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Spatio-Temporal Assessment of Groundwater Quality in the Town of Moundou in South-Western Chad

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ABSTRACT

Assessment of groundwater quality is becoming essential for effective resource management. In this study, we conducted a seasonal assessment of groundwater quality, hydrogeochemical processes, and statistical analyses in the city of Moundou. A total of 62 groundwater samples were taken in the 27 districts of the city, in August 2022 (rainy season) and May 2023 (dry season) respectively. From a geochemical point of view, the results highlighted two dominant geochemical facies in both the dry and wet seasons: the calcium-magnesium bicarbonate facies (Ca-Mg-HCO_3) and the sodium-potassium bicarbonate facies (Na-K-HCO_3). The multivariate analysis showed that the mineralisation of gypsum ($CaSO_4$, $2H_2O$), $CaCl_2$ salts, silicates, carbonates and the decomposition of organic matter are the main processes affecting the quality of Moundou's water. The physico-chemical results show that of the parameters monitored, only pH, iron and ammonium do not comply with the WHO standard, and almost 89% of the sites sampled are considered acceptable according to QWI values. Only the sites in the north-east of the city showed poor water quality during the rainy season. On the whole, this water is of better quality for irrigation.

INTRODUCTION

The degradation of groundwater quality worldwide has intensified in recent years due to uncontrolled industrial discharges, excessive use of chemical fertilisers in agriculture and inefficient management of water resources. (Khaldi et al., 2018). These factors alter the chemical composition of water, making it unsuitable for its intended uses. (Naima et al., 2022). Water resources, whether groundwater or surface water, are used by humans for a wide range of purposes (Ahoussi et al., 2010). The chemical composition of water from the natural environment varies considerably. It is influenced by the geological nature of the soil from which it comes, as well as by the reactive substances in contact during its flow. The presence of suspended and dissolved matter, whether of mineral or organic origin, affects the quality of groundwater, both quantitatively and qualitatively. (NGOUALA MABONZO, 2020). In developing countries, groundwater is a key resource for supplying people with drinking water. They generally offer satisfactory quality at a low cost, unlike surface water, which is expensive to treat and often inaccessible to nations with fragile economies, as is the case in many African countries (A. B. Yao et al., 2016).

In many parts of the world, particularly in developing countries, access to water is now essential for public health and socio-economic growth (Kettab et al., 2008). Of all the freshwater on Earth (2.53%), only 0.63% is groundwater. Groundwater is the world's main source of drinking water, as it is generally better protected from pollution than surface water (Edith et al., 2023). Groundwater quality can deteriorate when it is exposed to harmful or even toxic substances as a result of human activities. Although essential to life, water can also become a vector for water-borne diseases due to its contamination by various mineral and organic wastes, as well as by excrement (Ndahama et al., 2014). +-In Chad, the expansion of major urban centres is leading to the establishment of new neighbourhoods in areas that are sometimes unsuitable for housing. At the same time, the water supply network is not expanding at the same pace as this growth, and the few neighbourhoods that are served suffer frequent interruptions. Faced with this situation, the most affluent households invest in human-powered boreholes, whose water quality is not systematically checked by qualified experts. On the other hand, the most precarious households, located far from these boreholes, are resigned to using water from traditional wells (Mahamat et al., 2015). For several decades now, water quality has been a major issue, contributing to the spread of diarrhoeal diseases. In Chad, this problem affects almost the entire country, with greater intensity in the Saharan and Sahelian regions. To meet their water needs, whether domestic, agricultural or for livestock, people draw on traditional and modern boreholes, as well as rivers and ponds (KRIGA et al., 2016).

Like most towns in Chad, the city of Moundou has a low drinking water supply. This situation can be explained on the one hand by strong urbanisation and exponential population growth. On the other hand, the drinking water supply network, with a coverage rate of 47% (PIR, 2019), is not keeping up with the high rate of urbanisation. In addition, the network is outdated, leading to water leaks. In addition, residents of neighbourhoods not served by the current network obtain their water directly from the river or from the surface water table, via boreholes and private wells. However, due to a lack of sanitation, these sources are often contaminated by the infiltration of wastewater, black water and other pollutants, leading to cases of water-borne diseases among the population (urbaplan, 2008). Despite this high anthropogenic pressure on water, very few studies have looked at the quality of groundwater in the town of Moundou. The only studies identified in the literature are those by Bande (2016) and Schneider and Wolff (1992), which looked at hydrochemical facies, among other things. No study has examined the spatial and seasonal variation in water quality in the town of Moundou. This study was initiated to fill this information gap, which is crucial for the integrated management of the city's water resources. The aim of the study is therefore to assess the spatial and seasonal distribution of water quality in Moundou. This will involve determining the hydrochemical facies of the water, assessing the spatial and seasonal variability of the physico-chemical parameters and, finally, the potential uses (drinking water and water for agriculture).

2. MATERIALS AND METHODS

2.1. STUDY AREA

Moundou is located in south-western Chad, in the Logone Occidental region, of which it is the capital. The country's second most populous city after N'Djamena, Moundou is considered to be the economic capital of Chad, due to the presence of numerous industries, particularly agri-food and brewing. It lies between 8°33‘ and 8°36’ North and 16°03‘ and 16°06’ East (Djako, 2018). Moundou lies between 382 and 439 metres above sea level (Schneider & Wolff, 1992). Demographic growth and accelerated urbanisation are leading to increasing pressure on water resources, with risks of pollution and overexploitation of groundwater (Mahamat et al., 2015). Moundou is located in the Sudanian climate zone, characterised by two contrasting seasons (the dry season and the rainy season). The rainy season runs from May to October, with average annual rainfall of between 900 and 1,200 mm, while the dry season extends from November to April and is dominated by the harmattan, a dry, dusty wind from the Sahara (Djebe et al., 2022). Temperatures are high, averaging between 25 and 35°C, with peaks reaching 40°C during periods of intense heat (Khaldi et al., 2018). The Moundou region belongs to the geological formations of the Terminal Continental, characterised by varied sedimentary deposits composed mainly of obliquely stratified sands and sandstones, multicoloured clays and kaolin and gravel and conglomerate lenses, bearing witness to ancient fluvial environments (J. L. SCHNEIDER & J.P. WOLFF, 1992). Underlying these formations is the Precambrian crystalline and metamorphic basement, which forms an impermeable barrier limiting the storage of groundwater (P. Mathieu, 1980). The hydrogeology of Moundou is dominated by two types of aquifer. The Continental Terminal water table, which is shallow (between 5 and 15 metres), is rapidly recharged in the rainy season and is highly vulnerable to anthropogenic pollution (latrines, waste water, solid waste, etc.). The Precambrian basement aquifers, which are continuous and located in rock fractures, are deep (between 50 and 150 metres) and generally of better quality, but require costly drilling (J. L. SCHNEIDER & J.P. WOLFF, 1992). Groundwater supply is therefore based on the joint exploitation of these aquifers, with disparities in quality and availability. The Logone River, which is the main watercourse and a source of supply for a number of uses (domestic, agricultural and industrial); Lake Wey and Lake Taba, located to the west and east of the town respectively, which contribute to groundwater recharge by infiltration during flood periods; Lake Taba and the numerous temporary pools, which form during the rainy season and can influence the recharge of surface water (Djebe et al., 2022)..

