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RESEARCH ARTICLE

HYDROCHEMICAL CHARACTERIZATION OF GROUNDWATER IN THE CONTINENTAL TERMINAL AQUIFER OF MOUNDOU AND ITS SURROUNDINGS (SOUTHWEST CHAD)

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Introduction

Abstract

Our study aims to characterize the physicochemical and bacteriological parameters of the groundwater of the city of Moundou and its surroundings. These waters of this locality, contained in formations of the continental Terminal, are made up exclusively of sand and sandstone. Two campaigns carried out in December 2023 and March 2024 made it possible to collect sixty (60) samples. Forty (40) samples were used for physicochemical analyses (iron, zinc) and twenty (20) for bacteriological analyses (fecal and total coliforms, total aerobic mesophilic flora, Escherichia coli and total germs). The results of the physicochemical parameters indicate that these waters are acidic (average pH value between 6.3-6.94), and that their mineralization has an origin resulting from both natural and anthropogenic factors. The maximum values of potassium (93.09 mg/l in low water and 56.28 mg/l in high water) and silica (54.92 mg/l and 43.97 mg/l respectively in low and high water) are mostly higher than the WHO standard (2017). The maximum nitrate content is 44.19 mg/l (low water) and 39.09 mg/l (high water). That of nitrite and phosphate are respectively 2.39 and 2.73 mg/l in low water on the one hand, and 2.89 and 2.016 mg/l in high water on the other. The evolution of the concentrations of pollutants (nitrate, nitrite and phosphate) suggests an anthropogenic involvement in the degradation of groundwater although the nitrate content in all the waters analyzed is in accordance with the WHO standard (2017) for water intended for human consumption. These levels, although in accordance with the WHO standard (2017), suggest an anthropogenic implication because they sometimes exceed the natural contribution. The groundwater in the study area is dominated by the calcium and magnesium bicarbonate facies, followed by the calcium and magnesium chloride and sulfate facies. The GWQI values vary from 19.37 to 78.48, indicating that these waters are excellent and of good physicochemical quality for human consumption, although the mineralization results from anthropogenic action. However, the bacteriological study shows that the waters of the surface and deep aquifers are of poor quality and imperatively require filtration and disinfection before any consumption.

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Introduction:-

Essential for life and health (Niambele et al, 2020 ; WHO, 2011 ; Adetunde et al., 2011, WHO and UNICEF, 2018; Diallo, 2017), water actively participates in agricultural and industrial development and energy production. One of the causes of various human pathologies results from the consumption of polluted and/or contaminated water (Haslay and Leclerc, 1993 ; Adetunde et al., 2011; Dovonou et al, 2011; Adesakin et al, 2020; WHO & UNICEF, 2018; Ounokis and Achour, 2014). It is evident that the quality of drinking water depends on its physicochemical and bacteriological characteristics (Adesakin et al, 2020 ; Sila, 2019 ; Esharegoma et al, 2018 ; Bello et al, 2013 ; Okoli, 2012).

In Chad, groundwater is the most consumed with a rate of 65% (INSEED, 2015). According to UNICEF (2019),22% of children under 5 years old suffer from diarrheal diseases caused by contaminated water. The Chadian Ministry of Water supports this assertion by concluding that waterborne diseases represent the second leading cause of infant mortality and morbidity after malaria (MEEP, 2019).

The health issue linked to the consumption of poor quality water remains a concern in Moundou and its surrounding areas.According to,the African Development Bank (2015), only 36.5% of the inhabitants of these localities have access to drinking water compared to 53% at the national level while the shutte rsnational sanitation and the study sector each cover 16% (PAEPA: Drinking Water Supply and Sanitation Program, 2015). This is why it is interesting to be able to characterize the physicochemical parameters of water from wells and boreholes as well as from supply structures in order to better understand the contamination mechanisms and to develop protection strategies in accordance with the recommendations (which) of previous work (Fehdi et al., 2009); Bouchemal et al.,2015 ; Gnazou, 2015)

The population of Moundou and its surroundings, which was 99,530 inhabitants in 1993, increased to 150,115 inhabitants in 2009 (RGPH2 is now estimated at more than 347,058 inhabitants (INSEED, 2024). Faced with the galloping demography of Moundou coupled with human actions, we observed on the ground: (1) the discharge of wastewater and the anarchic discharge of household and industrial waste, (2) the anarchic installation of water production and sanitation works, (3) the absence of water treatment plants; (4) the poor drainage of runoff water and the poor operation of landfills, (5) the lack of adequate sanitation works and the use of traditional pit latrines, (6) the abusive and uncontrolled use of agricultural inputs, (7) the failure to respect the average distance between latrines and water points, (8) the absence of waste collection and treatment services, (9) periodic flooding adjacent to water production works, (10) the anarchic presence of livestock sites.

Faced with all these observations, the main question that arises is : What is the quality of the groundwater in the city of Moundou in the face of the various sources of pollution ?

A study on the quality of groundwater in Moundou and its surroundings is necessary in order to know the quality of said water in order to preserve the health of the population through the protection of groundwater resources as recommended by the works of : Fehdi et al. (2009), Bouchemal et al. (2015) as well as Gnazou (2015.The protection and preservation of groundwater quality is increasingly important because this resource, once contaminated, becomes unsuitable for consumption (Jourda et al., 2007). The main objective of this study is to assess the quality of groundwater in Moundou and its surroundings. From this general objective, the following specific objectives emerge : (1) to take stock of the water production structures ; (2) to assess the physicochemical and bacteriological quality of groundwater ; (3) to establish the piezometric map ; (4) to determine the evolution of waterborne diseases over the last ten (10) years.

I.1. Presentation of the study sector

I.1.1 Geographical, climatic and economic framework of the study area

Belonging to the Western Logone Province, the study area, located in the southwest of Chad about 480 km from the capital N'Djamena, is geographically located between 8°28'27.40"-8°41'51.59" North latitude and 15°55'19.34"-16°10'6.85" East longitude (Fig.1.a). This sector covers an area of 230 km2 with an estimated population in 2020 of 347,058 inhabitants (INSEED, 2020). The altitude of the study area varies from 377 to 498 m.Of types Sudanese,The climate of the study area is governed by the Inter Tropical Front (BRGM, 1992; Djoret, 2000). The latter results from the clash between the Harmatan, hot and dry air coming from the Saharan high pressure zone to the North, and the monsoon, humid air originating from the Atlantic. Climate data for Moundou and its surroundings (precipitation and temperatures) combined for the period from 1980 to 2019 (ANAM, 2019), are characteristic of two seasons usually putshighlighted in this type of climate : a dry period extending from November to April and the other wet period extending from May to October with a concentration of precipitation in July and August (Fig.1.b). The population of the study area lives from food and market gardening, livestock farming and fishing.

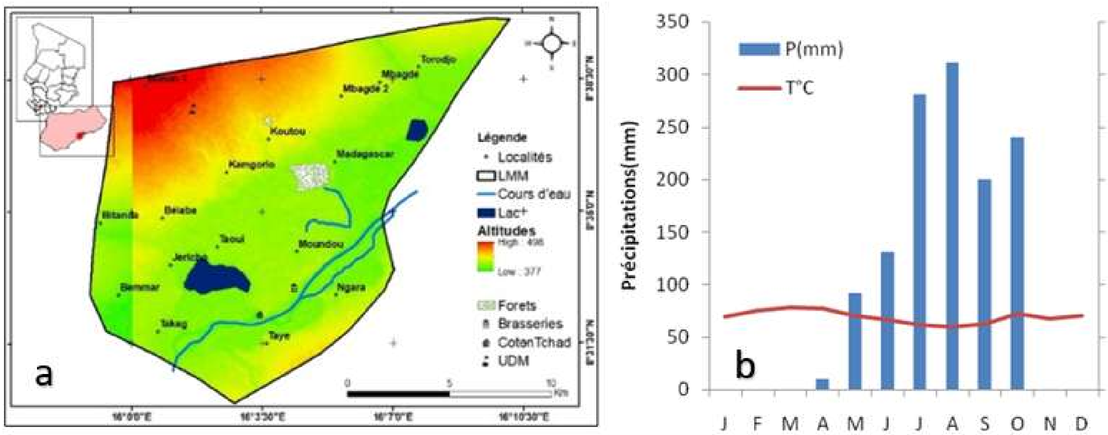

Figure1: Location of the study area in Chad (a) and ombrothermic diagram (b) of the study area

1. 2. Geological and hydrogeological context

Belonging to the Doba-Salamat basin, the formations in the study area date from the Continental Terminal and are made up of sands and sandstones with cross-stratifications, versicolored clays, kaolin lenses, concretionary or pisolitic ferruginous levels (BRGM, 1992 ; SDEA, 2003). On the hydrogeological level, the authors (Garin, 1979 ; Wolf, 1992) have shown that The aquifer in the study area is made up of fine and coarse sand. This is confirmed by the recentdrilling work carried out by the Ministry of Water and Sanitation showing Asector made up of sedimentary formations (sands, clayey sandstones, sandy clays and argillites) and residual formations (lateritic cuirasses). (Fig.2). The aquifer mainly East recharged by rainwater(BRGM, 1987). The piezometric surface of the aquifer is low, located less than 10 m from the ground in the valleys (BRGM, 1987, SDEA, 2003). However, it can exceed 80 m in the plateau sector, particularly the Koros region (Fig. 2).

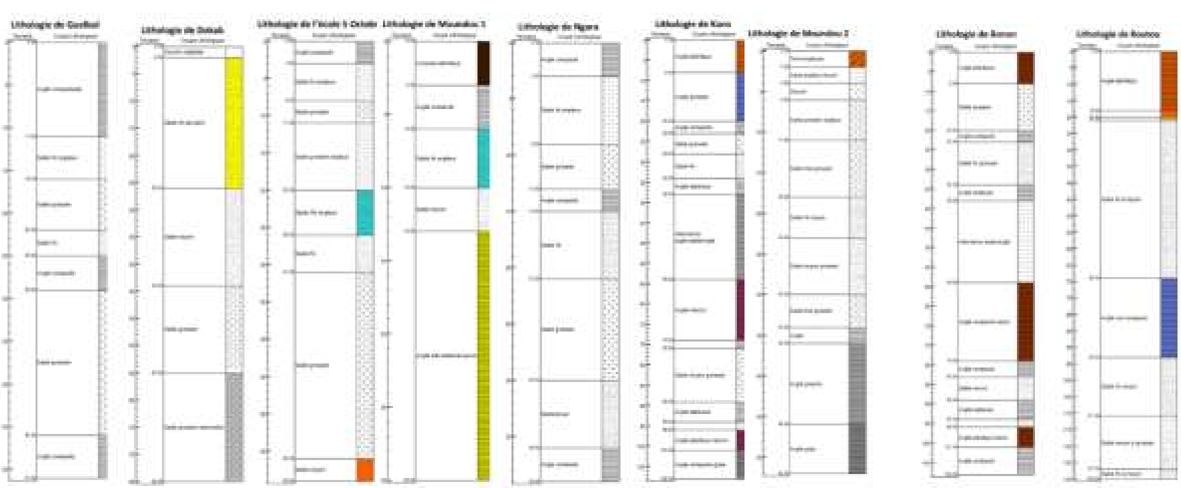

Figure2: Lithological section of the drillings(source, MAE, 2013)

Methodology:-

I.2.1 Field work

- **Health survey**

It took place at the Logone Occidentale health delegation through oral questions followed by ratings. The oral interview with the head of health statistics made it possible to collect information relating to waterborne diseases frequently diagnosed and treated in health centers and hospitals in Moundou and its surrounding areas.

- **Piezometric and hydrochemical monitoring**

Piezometric monitoring

Piezometric monitoring is carried out during thetwo campaigns:- Lat firstcampagne s'est déroulés in December 2023 andla seconde in March 2024. The measurement of static levels is carried out using a 150-meter dual-signal (sound and light) piezometric probe. The measurement of piezometric levels consists of placing the probe on the edge of the well and unroll the tape. When the lower end of the electrode touches the water surface, the light and sound indicators are activated,which therefore allows us to readdirectly the distance Zp (water depth from the upper limit of the coping) which corresponds to the distance between the surface of the water in the well and the upper level of the coping in meters. Subsequently, using the same ribbon of the piezometric probe, we measure the height of the edge (Hm). Then, the geographical coordinates of the various structures concerned are recorded using a Garmin brand GPS (Global Positioning System) receiver by placing it on the upper limit of the edge. All this data issaignement marked on a collection sheet(Tab.1) provided for this purpose(Tab.1).

Painting1:example of a piezometric monitoring sheet

Type of Work	Geographic coordinates			Zp	Hm	neighborhood
	Longitude	Latitude	Altitude			
Well	16.4°	8.51°	411m	13.8m	1.3m	Doumber 3
drilling	16.01°	8.52°	421m	38m	2m	Doumber 1

Hydrochemical monitoring of water points

Hydrochemical monitoringEastcarried out in two campaigns, one during the high water period (December 2022) and the other during the low water period (March 2024). During each campaign we collected thirty (30) water samples, twenty (20) for physicochemical analyses and ten (10) for bacteriology.(Fig.3).

