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Research Article

Alteration of Mineral Balances in Groundwater and Surface Waters of Mangalmé: Correlation Matrix and Heterogeneous Critical Anomaliese

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Abstract

This study focuses on a semi-arid area of Chad—the Mangalmé department—where access to drinking water remains a major concern. The population relies primarily on groundwater (wells) and surface water (ponds/reservoirs) for drinking and domestic use. These resources are affected by climate change, notably through declining water table levels, the disappearance of water bodies, drought, and the degradation of vegetation cover. Compounding these issues are anthropogenic pressures linked to agriculture, livestock farming, and sanitation. The aim of this study is to assess the physicochemical quality of these waters, identify critical anomalies, and determine the sources of contamination in order to provide data useful for health and environmental management. To this end, ten (10) localities were monitored over a three-month period (March, April, and May). Water samples from wells and ponds were collected, georeferenced using GPS, stored in cool boxes, and analyzed in the laboratory. In situ measurements included pH at 25 ℃, electrical conductivity, total dissolved solids, and turbidity. Chemical analyses covered total hardness ($CaCO_3$), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), bicarbonates (HCO_3^-), chlorides (Cl^-), sulfates (SO_4^{2-}), nitrates (NO_3^-), fluorides (F^-), iron (Fe), and ammonium (NH_4^+). The methods employed included volumetry, flame photometry, and HACH 2800 spectrophotometry. A correlation matrix and a normalized multiparameter comparison were used to interpret the relationships between parameters. The results reveal heterogeneous mineralization. Some water sources exhibit high conductivity and dissolved solids, very high turbidity, iron and fluoride concentrations exceeding WHO guidelines, and alarming ammonium levels. pH values vary, reflecting distinct geological and anthropogenic conditions. The correlation matrix reveals a strong interdependence among conductivity, dissolved solids, calcium, magnesium, chlorides, and sulfates, suggesting a common origin or similar chemical interactions. In conclusion, none of the ten sources analyzed fully meet potability criteria without treatment. The contamination is twofold: natural—linked to the weathering of sedimentary rocks (sandstone, carbonates, fluorite) that release fluoride and iron—and anthropogenic, involving ammonium from domestic, agricultural, and livestock waste. These findings necessitate regular monitoring, appropriate treatment, and measures to protect water resources.

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Keywords

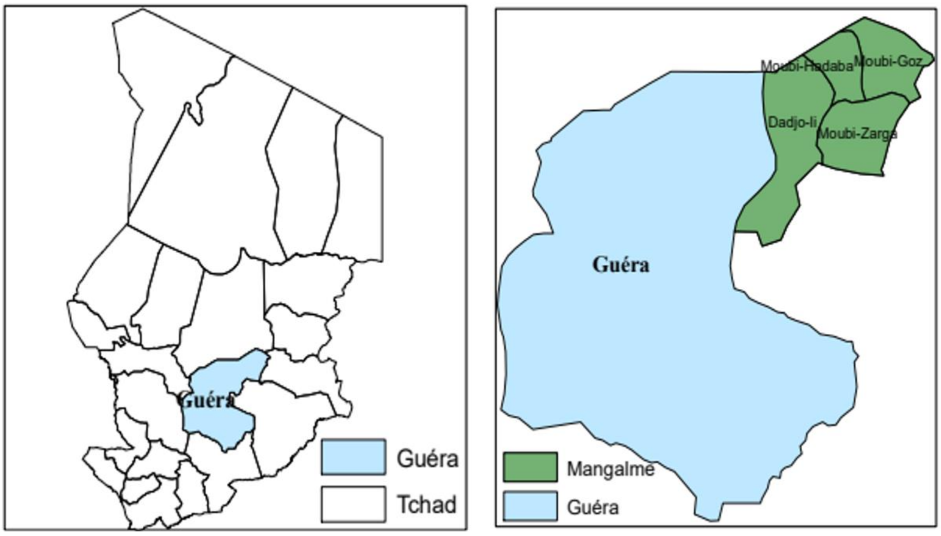
Water, Mangalmé, Wells, Basins, PH, Conductivity

1. Introduction

Water is a precious and essential natural resource for multiple uses, including food consumption and hygiene, thus requiring impeccable physicochemical and microbiological quality [1]. It has always been an indispensable element for the life of living beings, especially humans. Having this high-quality resource available in sufficient quantity contributes to maintaining the health of every living being on Earth. The United Nations (UN) advocates for universal access to water and sanitation, as well as the sustainable management of this resource [2]. However, according to UNICEF/WHO figures (2019), one-third of the world's population does not have access to a safe drinking water source; half of this population lives in Africa [3]. In addition, 2.5 billion people worldwide lack access to adequate sanitation services [4]. Limited access to drinking water remains linked to the unequal distribution of available resources on the one hand, and to the adverse effects of climate change on the other. Furthermore, the high temperatures in the semi-arid zones of Sub-Saharan Africa result in significant water evaporation [5]. Several studies have also highlighted poor chemical and bacteriological water quality in developing countries [6-8]. However, the production of drinking water is not feasible when it exceeds a certain contamination threshold [9]. Therefore, water intended for human consumption is potable when it is free from chemical elements (toxic substances, excess mineral and organic matter) and biological elements (pathogenic germs) likely to cause waterborne diseases in the short or long term [10, 11]. According to the WHO (2005), 1.8 million people, 90% of whom are children under five, mostly living in developing countries, die each year from waterborne diseases (including cholera). 88% of diarrheal diseases are attributable to poor water quality, inadequate sanitation, and poor hygiene. The study area, particularly Mangualmé, is facing the adverse effects of climate change, evidenced by the disappearance of ancient lakes and their tributaries, falling groundwater levels, drought, loss of vegetation cover, and desertification. Access to drinking water in this area is therefore becoming a real problem for the population. This work involves analyzing samples from a part of the city of Mangualmé. The results of this study can provide valuable information on the safety of drinking water, as well as on the possible environmental impacts associated with its use [12].