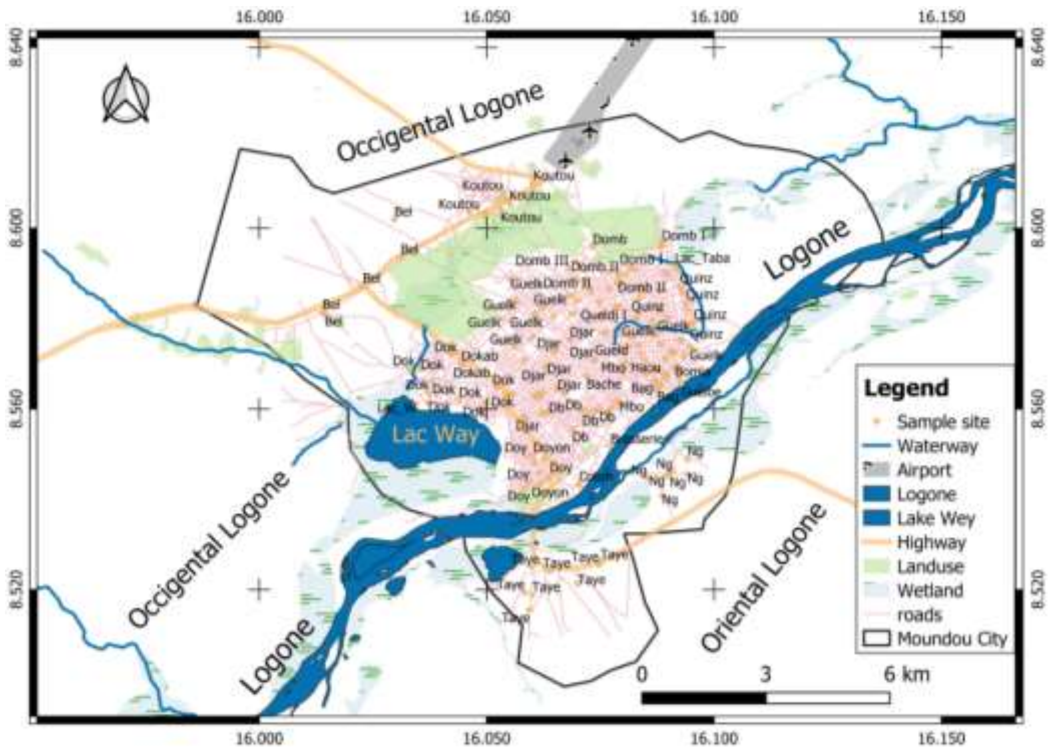


Figure 1: Map of the study area and sampling points

2.2. SAMPLE COLLECTION AND LABORATORY ANALYSIS

A total of 62 groundwater samples from wells and boreholes were collected during the dry and rainy seasons. These samples were analysed at the Laboratoire National des Eaux (LNE) to assess their quality. The analyses focused on chemical parameters such as Na+, K+, Mg2+, Ca2+, HCO3-, SO42-, NO3- and Cl-. As soon as they were collected, the samples were placed in a refrigerated cooler and transported to the analysis laboratory. Samples were taken in the 27 districts of the town of Moundou, as shown in Figure 1, which shows the geographical distribution of the collection points. Physical parameters, including pH, temperature, conductivity and turbidity, were measured directly on site using a multiparameter. The colour of the water was determined in accordance with French standard NF T 90-034. As regards chemical analyses, the concentrations of Fe2+, Na+, Cl-, SO4 2-, F-, HCO3-, NO3- and NO2- were assessed in a specially equipped laboratory (LNE) in N'djaména, the Chadian capital. These analyses were carried out using a spectrophotometer, in accordance with the standard methods recommended by the French standards AFNOR.

2.3. Hydrochemistry of groundwater

The Piper diagram is a widely used approach for identifying the hydrochemical type and facies of groundwater (OUSMANE et al., 2022). According to this classification, groundwater is divided into main groups according to the dominant cations and anions: Mg2+, Ca+, Na+ and K+; $SO_4$2-, HCO_3-, Cl-. This diagram thus provides a better understanding of mineralisation processes and the geochemical evolution of groundwater. The factors influencing the chemical composition of groundwater will be analysed using the semi-logarithmic diagrams developed by (Gibbs & Mcintyre, 1970). These diagrams represent the relationship between TDS and the ratios $Cl/(Cl+HCO_3)$ for anions, and Na/(Na+Ca) for cations. According to this approach, the main mechanisms controlling the hydrochemical characteristics of groundwater can be grouped into three dominant categories:dominance of water-rock interaction, influence of precipitation, impact of evaporation (NGOUALA MABONZO, 2020). Interpretation of these diagrams provides a better understanding of the geochemical processes behind groundwater mineralisation.

2.4. Multivariate statistical analysis

For the study of groundwater in the city of Moundou, multivariate statistical analyses were performed to examine the interactions between the different hydrochemical parameters (AMROUNE, 2018). In addition, the Pearson correlation matrix was used to identify relationships between hydrochemical parameters. A correlation coefficient between 0.5 and 0.7 was interpreted as a moderate relationship, while a value greater than 0.7 was considered highly significant (Bourjila, 2023). Principal Component Analysis (PCA) was implemented to reduce the dimensionality of the data and identify the main sources of influence of groundwater hydrochemical parameters (G. Soro et al., 2019). When calculating the PCA, a rotation of the principal components was carried out using the Varimax method, allowing better interpretation of the results (Hassan & Firat Ersoy, 2022).