After having circumscribed the entire study area by identifying the types of structures as well as their condition (cleanliness, insalubrity, proximity to sanitation structures, presence or absence of anti-silt slab, etc.) an interview with the owners of the targeted structures for piezometric monitoring and/or for taking samples to be analyzed. The selected structures were positioned on the previously established map. The criteria for choosing the works to be sampled are: (1) the agreement of the owners, (2) the use made of its water, (3) the position and representativeness of the work in relation to disadvantaged households, (4) its position in relation to a source of pollution (latrine, garbage, gardens, fields, livestock and industrial sites), (5) its degree of protection and development, (6) ease of access to the works, (7) the rate of use of the work by residents, (8) topographical situation of the water point, (9) covering the study area.

The water samples were only taken from the selected structures and were carried out using the1.5-liter PVC bottles previously cleaned and washed with distilled water. A total of sixty water samples were collectedpour deux in periods oflow and high water)All samples were analyzed at the hydrochemical laboratory of Brasseries de Moundou. Temperature (°C), Hydrogen potential (pH), Conductivity (μS/cm), Total Dissolved Solid (mg/l) were measured in situ using a Hanna HI 9813-5 multi-parameter water tester previously cleaned and calibrated in the laboratory.

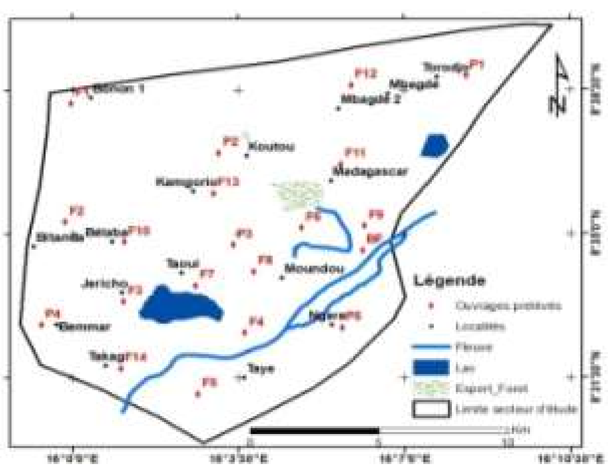

Figure3: Map of water sampling points

I.2.2 Laboratory work

- Physicochemical and bacteriological analysis of water
  - ✓Physicochemical analysis
    - **Turbidity assessment**

It was assessed using a Haffmans VOS ROTA 90 turbidimeter. The operation is carried out as follows :

- ➢ rinsing the glass with the water to be tested;
- ➢ pour the water into the glass and place in the Haffmans VOS ROTA 90 appliance;
- ➢ press the Start button;
- ➢ perform the reading.

- The concentrations of magnesium (Mg^{2+}), sodium (Na^+) and potassium (K^+), calcium (Ca^{2+}), sulfate (SO_4^{2-}), nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}) were determinedes using a LANGE DR6000 brand photometer. Measurement of iron (Fe), lead (Pb^{2+}), zinc (Zn^{2+}), chloride (Cl^-)haswas made with a NOVA 60 spectroquant. Bicarbonate (HCO_3^-),and silica were determined by titration.
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III.3.6. Calculation of the water quality index (GWQI)

The calculation of GWQI was carried out as follows :

- Assigning a weight to each parameter based on its importance on water quality and its effect on health (Khadri et al.,2018) on a scale of 1 to 5 (Tab.2);
- Calculation of relative weight (Wi) from the following equation [2]. $Wi=\frac{wi}{\sum_{i=1}^{n} wi}$

Wi = relative weight

Wi = weight of each parameter ;

n = number of parameters

- calculation of qi of each parameter by dividing its concentration for each sample by its limit value (standard) set by the WHO (2017) multiplied by 100 as indicated by the equation: $qi = \frac{Ci}{Si}*100$;

ci= concentrationof each chemical parameter in each water sample in mg/l; si = the sum of the weights assigned to the parameters according to the WHO standard (2017).

- Calculation of Sli by multiplying the qi by the relative weight (Wi) of each parameter for each sample : Sli = wi*qi
- The GWQI is obtained by the sum of the Sli. $QWQI=\sum_{i=1}^{n} Sli$

Painting2: Example of calculating the GWQI of water

Physical Parameters	P2	WHO Standard (2017)	Weight (Wi)	Relative weight (wi)	Qi	Sli
pH	5.78	8	4	0.08	72.3	5.8
Cond (µs/Cm)	309	2500	5	0.1	12.4	1.2
TDS (mg/l)	153	500	5	0.1	30.6	3.1
Na+ (mg/l)	28.71	200	4	0.08	14.4	1.1
Mg2+ (mg/l)	9.12	50	2	0.04	18.2	0.7
K+ (mg/l)	42.2	12	4	0.08	351.7	28.1
Ca2+ (mg/l)	48.4	100	2	0.04	48.4	1.9
Fe2+ (mg/l)	0.08	0.3	4	0.08	26.7	2.1
Cl-(mg/l)	4.8	230	4	0.08	2.1	0.2
NO2-(mg/l)	0.3	230	5	0.1	0.1	0.0
NO3-(mg/l)	44.2	50	5	0.1	88.4	8.8
SO42-(mg/l)	8.1	250	2	0.04	3.2	0.1
HCO3-(mg/l)	41.2	500	4	0.08	8.2	0.7

			∑wi=50			QWQI= 53.96

- **Bacteriological analysis**

The bacteriological analysis of the samples aims to search for and count five germs (total coliforms : CT, total germs : GT, Escherichia coli : E. coli, Mesophilic flora : FM, fecal enterococci : EF). The concentrations of these bacteria in the water of the study area were determined by the membrane filtration method. It consists of filtering 100ml of the sample through a membrane with pores of 0.45 micrometer in diameter. This small diameter allows the membrane to retain bacteria on its surface. These membranes are then placed in a petri dish containing selective culture media (PlateCount Agar : PCA for FM and GT ; Slanetz and Barthey for EF ; Chromocult for CT and E. coli). The culture media, the bacteria sought, the quantity of water to be analyzed, the temperature and the duration of incubation for each medium are summarized below (Tab.3).

Painting3: Conditions for preparing the different environments and bacteria sought.

Culture media	Technical	Sample volume	Incubation period	Incubation temperature (°C)	Bacteria sought
Plate Count Agar (PCA)	Filtration: Ø=0.45µm	100ml	4 days	28°C	total germs and mesophilic flora
chromocult	Filtration: Ø=0.45µm	100ml	24h	37°C	E. Coli and Total Coliforms
Slanetz Bartley	Filtration: Ø=0.45µm	100ml	48 hours	37°C	Fecal enterococci

Counting bacteriais done directly after incubation. It consists of examining the medium at the end of incubation through a magnifying glass and/or optical microscope and counting the colonies formed on its surface. The colonies are generally in the form of an ampoule. The number found is expressed in Colony Format Unit per 100 ml (CFU/100mL) of the initial sample

III.3.2.2. Establishment of diagrams

Diagrams such as those of Piper, Stiff, and Korjinski were created using the Avignon Hydrochemical 5.3 software from physicochemical data. These data were previously entered into Microsoft Excel spreadsheets and then exported to the hydrochemical software. However, the Gibbs diagram, the ombrothermic diagram, and the histograms were created using Microsoft Excel.

III.3.3. Processing of hydrochemical data

The results of the physicochemical analyses were processed by the multivariate statistical analysis method and the method hydrochemical. The hydrochemical method consisted of using the Piper diagram, the Korjinski diagram, under the software Hydrochimique d'Avignon 5.3, as well as the Gibbs diagram under Excel. The Piper diagram makes it possible to determine the chemical facies of the waters, whileThe Korjinski diagram allows to determine the existence of a possible alteration of silicates. The Gibbs diagram allows to determine the origins of mineralization of waters. The multivariate statistical analysis method is based on the use of principal component analysis (PCA) under the R studio software. PCA, allows to understand the phenomena at the origin of the mineralization of ions in groundwater.

III.3.4. Resultsand interpretations

The results of the physicochemical and bacteriological analyses were discussed in comparison with the WHO standard values (2017) for water intended for human consumption.

RESULTS:-

✓ Inventory of water production facilities

Field observations showed that the most commonly used structures for exploiting groundwater in the study area are boreholes equipped with human-powered or submerged nozzles, and roughly constructed wells. The vast majority of these structures have an unclean environment (presence of stagnant water containing all kinds of debris).

✓ Health survey

Investigations carried out with the health delegation of Western Logone,ont ont recueillies surthree (03)mainwaterborne diseases prevalent in the study areanamely: diarrhea, typhoid fever and cholera. Only the first two (02) are frequently encountered in the locality (Tab.4). The data in this table show that over the last ten years no cases of cholera have been recorded while typhoid fever and diarrhea have reachedpeaks in 2018 and 2021respectively.

Period	Typhoid fever	Diarrheal diseases	Cholera	Period	Typhoid fever	Diarrheal diseases	Cholera
2015	450	300	0	2020	564	7201	0
2016	259	379	0	2021	749	8484	0
2017	214	3658	0	2022	597	3089	0
2018	467	17448	0	2023	334	2802	0
2019	349	16211	0	2024	445	2226	0
2020	564	7201	0	2020	564	7201	0
2021	749	8484	0	2021	749	8484	0
2022	597	3089	0	2022	597	3089	0
2023	334	2802	0	2023	334	2802	0
2024	445	2226	0	2024	445	2226	0

Painting4:mainwaterborne diseases in the last ten (10) years

Source : Health Delegation of Logone Occidental (2024).

- ✓ Piezometry of the city of Moundou and its surroundings

The piezometric maps (Fig.4) established from the data collected inperishedoofsofBoth low and high water levels highlight two piezometric domes. The first dome is located in the West and the second in the North center of the study area. From the first, groundwater flows from the West center to the North, East and South, while from the second, groundwater flowstowards the North and East to accumulate in piezometric depressions located to the South and East under the Logone River (Fig.4). It can be seen that in high (Fig.4.a) as well as low (Fig.4.b) waters, the piezometric domes and depressions always occupy the same positions. These maps show that, the groundwater has two directions of flow following the slope of the isopiezes, the water flow**shas**steep slopes to gentle ones. They flow from North and West to South and East to concentrate in the piezometric depressions located in this part of the study area.whotowards the North and the Northwest will flowcertainlyin a depression located outside the study area beyond Torodjo.

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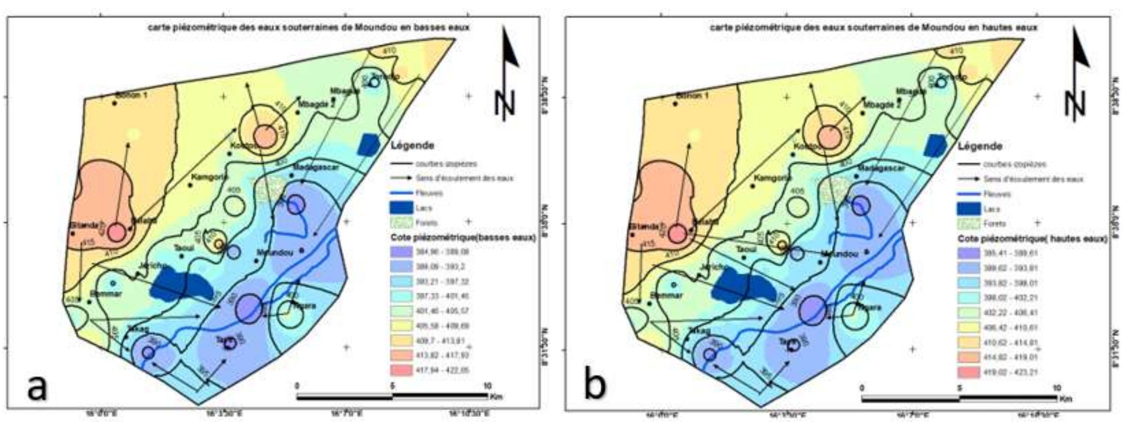


Figure4: piezometric map of Moundou and its surroundings in low (a) and high (b) waters.

