



Groundwater quality assessment for drinking and agricultural purposes under arid climate in N'Djamena, Chad (Central Africa)

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Abstract

The present study was carried out in the N'Djamena and Hadjer-Lamis localities (Lac Chad basin). The main objective was to examine the groundwater quality for domestic and agricultural purposes, using hydro-chemical modeling, Water Quality Index and Geographical Information System Technics. Thus, 66 groundwater samples were collected from 22 boreholes for physicochemical and biological analysis. The analytical parameters considered were: pH, electrical conductivity, Ca^{2+} , Mg^{2+} , Na^+ , K^+ , NH_4^+ , HCO_3^- , NO_3^- , F^- , SO_4^{2-} , Fecal Coliform, Total Coliform, Escherichia Coli, Fecal enterococci and Mesophyll Aerobic Flora. The results revealed that groundwater of the studied zone presents a neutrality ($6.40 \leq \text{pH} \leq 7.57$), very weakly to weakly mineralized ($92 \leq \text{electrical conductivity} \leq 590 \mu\text{S/cm}$) with only one water type (Ca-Mg-HCO_3), characteristic of the homogenous quaternary aquifer, the most used. The decreasing order of magnitude of the cations is as: $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$, while that of anions is $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{NO}_3^-$. The Water Quality Index varied from 188.41 to 866.89, corresponding to poor (9.09%), very poor (18%) and unsuitable (72%) for drinking. The poor quality is linked to the presence of bacteriological species. It should therefore be noted that groundwater in N'Djamena and Hadjer-Lamis can be used to irrigate crops, but it should be purified before being used for drinking purposes. In general, this study provides an overview of the aquifers characteristic in the Lake Chad Basin, and calls on local and administrative authorities and development partners to effectively cooperate in the permanent monitoring and preservation of the quality of this water. This would undoubtedly guarantee their sustainable and efficient management.

Keywords Bacteriological species · Geographical information system · Hydro-geochemistry · Lake Chad · Water quality index

Introduction

Water is a natural resource that is essential for the full development of communities (United Nation, 2018; Tontsa et al., 2022; Kouassy Kaledjé et al., 2023). It is considered as a vector of socio-economic and cultural development. To corroborate that, it is used in households for drinking and other tasks, in the agri-food and brewing industries, and in agro-sylvo-pastoral activities for the production of goods and services, including the field of leisure (Frsat et al., 2023; Subba Rao et al., 2021a). Access to this precious resource remains a major concern for the international community (Frsat et al., 2023). In term of statistics related to water supply and sanitation around the world made by the World Health Organization (WHO), a single human being requires between 50 and 100 L of water to ensure that its most basic needs are met. In fact, currently, approximately 884 million

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people still lack access to safe drinking water and more than 2.6 billion do not have access to basic sanitation (Barrie et al., 2023). It is also estimated that approximately 1.5 million children under 5 years of age die each year as a result of water and sanitation-related diseases (Barrie et al., 2023).

On a global scale, water resources face enormous pressures that are both natural and anthropogenic (Sorlini et al., 2013; Seeber et al., 2014; Vetrimurugan Elumalai et al., 2017; Yenugu et al., 2020; Seben et al., 2021; Ngo Billong et al., 2023; Bekele et al., 2023). Indeed, the growing population coupled to numerous community wars, insecurities and climate changes have led to increase demand for water for drinking and irrigation usages. All of these pressures negatively impact these resources from both a qualitative and quantitative perspective. It is why assessment of groundwater quality for drinking and irrigation usages in developing countries is important, since water quality is a fundamental aspect of groundwater management (Li et al., 2019; Wu et al., 2019; Gad et al. 2020).

Central Africa in general and Chad in particular are no exception to the rule, due to its geographical position. The latter is entirely located in a Sudano-Sahelian climate with low rainfall (less than 600 mm/year) that decreases from south to north (Mahamat Nour et al., 2019; Mbadngonel Morbe, 2018; Roudouane et al., 2020). Access to water for domestic needs in most areas of the Lake Chad Basin is primarily from groundwater through boreholes and wells (Abderamane, 2012; Abderamane et al., 2013 and 2017, Mbadngonel Morbe, 2018). Besides, neither the quality nor the productivity of these aquifers are sufficiently known. Likewise, these water resources are subject to multiple problem including, agriculture, industry, high demand for human consumption, lack of hygiene and sanitation and climate change (Frsat et al., 2023; Subba Rao et al., 2021a). According to United Nation (2013), Song et al. (2023), the Sahel is a semi-arid region with a surface area of 3 million km², representing about 10% of the total area of the African continent. It is among the areas most affected worldwide by the issue of water scarcity as it is vulnerable to the effects of climate change, not only because of the aridity of the climate but also because of environmental degradation.

The city of N'Djamena in particular counts about 1,000,000 inhabitants, but less than 41% have access to drinking water (Abderamane, 2012; Abderamane et al., 2013, 2017; Mahamat Nour et al., 2019). Those authors revealed that access to drinking water in the region is 56%, compared to 16% for sanitation. Based on the literature, current knowledge of the water resources of the Lake Chad basin which is considered as a vulnerable ecological zone is still patchy (Abderamane, 2012; Bon et al., 2020; Mahamat Nour et al., 2019; Ombolo et al., 2016). Some of the research carried out there mostly focused on the surface waters of the Logone and Chari in relation to the alteration and transport

of sediment flows. Even though there are recent works on water quality such as those of Bon et al., (2020), Song et al., 2023; they mostly focused on the physico-chemical and isotopic aspects. According to the first authors, the quality of groundwater in the Lac Chad basin, revealed a general good quality for both drinking and irrigation, with the exception of certain boreholes in the 1st, 5th, 8th, and 9th districts of N'Djamena. However, this study did not take into account biological parameters. Song et al., (2023) at the transboundary quaternary aquifer of the Lake Chad Basin scale show that: (1) the multi-layered structure of the regional aquifer was highlighted with shallower and intermediate to deep flow paths; (2) the shallower aquifer is recharged with rainwater and inter-connected with surface water; (3) groundwater chemistry indicates geogenic influences in addition to a strong anthropogenic fingerprint and the intermediate to deep aquifer shows a longer residence time of groundwater, less connection with the surface and no to only a little anthropogenic influence. This work and many other does not in any way state whether these waters are of good quality for human consumption or not. This lack of information regarding the hydro-geochemical and hydro-biological aspects does not favour the rational and objective management of this resource, and even less so in the future when additional needs will be felt even more (intensification of agriculture and use of chemical fertilizers, grazing, population growth and the need for security in relation to climate change). This lack of understanding of water resources and the resulting health, economic, environmental and conservation consequences contrasts with several African and global development agendas, including the Sustainable Development Goals (SDGs). Hence, groundwater quality is an important environmental concern that must be addressed and monitored; indeed, the locality of N'Djamena with arid climate that is sensitive to climate change face a delicate and crucial issue with water quality. Public awareness is needed to ensure water quality preservation. In this regards, the present study intends to (1) investigate groundwater quality based on hydrogeochemical and bacteriological conditions; (2) assess the suitability of the groundwater for drinking and irrigation purposes using Water Quality Index (WQI) and hydro-chemical modeling; (3); to identify the environmental factors controlling mechanisms affecting water quality.

The specificity of the present study is linked to the fact that water quality assessment using the WQI takes into account the biological species which are the pollutant parameters, contrary to several other works which focused exclusively on physicochemical parameters and accessorially on heavy metals. Likewise, statistical analysis was also used to discriminate the studied parameters in order to better understand the N'Djamena hydro-system characteristics. The integration of physicochemical and bacteriological parameters, hydro-geochemical modeling, and WQIs

calculation coupled to the geo-statistical analysis and GIS techniques provides a valuable framework for assessing patterns, defining particular environmental problems, and sharing knowledge on water resources, geochemical processes, and water quality. This study is a contribution to a better understanding of groundwater quality in the study area, which would undoubtedly contribute to their efficient management such as the different methods of treatment before consumption and other domestic uses.

Materials and methods

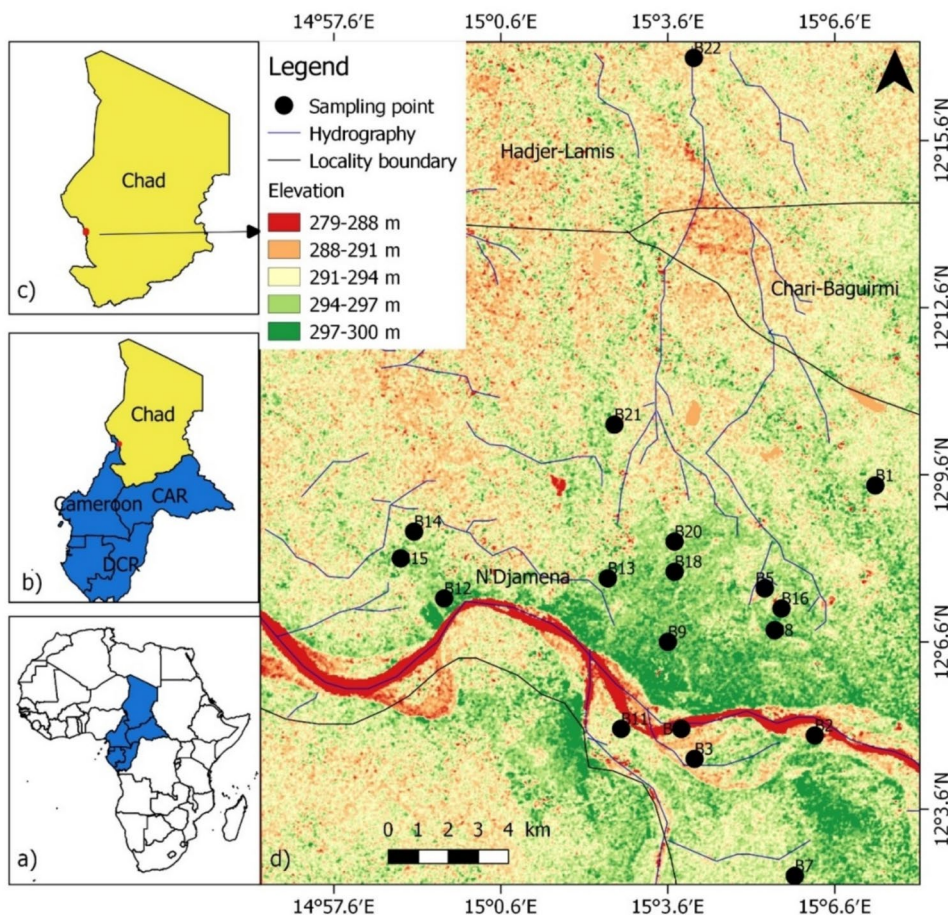
Study area

The studied zone is situated in the southwestern part of Chad, particularly in N’Djamena and Hadjer-Lamis localities, in Central Africa (Fig. 1). The climate is humid monsoon of oceanic origin in the south-western part and the dry Harmattan of continental origin in the north-east (Mbadn-gonel Morbe, 2018; Souabe, 2013). Based on the hydrological data (precipitation and temperature) obtained in the “*Direction des Ressources en Eau et de la Météorologie*”

of N’Djamena covering the period from 2010 to 2016, annual rainfall varied between 400 and 1000 mm, for the inter-annual mean of 593.5 mm; five rainy months (April to August) and seven dry months (September to March) are observed. The temperature fluctuates from 27.9 to 44.8 °C. The highest temperatures are observed within April–May, while the lowest are observed within December-January. From a geomorphological point of view, altitude varies between 279 and 300 m (Fig. 1).

From a geological point of view, the Lake Chad basin is made up of largely homogenous and continuous sedimentary deposit throughout the basin (Djoret, 2000; Djoret & Favreau, 2014; Louis, 1970; Roudouane et al., 2020). At a local level, however, there are strong horizontal lithological and granulometric heterogeneities. According to Djoret and Favreau (2014), most of the zone is covered by Quaternary sands, below the sands, at about 75 m depth, appear the clays of the Pliocene with a mean thickness of approximately 280 m. Further down, a layer of sand of about 30 m thickness and belonging to the Lower Pliocene is encountered. After that appear sandstones of the Continental Terminal (Tertiary) with a thickness of about 150 m.