2. Materials and Methods

2.1. Presentation of the Study Area



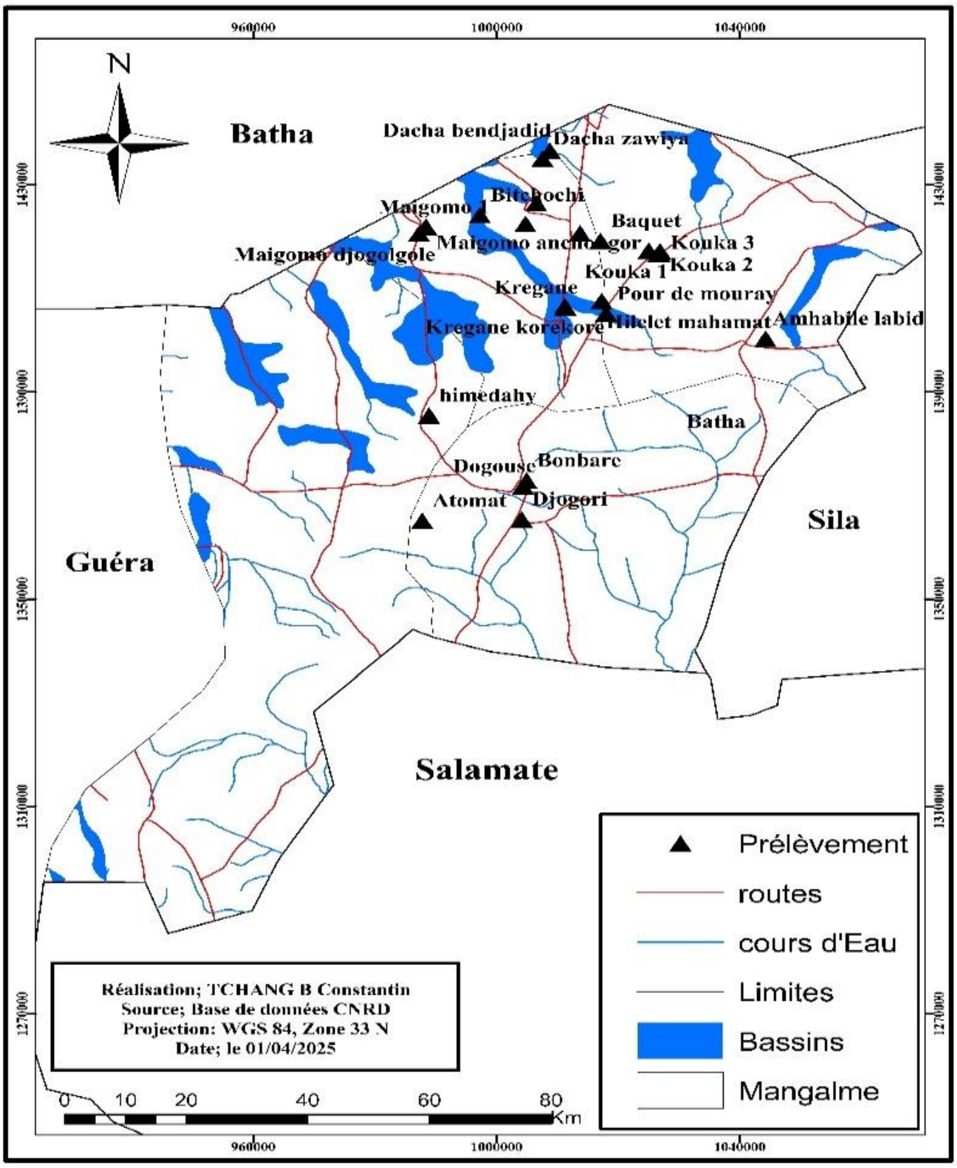


Figure 1. *Location of the study area.*

The Department of Mangalmé is located 133 km from Mongo, the capital of the Guera Province (12° 21' 17'' North, 19° 36' 50'' East), and is bordered to the north by the Department of Batha East, to the south by the Department of Aboudeia, to the west by the Department of Guera, and to the east by the Department of Djourouf-al-amar.

Mangalmé was established as a Department by Decree No. 1156/PM/MISP/2008 of October 9, 2008. Its territorial jurisdiction includes the communes of Mangalmé, Kouka, Bitchotchi, and Eref and Katalog (newly created).

The Department of Mangalmé covers an area of 11,550 km^2 and comprises four (5) sub-prefectures, one urban commune, four (4) cantons, 212 villages, and 51 hamlets, for a population of 194,568 inhabitants. In addition, there is a new sub-prefecture, Katalog, whose map is not yet available. The Department of Mangalmé also possesses enormous potential in terms of diverse natural resources (arable land, forest products, etc.), but these are insufficiently exploited. It faces a problem of access to drinking water and healthy food due to the extreme poverty affecting 90% of the rural population. This article will therefore attempt to provide a solution.

2.2. Sampling Process

After surveying the area, 10 water sampling points were randomly selected to cover the study zone. The coordinates of these points were determined using a Garmin GPS. After being filled with the water to be analyzed, the bottles were hermetically sealed before being transported in coolers. Each bottle was marked in indelible ink with the project code, location, date, sample number, and the elements to be analyzed.