IV.4. Physicochemical parameters measured in situ
IV.4.1. pH of water in period of low and high water
The minimum pH values of the water (Table 5) of all the works are below the WHO standard value (2017) between 6.5-8.5. As for the maximum values, only those of the water of the wells in low water are below the WHO standard (2017). In the period oflow water, the pH values of well water are between 5.78 (P2) and 6.46 (P1) for an average of 6.16 with a standard deviation of 0.2. During periods of high waters, these values are between 5.98 (P2) and 6.79 (P4) for an average of 6.44 with a standard deviation of 0.34 (Tab.3). The well waters are acidic and do not comply with the WHO standard (2017). In low water periods, the pH values of borehole waters are between 5.09 (F5) and 6.91 (F12) for an average of 6.06 and a standard deviation of 0.58, on the other hand, in high water periods, they are between 5.19 (F5) and 6.98 (F10) for an average of 6.32 with a standard deviation of 0.59 (Tab.3). The pH of most of these waters are below the minimum value set by the WHO (6.5-8.5). It is noted that, at both high and low water levels, the groundwater from the sampled structures is mostly more acidic, regardless of the type of structure. This shows that the depth of the structures (boreholes are deeper than wells) has no impact on the pH.
Painting5: variation in groundwater conductivity

water points		well		Drilling		Fountain terminals	
Setting		pH					
Collection period		Basses	High	Basses	High	Basses	High
Statistical Settings	Mini.	**5.78**	**5.98**	**5.09**	**5.19**	**5.79**	6.94
	Max.	**6.46**	6.79	6.91	6.98	**5.79**	6.94
	Avg.	6.16	6.44	6.06	6.32	5.79	6.94
	T-Gap.	0.25	0.34	0.58	0.59	0.00	0.00
WHO Standard (2017)	6.5 -8.5						

IV.4.2. Water temperature
For well water, temperatures vary between 27.90 °C (P3) and 29.5°C (P2) for an average of 28.66 and a standard deviation of 0.57, while in high water periods they oscillate between 27.80 °C (P3) and 28.5°C (P2) for an average of 28.20 and a standard deviation of 0, (Tab.6). The values of borehole temperatures vary between 26.9 °C (F9) and 29.1°C (F11) for an average of 28.06°C and a standard deviation of 0.64 in low water and 26.7 °C (F10) and 28.5°C (F12) for an average of 27.46 and a standard deviation of 0.56 in high water (Tab. 6). The temperature value is 29.3°C at low water and 28.2°C at high water for the water from the standpipe.Thesevalues non conformes to the standard recommended byWHO (2017) is between 8-25°C. Note that well water has a high temperature compared to borehole water.

Painting6 :variation in groundwater temperature

water points		Well		Drilling		Fountain terminals	
Setting		Temperature (°C)					
Collection period		Basses	High	Basses	High	Basses	High
Statistical Settings	Mini.	27.90	27.80	26.90	26.70	29.3	28.2
	Max.	29.50	28.50	29.10	28.50	29.3	28.2
	Avg.	28.66	28.20	28.06	27.46	29.3	28.2
	T-Gap.	0.57	0.33	0.64	0.56	0.00	0.00
WHO Standard (2017)	8-25						

IV.4.3. Groundwater conductivity

Electrical conductivity data (Table 7) show that these values are low (21.5 µS/cm: microsiemens per centimeter) and medium (309 µS/cm). These values are very low compared to the WHO (2017) standard (2500 µS/cm). Well water has a higher conductivity than borehole water.

Painting7: variation in groundwater conductivity

water points		well		Drilling		Fountain terminals	
Settings		Conductivity (µs/cm)					
Collection period		Basses	High	Basses	High	Basses	High
Statistical Settings	Mini.	21.50	20.50	15.60	25.58	102	144.91
	Max.	309.00	409.00	302.00	309.00	102	144.91
	Avg.	121.02	144.42	88.54	112.61	102	144.91
	T-Gap.	113.85	156.87	71.13	83.71	0.00	0.00
WHO Standard (2017)		2500					

IV.4.4. Turbidity of groundwater in low and high waters

Turbidity values(Tab.8) from 0.09 (P4) and 44.10 (NTU : Formazin Nephelometric Unit) to 54.1 NTU. Well water is more turbid than that of other structures. The maximum turbidity values of well and borehole water as well as the minimum turbidity values of well water at all times as well as that of borehole water at high water are above the standard value (5NTU) of the WHO (2017). On the other hand, that of standpipe water complies with the standard.

Painting 8: variation in groundwater turbidity

water points		Well		Drilling		Fountain terminals	
Setting		Turbidity (NTU)					
Collection period		Basses	High	Basses	High	Basses	High
Statistical Settings	Mini.	0.09	1.60	0.38	1.51	1.88	0.9
	Max.	44.10	54.10	7.30	13.00	1.88	0.9
	Avg.	13.87	15.20	1.49	5.41	1.88	0.9
	T-Gap.	20.74	25.95	1.84	3.36	0.00	0.00
WHO Standard (2017)	5 NTU						

IV.4.5. TDS of groundwater in low and high waters

LThe maximum values of STD (Total Dissolved Solids) in well and borehole water are respectively 153 and 168 mg/l in low water, while in high water they are 179 and 185 mg/l. That of the standpipe is 102.6 in low water and 8.4 mg/l in high water (Tab.9). These values are below the WHO standard (2017). It should be noted that the STD values of well and borehole water have seen a slight increase in high water compared to low water.

Painting 9:variation of groundwater STD

Water point		Well		Drilling		Fountain terminal	
Settings		TDS (mg/l)					
Collection period		Basses	High	Basses	High	Basses	High
Statistical Settings	Mini.	36.50	26.50	7.80	8.52	102.6	8.4
	Max.	153.00	179.00	168.00	185.00	102.6	8.4
	Avg.	75.54	79.70	53.89	64.69	102.6	8.4
	T-Gap.	45.89	59.25	45.95	50.98	0.00	0.00
WHO Standard (2017)	500 mg/l						

IV.5. Chemical parameters
Alkali
Among the major cations, calcium appears to be the dominant element,followed bysodium, then magnesium and finally potassium for drilling. At the well level, sodium is predominant,followed bycalcium, then potassium and finally magnesium. For alkalis, sodium is dominant in well and borehole water (in high water) then in standpipe water in high water, while potassium is dominant only in standpipe water and in borehole water in low water. All average values of sodium and that of potassiumin high water in the water from the standpipe comply with the WHO standard (2017)that is to saywater intended for human consumption. These standard values are 200 mg/l for sodium and 12 mg/l for potassium.

Alkaline earth metals
The most abundant alkaline earth metal in the groundwater of Moundou and its surroundings is calcium (Fig.5.b). It is worth noting a dominance of magnesium in high-water borehole waters. These average values are all in accordance with the WHO standard (2017) set respectively at 50mg/l for magnesium and 200mg/l for calcium.

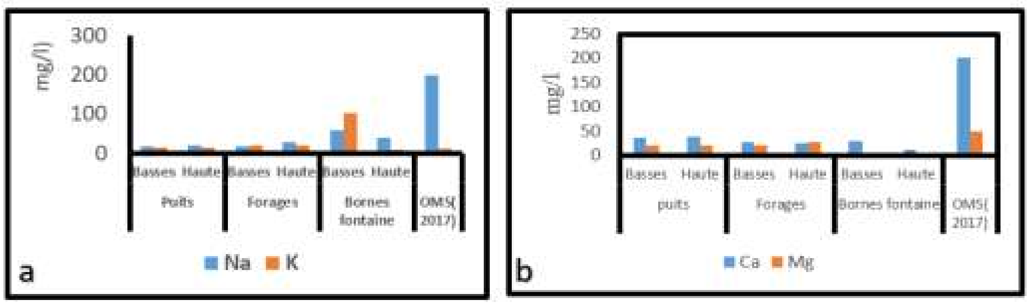
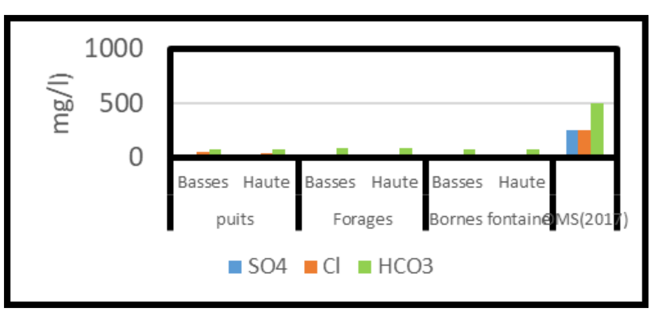


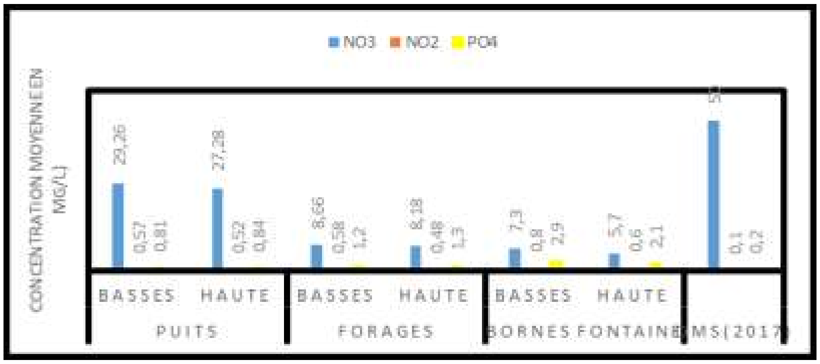
Figure 5:Contents of alkali(a) and alkaline earth(b) in groundwater
IV.5.6. Major anions
For the major anions (Fig.6), we note a predominance of bicarbonate(94.83in all waters,follow upsof that of chloride in well waters while sulfate occupies a second position after bicarbonate in borehole waters. These average values areconform todirectivesof the WHO (2017: 250 mg/l for sulfate and 500 mg/l for bicarbonate) for water intended for human consumption.
Figur
e6: Contents of major anions in groundwater

IV.5.7. Pollutants

Groundwater in the study area is dominated by nitrate relative to nitrite (Fig.7) supported by phosphate but only the average values of nitrite (0.8 mg/l) and phosphate (2.9 mg/l) are higher than the WHO standard value (2017: 50 mg/l for nitrate, 0.2 mg/l for phosphate and 0.1 mg/l for nitrite).

Figure76: Levels of pollutants in groundwater





IV.5.8. Trace metal elements

The concentration of iron and zinc in the groundwater of Moundou and its surroundings (Fig.8), we note a dominance of iron in the borehole waters in high and low waters and that of zinc in the waters of the wells and the standpipe. The average values of iron (0.5 mg/l) in the borehole waters are higher than that set by the WHO (2017) which is 3 mg/l for water intended for human consumption.

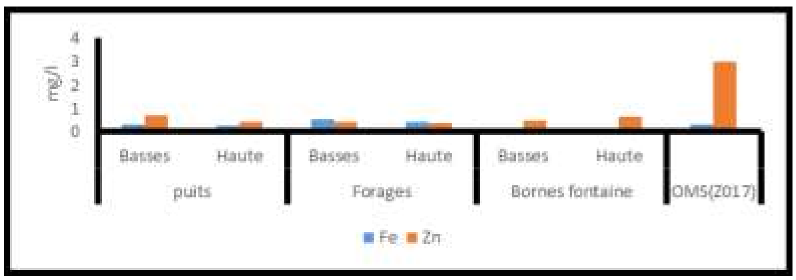


Figure 8: Metal levels in groundwater

IV.5.9. Silica

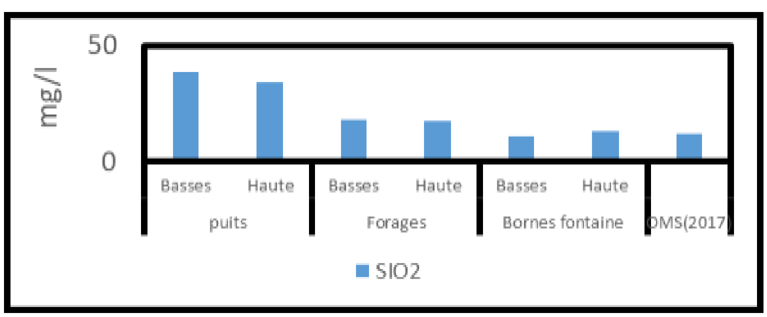
The average value(Fig.9) of silica decreases (38.8 to 113 mg/l) from well water to standpipe water and borehole water. The WHO (2017) standard value for this element for water intended for human consumption is 12 mg/l. The average values of silica in the local water are inmost casessuperiorsto the WHO standard (2017) except for that of the water from the standpipe at low water. The water richest in silica comes from wells.