Fig. 1 Location of the study area (a): Central Africa in the continent; (b): Republic of Chad in Central Africa; (c): Republic of Chad; (d): Study site



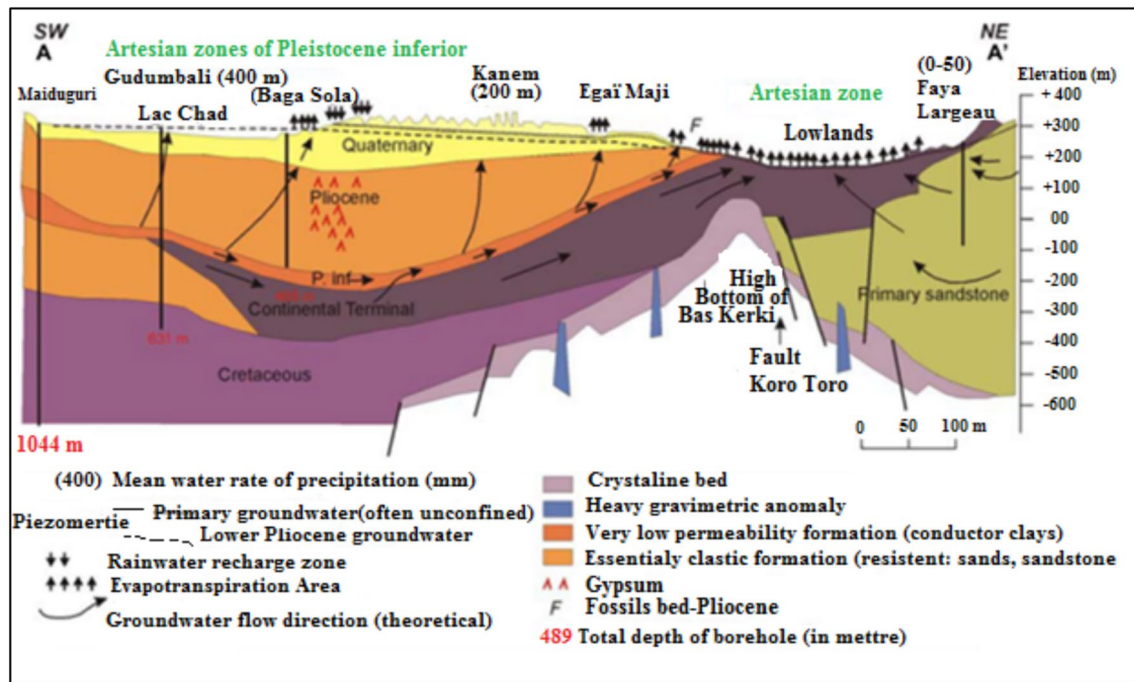


Fig. 2 hydrogeological cross section in the Lac Chad basin including the study area according to Schneider and Wolf (1992); Lemoalle and Magrin, (2014)

At the hydrogeological aspect, illustrated in Figs. 2 and 3, Schneider and Wolf (1992); Schneider (2001); Ngounou Ngatcha (2009); Vassolo (2012); Abderamane et al., (2013) Lemoalle and Magrin (2014) highlight several aquifer types. There are: (1) the recent quaternary aquifer which is made up of small perched aquifers (10–15 m depth). (2) The ancient quaternary water table made up of sandy-clay formations from the quaternary period. (3) The deep aquifers which are found in the middle and lower Pliocene formations and contain a confined aquifer under the clayey sequences of the upper Pliocene (United Nation Development Programme, 2002).

Sampling and analytical methods

Two field campaigns were conducted in August and February 2018, covering the rainy and dry periods. During the August field trip, 22 boreholes were identified (Table 1) in the urban environment. It is important to note that the choice of the sampling sites was made at random, according to the availability of the boreholes and the authorization of the owners or the maintenance agent. The surroundings of these boreholes were also described in order to better explain and discuss the analytical results. After that, these points were spatially represented using SRTM (Shuttle Radar Topography Mission) satellite image. Apart from borehole 7 (B7) and 14 (B14), all others have minimum depth of 30 m. During the same period, the physicochemical parameters like

pH, temperature, turbidity, electrical conductivity (EC) were measured in situ using the pH-meter calibrated with two solutions such as pH = 4, and pH = 7 respectively. The turbidity was measured with the turbidity-meter calibrated with the solutions of 00 NTU (nephelometric turbidity units) and 100 NTU. Samples for chemical analysis were collected respecting scrupulously the method described by Rodier (2009); Fahmida et al., (2021); Tontsa et al., (2022). Thus, the bottles intended for sampling were previously rinsed in the laboratory with distilled water. During the sampling, they were also cleaned at least three times with sample water. A few drops of acid (0.1 N HNO₃) were added to sample bottles for cations analysis in order to avoid any mineral precipitation. The analyses were carried out in the « *Laboratoire d'Analyse des Eaux (LAE) du Ministère de l'Hydraulique et de l'Élevage* » of N'Djamena, using high-performance liquid chromatography (HPLC). The concentrations of Ca²⁺, Mg²⁺, and SO₄²⁻ were measured using EDTA titration method with errors of ± 1%, ± 1%, and ± 0.5% respectively. The K⁺ and Na⁺ concentrations were determined using flame atomic absorption spectrophotometry with an accuracy of 0.1 mg/L. The anions concentrations were analyzed using argentometric titration with a relative error of ± 1%. All the analyses have been made observing the standard procedures proposed by American Public Health Association (APHA, 2012; Bon et al., 2020; Ngo Billong et al., 2023; Subba Rao et al., 2021a, 2021b). Regarding the bacteriological analyses, samples were collected in August and February. The samples

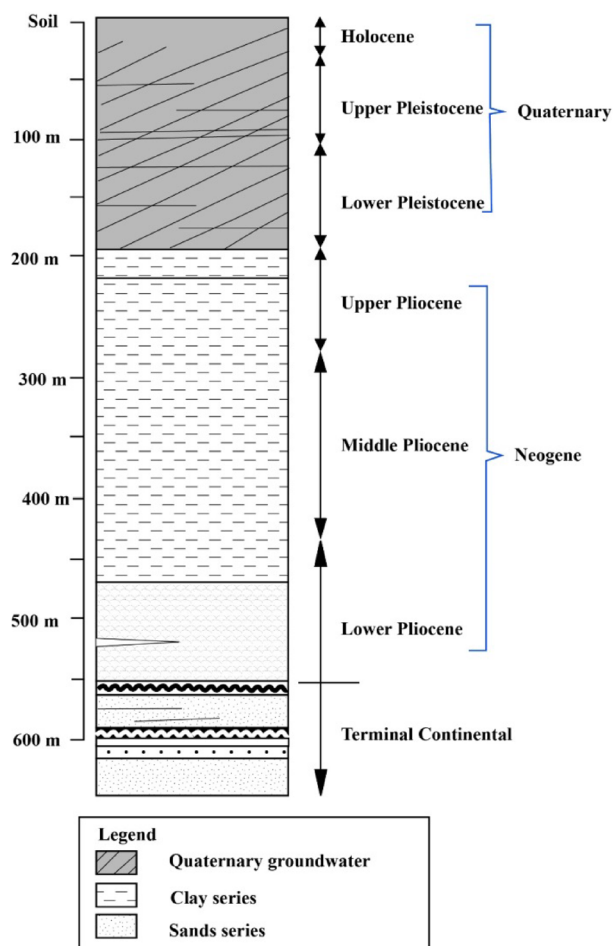


Fig. 3 Hydrogeological vertical section showing different aquifers of the study zone

were taken in bottles sterilized by autoclave and with alcohol at 90°. All samples were stored in ice chests at 4 °C and transported in the Wastewater Research Unit laboratory of the University of Yaoundé 1 (Cameroon). The determination of the bacteriological parameters in the samples was carried out by the method described by Djaouda et al., (2014); Sana et al., (2019); Getachew et al., (2021); Tontsa et al., (2022). The bacteria were identified and counted by filtering 100 ml of the water sample through a cellulose ester membrane with a porosity of 0.45 µm. The membranes were then placed on selective media for 24 h at 44 °C. ENDO AGAR lactose medium, Slanetz medium, Slanetz, and Bartley medium were, respectively, used to select and grow bacteriological species (Tontsa et al., 2022).

The concentration of measured bio-indicators is expressed as Colony Forming Unit (CFU) per unit volume of 100 mL based on Eq. (1) below:

$$CFU = \frac{\text{Number of colonies counted}}{\text{quantity of sample filtered (ml)}} \times 100 \text{ ml} \quad (1)$$

Hydro-geochemical data validation

After the physicochemical analysis, the analytical results were validated by calculating the Ionic Balance Error (IBE) of the hydro-chemical elements whose formula is as follows (Eq. 2) (Gad & El Osta, 2020; Mfonka, 2019; Mfonka et al., 2015; Subba Rao et al., 2021a). All the values varied between ± 10 percent, reflecting the good analytical results.

$$IBE = \sum \frac{(\text{cations} - \text{anions})}{(\text{cations} + \text{anions})} * 100 \quad (2)$$

In conclusion, based on the data collection and treatment, the similarity among the analytical results and the fact that they are managed by the specialized laboratories and academic researchers must be noted, for that assures the measurement methods homogeneity and the quality of the results.

Drinking water quality

WQI calculation

There are many methods used to evaluate the water quality index such as Drinking Water Quality Index (DWQI) or Water Quality Index (WQI), Irrigation Water Quality Index (IWQI) and Entropy Weighted Groundwater Quality Index (EWGQI) (Chimankpam Ezugwu et al., 2019; Ngo Billong et al., 2023; Obiri et al., 2021; Prusty & Farooq, 2020; Şener et al., 2017; Yenugu et al., 2020). The WQI is the widely used method (Ngo Billong et al., 2023; Obiri et al., 2021; Yenugu et al., 2020). To evaluate the water quality index in the present study, each of the chemical and biological parameters were assigned different weights (w_i) in a scale of 1–5 (Table 2), representing the least effect to the highest effect on water quality respectively, based on their perceived effects on primary health and according to its relative importance in the drinking water quality (Chimankpam Ezugwu et al., 2019; Ngo Billong et al., 2023; Obiri et al., 2021; Prusty & Farooq, 2020; Şener et al., 2017; Yenugu et al., 2020). The highest weight of 5 was assigned to parameters that have critical health effects and whose presence above the critical concentration limits could restrain the usability of the resource for domestic and drinking purposes (Ghouili et al., 2018; Obiri et al., 2021; Yenugu et al., 2020). The relative weight (W_i) is computed from the following equation (Eq. 3):

