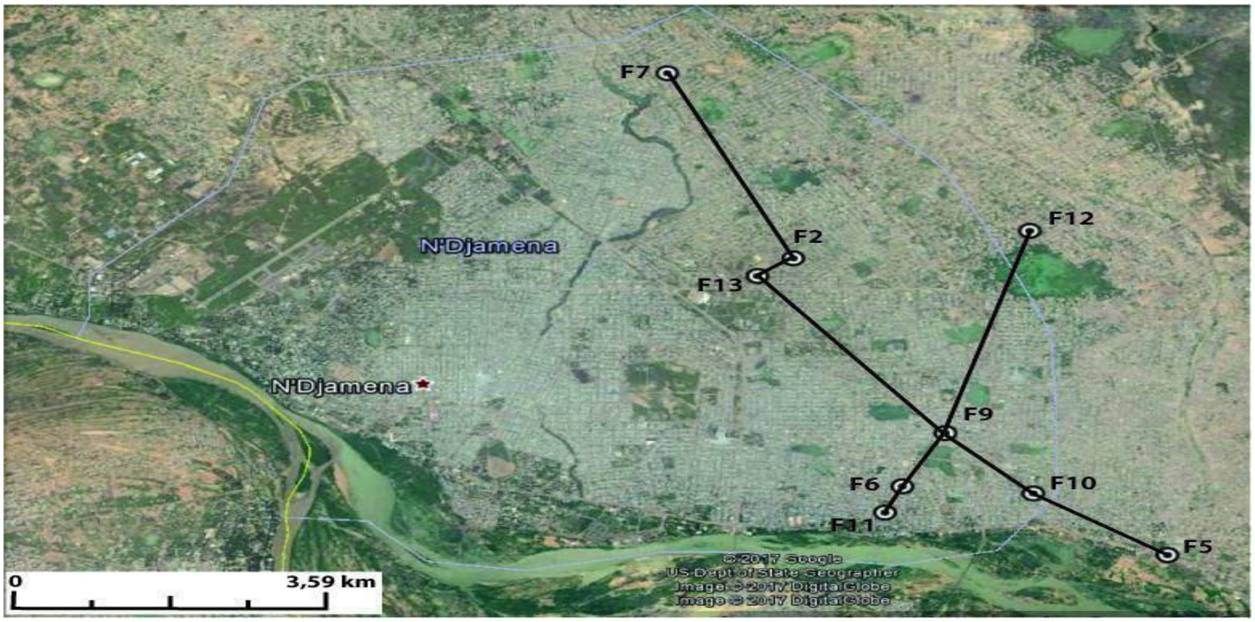


Figure.5 Location map of sampling points

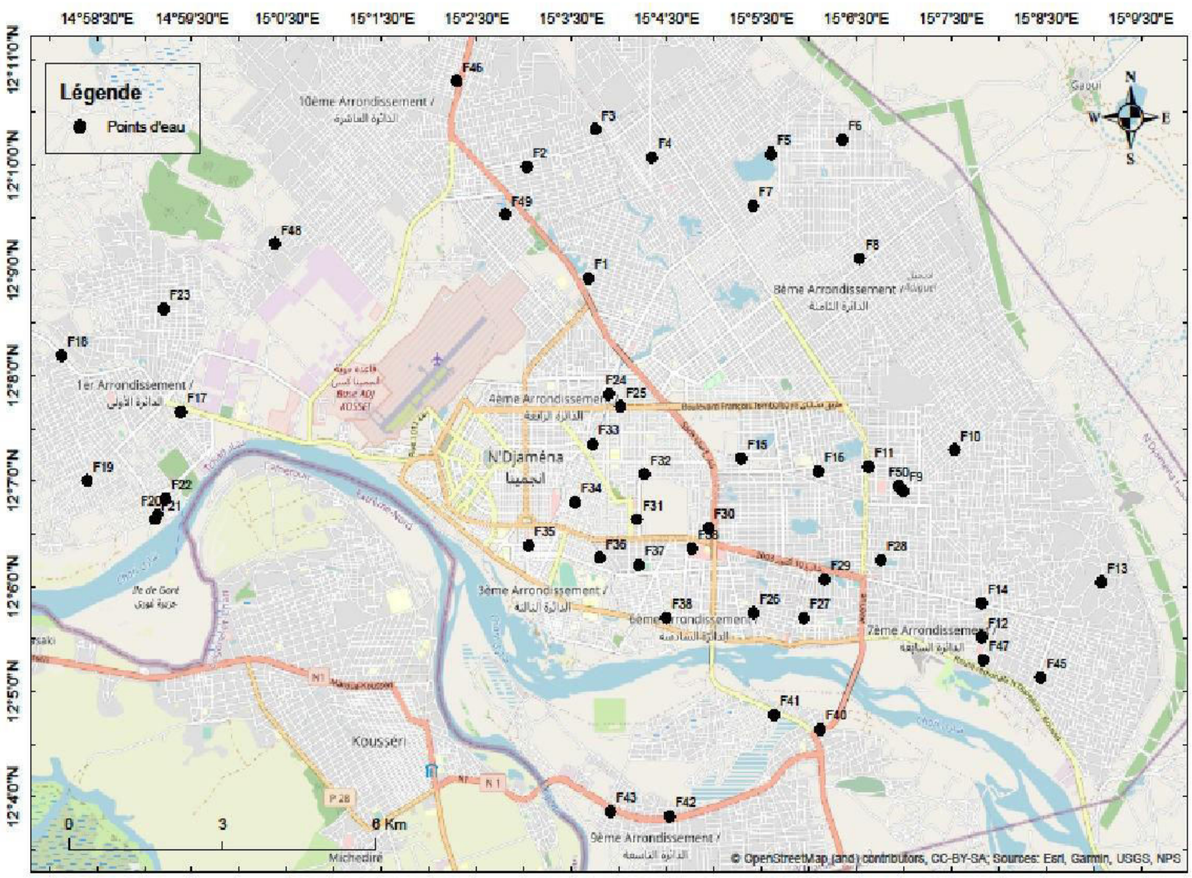


Figure.6 Borehole correlation (section 1)