Figure9:Silica levels in groundwater

IV.8. Hydrochemical facies of the groundwater of Moundou and its surroundings

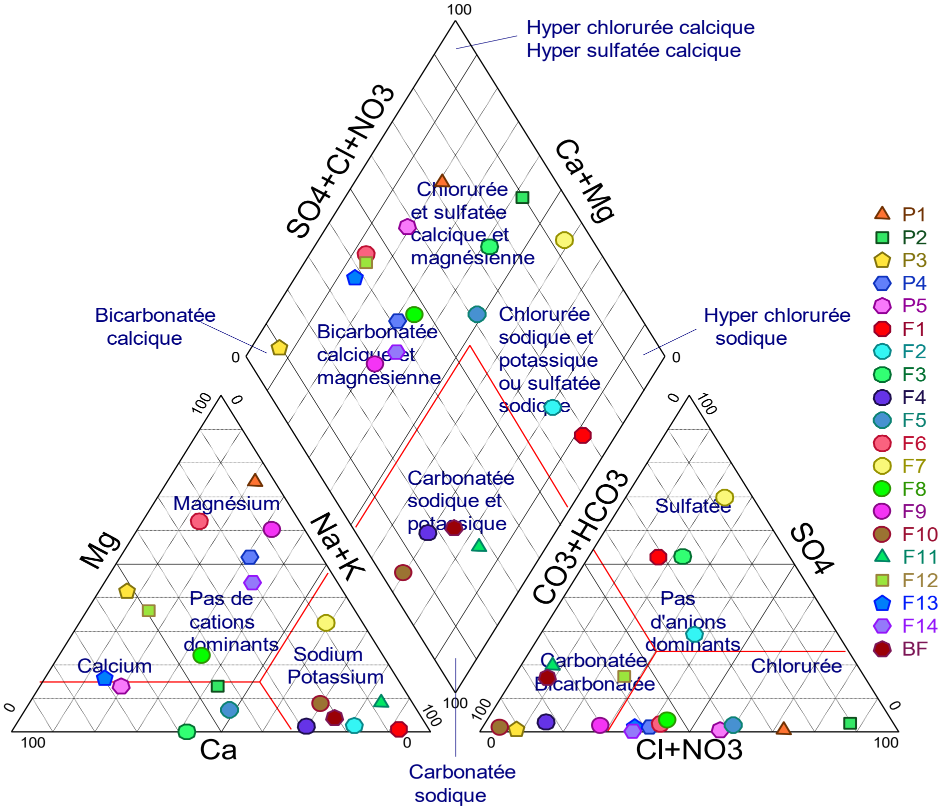
IV. 8.1. Classification of waters using the Piper diagram

The representation of the chemical analysis results in the Piper diagram shows that the groundwater of



Moundou and its surroundings are dominated by the calcium carbonate facies (Fig. 11 and Fig. 12). It is noted that 35% of the waters analyzed during the low water period belong to the calcium and magnesium bicarbonate facies (F6, F12, F13, F8, P4, F14, F9), 25% to the calcium and magnesium chloride and sulfate facies (P1, P2, P5, F3, F5), 20% to the sodium and potassium bicarbonate facies (BF, F10, F11, F4), 15% to the sodium and potassium chloride or sodium sulfate facies (F7, F2, F1) and 5% to the calcium bicarbonate facies (P3).In high water,50% of the waters analyzed during low water periods belong to theCalcium and magnesium bicarbonate facies (F6, F12, F13, F14, F4, F9, P3, F10, F8, P4), 25% in Calcium and magnesium chloride and sulfate facies(P2, F3, F1, P5, P1),10% in the sodium and potassium carbonate facies (F11 and BF).15% in the sodium and potassium chloride or sodium sulfate facies (F5, F7, F2).

Fig



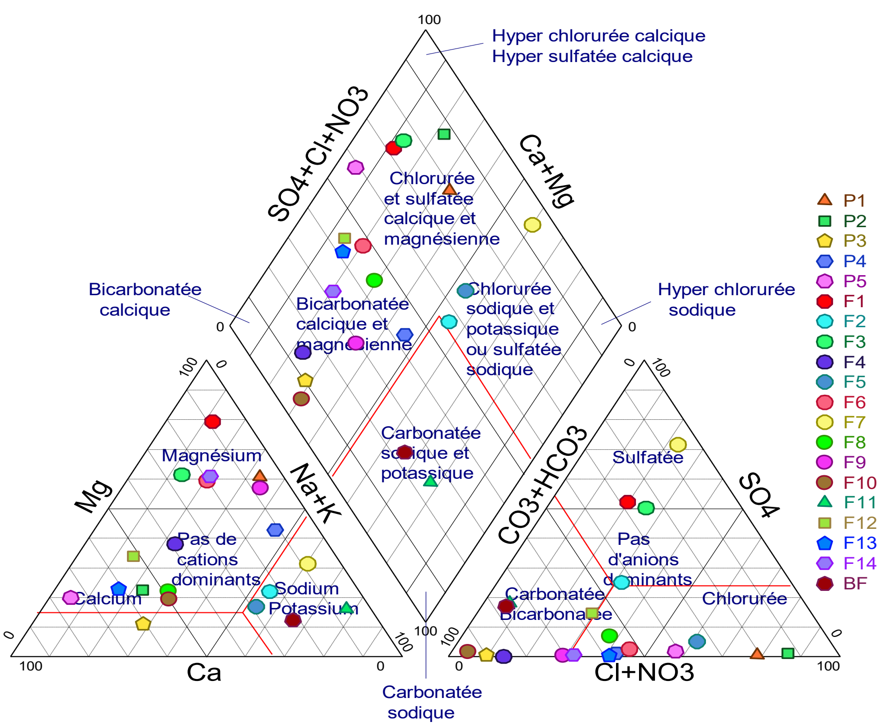


Figure11: Hydrochemical facies of groundwater (December, 2023).

IV.9. Principal component analysis (PCA)

The processing of data from the analyses by the PCA method shows that the correlation circle established from 19 variables (Fig.12) shows that the total inertia expressed by factors 1 and 2 is 33.1 and 32.4% in high water. Factor 1 (F1) represents 19.7% and factor 2 (F2), 13.4% (Fig.12. a) in low water period. In high water, F1 and F2 represent respectively 16.7% and 15.7% (Fig.12. b).

The correlation circle of the correlations of the physicochemical elements shows that in :
Low waters the upper right quarter of the circle is occupied by nitrate, TDS, conductivity, zinc, chloride and calcium, temperature while the upper left quarter is occupied by potassium, phosphate, nitrite, bicarbonate, sulfate and sodium. Its upper left quarter is occupied by sodium, sulfate and bicarbonate. Its lower right quarter is marked by Pb, pH, turbidity, magnesium while the left is occupied only by iron. We also note that chloride, conductivity, nitrate, silica, calcium and zinc are positively correlated with axis 1 while bicarbonate, sulfate and sodium are negatively correlated with this axis. Temperature, potassium, phosphate and nitrite are positively correlated with axis 2 (F2) while pH, iron and magnesium have a negative correlation with this axis.

High water, the positive right quarter is marked by conductivity, chloride, TDS, phosphate and iron ; other times the upper left quarter is occupied by turbidity, magnesium, sodium and potassium. Nitrate, silica, calcium, temperature, Pb occupy the lower right quarter and pH, sulfate, bicarbonate, nitrite and zinc occupy the lower left quarter. The elements (conductivity, chloride, nitrate, silica and calcium) have a positive correlation with axis 1. Bicarbonate, sulfate and sodium are negatively correlated with axis 1. Axis 2 is positively correlated with the elements (TDS, magnesium, turbidity, phosphate and iron) and negatively with pH, Pb, zinc, bicarbonate, temperature and Pb.

Factor 1 In both low and high waters, is materialized in its positive part by materialization under anthropic influence (presence of nitrate in high waters ; nitrate, lead and zinc in low waters). Its negative part materializes a mineralization of natural origin linked to the water-rock interaction (presence of bicarbonate, sulfate and sodium in low waters ; sodium, potassium and sulfate in high waters). Factor 2, during both periods (low and high waters) is characterized in its positive as negative part of the elements some of which constitute a source of anthropogenic pollution (nitrite, lead, zinc, phosphate, iron, turbidity) and natural for others (magnesium, pH, TDS, bicarbonate, temperature), which shows that this axis is that of both anthropogenic and natural mineralization.

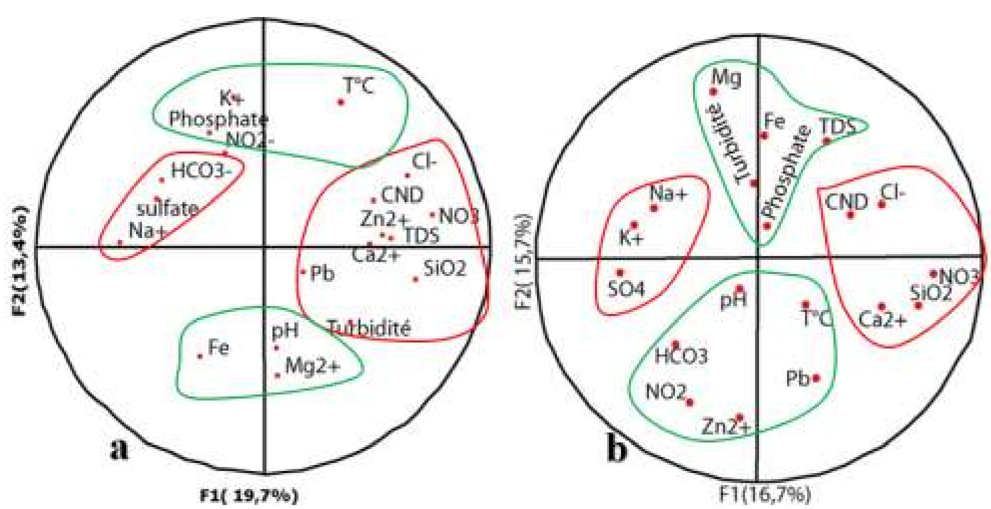


Figure 12: Correlation circle of variables (physicochemical parameters) in the plane formed by the F1 axis and the F2 axis.

The correlation matrices (Table 1 and Table 2) from the high and low water data highlight a strong correlation between certain parameters. Two parameters have a strong correlation when the correlation coefficient between them is greater than or equal to 0.50 (Kouadio, 2018). These are :

- Conductivity with : TDS and chloride with r=60 (in low and high water);
- Chloride and nitrate in low and high water (r= 0.57);
- Nitrate and silica in low water (r=0.55).

Average correlations are also observed between certain parameters :

- TDS with chloride (r=0.46 in low and r=0.45 in high water);
- Temperature with : potassium (r= 0.42 in low water), chloride (r=0.43 in low water and r= 0.44 in high water), nitrate in high water (r= 0.47);
- Turbidity with potassium (r= 0.49) and iron (r=0.44) in high water ;
- Silica with : calcium (r=0.44) in low water and lead in high water (r= 0.44)
- Magnesium and sodium in high water (r=0.44) ;
- Sodium with : sulfate, bicarbonate (r=0.45) in low water and potassium (r=0.43) in high water ;
- Potassium with : phosphate (r= 0.47) in low water and bicarbonate (r=0.46) in high water ;
- Bicarbonate with : nitrate (r= 0.47) in high water, nitrite in low water (r=0.45) and high water (r=0.49)

It should also be noted that certain parameters are negatively correlated, for example temperature and magnesium in low water (-0.44).

These correlations reflect the influence of each parameter in the mineralization (Ngouala et al., 2020) of groundwater, particularly those of Moundou and its surroundings.

The strong and medium correlation between certain elements indicates a probable origin or even a process of dissolution for the latter. Those with a negative correlation are antagonistic, that is to say, the increase in theconcentration of one leads to a decrease in the concentration of the other.

	TDS	T,C	Ph	CND	Turb	That	Mg	N / A	K	Fe	Cl	SO4	NO3	HCO3	Sio2	Zn2,	Pb	PO43,	NO2,
TDS	1.00																		
T,C	0.04	1.00																	
Ph	0.17	-0.19	1.00																
CND	0.60	0.07	0.21	1.00															
Turb	0.16	0.17	0.12	0.07	1.00														
That	0.19	0.08	0.19	0.25	-0.15	1.00													
Mg	0.24	-0.44	0.16	0.11	0.33	-0.05	1.00												
N / A	-0.24	-0.31	0.15	0.08	-0.21	-0.13	0.02	1.00											
K	0.11	0.42	-0.11	0.32	-0.04	-0.07	-0.03	0.28	1.00										
Fe	-0.19	-0.04	0.31	-0.15	0.38	-0.17	0.23	0.32	-0.18	1.00									
Cl	0.46	0.43	-0.07	0.60	0.26	0.16	-0.05	-0.07	0.18	-0.09	1.00								
SO4	-0.19	-0.24	0.04	0.18	-0.19	-0.39	-0.22	0.45	0.15	0.03	-0.03	1.00							
NO3	0.24	0.43	0.01	0.21	0.36	0.29	-0.18	-0.47	-0.15	-0.07	0.57	-0.19	1.00						
HCO3	-0.27	0.21	0.01	-0.15	-0.09	0.07	-0.19	0.45	0.24	0.20	-0.11	0.14	-0.24	1.00					
Sio2	0.10	0.14	-0.09	0.21	0.14	0.44	0.07	-0.45	-0.37	-0.16	0.26	-0.35	0.55	-0.23	1.00				
Zn2,	0.16	0.12	0.11	0.33	0.21	0.29	-0.01	-0.18	0.10	-0.43	0.25	-0.17	0.30	-0.32	0.08	1.00			
Pb	0.07	-0.13	0.05	0.13	0.15	0.13	0.01	-0.21	-0.18	-0.19	-0.12	-0.13	0.05	0.24	0.50	-0.14	1.00		
PO43,	0.05	0.17	-0.24	0.08	-0.41	0.01	-0.20	0.17	0.47	-0.18	-0.11	0.08	-0.29	0.02	0.05	-0.31	0.08	1.00	
NO2,	-0.14	0.27	-0.21	-0.28	0.07	-0.19	-0.16	-0.24	0.24	-0.26	-0.06	0.18	0.01	0.45	-0.20	-0.08	0.14	-0.06	1.00

Painting10: Correlation matrix of physicochemical parameters during low water periods.