Table 1 Description of the environments of the sampling points

Sample points	Locality	Longitude	Latitude	Altitude (m)	Depth (m)	Description of the environment of the sampling point
B1	Walia p	15°07'19.2"	12°09'24.5"	306.10	45	There are three septic tanks at depths of 3, 5, and 6 m and a rubbish head upstream of the borehole
B2	Walia Gor	15°06'14.4"	12°04'55.2"	300.80	45	Presence of a pit about 6 m depth in the vicinity of the borehole
B3	Ngueli	15°04'4.8"	12°04'30"	305.50	45	A 5 m deep cesspit is found in the vicinity of the borehole
B4	Sabangali	15°03'50.4"	12°05'2.4"	302.50	30	Presence of stagnant pool water and open channel adjacent to the borehole
B5	Moursal 3	15°05'20.4"	12°07'33.6"	290.50	30	Flood zone
B6	Moursale 1	15°05'31.2"	12°06'48.6"	299.50	30	Presence of a septic tank next to the borehole, as well as the proximity of the Chari river (at 250 m)
B7	Chagoua C15	15°05'52.8"	12°02'24"	289.50	18	Presence of 9 m depth cesspit in the vicinity of the borehole
B8	Moursal 2	15°05'31.2"	12°06'48.6"	290.50	30	Flood zone
B9	Ambasatna	15°03'36"	12°06'36"	295.50	30	Presence of a latrine only 3 m from the borehole
B10	Radina	15°03'50.4"	12°05'2.4"	298.50	30	There is a drainage system and septic tank in a few meters from the borehole
B11	Djambalbar	15°02'45.6"	12°05'2.4"	302.00	45	Borehole located near the Chari River
B12	Farcha Carré 2	14°59'34.8"	12°07'22.8"	305.00	30	Presence of rubbish heaps and lack of drainage around the borehole
B13	Klemat	15°02'31.2"	12°07'44.4"	295.10	45	-
B14	Madjorio	14°59'2.4"	12°08'34.8"	286.00	18	Presence of septic tank at 3.5 m around the borehole
B15	Coque-ville	14°58'48'	12°08'6"	305.00	45	Presence of rubbish heaps and lack of drainage around the borehole
B16	Djari	15°05'38.4"	12°07'12"	293.40	45	There is a drainage system a few meters from the borehole
B17	Diguel Est	15°05'20.4"	12°07'33.6"	300.20	45	There is a drainage system a few meters from the borehole
B18	Repos 1	15°03'43.2"	12°07'51.6"	300.00	30	Presence of septic tank of 13 m depth around the borehole
B19	Ameriguebé	15°03'50.4"	12°05'2.4"	296.30	45	Flood zone
B20	Repos 2	15°03'43.2"	12°08'24"	290.60	30	Presence of a latrine only 3 m from the borehole
B21	Goudji	15°02'38.4"	12°10'30"	295.00	40	Flood zone
B22	Goudji Charfa	15°04'4"	12°17'05"	297.00	45	Presence of a latrine only 3 m from the borehole

B = Borehole

$$W_i = w_i / \sum_{i=1}^n w_i \quad (3)$$

In this equation, W_i expresses the relative weight, w_i the weight of each parameter and "n" the number of parameters. The calculated relative weight (W_i) values of each parameter are given in Table 2. The quality rating (q_i) for each parameter is assigned by dividing its concentration in each water sample by its limit values given by World Health Organization (2017).

q_i is calculated as follow (Eq. 4):

$$q_i = \frac{C_i}{S_i} \times 100 \quad (4)$$

where q_i , S_i and C_i are respectively the quality rating, the concentration of each hydro-chemical parameter in each water sample and the drinking water standard for each

chemical parameter in milligrams per liter, according to the guidelines for the World Health Organization (2017).

Before gating WQI index value, SI was calculated based on the equation below (Eq. 5):

$$SI = W_i \times q_i \quad (5)$$

Finally, the WQI value is calculated with the following equation (Eq. 6):

$$WQI = \sum_{i=1}^n SI \quad (6)$$

In Eq. (6), SI is the sub-index of i^{th} parameter; the computed WQI values are classified into five categories presented in Table 3. With regard to the limitations of the method based on the WQI used in the present study, it is important to specify that several authors do not take bacteriological species into

Table 2 Assigned and relative weights of water quality parameters with their WHO acceptable limit

Parameter	Unit	WHO standards	Weight (Wi)	Relative weight (wi)
[Ca ²⁺]	mg/l	75	2	0.042
[Mg ²⁺]	mg/l	125	2	0.042
[Na ⁺]	mg/l	200	2	0.042
[K ⁺]	mg/l	12	1	0.021
[NH ₄ ⁺]	mg/l	1.5	2	0.042
[NO ₃ ⁻]	mg/l	50	5	0.104
[SO ₄ ²⁻]	mg/l	250	4	0.083
[Cl ⁻]	mg/l	250	3	0.063
[HCO ₃ ⁻]	mg/l	125–130	3	0.063
[F ⁻]	mg/l	1.5	4	0.083
pH	mg/l	6.5–8.5	4	0.083
EC	μS/cm	1400	4	0.083
FC	CFU	0	3	0.063
TC	CFU	0	3	0.063
E. Coli	CFU	0	3	0.063
Aer. F	CFU	0	3	0.063
			∑Wi = 48	∑wi = 1.000

The limit used as standard is those prescribed by World Health Organization (2017)

Table 3 Classification of water quality according to WQI values

Range	Quality
< 50	Excellent water
50 < WQI < 100	Good water
100 < WQI < 200	Poor water
200 < WQI < 300	Very poor water
> 300	Unsuitable for drinking

account in the process of assessing the drinking water quality. In addition, the weights assigned to certain parameters are random, which does not always guarantee the accuracy of the method.

Irrigation water quality

Sodium absorption ratio (SAR)

The sodium absorption ratio is an important index for determining the suitability of water used in irrigation (Ghouili et al., 2018; Shwan Seeyan, 2020; Abugu et al., 2021). According to these authors, the excess of sodium concentration in groundwater affects the soil properties and reduces the soil permeability. The SAR is calculated from the ratio of sodium to calcium and magnesium, using the following formula (Eq. 7):

Table 4 Water suitability for irrigation based on quality indexes classification

Quality indexes	Signification	Ranges
SAR	Suitable	0.00–3.00
	Moderate	3.00–9.00
	Unsuitable	> 9.00
%Na	Good	20.00–40.00
	Permissible	40.00–60.00
PI	doubtful	60.00–80.00
	Unsuitable	> 80.00
	Class 1	75.00 <
%MI	Class 2	25.00–75.00
	Class 3	< 25.00
	Suitable	< 50.00
	Harmful and unsuitable	> 50.00

$$SAR = \frac{Na^+}{\frac{\sqrt{Ca^{2+} + Mg^{2+}}}{2}} \tag{7}$$

Depending on the sodium absorption ratio value, water can be subdivided in to 3 categories: water with SAR ranging from 0 to 3 considered as good, SAR value ranged between 3 and 9 characterized by moderate type and greater than 9 considered unsuitable for irrigation purpose (Ghouili et al., 2018; Shwan Seeyan, 2020; Abugu et al., 2021; Ngo Billong et al., 2023) (Table 4).

Sodium percent (Na%)

Sodium percent is defined as the percentage of soluble sodium in water (Abugu et al., 2021; Ahamed et al., 2015). It is calculated to assess the suitability of groundwater for agricultural purposes. This parameter represents a significant sodium hazard in surface and groundwater. It contributes significantly to the deterioration of the subsoil structure and consequently, reduces its permeability (Ayed et al., 2017; Chimankpam Ezugwu et al., 2019; Gad & El Osta, 2020). According to Ayed et al., (2017), a high sodium concentration in irrigation water leads to its absorption by the clay particles, and it will be substituted by Magnesium and Calcium ions. This substitution reduces the soil permeability. The Sodium percent was calculated as follows (Wilcox, 1955) (Eq. 8):

$$\%Na = \frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + K^+} \times 100 \tag{8}$$

Permeability index (PI)

The Permeability Index is an irrigation water assessment index used in quantifying the suitability of water for irrigation purposes (Sanjoy et al., 2019). Based on the PI value, irrigation water can be categorized into three classes, namely Classes 1, 2 and 3 (Table 4). Classes 1 ($PI \geq 75\%$) and 2 ($25\% < PI < 75\%$) are considered as suitable for irrigation, while Class 3, with $PI \leq 25\%$ is considered unsuitable for irrigation use. The Permeability Index parameters are evaluated using the equation below (Eq. 9), proposed by Richards (1954) and Wilcox (1955).

$$PI = \frac{Na^+ + \sqrt{(HCO_3^-)}}{Ca^{2+} + Mg^{2+} + Na^+} \times 100 \quad (9)$$

Magnesium percent (%Mg)

The magnesium percent is another parameter which describes the water quality for irrigation as long as magnesium and calcium keep the equilibrium state in most waters. The excess of magnesium affects the soil quality (increases the construction of alkalinity) which can decrease the productivity (Frsat et al., 2023; Ramesh & Elango, 2012). The Magnesium percentage was obtained using the equation below (Eq. 10), with the ions concentrations which constitute the formula in meq/l (Ayed et al., 2017; Chimankpam Ezugwu et al., 2019):

$$\%Mg = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \times 100 \quad (10)$$

Identification of the factors controlling groundwater quality in the study area

Saturation index calculation

The saturation index (SI) is useful to understand the different stages of hydro-geochemical evolution. It also helps in identifying the geochemical processes responsible for hydro-geochemical characteristics (Mfonka et al., 2021; Singh et al., 2017). In this study, the SI has been calculated using Diagram software, following the formula 11 below (Eq. 11):

$$SI = \log (IAP)/Kt \quad (11)$$

where, IAP is the ion activity product of the dissociated chemical species in solution and Kt = equilibrium solubility product of the mineral.

According to Merchán et al., (2015), Paternoster et al., (2016), Yang et al., (2017), Singh et al., (2017), When $SI < 0$, the solution is considered under saturated. When $SI = 0$, the solution is saturated, and equilibrium is achieved between mineral dissolution and precipitation. When $SI > 0$, the solution is oversaturated, and extra minerals precipitate.

Gibbs model (1970)

The Gibbs model is the method used to identify and understand the source of groundwater mineralization between water–rock interaction, precipitation and evaporation phenomenon (Venkatesan et al., 2021; Al Haj et al., 2022; Ngo Billong et al., 2023). The Gibbs value and the diagram have been obtained using Diagram software which use the equation below (Eq. 12)

$$TDS = f(Na^+ / Na^+ + Ca^{2+}) \text{ and } TDS = f(Cl^- / Cl^- + HCO_3^-) \quad (12)$$

Statistical analysis method

In this research, the statistical analysis related to correlation matrix (CM) and Q-mode hierarchical clustering where specifically performed to identify the most important mechanism affecting the groundwater chemistry and the hydrochemical dynamic in the various groundwater reservoirs of the study. Those technics are used due to their efficiency, specifically in water sciences (Rakotondrabe et al., 2018; Diani et al., 2021; Johnbosco Egbueri and Johnson Agbasi 2021; Tanushree Chakravarty and Susmita Gupta, 2021; Ramadhani Mussa & Chikira Mjemah, 2023). According to Johnbosco Egbueri and Johnson Agbasi 2021; Güler et al., (2002), HCA is one of the most used classification methods in hydrogeochemistry which uses a dissimilarity matrix based on Euclidean distance in order to group samples into groups of relatively similar characteristics. It identifies the differences between samples and group them into several clusters based on their differences (Jiang et al., 2015). The clusters are generated by minimizing the sums of square distance to the mean center, while the correlation matrix makes it possible to establish direct, sometimes indirect or even inverse relation between the parameters taken in pairs, the hierarchical clustering analysis proposes similarity or dissimilarity links between these same parameters which are either variables or labels. These technique require an abundant range of data and quite satisfactory results, which is sometime difficult when using simple processing techniques. The 2014 XLSTAT software version was used for this purpose.

Inverse distance weighting (IDW) interpolation

In this study, Inverse Distance Weighting (IDW) interpolation method was used to construct the thematic maps which illustrate the spatial distribution of some parameters (WQI, PI and Mg). According to Rakotondrabe et al., (2018); Cabalar et al., (2021) this method is widely used in geology, particularly in hydrogeology, hydro-geochemistry for their subtlety. The general formula is presented as follow (Eq. 13):

$$Z(S_0) = \sum_{i=1}^N \lambda_i Z(S_1) \quad (13)$$

where: $\hat{Z}(S_0)$ is the value we are trying to predict for location S_0 ; N is the number of measured sample points surrounding the prediction location that will be used in the prediction; λ are the weights assigned to each measured point that we are going to use. These weights will decrease with distance; $Z(S_1)$ is the observed value at the location S_1 .

The formula to determine the weights is the following (Eq. 14):

$$\lambda_i = d_{i0}^{-p} / \sum_{i=1}^N d_{i0}^{-p} \sum_{i=1}^N \lambda_i = 1, \quad (14)$$

As the distance becomes wider, the weight is reduced by a factor of p .