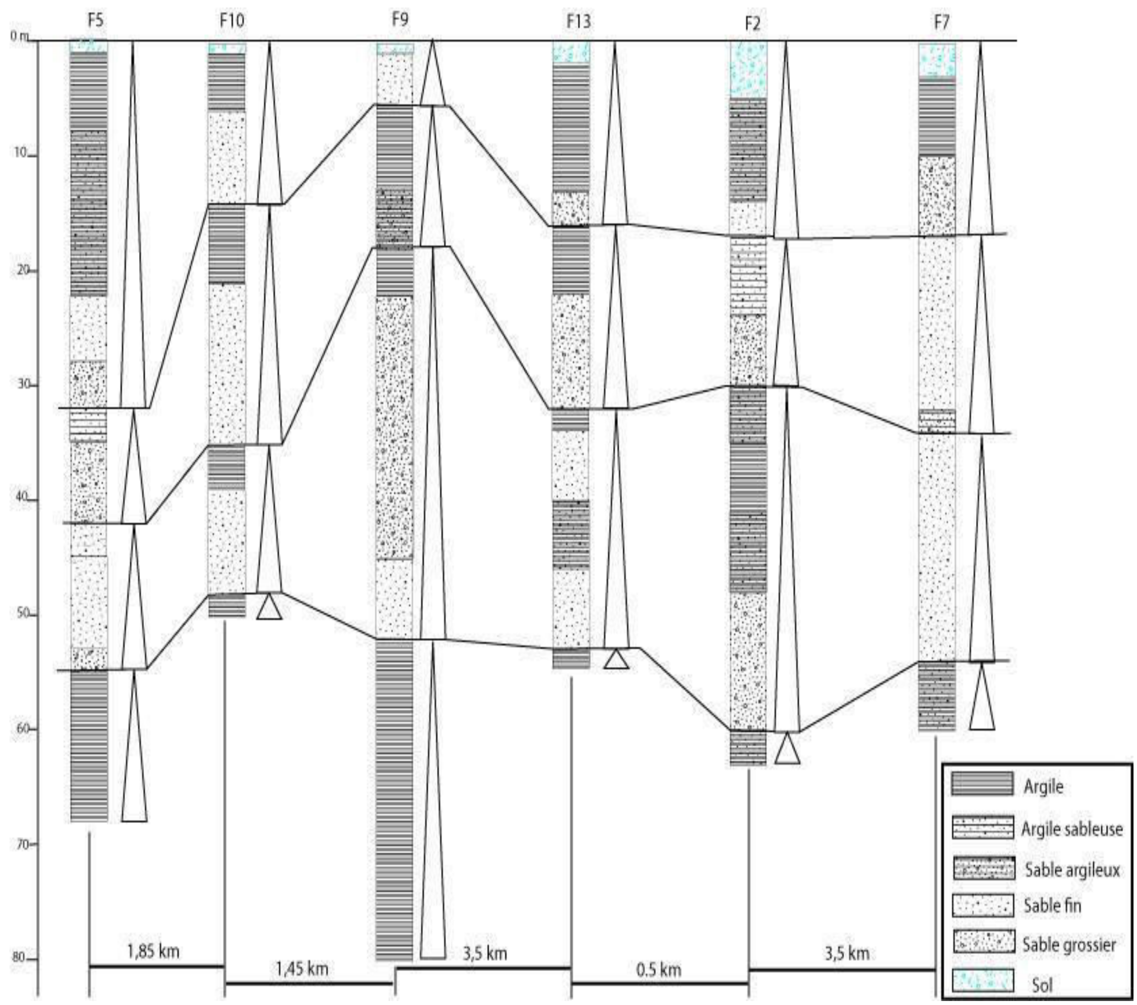


Figure.7 Borehole correlation (section 2)