2.5. Water quality for drinking

The Water Quality Index (WQI) is an essential tool for the overall assessment of the quality of groundwater intended for human consumption (Chaima, 2024). It is calculated by assigning weights, ranging from 2 to 5, to the various hydrochemical parameters, according to their influence on water quality. First, the relative weights (Wi) were determined using equation (1), making it possible to quantify the impact of each parameter on water classification.

$$\mathrm{Wi} = \frac{wi}{\sum_1^n wi} \quad (1)$$

The weights assigned and the relative weights of each parameter are listed in Table 1 (T. D. Soro et al., 2022). In the second phase, the quality index (Qi) for each hydrochemical parameter was determined by calculating the ratio between the measured value and the reference standard established by (WHO, 2011), in accordance with equation (2).

$$Q_i = \frac{C_i}{S_i} \mathrm{x} 100 \quad (2)$$

Ci: the measured value of the parameters, Si: standard value of the parameters

Table 1: Standard values, weights and relative weights of hydrochemical parameters (WHO, 2011)

Hydrochemical parameters	Unit	Standard value (WHO, 2011)	Weight (Wi)	Relative weight (Wi')
pH	-	6,5 - 8,5	4	0,085
Conductivity (CE)	µS/cm	2500	5	0,106
TDS (Dissolved Solids)	mg/L	500	5	0,106
Calcium (Ca^{2+})	mg/L	100	2	0,043
Magnesium (Mg^{2+})	mg/L	50	2	0,043
Sodium (Na^{+})	mg/L	200	4	0,085
Potassium (K^{+})	mg/L	12	4	0,085
Bicarbonates (HCO_3^-)	mg/L	500	4	0,085
Chlorides (Cl-)	mg/L	250	4	0,085
Sulphates (SO_4^{2-})	mg/L	250	2	0,043
Nitrates (NO_3^-)	mg/L	50	5	0,106
Iron (Fe^{2+})	mg/L	0,3	3	0,064
Ammonium (NH_4^+)	mg/L	0,5	3	0,064
			47	

In the final step, the water quality sub-index and the WQI are obtained using equation (3) and equation (4)

$$\boldsymbol{SL_I = Q_i x W_i} \quad (3)$$

$$\mathbf{WQI} = \sum_1^n \boldsymbol{SLi} \quad (4)$$

Table 2: WQI water quality index classification

Classification	Groundwater quality
WQI <25	Excellent water
25 < WQI < 50	Good water
50 < WQI < 75	Poor water
75 < WQI < 100	Very poor water
WQI > 100	Unsuitable water

After calculating the WQI, Table 2 is used to classify the different types of groundwater quality.

In order to determine the areas where the risk of water pollution is high, the groundwater quality indices (WQI) calculated at each site were used as input data for extrapolating the WQI in the non-sampled areas using the inverse distance interpolation (IDW) method.

2.6 Water quality for agriculture

To assess the suitability of groundwater for agricultural purposes, Wilcox diagrams have been drawn using the value of the sodium absorption ratio (SAR) as a function of EC (Wilcox, 1955). The SAR can be calculated by equation (5).

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Mg^{2+} + Ca^{2+}}{2}}} \quad (5)$$

The groundwater quality for irrigation was categorized into four classes as presented in Table 3

Table 3: The quality of groundwater for irrigation has been classified into four categories (Fallahati et al., 2020).

Class	Water quality for irrigation
C1S1	Sweet
C1S2 C2S2 C2S1	A little salty
C1S3 C2S3 C3S1 C3S2 C3S3	Salty
C1S4 C2S4 C3S4 C4S4 C4S3 C4S2 C4S1	Very salty

3. RESULTS OR RESULTS AND DISCUSSIONS

3.1. Global Statistical of physicochemical analyses

The overall characteristics of the hydrogeochemical variables used in this study concern the minimum-maximum values, the mean, the standard deviation and the coefficient of variation (Table 4). The average contents in the rainy season and in the dry season were compared with the admissible values for drinking water proposed by the WHO (2011). The results show that the pH of the groundwater of the city of Moundou was acidic, with an average of 5.14 in the rainy season and 5.77 in the dry season, i.e. an overall average of 5.45 which is lower than the limit recommended by the WHO (2011). The low conductivity values recorded suggest that the waters of this city are weakly mineralized. The average value of electrical conductivity in the rainy season (427 µS/cm) is significantly higher than that in the dry season (262 µS/cm), which corroborates well with the fact that the average value of most ions measured in the rainy season are also higher than that measured in the dry season. This seems contradictory because of the dilution phenomena that take place in the rainy season. This phenomenon could be explained by anthropogenic pollution sources such as wastewater or agricultural activities that contribute to an increase in ions in groundwater during the rainy season following infiltration and runoff. These waters are also soft and very aggressive whatever the season. Of all the parameters monitored, only iron and ammonium are higher than the WHO standard. Iron would come from rocks, such as silicates, oxides, hydroxides, carbonates and sulfides or from organic matter while ammonium has a purely organic origin. In the rainy season, in addition to temperature and pH which have their standard deviation significantly lower than the mean, most of the monitored parameters have their standard deviation close to or higher than the mean, suggesting that all parameters except temperature and pH vary greatly from one sampling site to another. The same observations were made in the dry season, except that nitrate and ammonium did not experience a strong spatial variation. This low spatial variation of nitrate and ammonium indicates that runoff plays an important role in the contamination of groundwater with nitrogen in this city.