The quantity d_{i0} is the distance between the prediction location, S_0 and each of the measured locations S_i . The power parameter p influences the weighting of the measured location's value on the prediction location value; that is, as

the distance increases between the measured sample locations and the prediction location (Vetrimurugan Elumalai et al., 2017). The weights for the measured locations that will be used in the prediction are scaled so that their sum is equal to 1. The methodology used in the present study is summarized in the flowchart presented in Fig. 4.

Results and discussion

Physicochemical characteristics of major elements

The statistical description summary of the physicochemical characteristics of the groundwater in the southwestern part of N'Djamena is presented as a box plot in Fig. 5. Globally, it appears that the quality of groundwater is not uniformly distributed, which suggests a high spatial variability due to the involvement of different sources and/or geochemical processes, taking place in the aquifer system (Subba Rao et al., 2021a, 2021b). The pH values of the 22 samples varied from 6.40 to 7.57, with a mean value of 6.75 ± 0.33 . These results indicated that, the groundwater of N'Djamena locality are slightly acid to alkaline. Temperature values fluctuated between 28.00 and 31.0, with a mean of 29.40 and a median of 29.45 °C. These high values can be explained by the depths of the boreholes, as well as the arid climate that characterises this environment. For electrical conductivity (EC), the values range from 92 to 590 $\mu\text{S}/\text{cm}$, for a mean of $278.32 \pm 139 \mu\text{S}/\text{cm}$. These indicate the freshwater quality (Rakotondrabé et al., 2017; Ayed et al., 2017). The standard deviations obtained through statistical calculations confirm

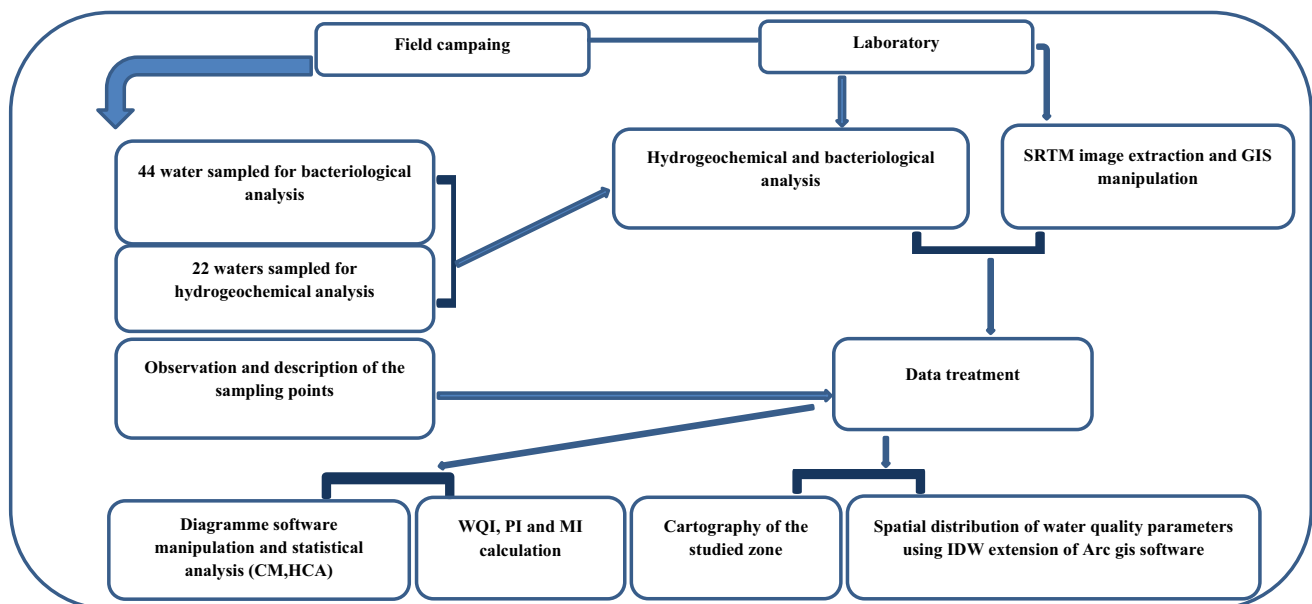


Fig. 4 Flowchart illustrating the methodology of the present study

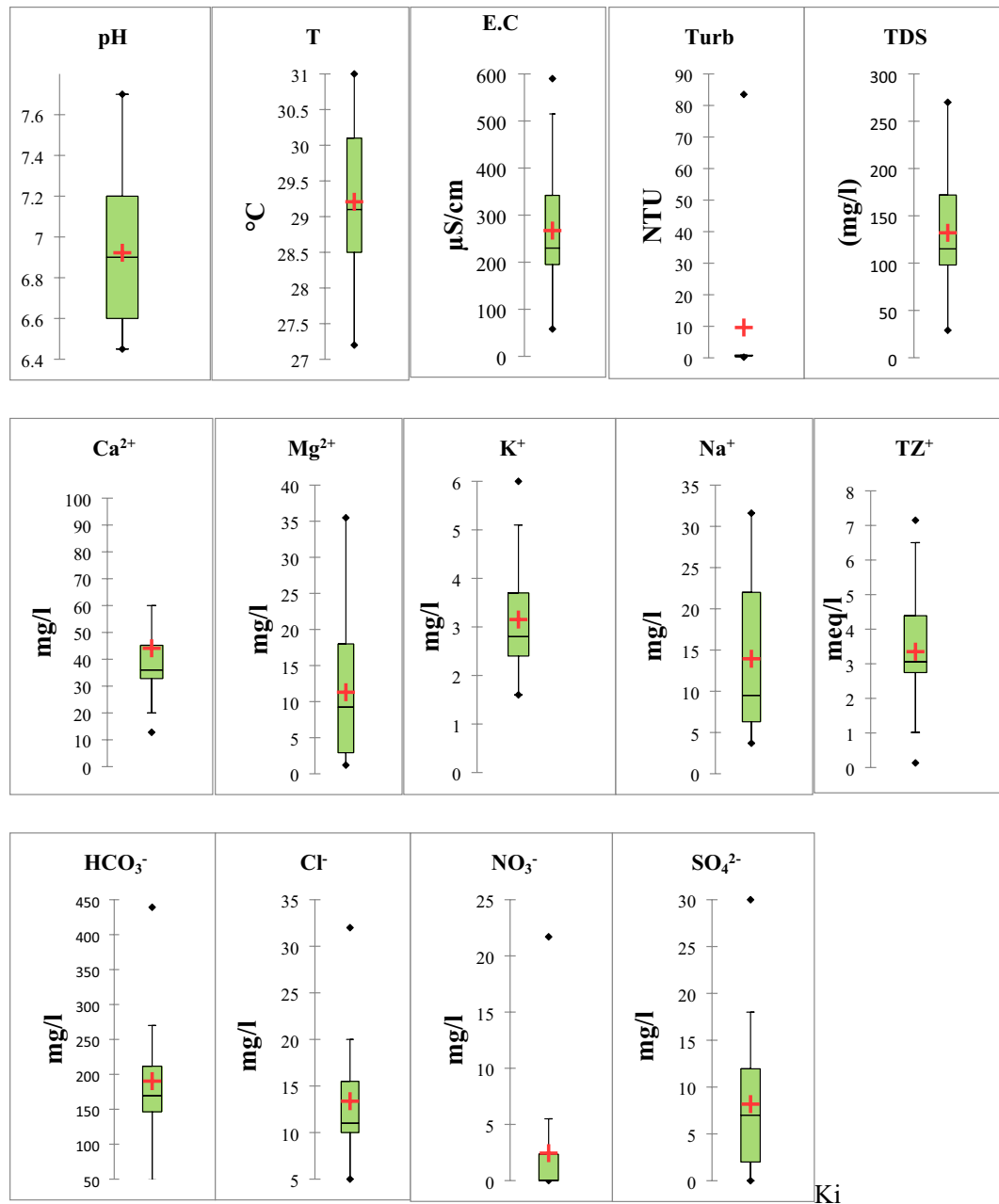


Fig. 5 Boxplot presenting the statistical variation of the physico-chemical parameters in the study zone

the opinion of Subba Rao et al., (2021a, 2021b) presented above, indicating that there are many sources and/or geochemical processes taking place in the studied zone. The relatively high values of EC are probably related to (1) the long residence time of the water in the different reservoirs of the studied zone, and (2) the slow renewal of groundwater resources due to the long dry season that characterizes this environment. Some elements present the outlier/extreme values like EC, Turbidity, K⁺, HCO₃⁻, Cl⁻, NO₃⁻, SO₄²⁻. According to Ramadhani Mussa et al., (2023) it is due to the influence of anthropogenic activities and the topography

variation of the studied zone (presence of recharge and stagnant groundwater zone). These values are in the same order of magnitude with those obtained by Ayşen Davraz and Burcu Batur (2021) in Yalvaç-Gelendost basin in Turkey. The turbidity's values are very low (Turb ≤ 4 NTU). Nevertheless, there is an outlier value of about 83 NTU. As regarding the hydrochemical parameters related to cations (Ca²⁺, Mg²⁺, K⁺, Na⁺) and anions (HCO₃⁻, Cl⁻, NO₃⁻, SO₄²⁻) analytical results have revealed concentration which does not exceed those prescribed by the World Health Organization for human consumption. The decreasing order of

magnitude of the cations is as: $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$, while that of anions is $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{NO}_3^-$. It is noted that the concentration of some elements in this study such as Cl^- are much lower compared to those obtained by Ayed et al. (2017), Aouiti et al. (2020) in the sedimentary environment of North Africa. These differences are probably linked to the fact that the N'Djamena locality is located in an endoreic sedimentary basin, unlike the other environment which is open to the sea characterized by the saline intrusion in some places and characterized by high evaporation and the presence of salty marshes.

Piper's diagram

The water types given by the Piper's diagram is presented in Fig. 6. It reveals in its lower left part that the dominant cations in all the samples are Calcium, followed by Magnesium; whereas anion in its lower right is dominated by HCO_3^- only. This results in Ca-Mg- HCO_3 water type mainly. The only water type obtained by the diagram software reflects the local homogeneity of the geology of the Lake Chad, as indicated by Louis (1970); Djoret and Favreau (2014). Aquifers in sedimentary environment are more or less continuous; the contrast to those of the basement milieu, where several studies revealed the discontinuous nature of the latter environment; this being linked to the polyphase alteration that occurs there (Mfonka et al., 2021). These results are comparable to those obtained by Song et al. (2023) on a large scale of transboundary quaternary aquifer of the Lake Chad Basin.

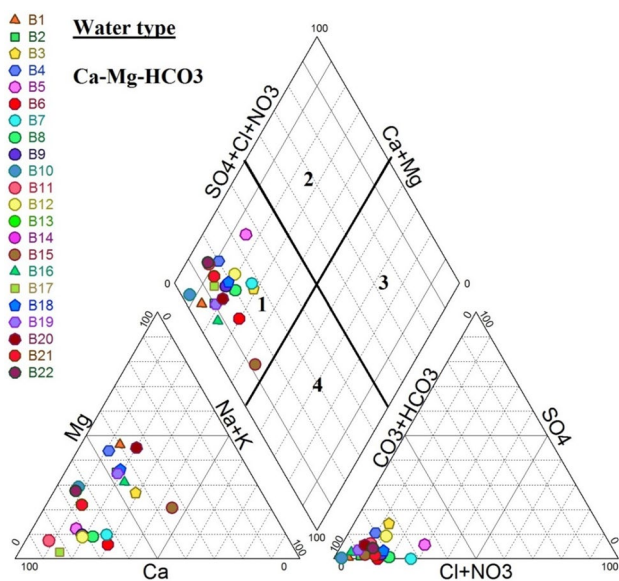


Fig. 6 Water type of the study zone on the Piper diagram

Bacteriological investigation results

Table 5 shows that all the samples from the study area contain bacteriological parameters in varying proportions during the dry and rainy seasons. In general, there is an almost complete absence of faecal enterococci in all the investigated boreholes, with the exception of B3, B4, B5 and B11, which contain these parameters either in the dry season (B3), or in the rainy season (B4 and B11), or during both periods (B5). Another peculiarity can be observed in borehole B20 where only TMAFs are displayed. All the water samples of the study zone are not recommended for human consumption based on the bacteriological species. The presence of these pollution indicator parameters in the groundwater of the city of N'Djamena during the two sampling seasons indicates pollution linked to the lack of sanitation facility in the city. Sewerage systems, septic tanks, solid waste, inadequacy of sanitation facilities and the poor waste management could be the various sources of groundwater pollution in the study area as illustrated in Fig. 7 and Table 1 (samples site description). From a health point of view, there are many water-related diseases such as typhoid, amoebic dysentery, cholera, which sometimes leads to epidemics, and other gastroenteritis. These results for parameters such as *E. Coli*, Total Coliform are significantly lower than those obtained by Akintayo Ojo et al., (2021) in the Ilaro sedimentary environment of southwestern Nigeria.