Figure 2. Work chain from sampling to laboratory analysis.

2.3. Analysis of Physicochemical Parameters

Temperature, pH, and electrical conductivity were measured in situ using a multiparameter instrument. Chemical analysis of Ca^{2+}, Mg^{2+}, Cl^{-}, and HCO_3^{-} ions was performed in the laboratory using the conventional volumetric method. K^{+} and Na^{+} ions were determined photometrically using a flame photometer. Ions were determined spectrophotometrically with the HACH2800 spectrophotometer.

3. Results and Discussion

pH Analysis

Observable trends include:

For basin waters, the pH is slightly neutral to slightly alkaline, varying between 7.0 and 8.5 during the dry season, but decreasing during the rainy season (dilution by acidic rainwater).

For well waters: The pH is more stable, varying between 7.5 and 8.5, due to the buffering effect of the subsoil rocks (sediments/sandstone). However, some risk can also be identified [13, 14].

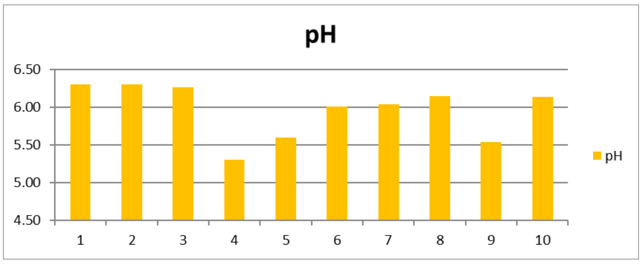


Figure 3. Evolution of pH in basins and wells (e.g., seasonal or spatial variations).

1) A pH < 6.5 in the basins could indicate organic contamination (decomposing vegetation) or acidity (agricultural runoff).
2) A pH > 8.5 in the wells suggests high mineralization (dissolving carbonates).

According to the literature, WHO standards in this case give an ideal range between 6.5 and 8.5. A deviation could alter the taste and corrode infrastructure if used in an industrial setting [14-16].

Parameter Analysis: Electrical Conductivity

The analysis of electrical conductivity shows a variation in conductivity (an indicator of dissolved salts) [16]. Two observable trends are observed:

In the case of basins, we note a peak in conductivity at the end of the dry season (evaporation concentrating the salts). Low values are observed during the rainy season.

In the second case, in wells, we see a relatively stable but high conductivity (500-1500 µS/cm), reflecting the dissolution of subsoil minerals (gypsum, halite) [14-17].

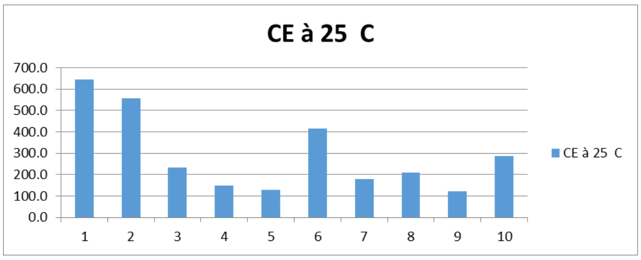


Figure 4. Electrical conductivity parameters at 25 ℃.

This could be interpreted by the fact that, for one, a conductivity > 1000 µS/cm in wells indicates "hard" water, unsuitable for irrigation (risk of soil salinization). Conversely, for ponds, sudden spikes could indicate sewage intrusions. Furthermore, the risk of health impacts should not be overlooked, as, following experiments analyzing certain parameters, high values linked to diarrhea or kidney problems (depending on dominant ions: Na^{+}, Cl^{-}) must be taken into account [1, 14].

Calcium (Ca^{2+}) mg/L Analysis Results

Calcium analysis reveals a calcium concentration (mg/L) at various points. The observed concentrations at the well are high (60-120 mg/L), linked to the dissolution of limestone or sandstone. In contrast, the concentrations in the basin are lower (20-50 mg/L), except during periods of intense evaporation. This contributes to the water hardness. It is associated with Mg^{2+}, which can form scale deposits [13, 16]. The results rarely exceed health thresholds (WHO: no strict limit), but affect potability (taste). Given the geological origin of this region of Guera, it is highly probable that we are dealing with an aquifer traversing sedimentary formations.

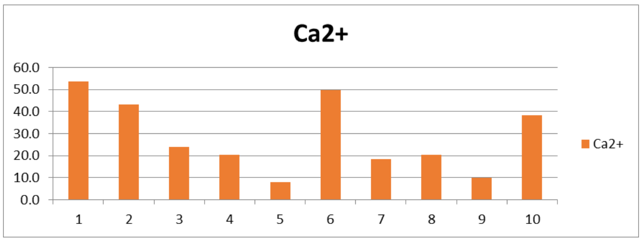


Figure 5*. Calcium concentration (mg/L) at different points.*

Turbidity Analysis

The figure shows a fluctuation in turbidity (suspended solids content).

Two observable trends are observed:

For the basin: High turbidity during the rainy season (> 50 NTU) due to runoff from eroded soils. For the wells: Turbidity is generally low (< 5 NTU), except after heavy rainfall (particle infiltration). In this context, there may be some risk depending on the turbidity > 5 NTU, thus reducing the effectiveness of disinfection (possible pathogens: bacteria, parasites) [18]. However, a correlation with the presence of heavy metals (adsorption onto particles) in the local context leads us to conclude that the sandy soil type of the Guéra region promotes erosion, explaining the peaks in the basins.