	TDS	TC	Ph	CND	Turb	That	Mg	N / A	K	Fe	Cl	SO4	NO3	HCO3	Sio2	Zn 2.	Pb	PO4 3.	NO2 .	
TDS	1.00																			
TC	-0.17	1.00																		
Ph	0.17	-0.19	1.00																	
CND	0.60	0.04	0.06	1.00																
Turb	0.07	0.26	-0.01	-0.08	1.00															
That	0.13	-0.14	0.23	0.07	-0.16	1.00														
Mg	0.39	-0.24	-0.02	-0.06	0.24	-0.15	1.00													
N / A	0.22	0.10	-0.03	0.03	-0.08	-0.29	0.44	1.00												
K	0.14	0.16	0.07	0.07	0.49	-0.26	0.13	0.42	1.00											
Fe	0.21	-0.26	0.18	0.07	0.44	-0.05	0.29	-0.28	0.16	1.00										
Cl	0.45	0.44	-0.24	0.58	0.29	0.15	-0.01	-0.10	0.15	-0.12	1.00									
SO4	-0.30	0.09	-0.05	-0.04	-0.07	-0.38	0.14	0.30	0.29	-0.16	-0.04	1.00								
NO3	0.12	0.47	0.07	0.30	0.31	0.33	-0.26	-0.45	-0.19	0.10	0.57	-0.26	1.00							
HCO 3	0.07	-0.14	0.28	-0.11	0.06	0.10	-0.29	-0.10	0.46	0.07	-0.11	0.16	-0.23	1.00						
Sio2	0.01	0.14	-0.16	0.07	-0.17	0.32	-0.11	-0.16	-0.46	-0.16	0.17	-0.43	0.47	-0.23	1.00					
Zn2.	-0.18	0.00	0.34	0.14	-0.22	0.27	-0.52	0.16	0.14	-0.53	-0.10	0.14	0.01	0.30	-0.05	1.00				
Pb	0.07	0.05	-0.03	0.10	-0.07	0.16	-0.20	-0.05	-0.21	-0.19	-0.14	-0.13	0.13	0.22	0.43	0.37	1.00			
PO43 .	0.19	-0.15	-0.14	0.24	-0.51	0.19	0.04	0.07	-0.18	0.06	-0.05	0.03	-0.28	0.10	-0.04	-0.09	-0.05	1.00		
NO2.	-0.36	0.31	0.04	-0.18	0.01	-0.21	-0.39	-0.16	0.32	-0.23	-0.14	0.17	-0.07	0.49	-0.08	0.32	0.32	-0.23	1.00	

Painting11: Correlation matrix of physicochemical parameters during high water periods.

IV. 10. Water quality index

The groundwater quality index of the study area varies from 19.37 to 75.48 in high water (Table 12); in low water, it varies from 12.47 to 82.64 (Table 13). These values show that the quality of the analyzed water varies from good (25% in high water and 30% in low water) to excellent (75% in high water and 70% in low water).

Painting12: Water quality index of Moundou and its surroundings (December, 2023).

High water period (December 2023)					
works	QWQI	Class	works	QWQI	Class
P1	78.48	Good	F6	47.03	Excellent
P2	39.86	Excellent	F7	45.33	Excellent
P3	21.59	Excellent	F8	46.34	Excellent
P4	33.74	Excellent	F9	40.96	Excellent
P5	34.65	Excellent	F10	68.11	Good
F1	21.12	Excellent	F11	56.94	Good
F2	24.01	Excellent	F12	33.61	Excellent
F3	52.00	Good	F13	23.14	Excellent
F4	19.72	Excellent	F14	58.61	Good
F5	20.70	Excellent	BF	19.37	Excellent

Painting13: Water quality index of Moundou and its surroundings (March, 2024).

Low water period (March 2024)					
works	QWQI	Class	works	QWQI	Class
P1	69.03	Good	F6	47.43	Excellent
P2	53.97	Good	F7	48.38	Excellent
P3	21.59	Excellent	F8	35.33	Excellent
P4	19.52	Excellent	F9	42.58	Excellent
P5	23.52	Excellent	F10	84.34	Good
F1	42.76	Excellent	F11	51.24	Good
F2	21.84	Excellent	F12	28.73	Excellent
F3	49.65	Excellent	F13	23.71	Excellent
F4	12.47	Excellent	F14	63.60	Good
F5	14.66	Excellent	BF	82.64	Good

IV.11. Bacteriological parameters

The results of bacteriological analyses (Tab.14, Tab.15 and Tab.16) show that in high and low waters, groundwater has a dominant concentration of E. Coli.

Painting14: Variation of bacteria in well waters in low and high waters

Work	Well							
period	low water				high water			
	Min.	Max.	Avg.	Gap.	Min.	Max.	Avg.	Gap.
E. Coli	53.00	566.00	240.60	212.96	123.00	353.00	272.00	129.20
Coli. Totals	67.00	270.00	143.20	87.49	70.00	205.00	138.33	67.52
F. Meso.	155.00	200.00	177.60	21.13	164.00	211.00	194.33	26.31
Germs T.	150.00	213.00	179.40	23.06	111.00	200.00	142.67	49.74
Entero. F	0.00	79.00	32.80	31.54	0.00	15.00	6.67	7.64

Painting15:Variation of bacteria in borehole waters in low and high waters

Work	Drilling							
period	low water				high water			
	Min.	Max.	Avg.	Gap.	Min.	Max.	Avg.	Gap.
E. Coli(UFC/100ml)	96	543	349.4	185.61	91	400	217.6	147.77
Coli. TotalsUFC/100ml)	21	200	99	82.43	39	164	99.2	49.62
F. Meso.UFC/100ml)	70	198	149.8	48.52	66	250	190.6	73.51
Germs T.UFC/100ml)	57	200	148	55.55	103	200	140	38.68
Entero. FUFC/100ml)	0	44	8.8	19.67	0	13	2.6	5.81

Settings	E. coliUFC/100ml)	Coli. totalsUFC/100ml)	F. aerobic mesophilic t.UFC/100ml)	Germ t.UFC/100ml)	Enterococci F.UFC/100ml)
low water	303	261	185	211	23
high water	656	261	190	205	40

Painting16: variation of bacteria in the water from the standpipe

DISCUSSION AND INTERPRETATION:-

V.1. Inventory of water production facilities in Moundou and its surroundings

Most of these worksare installed without any prior study and found in placess ont un alentours messys, marked avec sometimes the presence of animalsau on theimmediate perimeter. This is due either : (1) to the population's lack of awareness of the danger posed by stagnant water and debris of all kinds around these structures ; (2) to the installation of these structures in depressions and/or water passages. Awareness raising regarding the sanitation of the surrounding area and the installation of water catchment structures would eradicate these problems of notorious insalubrity ; (3) practice of backyard farming without enclosures, and this causes the animals to wander and approach water points in order to drink from the water poured at the edge of the structures and to take advantage of the humidity. The lack ofassainissemntsanitationaround drinking water supplies in urban areasont aussi has been noted by other authors (Djimrabaye,2018;Dingamadji, (2019, Kadjangaba et al.2023).

V.2. Health surveys

The results of the survey carried out at the Logone provincial health delegation show the increase in waterborne diseases such as typhoid fever and dysentery. These diseases are of fecal origin (George and Servais, 2002 ; Adetunde and Glover, 2011). The causes of the diseases are attributable to the ingestion of contaminated water,relatedto the'absence par manque des ouvrages sanitationworksadéquatsBetween 2015 and 2016, the prevalence of these diseases was low. (Fig.13), thisserait associée à la sa could be explained by growthdemographyétait average duringcette périodethese yearsDiarrheal diseases peaked between 2018-2019 while typhoid fever remained almost constant (Fig.13.a). Cthese episodescoincidewithpopulation growth (Fig.13. b),which probably exerts strong pressure on the works havingdonc l'augmentation de la population driveeethe degradation of the bacteriological quality of water ayant pour conséquence la recrudescence des maladies hydriques.After these peaks, the prevalences decrease while the population continues to increase, this is attributable to the WASH projects established by the Government and its partners in the city of Moundou since 2015 (DEA, 2024). This project intervened in the supply of drinking water and sanitation through the installation of latrines respecting health standards as well as hygiene practices. The results of these health surveys corroborate with those of Ndeko et al., (2018), Djimrabaye (2018), Digamadji (2019), Eloge (2015), Jean et al., (2013).

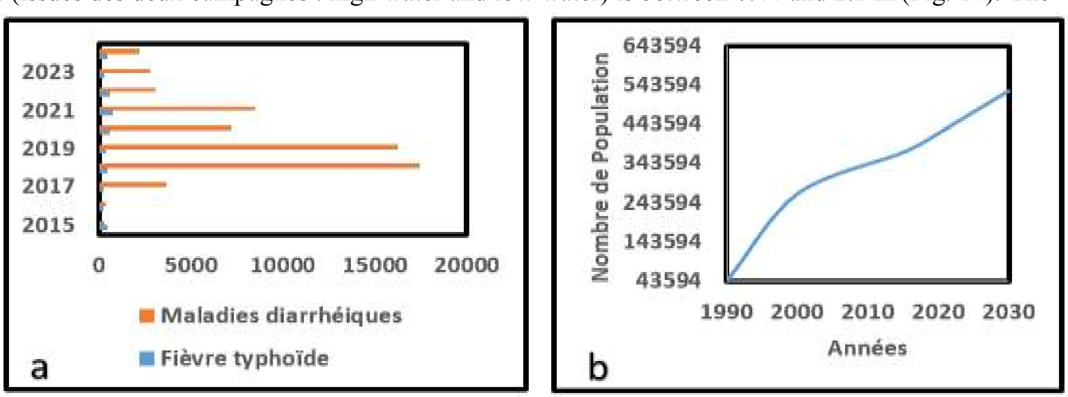
Figure 13 : Evolution of diseases (a) and of the population (b).

Sources : (a) Logone Occidental Health Delegation (2024); (b) City Fast (2019).

V. 3. Hydrodynamic parameters

V.3.1. Piezometry (December 2023-March 2024).

The processing of data from the piezometric campaigns shows that the difference in static levels between the two periods (issues des deux campagnes : high water and low water) is between 0.44 and 2.1 m (Fig. 14). The



increase in the static level at high water is probably due to the recharge of the water tablespendant cette période by the infiltration of rainwater.WhileSon L'loweringfrom the static level in periodofbasswatersis due to the exploitation of groundwater by the population and to evapotranspiration. According to Castany (1982), domes are areas of recharge of the water table while depressions are areas of discharge of the water table. For Archambault (1987), piezometric depressions are areas not subject to recharge but exposed to evapotranspiration, while Ngounou (1993) concludes that piezometric depressions are areas associated with evapotranspiration and the passage of the water table in the lower clays. In the study area, the recharge areas are located in the West and North, those of discharge are located in the West and South. The behavior of the piezometric level observed on the ground shows that in the study area the piezometric depressions would be due to: (1) overexploitation of groundwater; (2) a decline or lack of recharge following soil compaction in relation to intense urbanization; (3) overexploitation in relation to demography.cote sideThe piezometric pressure decreases as it approaches the watercourses, this shows that in addition to the direct recharge at the piezometric cones, the depression areas receive indirect recharge from the waters of the watercourses. Furthermore, this piezometric map provides us with information on areas suitable for the installation of test pumps and catchment structures for the APE (Drinking Water Supply) which are the piezometric depressions located to the South and East (in the Taye district and south of the Masdagascar district).

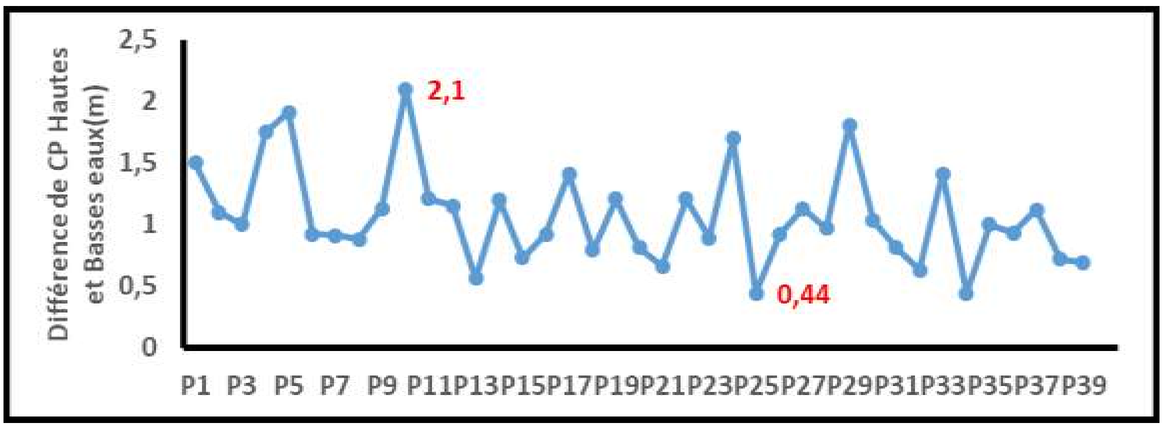


Figure 14 : Difference in static level between low and high water

V.4. Physicochemical and bacteriological parameters
V.4.1. Variation of physicochemical parameters
V.4.1.1. physical parameters

The average values of the physical parameters recorded in the tables (see Tab.5; Tab.6; Tab.7; Tab. 8; Tab.9) show that the TDS, conductivity and turbidity of the low water boreholes as well as that of the standpipe are in accordance with the WHO standard (2017). On the other hand, the average values of the temperature, pH and turbidity of the wells and boreholes in highwatersdoes not respectntnot the WHO standard (2017) for water intended for human consumption. How much are these average values ? and the normal value of theWHO ?