Water quality index (WQI) results

The WQI for the 22 groundwater samples in the study zone varied from 188.41 to 866.89, with a mean value of 456.75 ± 187.19 (Table 6, Fig. 8). These results correspond to three types of water: “poor”, “very poor” and “unsuitable” for drinking. Those types represent respectively 9.09, 18 and 72% of the total sampled water. The spatial distribution of the WQI (Table 6 and Fig. 8) reveals that, the higher values (> 300) are observed in B3, B4, B5, B6, B7, B8, B9, B10, B11, B12, B14, B16, B17, B18, B19, B21 and B22. The poor quality of these water resources based on the WQI is due to the presence of bacteria species (*E. Coli*, Fecal coliform, Total Coliform, Fecal enterococci and total mesophyll aerobic flora) in that water. This clearly illustrates the inadequacy of the sanitation system in the locality (Fig. 7), which is common to all countries in the south of Sahara region. According to Frsat et al. (2023), untreated domestic and industrial wastewater caused groundwater pollution, which was the main reason for a decrease in the water quality. The high population requires the city to be developed continuously, while a plan should be established to control the spread and hazards of pollution. Indeed, the majority of boreholes in the Sudano-Sahelian zone draw water from the ancient Quaternary sandy-clay formations,

Table 5 Bacteriological statistic results in the study site

Samples ID Season	TC		FC		FE		E.C		TMAF _{RS}	TMAF DS
	RS	DS	RS	DS	RS	DS	RS	DS		
B1	1.00	0.00	0.00	0.00	0.00	0.00	1.00	25.00	125.00	115.00
B2	10.00	17.00	5.00	10.00	0.00	0.00	2.00	12.00	148.00	114.00
B3	10.00	110.00	15.00	85.00	0.00	12.00	3.00	173.00	161.00	152.00
B4	110.00	102.00	85.00	155.00	12.00	0.00	173.00	167.00	152.00	138.00
B5	0.00	0.00	0.00	0.00	134.00	127.0	149.0	131.0	179.0	138.0
B6	48.00	0.00	36.00	0.00	0.00	0.00	47.00	15.00	122.00	130.00
B7	120.00	100.00	100.00	0.00	0.00	0.00	162.00	0.00	145.00	129.00
B8	96.00	93.00	89.00	82.00	0.00	0.00	23.00	11.00	130.00	117.00
B9	167.00	50.00	119.00	38.00	0.00	0.00	130.00	3.00	115.00	122.00
B10	77.00	162.00	40.00	143.00	0.00	0.00	7.00	125.00	138.00	112.00
B11	166.00	160.00	156.00	58.00	3.00	0.00	155.00	135.00	129.00	120.00
B12	56.00	13.00	50.00	4.00	0.00	0.00	18.00	3.00	163.00	173.00
B13	0.00	19.00	0.00	14.00	0.00	0.00	0.00	15.00	196.00	114.00
B14	30.00	100.00	20.00	98.00	0.00	0.00	26.00	14.00	188.00	113.00
B15	13.00	61.00	5.00	57.00	0.00	0.00	13.00	9.00	123.00	133.00
B16	86.00	79.00	70.00	41.00	0.00	0.00	16.00	0.00	108.00	113.00
B17	78.00	112.00	62.00	99.00	0.00	0.00	12.00	137.00	141.00	152.00
B18	197.00	4.00	148.00	0.00	0.00	0.00	178.00	88.00	200.00	126.00
B19	109.00	100.00	100.00	98.00	0.00	0.00	162.00	160.00	179.00	156.00
B20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	133.00	117.00
B21	64.00	102.00	54.00	54.00	0.00	0.00	62.00	45.00	195.00	182.00
B22	180.00	180.00	165.00	157.00	0.00	0.00	171.00	169.00	175.00	139.00
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	108.00	112.00
Max	197.00	180.00	165.00	157.00	134.00	127.00	178.00	173.00	200.00	182.00
Mean	73.50	71.10	60.00	54.20	6.80	6.30	68.60	65.30	152.00	132.00

RS rainy season, *DS* dry season, *TC* Total Coliform, *FC* Fecal coliform, *FE* Fecal Enterococci, *EC* Escherichia Coli, *TMAF* total mesophyll Aerobic Flora, *Min* minimum, *Max* Maximum

Fig. 7 Some water supply points facing the thorny sanitation problem in N'Djamena (Chad)



Table 6 Statistical data of MI, PI and WQI value in deferent boreholes of the study zone

Borehole	MI	PI	WQI
B1	88.31	41.34	188.41
B2	60.23	43.10	220.72
B3	51.10	50.99	474.47
B4	74.46	37.35	700.14
B5	24.99	23.99	573.20
B6	7.95	51.25	273.37
B7	10.58	63.84	483.62
B8	11.02	45.26	421.76
B9	11.20	42.42	483.71
B10	53.23	24.09	543.19
B11	8.80	29.24	704.91
B12	9.00	60.76	318.60
B13	27.54	37.10	245.87
B14	34.88	32.29	402.86
B15	43.74	72.72	279.55
B16	61.57	45.12	355.66
B17	3.20	33.20	520.94
B18	68.04	41.52	614.15
B19	63.66	41.04	688.70
B20	113.28	42.36	193.43
B21	27.54	37.10	494.32
B22	34.88	32.29	866.83
Min	3.20	23.99	188.41
Max	113.28	72.72	866.83
Mean	40.42	42.20	456.75
SD	29.97	12.16	187.19
Med	34.88	41.43	479.04

which are generally shallow aquifers or semi-captive below a few meters of Upper Holocene clay levels. Compared to the previous work, the results of the present study are similar to those obtained by Gad and El Osta (2020), in the El Fayoum Depression (Egypt) where the drinking water quality index (DWQI) results revealed that 58% of the groundwater samples are very poor quality, while 42% of samples are unsuitable for drinking uses. On the other hand, WQI in this study differs from those obtained by Aouiti et al., (2020) in the sedimentary zone of Tunisia, Ngo Billong et al. (2023) in the Littoral region of Cameroon, precisely in the Ngoua watershed (Douala). This difference is related to the fact that the latter did not include bacteriological parameters in the water quality assessment. Their results show four water classes. These are the group of excellent (29%) and good (57%) water for depths of less than 100 m and medium (7%) and poor (7%) waters in depths greater than 100 m. Yenugu et al., (2021) in the same sedimentary environments presents three groups of water, the poor, good and excellent water with a very strong dominance of good quality water. The

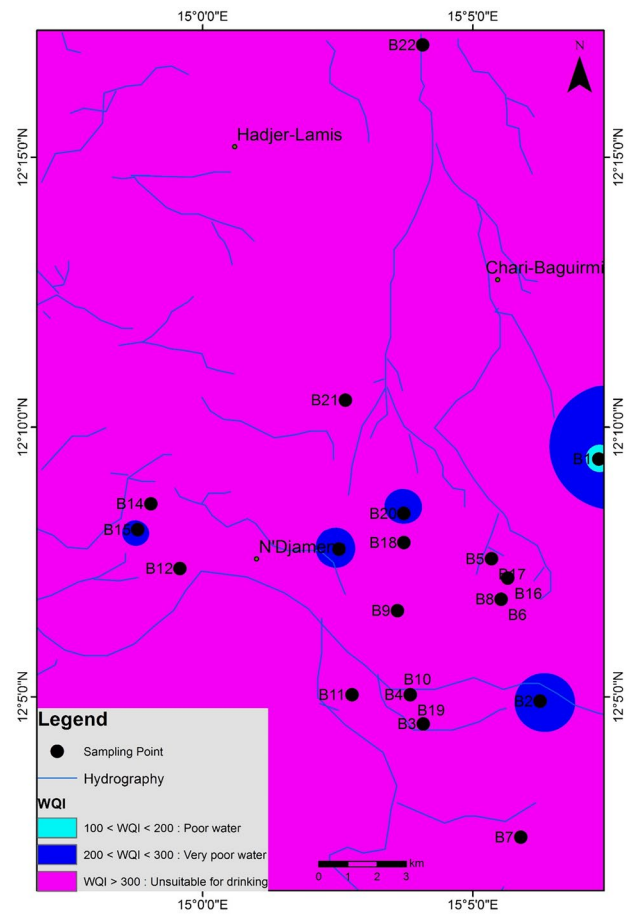


Fig. 8 Spatial distribution of the water quality index (WQI) in the study area

results of the present study are closer to those obtained by Prusty and Farook (2020). The latter obtained five classes of water, ranging between unsuitable to excellent water quality for drinking. Table 7 summarizes the work carried out to assess the water quality based on WQI. While in this study it is the bacteriological parameters that are responsible for the degradation of water quality, is rather the high mineralization that reduces the quality of the water in this coastal area. Based on the previous comparison (Table 7), it is finally concluded that the variations in the WQI of groundwater are not uniform in anywhere, depending upon the parameters used. Depending upon the socioeconomic developmental activities of the society, the researchers will take up the research work on various natural resources from time to time to suggest appropriate strategic management measures for socioeconomic improvement of common habitat from the adverse impacts. Also, assessment of water quality based on WQIs must take into account the local realities of each study area, the habits of the populations and their environment in terms of hygiene and sanitation. Groundwater in sub-Saharan Africa is generally poorly mineralized. It is

Table 7 Some physicochemical and biological parameters used to evaluate the WQI and the results obtained

N°	WQI values	Parameters used	Quality for drinking	Authors
1	12.00 < WQI < 14.00	Turb, T°C, pH, EC, TH, Ca ²⁺ , CaCO ₃ ⁻ TDS. (08) DO, TSS, F ⁻ , NO ₃ ⁻ , SO ₄ ²⁻ , K ⁺ , Cr, Fe ²⁺ , E. Coli and T. Coliform. (11)	Excellent quality	Barrie et al. (2023)
2		T°C, TDS, pH, EC, K ⁺ , Na ⁺ , Ca ²⁺ , Mg ²⁺ , CO ₃ ⁻ , Cl ⁻ , SO ₄ ²⁻ , CO ₃ ²⁻ , and NO ₃ ⁻ . (13)	Poor quality and unsuitable	Gad and El Osta (2020)
3	35.00 < WQI < 66.00	DO, pH, BOD, TDS, COD, TN, TP, ON, NH _{3a} , SO ₄ ²⁻ , NO ₃ ⁻ , Fe, Mn, O&G. (14)	Poor and good	Elsayed Gabr and Soussa (2023)
4	40.90 < WQI < 62.72	pH, EC, TDS, Mg ²⁺ , Ca ²⁺ , Cl ⁻ , SO ₄ ²⁻ NO ₃ ⁻ . (08)	Medium to bad	Alhassan Ismail et al. (2023)
5	12.00 < WQI < 178.00	Turb, pH, EC, TDS, Talky, TH, Ca ²⁺ , Mg ²⁺ , Na ⁺ , K ⁺ , Cl ⁻ , NO ₃ ⁻ , SO ₄ ²⁻ . (13)	Good, fair, poor and very poor	Frsat et al. (2023)
6	10.00 < WQI < 386.00 2.12 < WQI < 187.21	pH, TDS, Na ⁺ , Cl ⁻ , SO ₄ ²⁻ , NO ₃ ⁻ , and F ⁻ . (07) T°, pH, TDS, EC, Na ⁺ , K ⁺ , Ca ²⁺ ; Mg ²⁺ NH ₄ ⁺ , HCO ₃ , SO ₄ ²⁻ , NO ₃ ⁻ , PO ₄ ³⁻ , and F ⁻ (14)	Excellent to very poor Very poor to Excellent	Subba Rao et al., (2021a, 2021b) Ngo Billong et al. (2023)
7	188.41 < WQI < 866.83	pH, EC, Ca ²⁺ , Mg ²⁺ , Na ⁺ , K ⁺ , NH ₄ ⁺ , HCO ₃ ⁻ , NO ₃ ⁻ , F ⁻ , SO ₄ ²⁻ , F. Coliform, T. Coliform, E. Coli, F. enterococci and Mesophyll Aerobic Flora (MAF). (16)	Unsuitable and poor	Present study

TH total hardness DO dissolved Oxygen, TSS total suspended solids, TDS total dissolved solid, BOD biological oxygen demand

therefore the biological parameters identified in groundwater in N'Djamena that are the cause of frequent waterborne diseases (Typhoid, malaria...), resulting in serious hygiene and sanitation problems in this part of the world. It is important to remember that although the assessment of water quality for drinking purpose using the WQI presents some imperfections due to the relativity of the weights attributed to each parameters used in the technique, this method remains the least criticized and produces satisfactory results.