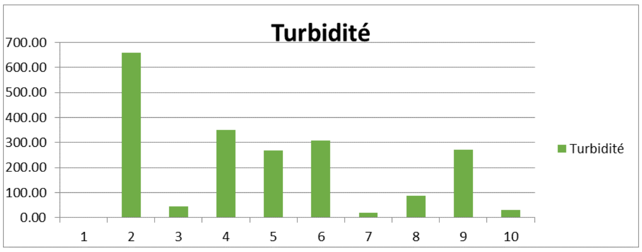


Figure 6*. fluctuation of turbidity (suspended matter content).*

TDS Analysis Results

Total dissolved solids are in the range of 0-350 mg/L, reflecting the total mineralization of the water. Some samples show high mineralization (>200 mg/L), which may indicate prolonged interaction with geological formations or contamination [19].

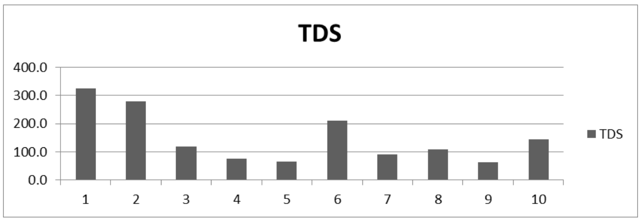


Figure 7*. Graphiques TDS.*

Résultat d'analyse des TH (Dureté Totale)

Total hardness (TH) ranges from 0 to 300 mg/L $CaCO_3$; the distribution is similar to that of total dissolved solids (TDS) but with different proportions, indicating that hardness is primarily due to calcium and magnesium ions. High values in some samples suggest the presence of carbonate rocks or other soluble minerals [20].

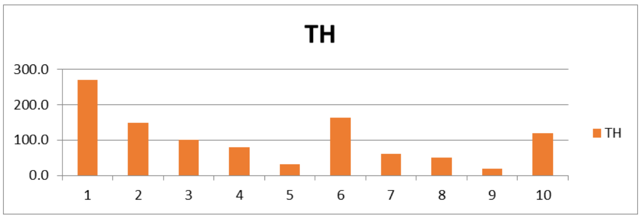


Figure 8*. plage de TH (Dureté Totale).*

Magnesium content analysis results

The figure shows us the presence of a concentration between 0-20 mg/L, varying according to the samples: the presence of magnesium generally comes from the dissolution of minerals such as dolomite. The observed concentrations are consistent with waters in contact with magnesian geological formations [21, 22].

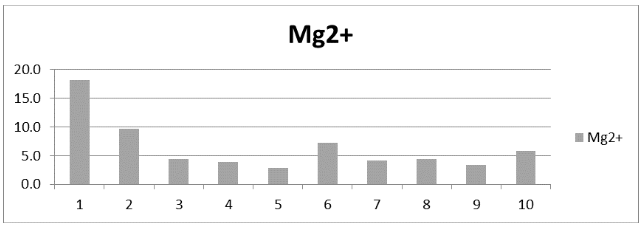


Figure 9*. Presence of magnesium in dolomite.*

Results of analysis for the presence of K^+ *(Potassium)*

In the case of potassium (K^+), the concentration is 0-8 mg/L lower than that of magnesium. Potassium is less abundant in natural waters than sodium. Its presence may indicate the alteration of minerals such as potassium feldspars.

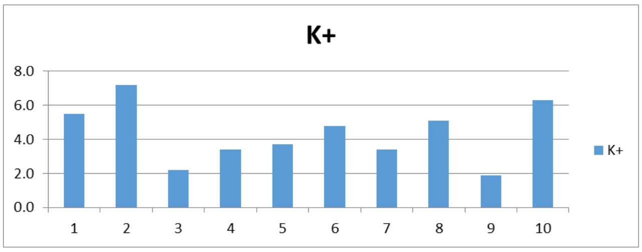


Figure 10. *presence of K^+ (Potassium).*

Sodium presence analysis results

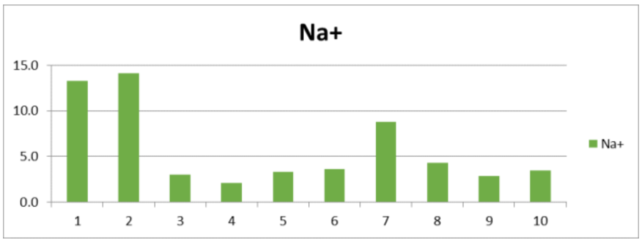


Figure 11. *Na^+ (Sodium) concentrations.*

For the case of the Na^+ (Sodium) graphs, sodium is a major ion in natural waters. High concentrations may indicate contamination by saline waters or anthropogenic activities.

Analysis result for the presence of HCO_3^- (Bicarbonate)

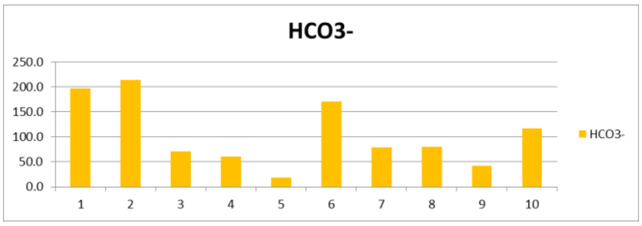


Figure 12. *presence of HCO_3^- (Bicarbonate).*

The pattern of the presence of HCO_3^- (Bicarbonate) in our analysis results reflects a dominance by the alkalinity of natural waters and probably resulting from the dissolution of atmospheric CO_2 and the alteration of carbonate rocks.

Chloride Analysis Results

For the following figure; Cl^- (Chloride). They are conservative ions. Their sources can be natural (dissolving salts) or anthropogenic (wastewater, salted roads).