- **STD**

THETDS(Total Dissolved Solids) is used to assess the total concentration of dissolved solids in a solution. This includescompris minerals, salts, metals and other substances present in water. The TDS from this study are inleur ensemble inférieurstheir lower setsto the potability standard set by the WHO (2017). This weakness isinrelationship with the nature of the sandy aquifer. The TDS from this study are in the same class as those determined by Allarassem et al., (2023), Digamnadji (2019) who worked under a similar environment.

The temperatures

The map (Fig.15.) of the distribution of groundwater temperatures in the study area shows a decrease in the latter when moving towards the watercourses. The waters with the highest temperatures (27.80-28.49°C) are located in the West, North-West and East of the study area. In addition, the average temperature values are getting closerof the average atmospheric temperature of the study area (29°C). This can be explained by : (1) the influenceofambient temperature on groundwater with shallow depth, (2) the effect of the geothermal gradient for deep waters (located to the West and Northeast of the study area), (3) the influence of the waters of the Logone through infiltration during low water periods for waters located in the vicinity of this watercourse. High values of groundwater temperature are favorable to the development of environmental microorganisms (Asaï et al.2023). These high values of groundwater temperatures have also been highlighted by other authors who have worked in a similar environment, including Kadjangaba (2023), Tomasbé (2015) andDingamadji, (2019), Djimrabaye (2018), Kamena (2021).

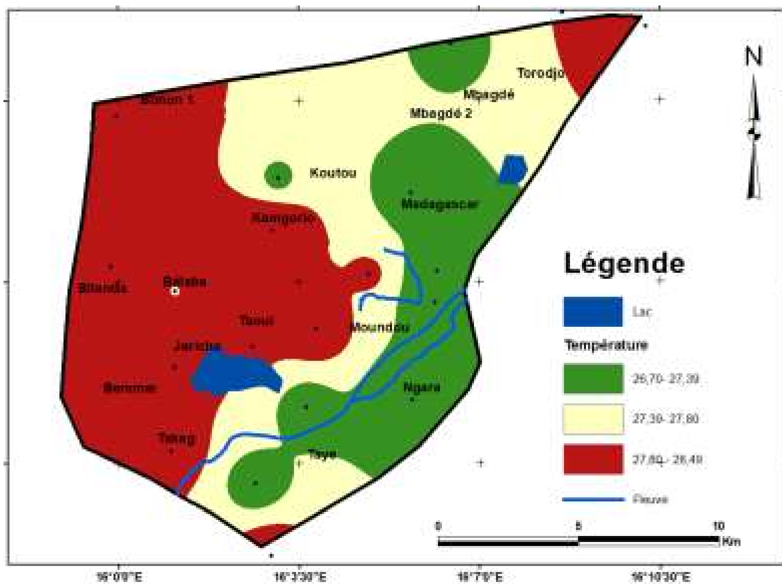


Figure 15 : Groundwater temperature distribution map

- **Turbidities**

Turbidity provides information on the presence of suspended matter, including clays, silts, fibrous particles, colloidal organic matter, plankton and microscopic organisms.(Frahtia and Nezzar,2016). The distribution map of-– turbidity (Fig.16) shows that the highest values are observed in Ngara and Kamgorio (in the East and the Center) where groundwater is mainly exploitedà l'aideInwells. We note that in generalthatThe waters of the wells in the study area are more turbid than the borehole waters. This may be linked to the exposure of the wells to aerosols because the latter are in most cases devoid of coping stones and/or closures on the one hand and on the other by the use of pushers dragging on the ground. The superiority of the turbidities of the waters in high waters compared to low waters is explained by the leaching and infiltration of geological constituents, in particular clays. The high turbidity of the waters of the wells associated with the erosion of the walls of the wells, most of which are not stabilized by a support (brick construction, nozzles or barrels) or even to the failure of the filtering of the materials crossed by the waters during their infiltration. The turbidities of these waters align with the range of waters determined byDingamadji (2019),Tomasbé (2015), Djimrabaye (2018), Kengni (2012),Ngoualaet al.,(2020).

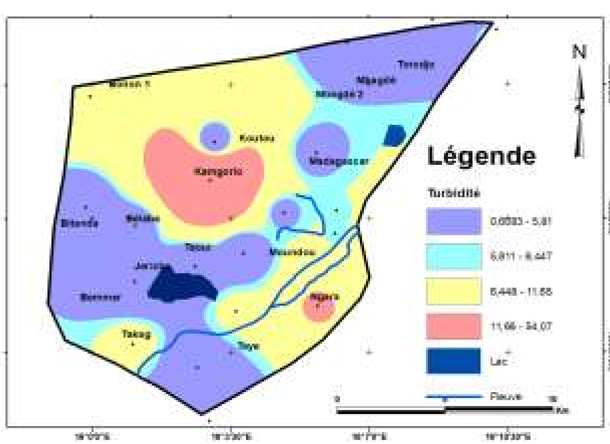


Figure 16: Groundwater turbidity distribution map

- **The pH**

The spatiotemporal distribution of pH(Fig.17) shows that the most acidic waters are located in the West (in the districts: Bonon, Bitanda, Bemmar, Jericho)qui coincidecoindecidingwith the piezometric cones (Cf. Fig.4), to the South (Taye district) to the East and to the North-East. The average pH values show that the water table is acidic. These acidic pHs could be linked: (1) tola infiltration of CO2-rich precipitation water; (2) dissolution and infiltration of humic acids from the decomposition of organic matter, particularly for the most acidic waters located in areas with high agro-pastoral activity; (3) the sandy nature of the geological formation, thereby reinforcing theresultsworks of (Tamonkem et al., (2024), comme le cas du secteur d'étude. This low pHcould bedueofto high levels of free CO2, themselves linked to the presence of microorganisms such as fungi and coliforms(Tamonkem et al.2024). For WHO (2017),la faible THEweak PH pHThe quality of water does not have a direct impact on consumers but is rather an indicator of the presence of microorganisms. These waters must be treated to eliminate microbes before consumption. Several authors have reported the acidic character of the waters of continental aquifersst Andsabloneuxsandy These are the works of Tchadanaye and Tarkodjiel (2009); Tomasbé (2015);Dingamadji,(2019); Kadjangaba et al., (2023); Kengni et al., (2012); Kamena (2021); Ngouala et al., (2020); Germain et al. (2019) ; Tamonkem et al., (2024); Photo et al., (2022); Germain et al., (2019). On the other hand, the work of Allarassem et al., (2023) carried out in a region neighboring the study area highlighted basic groundwater. This difference would lie in the lithological nature of the aquifers.

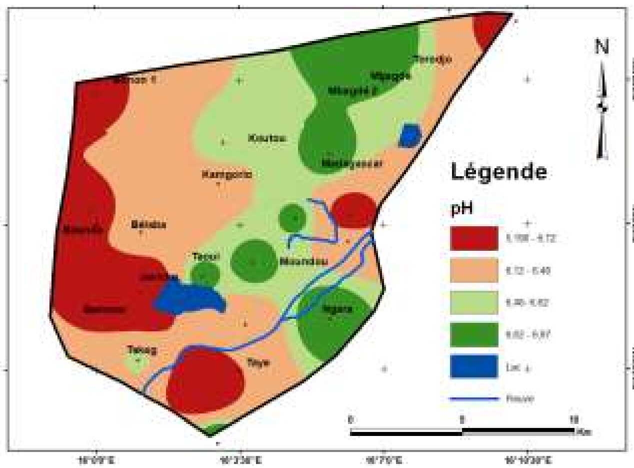
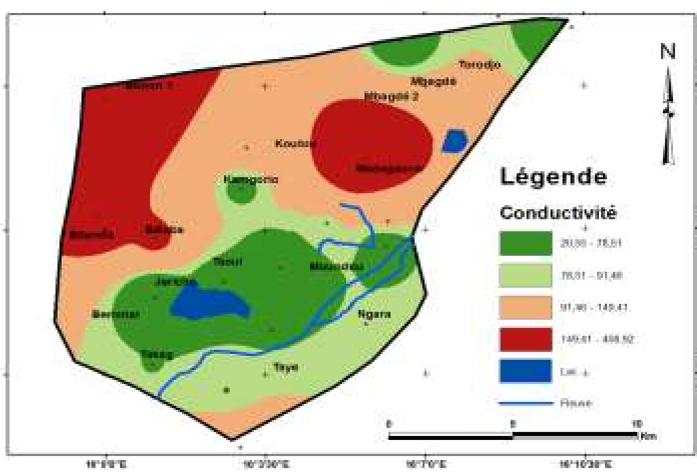


Figure 17: Groundwater pH distribution map

- **Conductivity**

The map (Fig.18) shows that waters with medium conductivity are located in the Northwest and the Central East. These medium (149.01-408.92 µS/cm) and low (20-149µS/cm) conductivity values are low due to the nature of the aquifer rich in sandstone and sand. In addition, The lowest values (Fig 18) are observed in the vicinity of watercourses, which shows an influence of surface water on the conductivity of groundwater by infiltration and dilution. For Tamonkem et al., (2024),LLLow conductivity values suggest a low rate of solubilization or exchange between groundwater and surrounding aquifer materials. These waters fall within the group of those determinedles othersauthors (Djoret, 2000; Kengni et al. 2012; Ngouala et al. 2020; Tomasbé, 2015; Mardochée, 2019, Allarassem et al. 2023).

- **Figure 18:Groundwater**
- **Conductivity distribution map**



V.4.1.2. Chemical parameters

The potassium distribution map in groundwater shows that the area occupied by higher concentrations (>12 mg/l) increases in high water (Fig.19.b) compared to low water (Fig.19.a), which emphasizes the leaching and percolation of potassium from chemical fertilizers into water tables. The highest concentrationsd'étend are recordedin peripheral areas with high pastoral agricultural activity. For White et al. (1999), potassium is mainly released by the alteration of alkali feldspars and especially biotite, while for Guy (2012) potassium in groundwater is explained by the exchange of bases with clays. The high potassium values in the waters of the study area are explained by anthropogenic actions, in particular the leaching and infiltration of chemical fertilizers called NPK, massively used in market gardening and other food crops in the peripheral districts. The work of Kadjangaba et al. (2023) and Tomasbé (2015) also noted high potassium levels in the groundwater of the area. For Léas (2024), excess potassium can, in fact, disrupt the functioning of thecoeurheartand cause heart rhythm disorders that can lead to cardiac arrest.

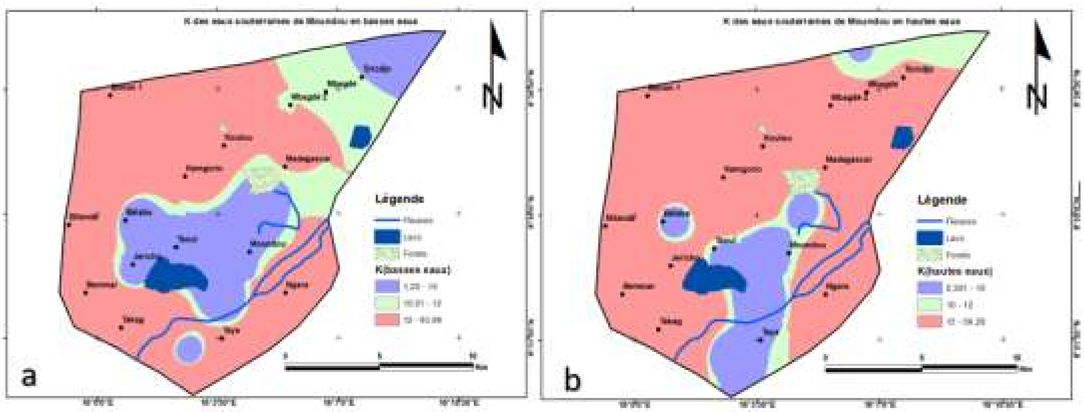


Figure 17 : Potassium concentration in low (a) and high (b) waters.

- **Silica**

Analysis of the silica content map (Fig. 18) in high and low watersindicates that'There are only three small pockets where the concentrations are in accordance with the WHO standard (2017). The excess silica can be explained by : (1) the nature of the formationsgeological features of the Continental Terminal, which are predominantly sandy ; (2) the phenomenon of monosialitization and bisialitization ; (3) the exposure of wells to aerosols most often loaded with altered materials. Indeed, the work of (Paul et al. 1969, Camille, 2015, Ngouala et al. 2020, Hamid, 2012) noted the excess of silica in groundwater. For the 2nd and 3rd author, The silica enrichment of water is linked to the exchange of bases between the water and the surrounding terrain and the second author characterizes the richness in silica as being the testimony of a long stay of the water in the geological formations while for the third author, the high content of silica in the groundwater finds its explanation in the alteration of plagioclases in particular that of albite. According to Eblin et al., (2014), the high contents of silica in the drinking water, as is the case in the study area could have as consequences pathological manifestations at the level of the lung.