Mineralization source of groundwater of the study area

In this study, three main methods were used to asses the factors controlling groundwater mineralization (Ramadhani Mussa et al., 2023) standard hydrochemical method through the saturation index calculation, the Gibbs model (Ramadhani Mussa et al., 2023) and the multivariate statistical analysis technic (correlation matrix, hirarchical clustering analysis).

Saturation indexes

The results on the Saturation Index (SI) calculation are summarized in Table 8. All the value are negative, indicating that all the water samples are under saturated with regard to minerals such as anhydride (CaSO₄), aragonite (CaCO₃), Calcite (CaCO₃), dolomite (CaMg(CO₃)₂), gypsum (CaSO₄.H₂O), halite (NaCl), which characterise the sedimentary rock. According to Singh et al., (2017), this under

saturation is linked to 1) the dissolution of these minerals, 2) a slow solubility of certains minerals in water (Silicate) and 3) the instability at ambient temperature and pressure of other minerals such as calcite (Singh et al., 2017; Yang et al., 2017). This last interpretation is in accordance with those of Paternoster et al., (2016) who establish the relationships between SI values and depth, They conclude that SI values are stratified with depth, moving from epilimnion to hypolimnion layer.

Gibbs model

According to the Gibbs model (Fig. 9), the entire sample falls under the water–rock interaction domain, characterised by low ratios of Na/(Na + Ca) and Cl/(Cl + HCO₃) and moderate concentrations of TDS. It represents the rock weathering as the dominant geochemical factor regulating the ionic chemistry. The fact that all these samples belong to a single domain would explain the continuous and homogeneous character of aquifer systems in the sedimentary zone in general and in the Lake Chad basin in particular on the one hand and the contribution of semi-arid climate source on the groundwater system on the other hand (Subba Rao et al., 2021a, 2021b). The latter results are in accordance with the water type (Ca–Mg–HCO₃). These results are similar to those obtained by Song et al., (2023) on a regional scale (transboundary quaternary aquifer of the Lake Chad Basin). These authors show that groundwater quality in the sahelian region are mainly influenced by water–rock interaction, followed by the anthropogenic activities.

Table 8 Saturation index of some mineral in the groundwater of the study area

Mineral	Anhydrite	Aragonite	Calcite	CO2 (g)	Dolomite	Gypsum	H2 (g)	H2O (g)	Halite	O2 (g)
Formula	CaSO4	CaCO3	CaCO3	CO2 (g)	CaMg (CO3)2	CaSO4:2H2O	H2	H2O	NaCl	O2
SI	- 4.14	- 1.51	- 1.37	- 1.17	- 2.55	- 3.92	- 20.8	- 1.51	- 8.92	- 41.52
B2	- 3.75	- 0.76	- 0.61	- 1.81	- 1.22	- 3.53	- 22.1	- 1.51	- 8.48	- 38.92
B3	- 2.52	- 0.72	- 0.58	- 1.69	- 1.25	- 2.30	- 21.94	- 1.51	- 7.84	- 39.24
B4	- 2.95	- 1.37	- 1.22	- 1.44	- 2.32	- 2.73	- 21.2	- 1.51	- 8.80	- 40.72
B5	- 2.51	- 0.06	0.09	- 2.00	- 0.46	- 2.29	- 22.4	- 1.51	- 7.58	- 38.32
B6		- 0.55	- 0.40	- 1.90	- 1.71		- 22.26	- 1.51		- 38.60
B7		- 1.78	- 1.64	- 2.20	- 3.96		- 1.51	- 8.80	- 8.80	- 39.52
B8	- 3.95	- 0.85	- 0.71	- 1.95	- 2.16	- 3.73	- 22.08	- 1.51	- 8.47	- 38.96
B9	- 3.65	- 0.91	- 0.76	- 1.90	- 2.26	- 3.43	- 21.98	- 1.51	- 8.60	39.16
B 10	- 3.76	- 0.44	- 0.29	- 0.98	- 0.79	- 3.54	- 21.10	- 1.51	- 8.78	- 40.72
B 11	- 2.60	0.37	- 2.15	- 0.19	- 2.38	- 23.14	- 1.51	- 8.62	- 8.62	- 36.84
B 12	- 3.09	- 0.76	- 0.62	- 2.26	- 2.02	- 2.87	- 22.72	- 1.51	- 8.82	- 37.68
B 13	- 3.67	- 1.07	- 0.93	- 1.58	- 2.20	- 3.45	- 21.50	- 1.51	- 8.61	- 40.12
B 14	- 3.20	- 1.17	- 1.03	- 1.48	- 2.30	- 2.98	- 21.3	- 1.51	- 8.94	- 40.52
B 15	- 3.90	- 0.70	- 0.56	- 2.20	- 1.20	- 3.68	- 22.74	- 1.51	- 8.10	- 37.64
B 16	- 3.11	- 0.85	- 0.71	- 1.06	- 1.46	- 2.88	- 21.1	- 1.51	- 8.17	- 40.92
B 17	- 2.79	- 0.97	- 0.82	- 1.24	- 3.00	- 2.57	- 21.06	- 1.51	- 8.58	- 41.00
B 18	- 3.15	- 1.14	- 1.00	- 1.17	- 1.96	- 2.93	- 21.00	- 1.51	- 8.03	- 41.12
B 19	- 3.13	- 1.05	- 0.91	- 1.21	- 1.82	- 2.91	- 21.10	- 1.51	- 8.33	- 40.92
B 20	- 2.77	- 0.97	- 0.83	0.93	- 1.42	- 2.55	- 20.90	- 1.51	- 7.86	- 41.32
B 21	- 3.67	- 1.07	- 0.93	- 1.58	- 2.20	- 3.45	- 21.50	- 1.51	- 8.61	- 40.12
B 22	- 3.20	- 1.17	- 1.03	- 1.48	- 2.30	- 2.98	- 21.30	- 1.51	- 8.94	- 40.52

It should also be noted that, in addition to the saturation index and the gibbs model, these authors used several other methods to understand the water mineralisation process. These include binary diagrams such as $\text{Ca}^{2+}/\text{Na}^+$ vs $\text{HCO}_3^-/\text{Na}^+$, $\text{Ca}^{2+}/\text{Na}^+$ vs $\text{Mg}^{2+}/\text{Na}^+$, Na^+ vs Cl^- , $(\text{Ca}^{2+} + \text{Mg}^{2+})$ vs HCO_3^- , $\text{Ca}^{2+} + \text{Mg}^{2+}$ vs $(\text{HCO}_3^- + \text{SO}_4^{2-})$ vs $(\text{Na}^+ + \text{K}^+ - \text{Cl}^-)$, and Ca^{2+} vs SO_4^{2-} (Nagaraju et al., 2018; Hussin et al., 2016 and Mukate et al., 2020) and multivariate statistical analysis. The results of the latter method are presented below.

Soft computing methods for groundwater quality classification in N'Djamena

Correlation matrix

The correlation matrix (Table 9) reveal the weak, ($r < 0.4$), acceptable ($0.5 \leq r \leq 0.7$), very good ($0.7 < r < 0.9$) correlations between the hydrochemical and bacteriological parameters analysed. These correlations are positive for some and negative for others. Very good, good and average correlations have been noted between the following pairs of parameters: Total Coliform vs Fecal Coliform

($r = 0.94$), Total coliform vs Escherichia Coli ($r = 0.63$), Fecal coliform vs Escherichia coli ($r = 0.68$) for bacteriological parameters. As for the physico-chemical species, the good positive relation between HCO_3^- and Mg^{2+} ($r = 0.72$), HCO_3^- and K^+ (0.86), HCO_3^- and TZ^- ($r = 1$), NO_3^- and Ca^{2+} (0.60), Cl^- and Ca^{2+} ($r = 0.62$), Na^+ and Cl^- ($r = 0.56$) have been identified. The good positive relation exist likewise between physico-chemical parameters and bacteriological species such as fecal enterococci and Cl^- ($r = 0.75$), fecal enterococci and NO_3^- ; fecal enterococci and Ca^{2+} ($r = 0.78$). This explains the same origin of these parameters (anthropogenic factor). Meanwhile, there are low correlation between the bacteriological species such as fecal enterococci and MAF ($r = 0.187$), *E. Coli* and MAF ($r = 0.371$), Total coliform and MAF ($r = 0.047$). According to American Ground Water Trust (2002); Tontsa et al. (2023), the bacteriological contamination of the water resource is not only faecal. Indeed, non-faecal coliform bacteria are very common and can be found almost everywhere on soil particles, insects, plants, animals, walls and furniture at the home.

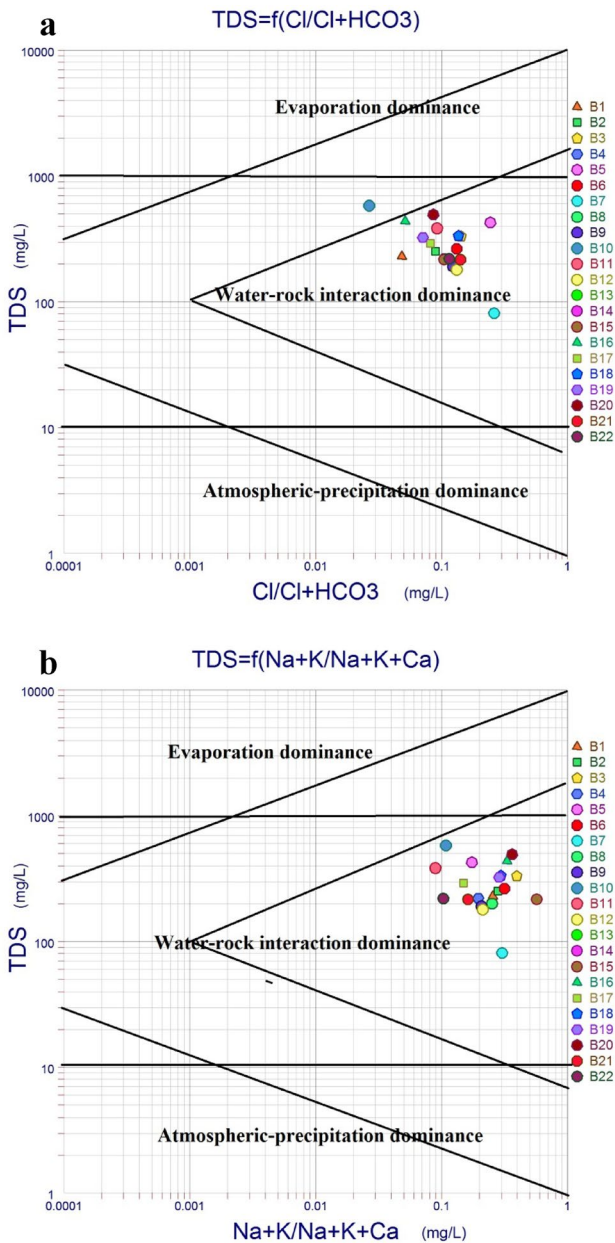


Fig. 9 Gibbs model illustrating the parameters controlling the hydrogeochemical process in the study area (a) TDS versus $Cl/Cl+HCO_3$; (b) TDS versus $Na+K/Na+K+Ca$