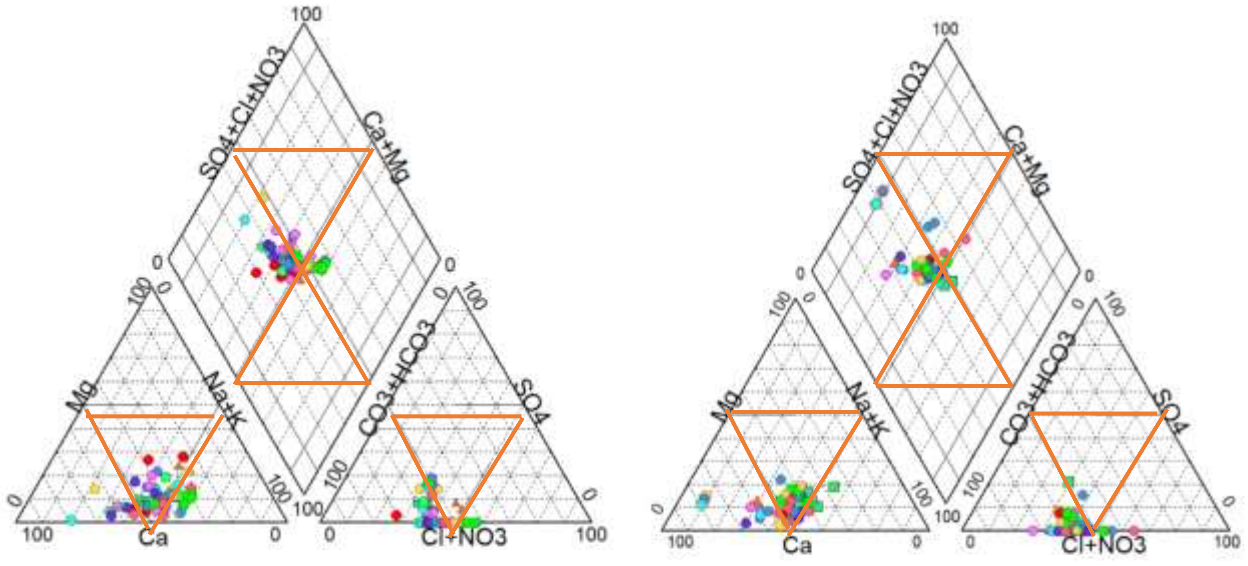
Table 4: Statistical characteristics of physicochemical analyses (August 2022 and May 2023)

	Moyenne			Écart-type			Minimum			Maximum			WHO
	RS	DS	AN	RS	DS	AN	RS	DS	AN	RS	DS	AN	
pH	5.14	5.77	5.45	0.632	0.441	0.629	3.26	4.32	3.26	6.30	6.47	6.47	6.5–8.5
CE (µS/cm)	427	262	345	572	266	452	14.5	15.5	14.5	3670	1000	3670	750
TDS (mg/L	213	152	182	287	176	239	7.27	3.86	3.86	1840	961	1840	500
Temp (°C)	29.2	30.0	29.6	1.21	1.60	1.46	26.2	25.1	25.1	33.0	33.7	33.7	-
Turb (NTU)	2.14	1.01	1.58	3.65	0.601	2.66	0.100	0.100	0.100	26.0	4.00	26.0	5
$CaCO_3$ (mg/L)	43.6	31.0	37.3	54.2	39.0	47.5	4.00	0.400	0.400	300	300	300	-
Ca^{2+} (mg/L)	12.9	9.58	11.3	14.8	10.6	12.9	1.40	0.100	0.100	80.0	80.0	80.0	75
Mg^{2+} (mg/L)	2.74	1.71	2.23	4.48	3.20	3.91	0.01	0.00	0.00	24.3	24.3	24.3	30
K^{+} (mg/L)	1.64	1.05	1.35	2.05	1.13	1.67	0.100	0.00	0.00	14.0	7.00	14.0	30
Na^{+} (mg/L)	16.4	9.30	12.8	17.8	10.1	14.8	0.400	0.200	0.200	89.0	66.0	89.0	200
HCO_3^- (mg/L)	53.2	35.3	44.2	66.4	34.8	53.6	3.70	0.500	0.500	366	244	366	500
Cl^- (mg/L)	14.2	10.3	12.3	16.2	12.2	14.4	0.800	0.200	0.200	100	90.0	100	250
SO_4^{2-} (mg/L)	4.73	2.66	3.70	7.71	8.80	8.30	0.00	0.00	0.00	36.0	63.0	63.0	250
NO_3^- (mg/L)	12.7	6.32	9.50	15.9	4.93	12.1	0.660	0.200	0.200	88.0	37.0	88.0	45
Fe^{2+} (mg/L)	0.0271	0.143	0.08	0.052	0.271	0.195	0.00	0.00	0.00	0.220	1.00	1.00	0.01
NH_4^+ (mg/L)	1.82	0.740	1.29	8.29	0.248	5.92	0.110	0.110	0.110	66.0	1.12	66.0	0.25

DS = Dry season, RS = Rainy season, AM = Annual mean, Temp = température, Turb = turbidity

3.2. Geochemical facies of groundwater

Piper's diagram allows us to characterize the chemical composition of the water by representing the distribution of the main cations (Ca2+, Mg2+, Na+, K+) and anions (SO42-, Cl-, HCO3-, etc.) (" Piper, 1944). As the 62 water points were sampled during both the wet and dry seasons, it makes sense to describe them by season. The geochemical facies given by Piper's diagrams are shown in Figure 2a and 2b, which represent Piper's diagrams for the rainy and dry seasons respectively. There was no significant difference between the two seasons, suggesting that season does not influence water facies in Moundou. In the lower left-hand section of each diagram, the dominant cations in all samples are calcium, followed by magnesium; while the anions, in the lower right-hand section, are dominated by HCO-3 and sulfates (SO42-), with a non-negligible contribution from chlorides (Cl-). This results in two types of geochemical facies dominated by the calcium-magnesium bicarbonate facies (Ca- Mg-HCO3), generally observed in recent, relatively undeveloped groundwater resulting from infiltration of precipitation and interaction with carbonate and silicate rocks (Olivier, 2015), and the sodium-potassium bicarbonate facies (Na-K-HCO3), which results mainly from chemical alteration processes of silicate rock minerals. A slight scattering of points suggests mixed influences, with possible anthropogenic input (urban and agricultural runoff) (Edmunds & Smedley, 2000). These hydrochemical facies obtained by the diagram software reflect the local homogeneity of the geology of the town of Moundou, as indicated by Bandé (2016). Aquifers in sedimentary environments are more or less continuous, unlike those in basement environments, where several studies have revealed the discontinuous nature of the latter environment; this being linked to the polyphasic alteration that occurs there (Mfonka et al., 2021). These results are comparable to those obtained by Mfonka et al. (2024) at N'Djamena in Chad.