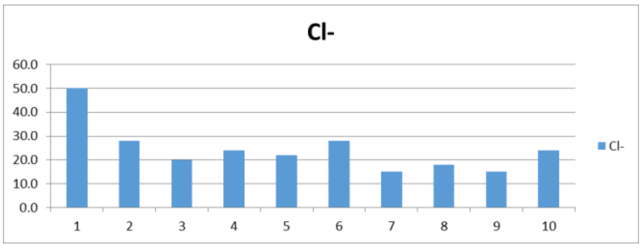


Figure 13. *Chloride Analysis Results.*

Result of analysis of the presence of Sulfate

Regarding SO_4^{2-} (Sulfate); Sulfates can originate from the alteration of sulfide minerals (pyrite) or from anthropogenic sources (fertilizers, industrial discharges).

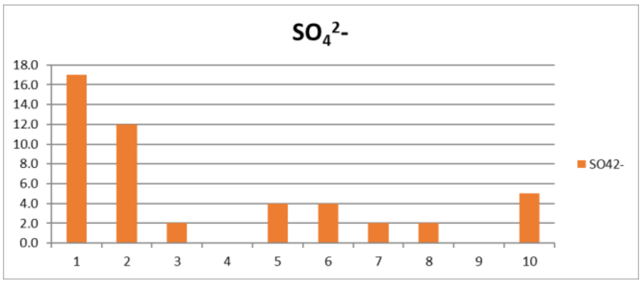


Figure 14. *presence of Sulfate.*

Results of analysis for the presence of F^- (Fluoride)

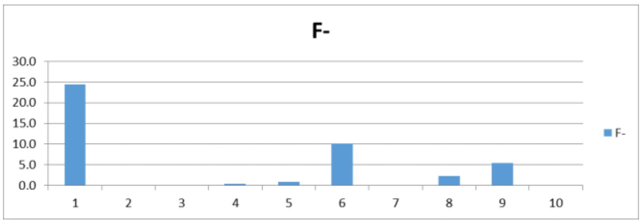


Figure 15. *presence of F^- (Fluoride).*

The results for the presence of F^- (fluoride) show a concentration ranging from 0 to 30 mg/L. For some samples observed, the concentrations are very high, far exceeding the WHO standard for drinking water (1.5 mg/L). This indicates a significant health risk (dental and skeletal fluorosis). The source is likely geological (alteration of fluorinated minerals such as fluorite).

Results of analysis for the presence of iron (Fe)

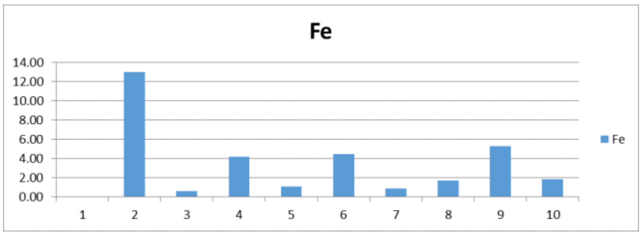


Figure 16. *presence of Fe (Iron).*

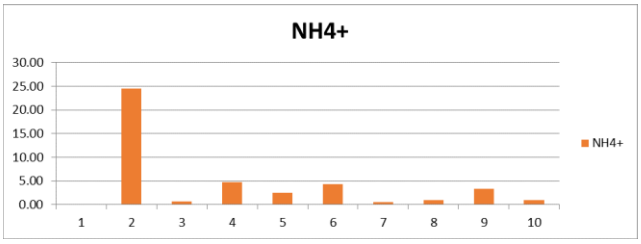


Figure 17. *concentration of* NH_4^+ *(Ammonium).*

The results show the presence of iron (Fe), with concentrations ranging from 0 to 14 mg/L, with some slightly elevated levels. These values exceed the drinking water standard (0.3 mg/L). This can cause taste and color problems and promote the growth of iron-oxidizing bacteria. The probable source is the dissolution of ferrous minerals under anaerobic conditions.

Results of ammonium concentration analysis

In the case of the NH_4^+ (Ammonium) graph, we have a concentration of 0-30 mg/L, with higher concentrations in some samples. These concentrations are alarming (standard < 0.5 mg/L). Ammonium indicates recent organic pollution (wastewater, fertilizers, animal waste). It presents health risks (conversion to nitrites/nitrates) and may indicate fecal contamination.