Q-mode hierarchical clustering

The hierarchical clustering analysis results with physico-chemical and bacteriological parameters as variables (Fig. 10a) present two principles clusters such as cluster A and cluster B; the latter being divided once into two sub-clusters: sub-cluster B1 and B2. Cluster A groups together all parameters that have almost a common origin, namely anthropogenic origin (majority) or not. These are Fecal Coliform (FC), Escherichia Coli (EC), Total coliform (TC),

Mesophyll Aerobic Flora (MAF) NH_4^+ and F^- . Cluster B highlights all the physico-chemical parameters that may have one or more origins such as geogenic (some cations and anions) or anthropogenic ((NO_3^-) , (SO_4^-) , (Na^+)). These results based on HCA are in accordance with those obtained by Rakotondrabe et al. (2018) who use the same technique to identify three main phenomena which control the water quality in Mari catchment (East-Cameroon) such as hydrolysis of silicate minerals, vegetation and soil leaching; and mining activities. With regard to the hierarchical clustering analysis results highlighting the sampling points as variables (Fig. 10b), two major clusters are identified such as: Cluster A and cluster B. The first cluster includes the following boreholes: B2, B4, B5, B6, B8, B9, B2, B11, B12, B13, B14, B15, B18 and B19 while the second which is subdivided into two sub-clusters (B1 and B2) contains only 08 boreholes which are distributed as follows: four boreholes (B3, B16, B17 and B21) for sub-cluster B-1 and four other for B-2 (B1, B7, B10 and B20). This large grouping of boreholes in a single cluster reflects the continuity, homogeneity and the broad geometric extension of the aquifers system in sedimentary environment. It should be noted that most of these boreholes, if they are not in contact with the archaic sanitation structures such as septic tanks, they are in permanent contact with the surface water reservoir which is essentially the Logone and Chari river. Based on Barrie et al. (2023) the HCA based on sampling point showed a clear distinction between the location of the point in the Rokel river in Sierra Leone and their closest distance. They also observed that the dendrogram is clustered seasonally, that is formed during the wet months and dry months respectively. All the results of this study relating to the phenomenon and/or mechanisms controlling water quality (geogenic and anthropogenic factors) in the study area are summarized as the conceptual model illustrated in Fig. 11. These results are similar to those obtained by Song et al. (2023). Based on hydrochemical aspect in the transboundary quaternary aquifer of the Lake Chad Basin scale; these authors confirm that groundwater chemistry indicates geogenic influences in addition to a strong anthropogenic fingerprint. The conclude that, the intermediate to deep aquifer shows a longer residence time of groundwater, less connection with the surface and no to only a little anthropogenic influence. This last result explains the absence of biological species in some borehole in N'Djamena locality.

Groundwater suitability for irrigation

Sodium absorption ratio (SAR)

According to the USSL Diagrams obtained by plotting the SAR value against electrical conductivity (Richards, 1954).

Table 9 Correlation matrix (Pearson) presenting the relationship between the physicochemical and bacteriological elements analyzed

Variables	TC	FC	FA	EC	MAF	T °C	pH	BI	TZ+	TZ-	Ca	Mg	Na	K	F(II)	NH4	HCO3	Cl	SO4	NO3	
TC	1																				
FC	0.94	1																			
FA	-0.30	-0.27	1																		
EC	0.63	0.68	0.29	1																	
MAF	0.04	0.10	0.18	0.37	1																
T °C	-0.40	-0.31	0.21	-0.19	0.03	1															
pH	-0.04	-0.14	0.24	-0.04	-0.07	-0.26	1														
BI	-0.24	-0.16	-0.06	0.02	0.04	0.10	0.19	1													
TZ+	-0.04	-0.05	0.78	0.30	0.01	0.35	0.09	-0.28	1												
TZ-	0.07	0.06	-0.05	-0.01	-0.30	0.36	-0.29	-0.32	0.47	1											
Ca	-0.04	-0.05	0.78	0.30	0.01	0.35	0.09	-0.28	1.00	0.47	1										
Mg	-0.22	-0.14	0.08	0.01	-0.12	0.39	-0.57	-0.09	0.25	0.72	0.25	1									
Na	-0.46	-0.43	0.43	-0.10	-0.16	0.41	0.10	0.18	0.37	0.29	0.37	0.42	1								
K	0.01	-0.01	0.08	-0.05	-0.27	0.40	-0.31	-0.31	0.53	0.86	0.53	0.61	0.31	1							
F(II)	0.07	0.11	0.55	0.16	0.03	-0.10	0.04	-0.31	0.46	-0.10	0.46	-0.09	0.12	-0.11	1						
NH4	0.21	0.29	-0.06	0.07	0.19	-0.16	-0.31	-0.23	-0.05	-0.07	-0.05	0.03	-0.25	-0.30	0.61	1					
HCO3	0.07	0.06	-0.05	-0.01	-0.30	0.36	-0.29	-0.32	0.47	1.00	0.47	0.72	0.23	0.86	-0.11	-0.07	1				
Cl	-0.27	-0.28	0.7	0.29	0.33	0.19	0.25	-0.10	0.62	0.05	0.62	0.16	0.56	0.04	0.31	-0.06	0.05	1			
SO4	0.01	0.07	0.18	0.31	0.20	0.30	0.06	-0.03	0.18	0.22	0.19	0.27	0.34	0.06	-0.07	-0.05	0.27	0.47	1		
NO3	-0.11	-0.12	0.77	0.23	0.05	0.05	0.37	0.04	0.61	-0.16	0.61	-0.15	0.31	-0.02	0.42	-0.13	-0.16	0.67	0.00	1	

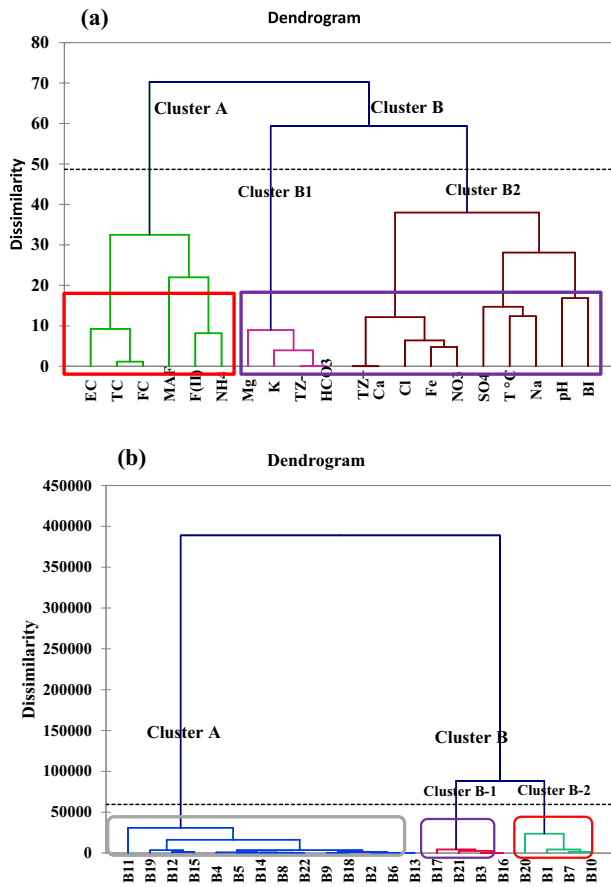


Fig. 10 Q-mode hierarchical clustering of water quality based on: (a) the similarity/dissimilarity between physicochemical and bacteriological parameters; (b) similarity/dissimilarity between all the sample points

The twenty-two samples of the study area are situated in two domains (Fig. 12), the C1S1 which corresponds to the low sodium and low salinity, and C2S1 domains which characterize the low sodium and medium salinity water. Those results imply that the groundwater of the study milieu is classified as suitable and moderate water quality for agricultural purpose (Ramesh & Elango, 2012; Rakotondrabe et al., 2017; Sanjoy Shil et al., 2019). According to Tamru and Gopalakrishnan (2021), Venkatesan et al., (2021), the use of groundwater with high content of sodium for irrigation purpose could increase the exchange of sodium content of the soil and thus can decrease the soil permeability and soil structure.

Sodium percent

The Wilcox diagram (Fig. 13) represents the Sodium percent (%Na) against the electrical conductivity. It reveals that the groundwater samples of the study zone are excellent for agricultural purpose with values ranging between 7.80 to 47%.

Permeability index

The permeability index (PI) value ranged from 23.99 to 72.72, with a mean of 42.20 ± 12 (Fig. 14, Table 6). According to Das and Nag (20,015); Sanjoy Shil et al. (2019), 21 samples (95%) belonging to class III are considered as moderately suitable for irrigation, while only one sample correspond to class II and is unsuitable. The strong predominance of class III, as well as the high concentration of samples for %Na, in the excellent range reflects also the geological homogeneity of the Lake Chad basin as described by Djoret and Favreau (2014).

Magnesium index

The groundwater of the South West of N'Djamena has a magnesium ratio in the range of 3.20 to 113.28 for a mean of 40.42 ± 29.97 (Fig. 15, Table 6); two types of water can be distinguished as follows:

- Suitable water for irrigation with magnesium percentage less than 50. This represents about 59% of the samples including B5, B6, B7, B8, B9, B11, B12, B13, B14, B15, B17, B21, B22;
- Harmful and unsuitable quality for agricultural purposes for the remaining 49% (B1, B2, B3, B4, B10, B16, B18, B19, B20).

Based on the four parameters (SAR, %Na, Mg%, and PI) used in this study to express the aptitude of groundwater for irrigation, sample B10 is the only one which presents doubtful qualities for irrigation expressed by Mg% and PI consecutively. Based on these previous results, the groundwater in the N'Djamena's locality are relatively good for irrigation. It can therefore boost the socio-economic development of the locality in general and the agricultural sector in particular.