(a) Rainy season (b) : Dry season

Figure 2: Piper diagram for the rainy and dry seasons

3.3. Groundwater type and facies control factors

The Gibbs diagram is a tool for identifying the dominant processes that control groundwater chemistry, as a function of total salinity (TDS - Total Dissolved Solids) and ionic ratios (Meryem, 2021). He distinguishes three major processes, namely Precipitation Dominance (Influence of precipitation), Rock Dominance (Water-rock interaction) and Evaporation Dominance (Concentration by evaporation). The diagram in figure 3 (a) shows that the majority of points are located in the 'Rock Dominance' zone, with a high concentration which reflects the influence of rock alteration on groundwater chemistry; the presence of Na+ and Ca2+ suggests mineral alteration processes such as the dissolution of carbonates (calcite, dolomite) and silicates (feldspars) and finally a small proportion of samples are located in the 'Precipitation Dominance' zones showing that precipitation has a relatively limited influence on water chemistry. The diagram in figure 3 (b) shows a high concentration of all points in the 'Rock Dominance' zone, confirming that water-rock interaction is the main factor influencing the chemical composition of Moundou groundwater. The Gibbs diagram for the dry season in Figure 4 (a) and (b) shows a similarity to that for the rainy season, but there is a slight scattering of points in both the cation and anion diagrams. This phenomenon can be attributed to an increased concentration of dissolved salts due to evaporation, leading to a change in ionic ratios and greater variability in dissolution and mineral precipitation processes, linked to fluctuations in water table levels and greater mineralisation of groundwater. This result is consistent with that of .(BOUCHAGOURA, 2019). This analysis confirms the major influence of water-rock interactions on groundwater mineralisation, with a possible impact of precipitation and evaporation depending on the season