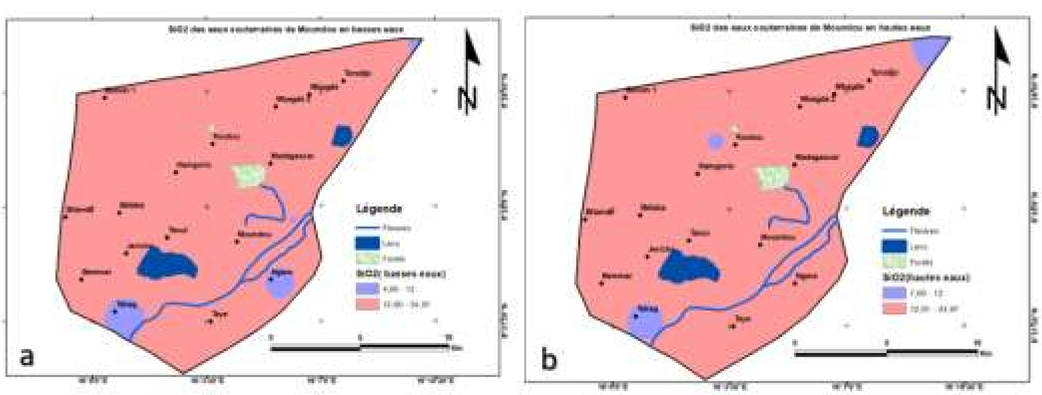


Figure 18 : Silica concentration in low (a) and high (b) waters (March, 2024).

- **Nitrate**

Nitrate concentrations in both low and high waters are in accordance with the WHO recommendation (2017) for water intended for human consumption but values above 10 mg/lfait makestill think about an anthropogenic involvement. According to Madison and Brunett (1985), a concentration of NO3- between (0.21-3 mg/l) suggests a possible anthropogenic action and 3.1-10 mg/l indicates a very clear influence of an anthropogenic action. Nitrate distribution maps show low to medium values in the south of the study area around the Logone River, this will probably beliéerelatedtheir dilution by surface water (Fig.19). Furthermore, the high nitrate values (> 3mg/l) in the groundwater of Moundou and surrounding areas could be linked to: (1) leaching and infiltration of chemical fertilizersutilisation utilisés dans les (2023),resulting fromagricultural activities; (2) the use of latrines with a lost bottom which allows communication between the water table and human waste, especially during periods of high water; (3) decomposition of organic matter of animal and plant origin; (4)léssivageleachingand infiltration of animal droppings.Les auteurs, Nesma et al., (2022); Djoret (2000), Kadjangaba et al. Mardochée (2019) and Tomasbé (2015) reported high nitrate values in groundwater in sedimentary and urban environments. These authors point to anthropogenic factors such as the origin of nitrates in groundwater. High nitrate levels can cause methemoglobinemia in infants and carcinogenic diseases in adults (Johnson, 2019).

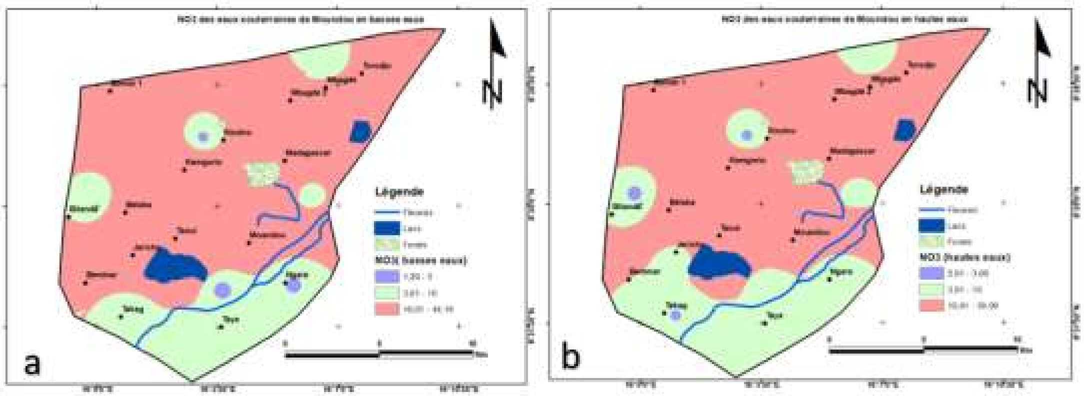


Figure 19 : Nitrate concentration in low (a) and high (b) waters.

- **Nitrite (Fig.20)**

The distribution of nitrites in groundwater shows that in both high and low waterleur their valuevallent vary respectivelyof28 and 23 timessuperior tothat set by the WHO (2017). Moreover, the presence of nitrites in water suggests a deterioration in its quality byprésence microbes (Vincent, 2019). We notice four small pockets (in gray color in the North, South, East and West) whose concentrations are consistentsto the potability standard,thismarque supportsthe weak anthropogenic action at the points concerned or the discharge of water from these points towards the piezometric depressions because these points coincide with the piezometric domes. In this locality,nitrites would come mainly from anthropogenic activitiess(incomplete oxidation of solid or liquid waste or chemical fertilizers used for soil fertilization by humans)as also attested.the work of Kadjangaba et al. (2023)And,Tomasbé (2015) ont également signalé des teneurs élévées des nitrites dans les eaux souterraines de la localité.

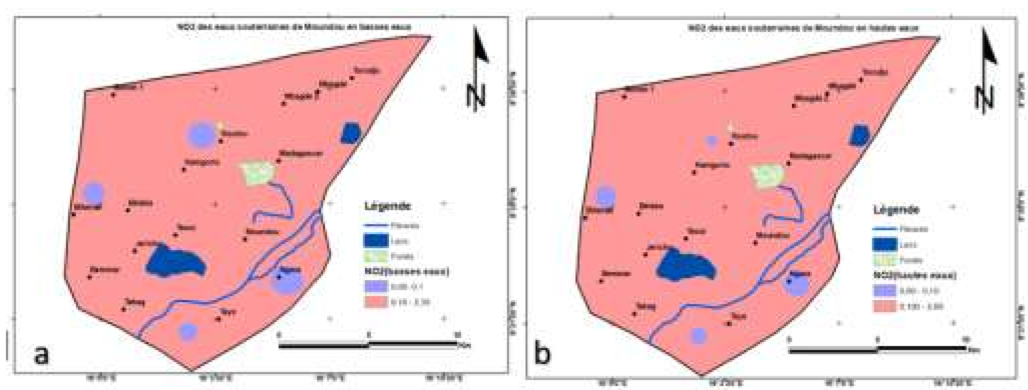


Figure 20 : Concentration of nitrites in low (a) and high (b) waters.

Phosphate

Phosphate distribution maps (Fig.21) in the groundwater of Moundou and surrounding areas show that the levels are 99% higher than the standard value set by the WHO (2017) for water intended for human consumption. In both high and low waters, the highest values are due to : (1) the use of phosphate-rich detergents, (2) infiltration of phosphates from human excrement, (3) high valuesobtainedin the peripheral districts would be linked to agropastoral activities (infiltration of chemical fertilizers). These waters are included in the class of those studied by Kundu et al. (2015), Ngouala et al.2020), who reported high concentrations of phosphates in groundwater and concluded that they come mainly from industrial discharges and domestic discharges (human excrement, detergents, laundry detergents).

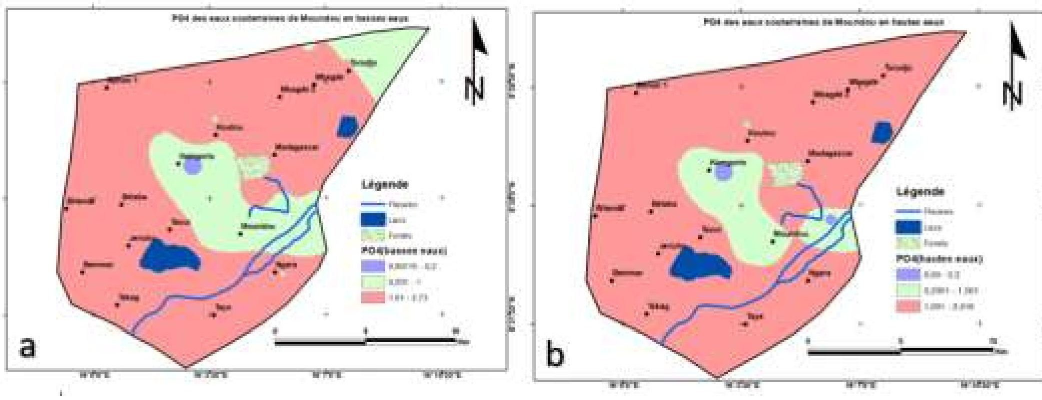


Figure 21 : Phosphate concentration in low (a) and high (b) waters.

Iron

The iron distribution map (Fig.22) highlights four pockets (Fig.22.a) in low waters with a content that complies with the WHO (2017) drinking water standard. In high waters (Fig.22. b) the waters located in the West comply with the WHO (2017) drinking water standard, while those located in the East and on the peripheries of the rivers have a concentration higher than the WHO (2017) standard. This is linked to the drainage of dissolved iron towards the rivers which in turn impact the quality of the groundwater located in their vicinity. The iron concentration values for boreholes are slightly above the standard in both high and low waters. The high contentinThe iron in these waters would have as source : (1) the oxidation of water exploitation equipment (for human-powered pumps), (2) degradation of the barrels used to stabilize the walls of latrines and/or wells or the burial of certain metals mixed with the garbage used to fill the depressions, (3) the leaching of iron-rich geological formations such as laterite/bauxite. With such iron contents, the waters of this study area fit into the group of those identified by Germain et al., (2019), Kadjangaba et al. (2023), Djimrabaye (2018). These studies,also reported the presence of iron at a high concentration in groundwater, for these authors, the high content will be linked to anthropogenic activities and the lithological nature.

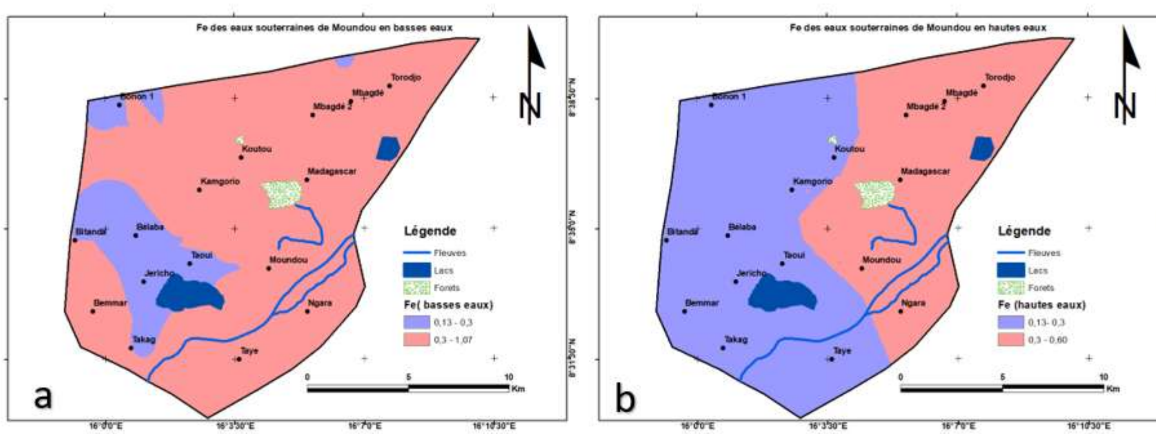


Figure 22 : iron concentration in low (a) and high (b) waters (March, 2024).

V.5. Hydrochemical facies

The water analysis results show that in low water 90% belong to the calcium and magnesium bicarbonate facies (Low and high water), 50%(25% low waterand 25% in high) of the waters belong to the calcium and magnesium chloride and sulfate facies, 10% in low waters and 20% in high waters belong to the sodium and potassium carbonate facies while the sodium and potassium chloride or sodium sulfate facies occupies respectively 15% of the waters in low waters and 15% in high waters.

Calcium and magnesium bicarbonate facies characterizes the immature waters of sedimentary aquifers (Hamit, 2012) and generally represents weakly mineralized waters and generally have conductivities lower than 1000 µs/cm (El Alaoui, 2010). The predominance of this facies in the waters of the study area would probably be linked to: (1) the dissolution of atmospheric CO2, followed by the percolation of these waters towards the water table, (2)from the alteration of dolomite or feldspars such as anorthite which gives kaolinite by alteration.

The presence of the sodium and potassium carbonate facies on the one hand and the sodium and potassium chloride facies as well as the calcium chloride facies on the other hand is explained by the phenomenon of base exchanges between the water and the surrounding rock. The calcium chloride facies are of alluvial origin (Seghir, 2014). The chemical facies of the waters in this study align with the class of facies determined by Djoret (2000), Kadja (2007), Hamit (2012). Tomasbé (2015), Mardochée (2019) under an environment similar to that studied.

V.6. ACP

V.6.1. Factor analysis

The correlation circle (Fig.22) allowed us to understand that in the study area there are two main phenomena of groundwater mineralization. These are the water-rock interaction and the anthropogenic involvement through the use of phytosanitary products, and bottomless latrines and the archaic discharge of household and industrial waste. These human practices cause the infiltration and percolation of pollutants (nitrate, phosphate, nitrite) to the water table.