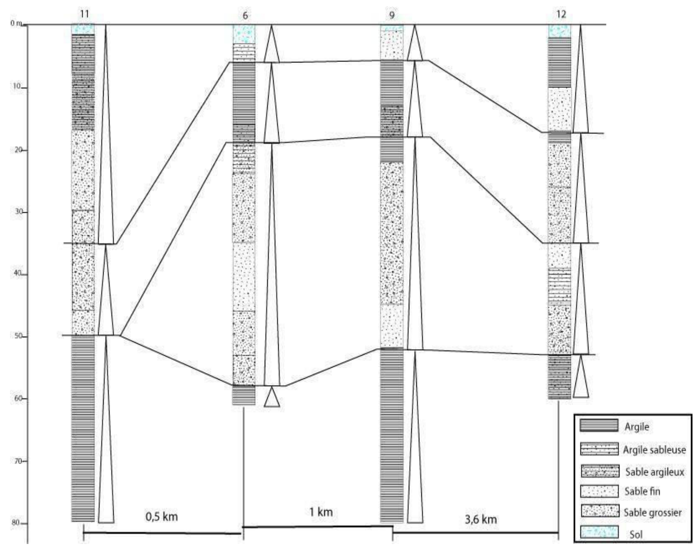


Figure.8 Spatial distribution of groundwater conductivity

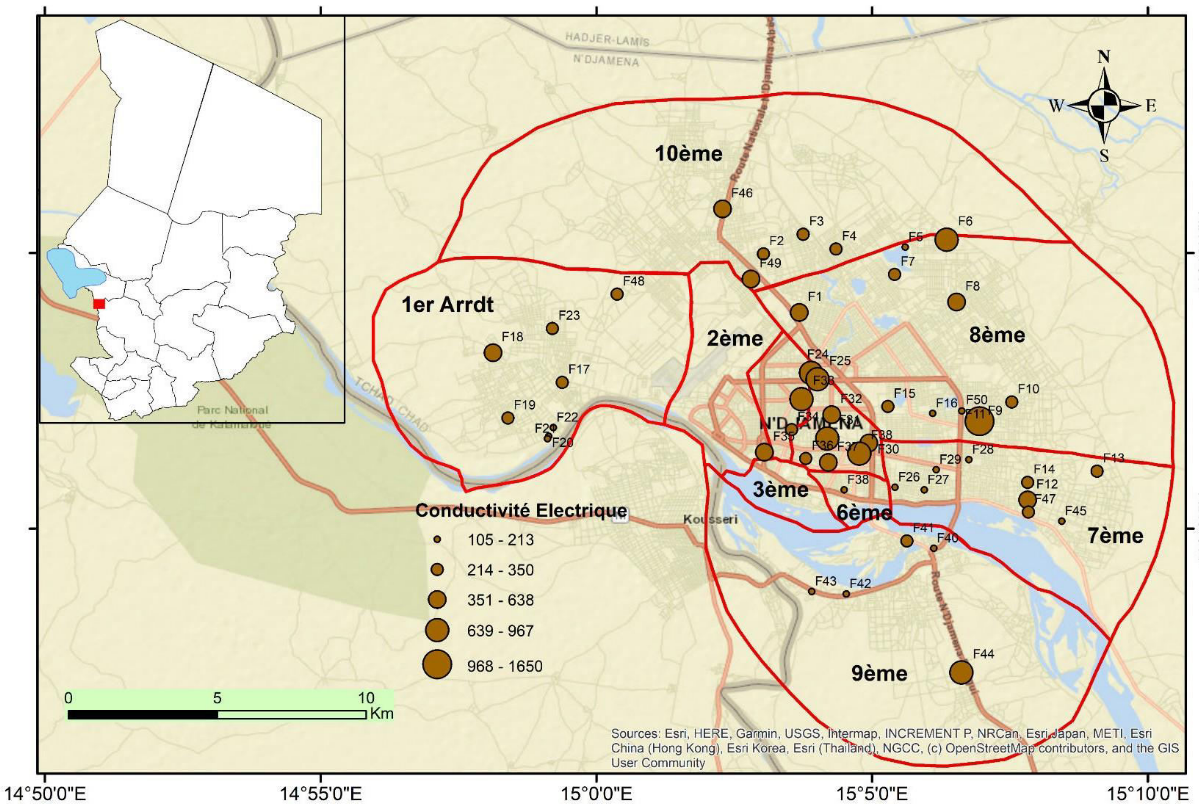