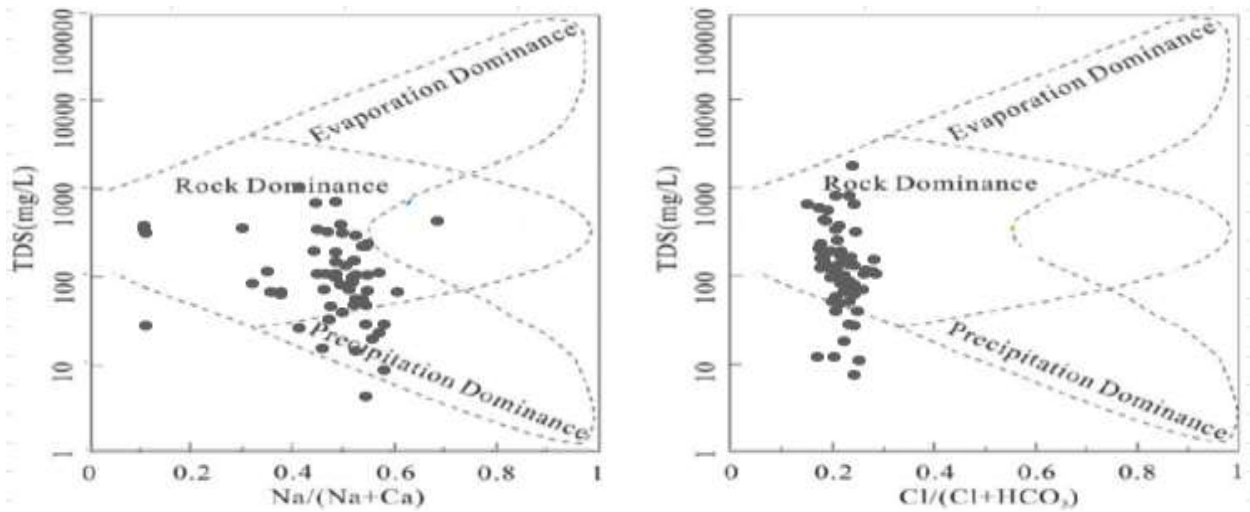


Figure 3: Gibbs diagram for the rainy season

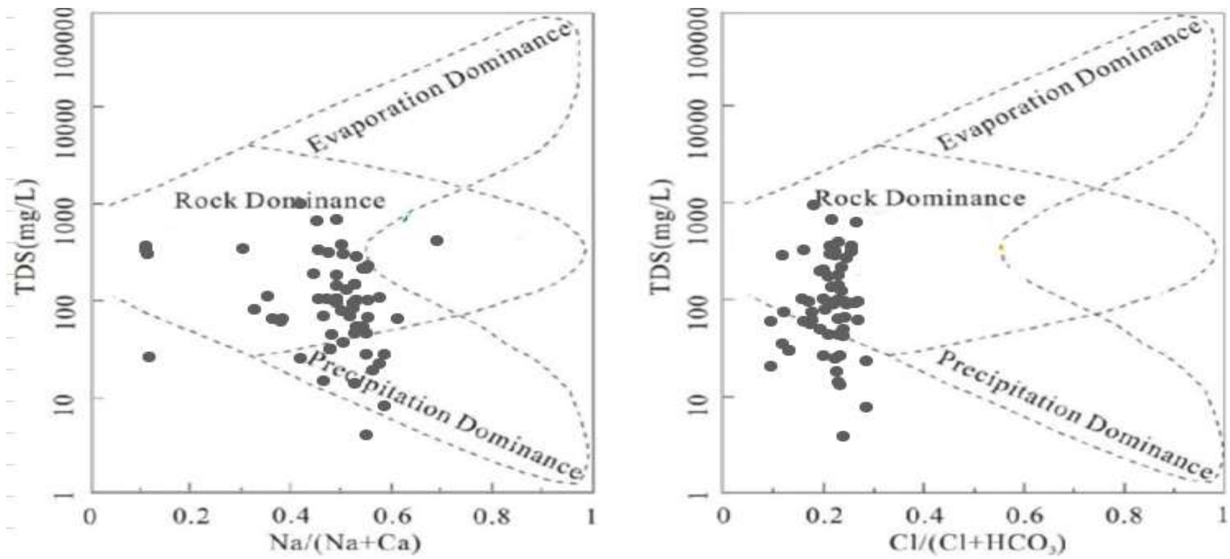


Figure 4: Gibbs diagram for the dry season

3.4. Multivariate Statistical Analysis (Correlation Analysis and Principal Component Analysis)

3.4.1 Correlation Analysis

The correlation matrix obtained from the rainy and dry season data is presented in Table 5. All the major ions showed a strong correlation with each other in both the rainy and dry seasons. Indeed, Ca^{2+} and Mg^{2+} correlated strongly with $CaCO_3$ (0.99 and 0.95 respectively), confirming their role in water hardness due to the dissolution of carbonates (calcite, dolomite). HCO_3- is also correlated with $CaCO_3$ (1.00), reinforcing the hypothesis of carbonate alteration as a major source of ions. Na^+ and Cl- show a strong positive correlation (0.96), suggesting a common origin, possibly the alteration of evaporitic rocks (halite) or anthropogenic inputs (saline intrusion, pollution). Sulphate (SO_4^{2}-) correlates well with Na^+ (0.86) and Cl- (0.77), suggesting a common source, such as dissolution of gypsum or other sulphide minerals. NO_3- was moderately correlated with CE/TDS (0.36), suggesting a possible influence of precipitation and infiltration containing nitrates of agricultural or domestic origin. In the dry season, iron showed no strong correlation with the other parameters, indicating that it could be due to reducing conditions (dissolution of iron oxides in oxygen-poor environments). In the rainy season, however, it was positively correlated with nitrate, indicating that some of the iron comes from anthropogenic activities. Ammonium (NH_4^+) is weakly correlated with the other parameters, which may indicate a local origin linked to organic sources (agricultural or domestic pollution or decomposition of organic matter). In the dry season, electrical conductivity (EC), total dissolved solids (TDS) and turbidity showed moderate positive correlation with all major ions, which was not the case in the wet season due to dilution

Table 5: Correlation matrix of physicochemical parameters in rainy seasons (SP) and dry seasons (SS)

SP	pH	CE	TDS	Temp	Turb	CaCO3	Ca2+	Mg2+	K+	Na+	HCO3-	Cl-	SO42-	NO3-	Fe2+	NH4+
pH	1															
CE	0,25	1,00														
TDS	0,25	**1,00**	1,00													
Temp	-0,37	-0,28	-0,28	1,00												
Turb	0,20	0,00	-0,01	-0,11	1,00											
CaCO3	0,20	0,32	0,32	-0,07	0,28	1,00										
Ca2+	0,21	0,29	0,29	-0,06	0,36	**0,99**	1,00									
Mg2+	0,16	0,36	0,36	-0,09	0,08	**0,95**	**0,90**	1,00								
K+	0,16	0,21	0,21	-0,06	0,10	**0,55**	**0,55**	**0,52**	1,00							
Na+	0,15	0,32	0,32	-0,02	0,21	**0,97**	**0,95**	**0,94**	**0,58**	1,00						
HCO3-	0,20	0,32	0,32	-0,07	0,28	**1,00**	**0,99**	**0,95**	**0,56**	**0,97**	1,00					
Cl-	0,17	0,32	0,31	-0,02	0,23	**0,99**	**0,98**	**0,94**	**0,53**	**0,96**	**0,99**	1,00				
SO42-	0,13	0,18	0,17	-0,01	0,16	**0,79**	**0,79**	**0,75**	**0,63**	**0,86**	**0,79**	**0,77**	1,00			
NO3-	0,07	0,36	0,36	0,05	0,23	**0,87**	**0,86**	**0,84**	**0,50**	**0,92**	**0,87**	**0,88**	**0,68**	1,00		
Fe2+	-0,04	0,09	0,09	0,25	-0,03	0,18	0,17	0,18	0,08	0,24	0,18	0,19	0,09	**0,35**	1,00	
NH4+	-0,21	-0,05	-0,05	0,13	-0,01	-0,05	-0,05	-0,05	-0,03	-0,04	-0,05	-0,03	-0,08	-0,02	-0,06	1,00

SS	pH	CE	TDS	Temp	Turb	CaCO3	Ca2+	Mg2+	K+	Na+	HCO3-	Cl-	SO42-	NO3-	Fe2+	NH4+
pH	1,00															
CE	0,24	1,00														
TDS	0,21	**0,92**	1,00													
Temp	-0,34	-0,13	-0,18	1,00												
Turb	0,13	0,33	0,37	-0,05	1,00											
CaCO3	0,27	**0,48**	**0,45**	-0,11	**0,59**	1,00										
Ca2+	0,29	**0,48**	**0,45**	-0,10	**0,58**	**0,99**	1,00									
Mg2+	0,23	**0,47**	**0,44**	-0,13	**0,59**	**0,97**	**0,94**	1,00								
K+	0,27	**0,60**	**0,63**	-0,15	**0,42**	**0,87**	**0,86**	**0,85**	1,00							
Na+	0,31	**0,48**	**0,40**	-0,13	**0,45**	**0,93**	**0,92**	**0,92**	**0,91**	1,00						
HCO3-	0,31	**0,50**	**0,45**	-0,13	**0,50**	**0,98**	**0,98**	**0,93**	**0,90**	**0,97**	1,00					
Cl-	0,29	**0,49**	**0,44**	-0,14	**0,55**	**0,99**	**0,98**	**0,96**	**0,89**	**0,96**	**0,98**	1,00				
SO42-	0,19	**0,49**	**0,44**	-0,08	**0,59**	**0,93**	**0,89**	**0,96**	**0,81**	**0,90**	**0,88**	**0,91**	1,00			
NO3-	0,31	0,42	**0,44**	-0,06	**0,56**	**0,88**	**0,88**	**0,84**	**0,83**	**0,83**	**0,86**	**0,85**	**0,79**	1,00		
Fe2+	0,03	0,23	0,28	-0,20	0,27	-0,12	-0,09	-0,17	-0,20	-0,24	-0,17	-0,16	-0,11	-0,14	1,00	
NH4+	-0,03	0,13	0,16	-0,12	-0,11	0,28	0,31	0,21	0,30	0,28	0,29	0,31	0,22	0,26	0,07	1,00

3.4.2. Principal Component Analysis (PCA)

Principal component analyses were carried out to determine the relationship between physico-chemical variables and potential sources of groundwater pollution in the dry and rainy seasons. With regard to the number of principal components to be retained, we chose the eigenvalue analysis method (Table 6); thus the factorial axes with eigenvalues of less than 1 were eliminated, which made it possible to retain the first four principal components in both the wet and dry seasons (Table 6). In the rainy season, the four principal components explained 78.5% of the total variance. The first principal component (PC1) explained 51.98% of the total variability and was positively correlated with all the major elements. The correlation matrix also showed a

strong correlation between all major elements. Thus, PC1 reflects mineralization of natural origin (water-casement contact). The inclusion of nitrates in this batch indicates that PC1 also highlights mineralization of anthropogenic origin . The second principal component (PC2) explains 11.65% of the total variability. PC2 correlates positively with pH and electrical conductivity (EC) and negatively with temperature, highlighting the influence of climatic conditions on the mineralisation process. With 7.59% of the total variance explained, the third principal component (PC3) is strongly and positively correlated with iron and ammonium. This component seems to highlight the process of decomposition of organic matter. The fourth principal component (PC4), associated negatively with electrical
conductivity and positively with turbidity, highlights the dilution process resulting from the infiltration of rain water.