V.6.1. Correlation

The observed correlations (see Table 11 and Table 12) between the physicochemical parameters of the groundwater in the study area highlight the links between some of them. Thus, there is the link between chloride and nitrate, nitrate and silica, temperature with potassium, chloride and nitrate, turbidity with potassium and iron, silica with calcium and lead, magnesium and sodium, potassium with phosphate and bicarbonate. These correlations (see Table 1) sometimes link elements of natural origin (silica, calcium, potassium and bicarbonate) with pollutants and heavy metals (nitrate, phosphate, lead and iron). This allows us to say that in the study area the dissolution of ions is carried out by the leaching and infiltration of agricultural soils as well as household waste, the contact of human waste and water table through the bottomless latrines (release of nitrates into the water), the interaction of water and rock

V.7. Groundwater quality index of Moundou and its surroundings

Groundwater quality indices show that overall, the groundwater of Moundou and its surroundings, compared to their sampling point, has a quality ranging from good to excellent. Although there is a non-conformity in the concentration of certain chemical elements (phosphate, nitrite, potassium, iron and silica) and physical (temperature, turbidity and pH), this has less impact on the physicochemical quality of Moundou groundwater. These results are not consistent with those of Kadjangaba et al. (2023) who highlighted, in addition to the classes obtained in this study, water from very poor to non-potable class. This could be explained either by the difference in the sampling sites or by the parameters chosen for calculating the index. Ces eaux salignent donc dans le groupe de celle déterminées par Tamonkem et al., (2024).

V.7. Origin of water mineralization

V.7. 1. The Gibbs diagram

The Gibbs diagram allows us to observe the evolution of the total mineralization of waters as a function of the ratio (Na+K) / (Na+K+Ca). This diagram makes it possible to distinguish between waters whose mineralization is controlled by evaporation and waters whose mineralization is due to the influence of water-rock interaction (WRI) or anthropogenic processes. The positioning of the waters of the study area in this diagram during the low water period shows their positioning in three areas while during high water they are positioned in two areas.

- ✓ In low water (Fig.23.a)

The water from the boreholes (F13, F12, F6, F3 and F8) falls within the scope of influence of both the water-rock interaction process and the evaporation phenomenon.

The water from the wells (P3, P5 and P2) falls within the scope of the evaporation phenomenon. The water from the boreholes (F5, F14, F10, F9, F11, F1, F7, F2, F4), the wells (P4, P1) and the standpipe (BF) falls within the scope of anthropogenic influence.

- ✓ In high water (Fig.23.b):

Seventy-five percent (75%) of the waters belong to the area of influence of evaporation, these are the waters, the boreholes (F13, F12, F3, F8, F6, F14, F1, F10, F5, F4, F2), the wells (P2, P3, P5,) and the standpipe (BF) belong to the area of influence of evaporation;

Twenty-five percent (25%) of the waters belong to the domain of anthropogenic influence, in particular the waters of boreholes (F11, F1, F9), wells (P4 and P1). The control of the mineralization of the waters by evaporation would be due to : (1) the shallow depth of the waters ; (2) the rise in temperature in high and low waters ; (3) the influence of the courses which are in contact with the water table; (4) the hydrolysis of evaporites such as halite, gypsum,anhydritereported in the study region by Schneider (2001). The influence of water by anthropogenic action would be linked to: (1) the proximity of the works to possiblessources of pollution such as garbage piles, dump holes,emptying of latrines and the presence of animals; (2) the unsanitary conditions around these structures (Cf. Fig.19.a, b and c); (3) the infiltration of household and industrial wastewater; (4) the infiltration of fertilizers and herbicides widely used in the study area; (5) open defecation; (6) use of waste-basin latrines. The work of Djoret (2000), Kadja (2007), Issa (2007), Hamit (2012), Kamnaye (2013), Siddick (2014), Mahamat et al. (2015) then Hamit et al. (2015), Djimrabaye (2028), Mardochée (2019), Kadjangaba et al. (2023) in urban and sedimentary environments highlighted the control of groundwater quality by evaporation, water-rock interaction and anthropogenic activities.

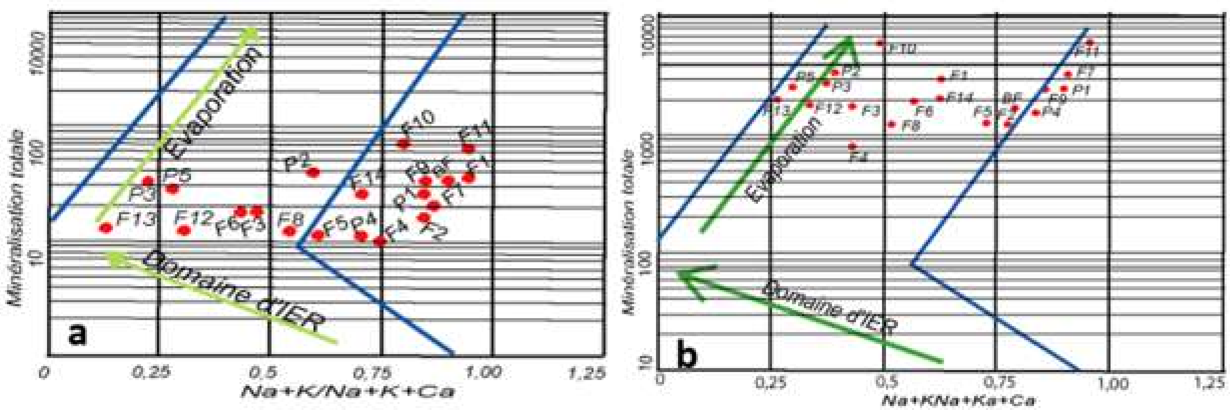
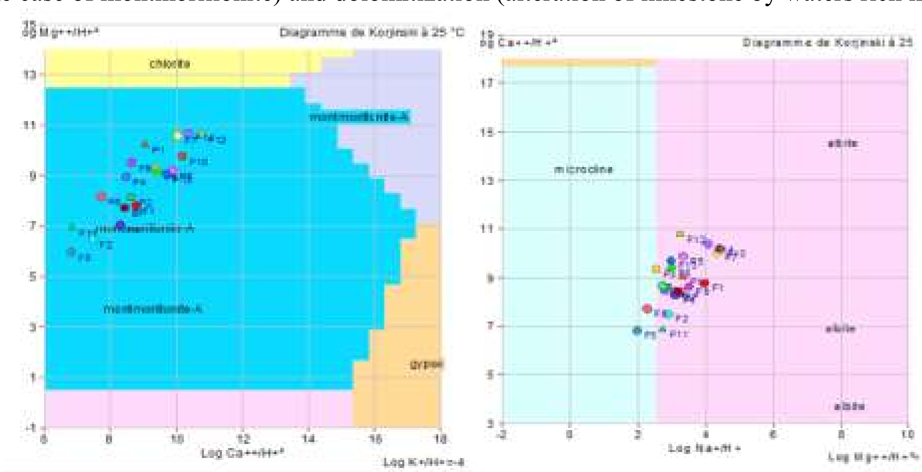


Figure 23 : Projection of waters (March, 2024) in the Gibbs diagram (1970)

V.7.2. Balanced state of the analyzed waters

The Korjinski diagram (Fig.24) shows that the analyzed waters are in equilibrium in order of abundance with secondary minerals such as montmorillonite ([(Si3.67 Al0.33) O10 Al(OH) 2 Ca2+ 0.167]), kaolinite ([Al2Si2O5(OH) 4]), albite (NaAlSi3O8), dolomite (CaMg [CO3]2) and microcline (KAlSI3O8). One of the alteration processes that influences the mineralization of the waters of Moundou and its surroundings would therefore be hydrolysis through allitization (total elimination of basic cations and silica giving rise to type 1/1 clays, the case of kaolinite) and bisiallitization (partial leaching of silica and basic minerals. K+ and Na+ giving type 2/1 clays; this is the case of montmorillonite) and dolomitization (alteration of limestone by waters rich in magnesium).



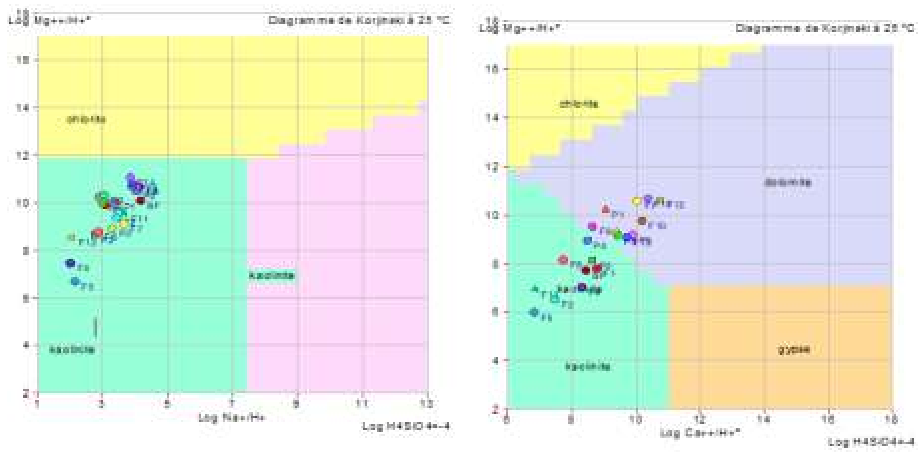


Figure 24 Korjinski diagramdonnant lesof themain minerals in balance with the analyzed waters.

CONCLUSION AND RECOMMENDATIONS: -

Conclusion: - The study aimed to determine the quality of groundwater in Moundou and its surroundings.Les descentes sur le terrain THEdifferent approacheshave shown that the most used water supply structures in the study area are equipped boreholesbyof human-powered pumps and traditional wells. These structures, located in ont an unclean environmentavec la présence d'ouvragesare missingsanitationindividuelle et desand mix with thehousehold waste dumps. Lpiezometric mapsmontrent quealso made it possible to identify les of thewater table recharge zones are locatedhasent in the West and North and Centraldlthe landfill area to the south and east of the study area, montrant highlightingthe flow of groundwater towards the Logone River.Physicochemical characterizationdes eaux échantillonnées highlighted the acidity (5.09 < pH < 6.98) and low to medium mineralization (15.60 µS/cm < CE < 409 µS/cm) of the groundwater of Moundou and its surroundings. This is related to the sandy aquifer of the Continental Terminal. These waters also have a turbid character related to the activities tantnatural and anthropogenic. The temperature of all the waters analyzed is higher than the WHO standard (2017). Chemical parameters show that the values of nitrites, phosphate and silica as well as that of iron in some waters are higher than the WHO standard (2017). The dominant chemical facies iscalcium and magnesium bicarbonate (Low and high waters). It is followed by the chloride and sulfate calcium and magnesium facies. The GWQI shows that the groundwater in the study areaare excellent andofgood qualityFrom a bacteriological point of view, the groundwater in the study area, both in low and high water, revealed contamination by microorganisms with levels above the WHO (2017) standard values for drinking water. The presence of these bacteria is proof of contamination of fecal origin and of the undrinkability of this water regardless of the number of germs, even 1 in 100 ml of sampled water. (OMS, 2006 ; Mehanned et al, 2014 ; Sila, 2019).This fecal contamination is linked to the massive use of bottomless latrines. The presence of E. coli is indicativeby feces.

Recommendations:-

To decision-makers:

- ✓ build pipelines for the evacuation of wastewater;
- ✓ have public waste bins for the collection of household waste;
- ✓ regulate and require compliance with standards in the installation of drilling;
- ✓ control the nature of chemical fertilizers used in agriculture and market gardening by the population by prioritizing the use of ecological fertilizers (recycling/composting of solid waste and their use as fertilizer to enrich the soil);
- ✓ raise awareness of the harmful effects of open defecation and the danger of emptying cesspools into the countryside, but rather to call on the competent services;
- ✓ establish regular monitoring of the quality of groundwater in Moundou and its surroundings;
- ✓ seek support from partners for the installation of slab-bottom latrines and advise against the use of latrines with a lost bottom;

- ✓ introduce the use of portable toilets (canaries, plastic barrels in areas with low water depth and emptying will be done by an appropriate service;
- ✓ impose a shallow depth ($\leq$ 3 m) for latrines with a fine sand filter for households that do not have the means for latrines with a slab bottom;
- ✓ impose the construction of anti-quag slabs and monitor activities around water catchment structures in order to minimize wastewater infiltration;
- ✓ raise awareness among the population about the rules of hygiene and individual and collective sanitation;
- ✓ encourage the population to systematically disinfect drinking water.

To the populations:

- ✓ respect a minimum distance between water production works and latrines depending on the ZNS according to (WEDC, 2015):
  - o 10m for the silt;
  - o 15 m for silty sand and 50 m for medium sand.
- ✓ consume only clean water (filtered or chemically treated with chlorine/ozone or solar);
- ✓ ensure the cleanliness of the environment of hydraulic structures;
- ✓ avoid filling abandoned depressions and wells with unsorted waste, otherwise incinerate the waste.

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