Figure.9 Variation of cations (a) and anions (b) in N'Djamena waters

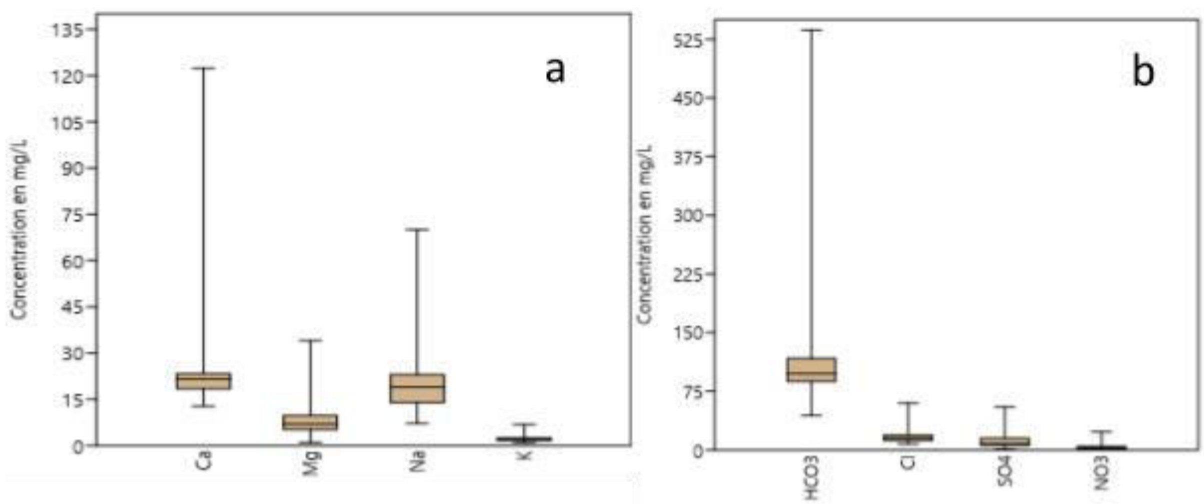


Figure.10 Chemical facies

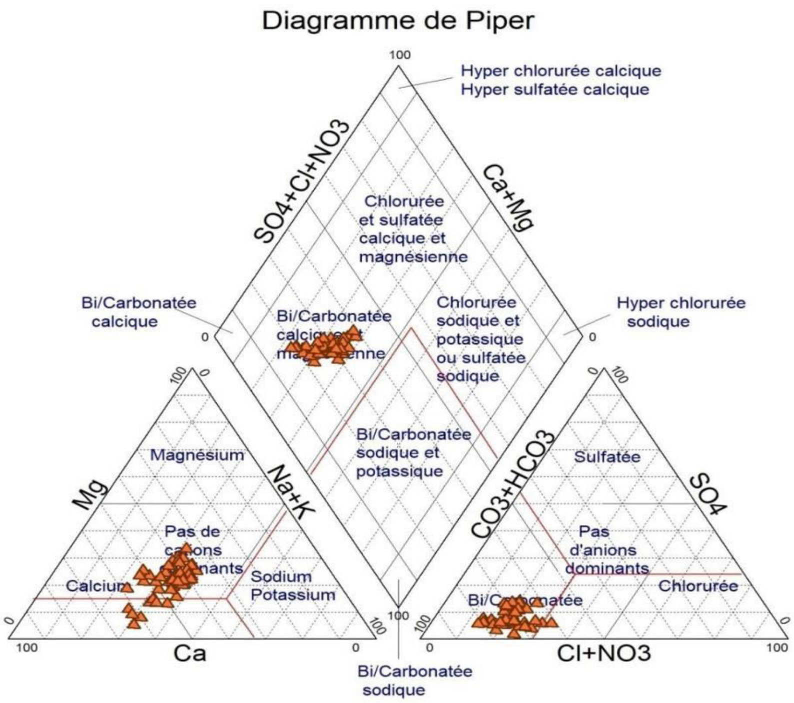