In the dry season, the four principal components explained 77.81% of the total variance (Table 6). The first principal component is positively correlated with all the major ions and electrical conductivity. PC1 explains the same processes in the wet and dry seasons. The absence of a strong correlation observed between major ions and electrical conductivity in the rainy season is linked to the dilution phenomenon. The second principal component (PC2) is positively related to pH and negatively related to temperature. PC2 also explains the same processes in the wet and dry seasons. PC3 is strongly and negatively correlated with ammonium and positively with turbidity, indicating pollution of organic origin. CP4 is positively associated with iron and turbidity, suggesting that iron is the cause of water turbidity.

Table 6: Contributions of the components

	Rainy season				**Dry season**			
	PC1	**PC2**	**PC3**	**PC4**	**PC1**	**PC2**	**PC3**	**PC4**
Eigenvalue	7.80	1.75	1.14	1.09	7.46	1.48	1.42	1.31
% variance	51.98	11.65	7.59	7.25	49.72	9.85	9.48	8.76
pH	0.11	**0.72**	0.22	0.18	0.23	**0.82**	0.21	-0.04
CE	0.34	**0.5**	0.09	**-0.5**	**0.49**	-0.03	0.07	**0.4**
Temp	0	**-0.82**	0.18	0.03	-0.02	**-0.83**	0.2	-0.12
Turb	0.22	0.15	0.01	**0.82**	0.07	0	**0.73**	**0.48**
CaCO3	**0.98**	0.09	0.06	0.08	0.96	0.12	-0.05	0
Ca2+	**0.96**	0.09	0.06	0.17	**0.91**	0.13	-0.07	0.02
Mg2+	**0.94**	0.09	0.05	-0.11	**0.91**	0.07	-0.01	-0.04
K+	**0.63**	0.11	-0.06	-0.06	**0.87**	0.07	-0.08	-0.1
Na+	**0.98**	0.03	0.09	0.01	**0.95**	0.09	-0.05	-0.13
HCO3-	**0.98**	0.09	0.06	0.08	**0.96**	0.12	-0.06	-0.07
Cl-	**0.97**	0.04	0.06	0.04	**0.94**	0.13	-0.11	-0.03
SO42-	**0.84**	0.02	-0.01	0.07	**0.77**	-0.09	-0.01	0.12
NO3-	**0.91**	-0.06	0.19	-0.03	**0.64**	0.16	0.17	-0.31
Fe2+	0.2	-0.34	**0.72**	-0.2	-0.23	0.11	-0.01	**0.85**
NH4+	0.04	-0.35	**-0.69**	-0.14	0.2	0.02	**-0.86**	0.19

3.4. Groundwater quality assessment

3.4.1. Water quality for drinking

Calculation of the WQI of 62 samples for the rainy and dry seasons made it possible to express the proportions of 5 classes of groundwater quality, as shown in Figure 5 (a) and (b). Figure 5 (a) shows a marked deterioration in water quality in the rainy season at certain points, such as the Lac Taba carré borehole, where the water was non-drinkable (1.61%); the Guelkoura 1 carré 4 well and the Guelbé Résidence Sœur borehole, where the water was of mediocre quality (3.23%); poor quality water was observed at the 15 ans II carré 3 well, the Doyon carré 2 well and the Mbomia carré 2 borehole (4.84%). The 48.39 samples were of excellent quality and 41.94% of the samples were of good quality. Unlike the rainy season, the dry season (Figure 5 (b)) shows a reduction in pollution, as no water point was found to be either undrinkable or of poor quality. The percentage of poor quality water (4.84%) fell to 3.23%. More than half (54.84%) of the samples had excellent water quality and 41.84% of the samples had good water quality. Figure 6 (a) and (b) for the rainy and dry seasons respectively show the spatial distribution of water quality indices on the map of the town of Moundou.

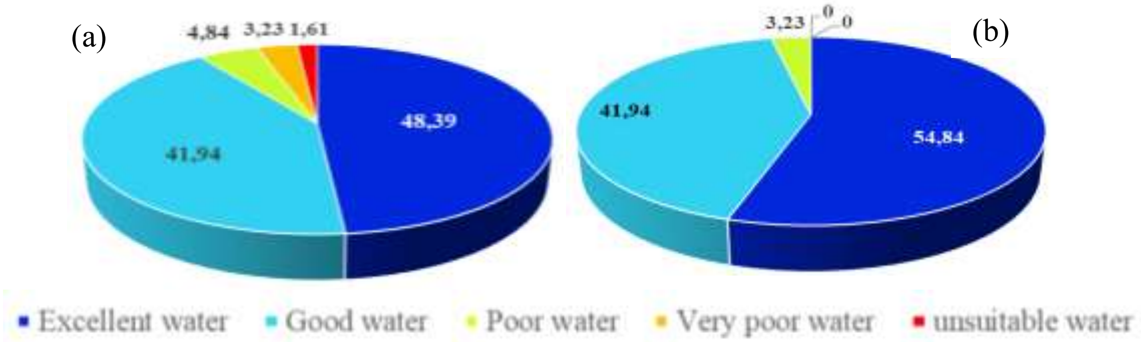


Figure 5: Proportions of groundwater quality classes for the rainy season (a) and the dry season (b)