Result of the correlation between physico-chemical parameters

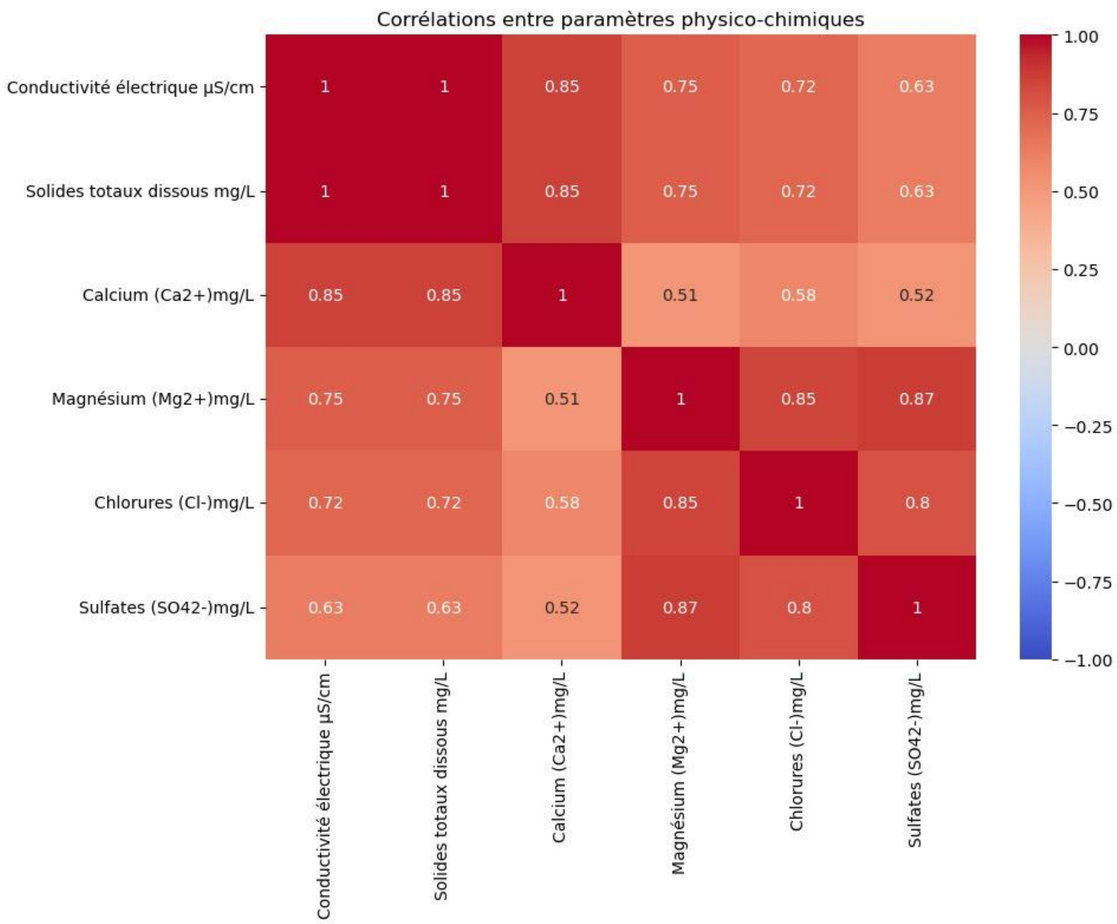


Figure 18. *Correlation matrix between different physicochemical parameters.*

We performed a correlation matrix which reveals significant relationships between different physicochemical parameters. Electrical conductivity and total dissolved solids show a perfect correlation (1), which is expected since these two parameters are closely related in aqueous solutions. Calcium ions (Ca^{2+}) show a strong correlation with conductivity (0.85), while magnesium (Mg^{2+}), chloride (Cl^{-}), and sulfate (SO_4^{2-}) ions show high correlations with each other (0.85 to 0.87), suggesting a common origin or similar chemical interactions. Sulfates, although correlated with magnesium (0.87), have a weaker correlation with chlorides (0.6), indicating differentiated behaviors within the studied system. These results highlight the interdependence of ions and their collective contribution to the conductivity and mineral composition of water [23-26].

Results of multi-parameter comparisons in normalized function

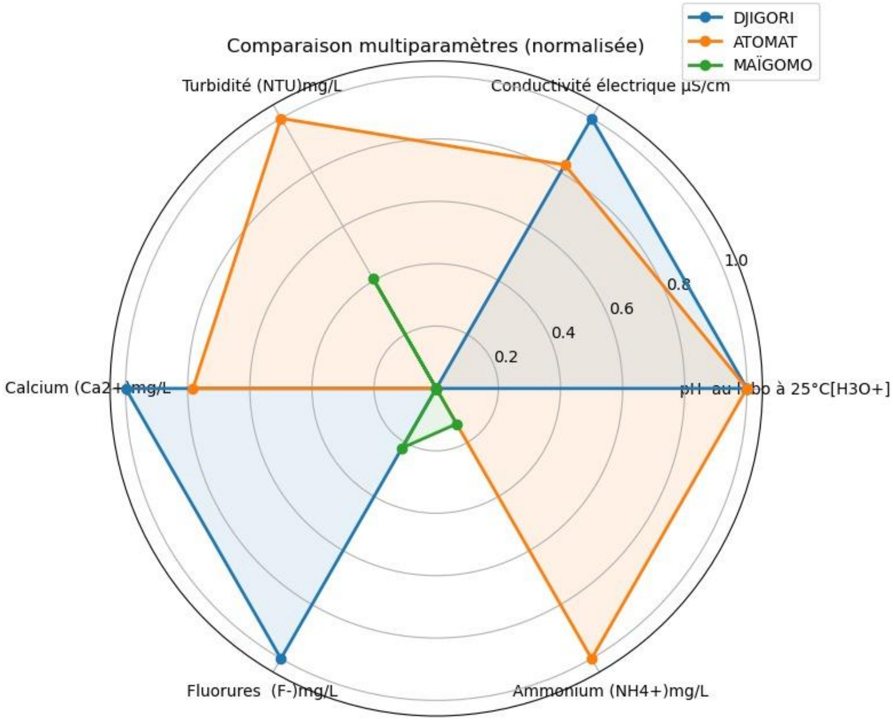


Figure 19. *A normalized multi-parameter comparison of different physicochemical characteristics of water.*

In the diagram opposite, we have established a normalized multi-parameter comparison: the diagram presents a normalized multi-parameter comparison of different physicochemical characteristics of water, including turbidity (NTU), electrical conductivity (µS/cm), concentrations of calcium (Ca^{2+}), ammonium (NH_4^{+}), fluorides (F^{-}), as well as pH at 25°C [24, 25].

RESULT of physicochemical analysis (Ionic balance)

Table 1 shows that none of the 10 samples taken met all the drinking water criteria. The vast majority presented serious chemical and/or physical risks, rendering the water unfit for consumption without extensive treatment.