Figure.11 Spatial distribution of bacterial colonies

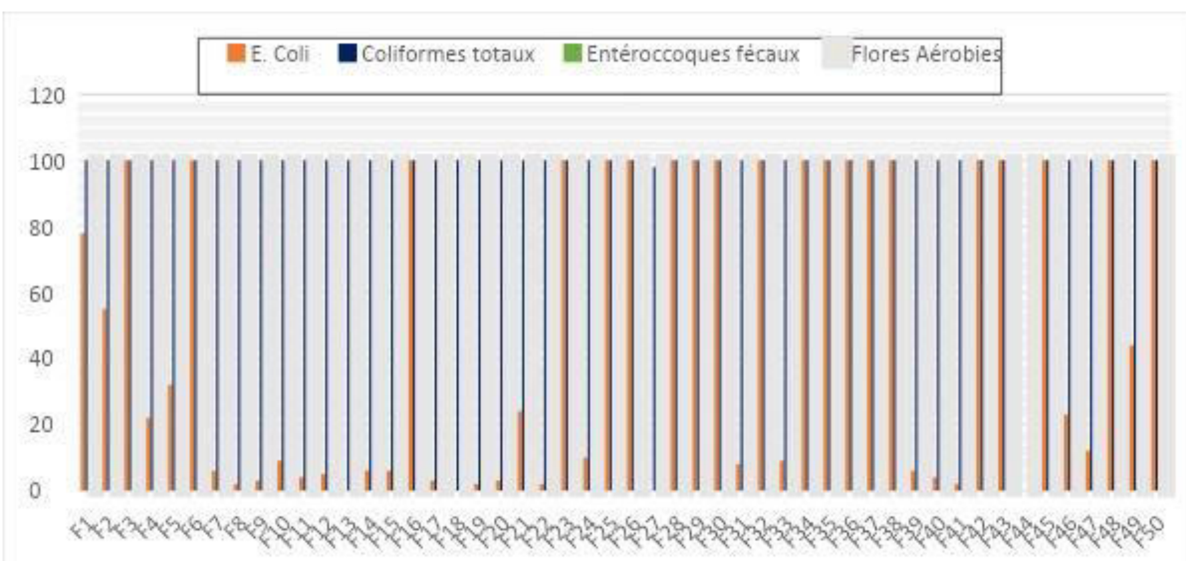
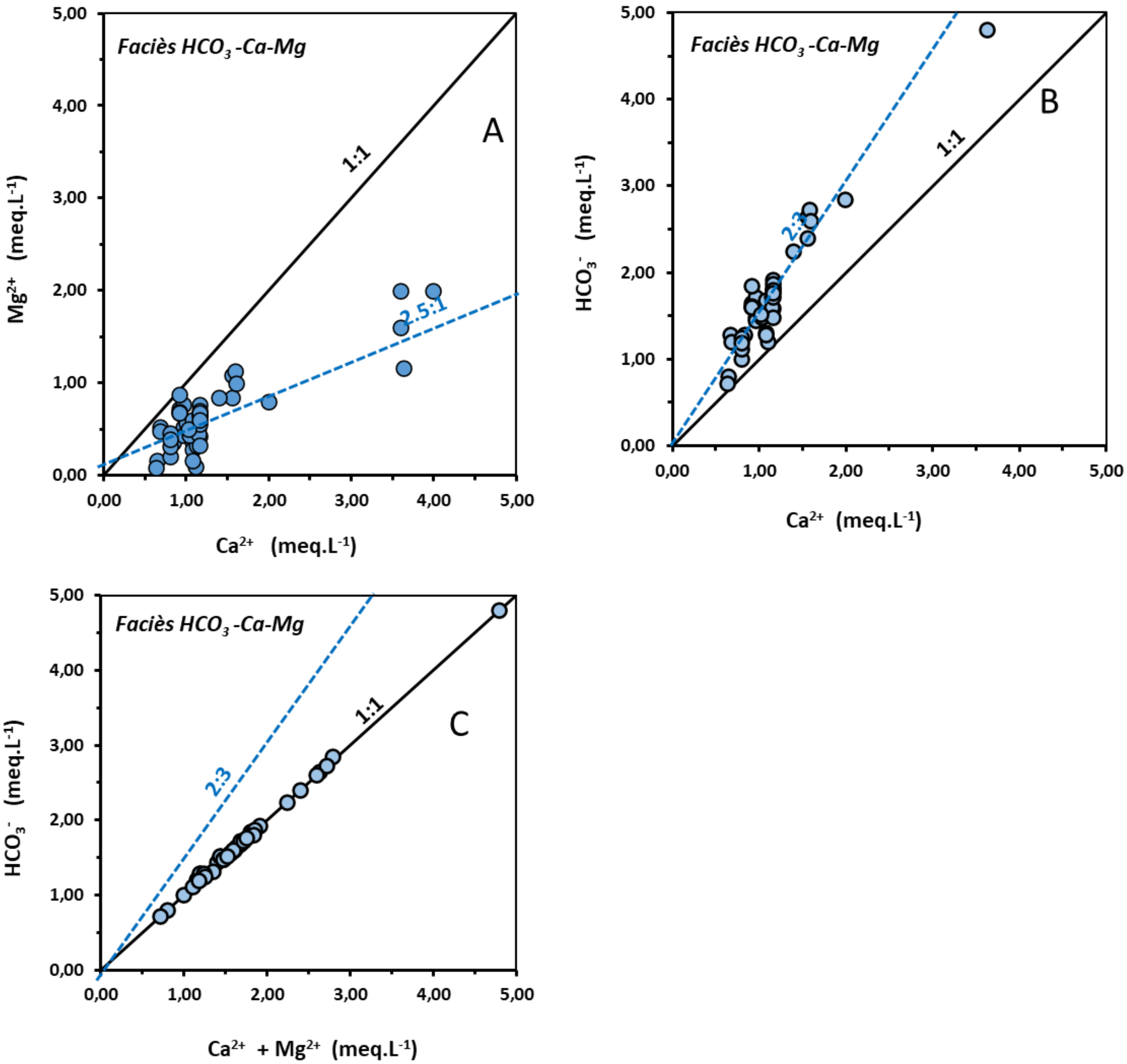