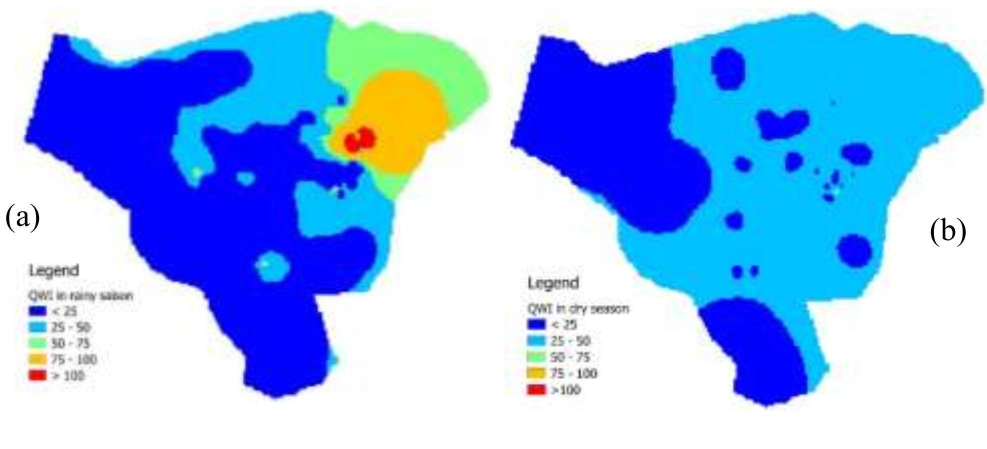


Figure 6: WQI spatial distribution map of groundwater for the rainy season (a) and the dry season (b)

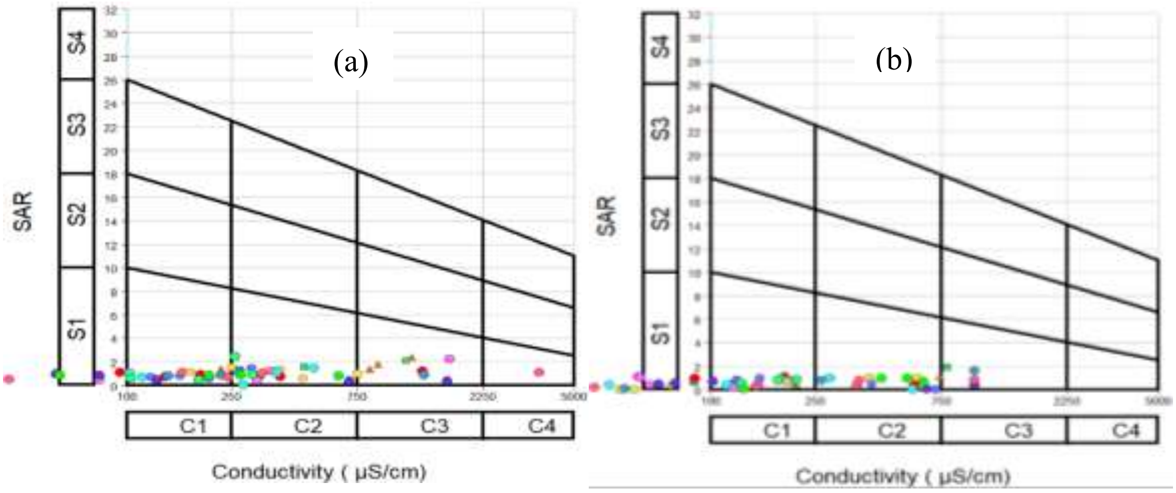


Figure 7: Wilcox diagram for the rainy season (a) and the dry season (b)

3.4.2. Water quality for irrigation

Overall, the distribution of points shown in Figure 5 for the wet season (a) and dry season (b) shows that the majority of points are found in zones C1-S1 and C2-S1, suggesting low to medium salinity with a low Sodicity Index (SAR). Very few points appear in zones C3 and C4, indicating a low accumulation of dissolved salts. Finally, no points are located in zones S3 and S4, confirming a low risk of soil sodification. In the Wilcox diagram in Figure 5 (a) for the rainy season, the majority of samples are located in zones C1-S1 and C2-S1, indicating that rainfall dilutes the salinity of the groundwater. The electrical conductivity (EC) is lower due to the freshwater input. One sample is located in zone C4S1, indicating high salinity, and a few samples are located in zone C3S1, reflecting medium salinity. In the dry season, a similar distribution of points is observed, but the electrical conductivity appears to be slightly higher, with the majority of points in zones C1S1 and C2S1, indicating a higher concentration of dissolved salts due to evaporation. A few points are also found in zone C3S1, suggesting average salinity. Nevertheless, the water is generally of good quality for irrigation, with no significant risk of sodification.

4. Conclusions

This study assessed the quality of groundwater in the town of Moundou according to seasonal variations and identified the main natural and anthropogenic influences on its chemical composition. Analysis of the hydrochemical facies revealed the predominance of calcium and magnesium bicarbonate facies (Ca-Mg-HCO_3), reflecting an interaction between seepage water and carbonate and silicate rocks. The sodium and potassium bicarbonate facies (Na-K-HCO_3) was also identified, resulting from alteration processes of silicate minerals. These facies were observed during the two seasons studied, with a slight dispersion in the dry season attributed to evaporation. Multivariate statistical analyses revealed sources of contamination of natural origin, linked to the weathering of rocks, as well as anthropogenic sources, notably industrial waste, fertilisers, pesticides, wastewater and metal carcasses. Assessment of drinking water quality revealed that pollution is more marked in the rainy season due to infiltration of run-off water, while in the dry season, quality improves with an increase in the number of samples showing good to excellent water quality. With regard to the suitability of groundwater for irrigation, the Wilcox diagram showed low to medium salinity, making the water suitable for irrigation in both seasons. However, vigilance is still required during the rainy season because of the increased risk of contamination. This study highlights the importance of rigorous monitoring of groundwater quality, particularly in urban areas, in order to prevent pollution risks and ensure sustainable management of water resources. Further investigations, including isotope studies and hydrogeological modelling, could provide a better understanding of the evolution of aquifers and the associated pollution mechanisms.

In the light of the results of our study, we suggest that the local authorities in the town of Moundou extend the public drinking water distribution network, which currently has insufficient coverage (47%), in order to limit the population's reliance on polluted surface water. In addition, the authorities must ban groundwater abstraction for drinking water supply in the north-east of Moundou, identified as the area most vulnerable to pollution. Set up a permanent groundwater quality monitoring programme, particularly in densely urbanised areas, as well as an awareness-raising programme.

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