Physically, electrical conductivity (EC) and total dissolved solids (TDS) indicate the amount of mineral salts leached from the ground by the water during its underground journey.

We also observed that the highly mineralized waters (high EC): DJIGORI (646 µS/cm) and ATOMAT (556 µS/cm) had a high ionic charge. Physically, this means that these are heavy waters, having stagnated for a long time in porous media (clay, sandstone, or limestone), which allowed them time to dissolve the rocks. Their density is slightly higher.

Regarding the low mineral content waters (low EC): MA ЇGOMO (123 µS/cm) and CHINGEAT (128 µS/cm) are light and young. Physically, they likely originate from rapid surface runoff or a very shallow aquifer, having had little contact with deeper geological layers.

Visual appearance and solid load (via Turbidity and Iron)

The most striking physical aspect of the table concerns colloidal and muddy waters: 9 out of 10 samples exhibit extremely high turbidity (up to 660 NTU for ATOMAT). Physically, this means that the water is not a homogeneous solution, but a raw suspension containing suspended solid particles (clays, silts, fine sands, organic debris). Light is completely blocked.

We also note that the iron oxidation-precipitation phenomenon is massive (up to 13 mg/L). In a physical context, this iron is present in ferrous form (Fe^{2+}) dissolved in anoxic (oxygen-free) water. As soon as the water is pumped and exposed to air, it physically oxidizes to ferric iron (Fe^{3+}), which precipitates instantly, forming visible rust/orange flocs. These flocs weigh down the particles and, combined with turbidity, make the water physically heterogeneous, thick, and muddy.

Physical hardness and aggressiveness (via total hardness, Ca, Mg, and pH)

Physically, hardness determines the mechanical behavior of water with matter (leaching, scaling). For hard (scaling) water: DJIGORI (270 mg/L) is physically hard water. It contains a high concentration of calcium and magnesium. When heated, it tends to form solid limescale deposits (tartar) that physically clog pipes and heating elements.

The aggressive (soft and acidic) waters of the localities of MA ÏGOMO (20 mg/L), CHINGEAT (32 mg/L), and KREGANE (pH 5.30) are physically very soft and aggressive. Their low mineral content and acidity give them a dissolving power: rather than depositing limescale, they physically corrode metals (lead, copper, or steel pipes), creating leaks or releasing metallic particles into the water.

***Table 1.** Result of the physico-chemical analysis (ionic balance).*

Sample name		**DJIGORI**	**ATOMAT**	**DOUGOUSBOUMBKRI**	**KREGANE KOROKOTEH**	**CHINGEAT**	**KOUKA 2**	**AMHABILE LABIO**	**MOURAYE**	**MA ÏGOMO**	**DACHABENDJEDIO**	***Directives OMS/Tchad pour l'eau de boisson***
Date of collection	*Unités*	14/03/2025	14/03/2025	14/03/2025	15/03/2025	15/03/2025	15/03/2025	15/03/2025	16/03/2025	16/03/2025	16/03/2025	
pH in the lab at 25 ℃	*[H3O+]*	6,30	6,30	6,26	5,30	5,60	6,01	6,04	6,14	5,54	6,13	*6,5 ≤ pH ≤ 9*
Electrical conductivity	*µS/cm*	646,0	556,0	233,0	148,6	128,8	414,0	180,8	210,0	123,2	287,0	*≤ 2500*
Total dissolved solids	*mg/L*	324,5	279,1	117,9	75,1	65,3	209,7	91,2	107,8	61,9	143,3	*≤ aucune mention*
Turbidity (NTU)	*mg/L*	1,55	660,00	44,50	351,00	269,0	309,0	20,0	86,0	271,0	29,8	*≤ 5*
Total hardness (CaCO3)	*mg/L*	270,0	148,0	100,0	80,0	32,0	164,0	60,0	50,0	20,0	120,0	*≤ aucune mention*
Calcium (Ca^{2+})	*mg/L*	53,6	43,2	24,0	24,0	8,0	60,8	13,6	15,2	5,6	38,4	*≤ 200*
Magnesium (Mg^{2+})	*mg/L*	33,0	9,7	9,7	4,9	2,9	2,9	6,3	2,9	1,5	5,8	*≤ 50*
Potassium (K^{+})	*mg/L*	12,4	29,0	2,2	4,4	3,7	4,8	8,3	5,1	2,6	6,3	*≤ 12*
Sodium (Na^{+})	*mg/L*	3,7	17,0	3,0	3,4	3,3	3,6	2,1	4,3	2,9	3,5	*≤ 200*
Bicarbonates (HCO_3^-)	*mg/L*	197,6	63,4	61,0	61,0	14,6	146,4	26,8	39,0	7,3	117,1	*≤ aucune mention*
Chlorides (Cl^-)	*mg/L*	50,0	28,00	20,0	24,0	22,0	28,0	35,0	18,0	15,0	24,0	*≤ 250*
Sulfates (SO_4^{2-})	*mg/L*	17,0	0,0	2,0	0,0	4,0	4,0	2,0	2,0	0,0	5,0	*≤ 250*
Nitrates (NO_3^-)	*mg/L*	3,9	22,80	4,7	0,9	0,0	0,0	0,0	0,1	0,0	0,0	*≤ 50*
Fluorures (F-)	*mg/L*	24,5	0,00	0,0	0,4	0,9	10,1	0,0	2,3	5,4	0,0	*≤ 1,5*
Fer (Fe)	*mg/L*	0,04	13,00	0,60	4,15	1,06	4,5	0,8	1,7	5,3	1,9	*≤ 0,3*
Ammonium (NH_4^+)	mg/L	0,16	24,50	0,61	4,68	2,47	4,26	0,58	0,99	3,35	0,91	≤ 1,5

4. Conclusion

This data represents the chemical quality of water from different sources. Variations between sites indicate distinct geological and anthropogenic contexts. The variable chemical quality of the waters exhibits heterogeneous mineralization depending on their geographical origin.