Figure.12 Evolution of the dominant elements of the calcium bicarbonate facies



Conclusion

In this work, the characterization of the Quaternary aquifer of the city of N'Djamena was studied. Stratigraphic, chemical and microbiological approaches were used to better understand the lithological characteristics and assess the quality of the city's Quaternary aquifer. The litho-stratigraphic study identified four retrograde genetic sequences. This highlighted the significant lateral and vertical variations in sedimentary facies in our study area. The dominance of the sandy formation favours the migration of chemical elements and bacterial germs towards the water table. In terms of hydrochemistry, the physical parameters of the groundwater studied revealed a temperature close to that of ambient air, indicating thermal equilibrium with the atmosphere. The pH of the water was generally weakly acidic to neutral, characteristic of carbonate environments. Electrical conductivity was highly heterogeneous, reflecting the distribution of mineral charges in the aquifer, which may be influenced by lithology or point source pollution. All the water in the study area is of the calcic bicarbonate type.

The presence of this type of facies is due to recent recharge by the Chari-Logone river and interactions between groundwater and geological formations rich in carbonate minerals such as limestone and dolomite.

Chemical levels in groundwater are not yet alarming. However, the situation may change as a result of human and industrial activities. Bacteriologically, more than 90% of the water from these boreholes contains bacterial germs. The presence of these bacterial colonies in the water is thought to be the result of household waste and overflow latrines located near the boreholes. Based on WHO standards, the current water samples studied are generally not fit for human consumption. However, the present comprehensive study marks a major step forward in the study and understanding of groundwater quality in N'Djamena. Despite these acceptable values in terms of chemical quality, the investigation of heavy metals would be necessary given the complexity of urban pollutants. So, regular monitoring of the water table and systematic control of surface activities are essential for the city's unique water resource.

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