Socio-economic impact of the groundwater quality on the population of the study area and water quality management measure

Water for human consumption requires well-defined quality standards. The universal standard is prescribed by the World Health Organization, which may be slightly modified in certain countries or regions according to local realities. When the concentration of a physicochemical (NO_3^- , $\text{F}^- \dots$) or microbiological parameters is abnormally represented in water, the water becomes a source of disease (Subba Rao et al., 2021b). The abnormally high levels of microbiological parameters in the groundwater of N'Djamena are due to the fact that this city and its surroundings do not have a functioning public sewer system; so water from toilets is directed to traditional latrines which, due to economic reasons, are

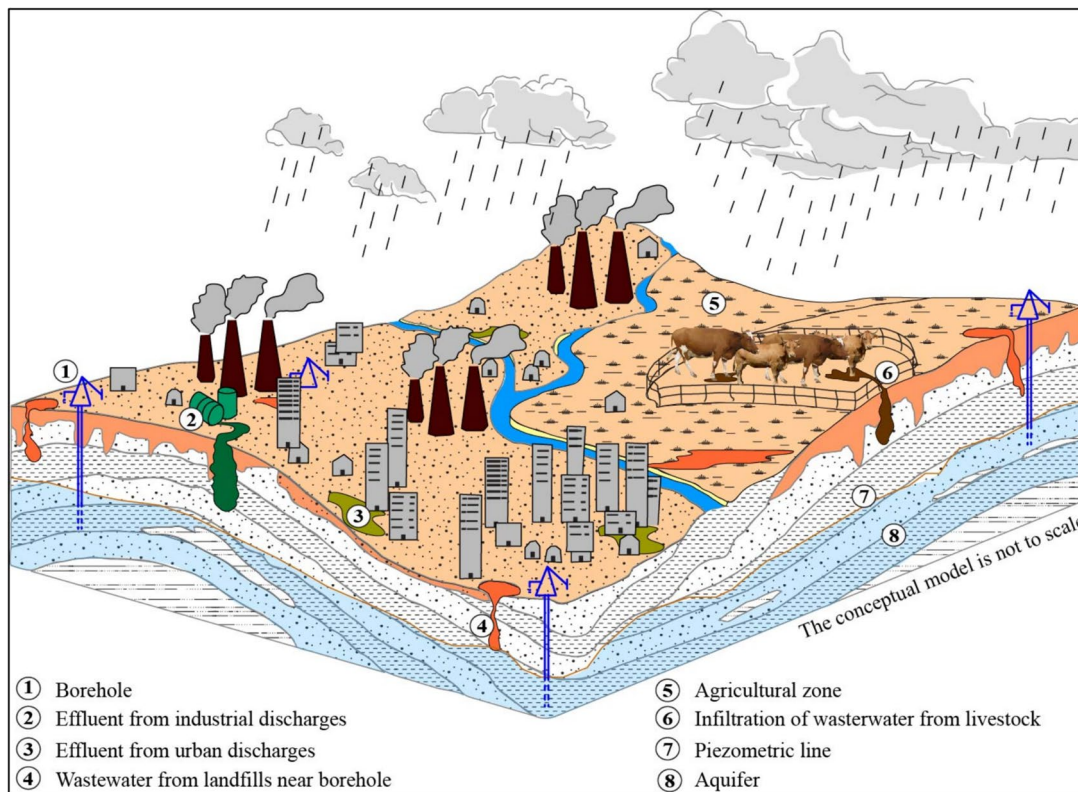


Fig. 11 Conceptual models reflecting the groundwater quality influenced by the human activities

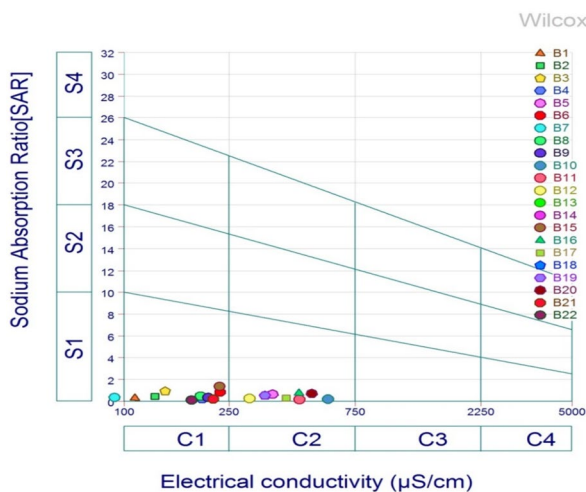


Fig. 12 Sodium absorption ratio (SAR) of the groundwater of N’Djamena

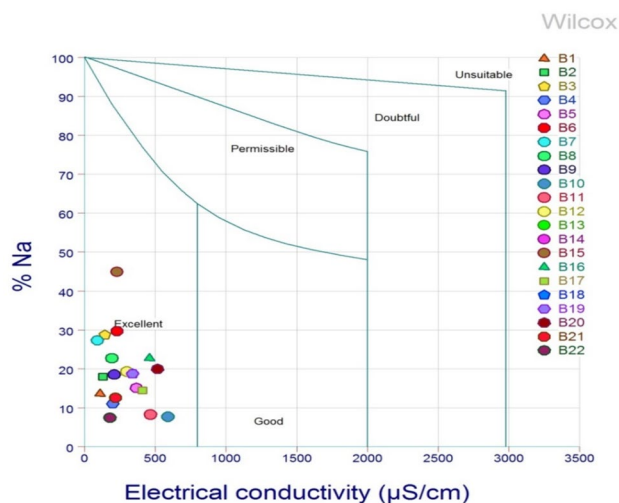


Fig. 13 Sodium percentage (%Na) of the groundwater of N’Djamena

often constructed without any proper casing to impede the contamination of groundwater with microbial parameters. This contamination and poor hygiene practices of the population cause serious diseases like diarrhea, typhoid, cholera and hepatitis A and E. Statistics from Seeber et al., (2014) reveal that 16.7% of the deaths were linked to the water,

sewage and hygiene sector. Furthermore, greywater from households is often directly poured into little trenches or fosses, which are located close to properties. This untreated greywater infiltrates, evaporates or accumulates in ponds of different sizes, detectable all around the city.

Fig. 14 Spatial distribution of the Permeability index in the study site

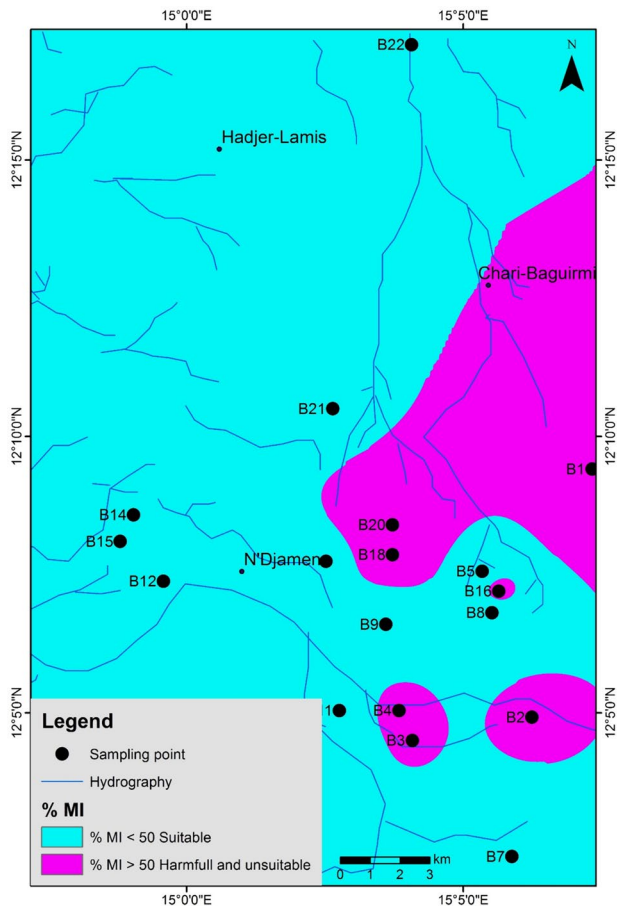
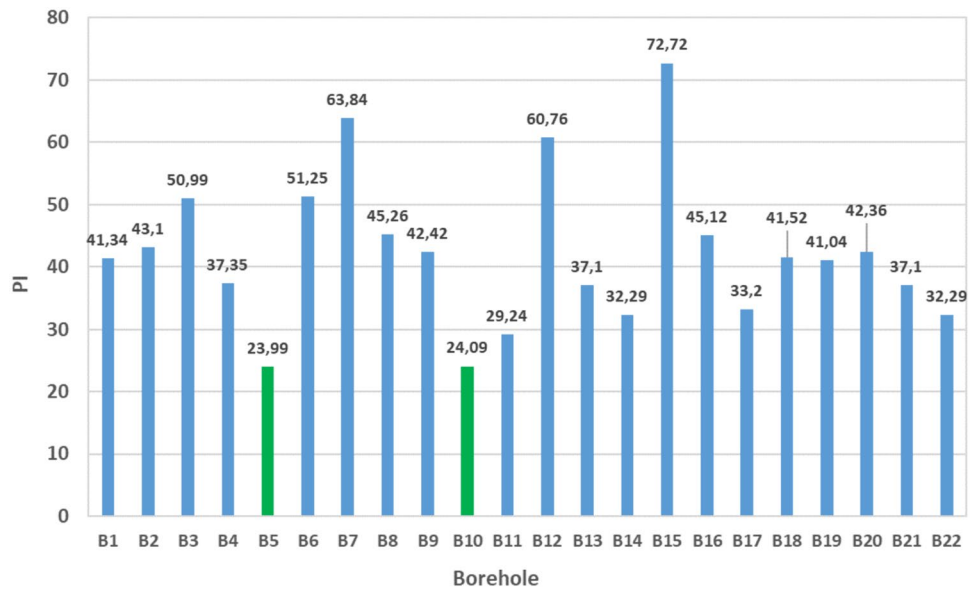


Fig. 15 Spatial distribution of the Magnesium index in the study site

This study has shown that groundwater quality in N'Djamena and its surroundings is not safe for drinking because it can cause several diseases and other gastrointestinal disorders. The following management measures are proposed to help preserve the water quality status: in view of the quality indices coupled with the environmental characteristics described in the methodology section (Table 1), these water should be subject to regular quality control and microbiological treatment, although they are collected at relatively high depths. However, it can be used for other household tasks such as washing vegetables and cooking food. For consumption, however, they require treatment ranging from simple heating to special treatment. Adequate sanitary systems such as landfills should be provided in order to efficiently and effectively manage the high volumes of agricultural and domestic wastes generated in the area. Beyond the socio-economic interest of the present study, scientifically, they provide better understanding of the hydro-geochemical functioning of aquifer system in the Lac Chad Basin as presented in the conceptual model. This model is the result of a method that is not conventional enough.

Conclusion

The main groundwater resource in the Lake Chad basin in general and N'Djamena (Chad) in particular is a Quaternary aquifer. It is heavily exploited and vulnerable, due to the considerable urbanization of the town. The main objective of the study was to examine the groundwater quality for domestic and agricultural purposes, using hydro-chemical modeling, Water Quality Index (WQI) and Geographical Information System (GIS) Technics. Based on the results obtained,

groundwater of N'Djamena has pH which tends to neutrality ($6.40 < \text{pH} < 7.57$). They are very weakly to weakly mineralized with one water type only (Ca–Mg–HCO₃). The quality of groundwater in N'Djamena and its surrounding is not uniformly distributed, which suggests a high spatial variability due to the involvement of different sources and/or geochemical processes, taking place in the aquifer system. The concentration of the physicochemical parameters (cations and anions) does not exceed those prescribed by the World Health Organization for human consumption. The decreasing order of magnitude of the cations is as: Ca²⁺ > Mg²⁺ > Na⁺ > K⁺, while that of anions is HCO₃⁻ > Cl⁻ > SO₄²⁻ > NO₃⁻. The WQI based on physicochemical parameters coupled to bacteriological species varied from 188.41 to 866.89, corresponding to poor, very poor and unsuitable for drinking; it means that the poor quality is due to the presence of bacteriological species. However, it should therefore be noted that groundwater in N'Djamena and Hadjer-Lamis should be purified before being used for drinking purposes. The Gibbs model, and the Q-mode hierarchical clustering indicate that the groundwater quality in the study zone is controlled by two main factors such as water–rock interaction (leaching, dissolution, and ions exchange) and anthropogenic activities. All the samples are under saturated (SI < 0) with regard to anhydrite, aragonite, Calcite, dolomite, gypsum, halite, which characterize the sedimentary rock.

Based on the agricultural aspect, the SAR and %Na value of all the samples show that, the groundwater of the study zone has moderate and excellent quality for irrigation, while the MI and PI value of some samples are harmful and unsuitable.

The results presented in this study, particularly the bacteriological analysis provide a baseline reference on the future monitoring of the groundwater in N'Djamena and its surroundings; as suggested strategies of water pollution prevention, the implemented and continuous measure for proper management in the study area is necessary. The local authorities could implement the strategy to limit groundwater contamination with the population collaboration. The great measure could be taken to protect the Quaternary aquifer by constructing the proximate and the near feed areas around the boreholes in the study area.

For the future, more models for hydro-geochemical analysis and isotopic studies can further extend this work. In the same time, the hydrogeological potential coupled to the hydrodynamic characteristics of the aquifer system of the studied zone could be assessed. These further studies will provide a better understanding of this aquifer. This will optimize and rationalize the exploitation of the quaternary aquifer of the Lac Chad basin in general and N'Djamena in particular.

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Author contributions Material preparation, data collection, analysis, conception and design, first draft were performed by MZ. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability All necessary data are included in the article.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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