The issue related to contamination observed in some samples analyzed in the laboratory states, among other things, that:

The presence of fluorides reveals that their concentration is dangerously high in some samples, thus posing a major health risk.

Regarding iron, the concentration is sometimes excessive. The problem in this case is related to the presence of organoleptic compounds.

We also have the presence of ammonium at a high level, indicating organic pollution with a health risk.

However, the origin of the contaminants in the analyzed waters is twofold: firstly, the contaminants present natural contamination through the presence of fluorides and iron, which likely have a geological origin.

The second origin is anthropogenic, as the presence of ammonium is often linked to human activities, namely agriculture, livestock farming, and sanitation.

Author Contributions

Hassan Souleymane Mahamat: Funding acquisition, Methodology, Resources

Haroun Ali Adannou: Conceptualization, Funding acquisition, Methodology, Resources, Writing – original draft, Writing – review & editing

Yaya Youssouf Yaya: Conceptualization

Ahmed Mohammed Mohagir: Supervision

Mohammedain Adam Allhgabo Belal: Supervision

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Haroun, A. A., Hédoua, H., Ganon, F., Salwa, A. F., Abouba kar, A. M., Hassane S. M., and Mohagir, A. M. (2026) Analysis of Pollutant Loads in the Wastewater of a Hydrocarbon Industry and Evaluation of the Effectiveness of Their Treatment. Open Journal of Inorganic Chemistry, 16, 1-16. https://doi.org/10.4236/ojic.2026.161001

[2] UN (United Nations). (2019). Sustainable Development Goals Report.

[3] UNICEF/WHO. (2019). Progress on Water, Sanitation and Household Hygiene 2000–2017: Focusing on Inequalities. UNICEF/WHO, Switzerland, 140 pp.

[4] WHO. (2013). Environmental Hygiene in Urban Planning. WHO, Geneva. Cairns J. E., Hellin J., Sonder K., Araus J. L., Macrobert J. F., Thierfelder C. & Prasanna B. M. (2013). Adapting maize production to climate change in sub-Saharan Africa, *Food Security*, 345 – 360.

[5] Yaka, D. A. M., Tiemeni, A. A., Zing, B. Z., Nenkam, T. L. L. J., Aboubakar, A., Nzeket, A. B., et Mewouo, Y. C. M. (2020). Physico-chemical and bacteriological quality of groundwater and health risks in some neighborhoods of Yaoundé VII, Cameroon. *International Journal of Biological and Chemical Sciences*, *14*(5), 1902-1920.

[6] Ntep F, Kengne IM, Mboudou EG, Nyochembeng N, Ekodeck GE. (2014). Influence of seasonal dynamics on groundwater resources quality in semitropical urban zone: case of the Biyémé upper stream catchment (Yaounde, Cameroon). *Int. J. Biol. Chem. Sci.*, 8(3).

[7] Kouam Kenmogne GR, Djomou Bopda SL, Rosillon F. (2013). Mutations urbaines et problématique d’accès à l’eau potable et à l’assainissement dans une zone urbaine d’un pays en développement: cas de la ville de Yaoundé (Centre-Cameroun). *Actes du 5ième colloque international « Ressources en eau et développement durable »*. 24-25 Février 2013, Alger (Algérie); 764-769.

[8] Carlier A. (2012). The drift of drinking water intakes. Pour, vol. 1, no. 213, pp. 53-59.

[9] Abdoulaye D., KhadijettouM. and Mohamed O., 2013. “Contribution to the study of the physical-chemical water quality of the water from the right bank of the Senegal River.” Larhyss Journal, No. 12, January 2013, pp. 71-83.

[10] BENNOUR Nesrine: Master's thesis Analysis of the Physico-Chemical and Bacteriological Quality of Well Waters in the Ras El Oued Region: Defended on: 23/06/2024: Mohamed El-Bachir El-Ibrahimi University - Bordj Bou Arreridj Faculty of Science and Technology Department of Environmental Engineering.

[11] Schneider, J. L. et Wolf, J. P. (1992). Geological and hydrogeological map at 1/1,500,000 scale of the Republic of Chad. Explanatory memorandum. BRGM No. 209, Vol. 2, 531p.

[12] BEN SEDIRA, A., & BEN BITOUR, S. E. (2025). *Variation spatio-temporelle et statistique de la qualité des eaux souterraines de la ville de Ghardaïa* (Doctoral dissertation, université Ghardaia).

[13] Haroun, A. A., Ahmat, S. F., Mahamat, H. S., Mahamat, A. A., & Mohagir, A. M. (2026). Physico-chemical and Bacteriological Evaluation, Based on the Water Quality Index (AQI) and the Inorganic Pollution Index (IPO) of Wastewater from an Oil Refinery. *Modern Chemistry*, *14*(1), 9-21.

[14] Nzeket, A. B., and Mewouo, Y. C. M. (2020). Physico-chemical and bacteriological quality of groundwater and health risks in some neighborhoods of Yaoundé VII, Cameroon. International Journal of Biological and Chemical Sciences, 14(5), 1902-1920.

[15] KADJANGABA, E., LE BANDOUMEL, M., DJIMOUKO, S., MAHMOUT, Y., and MBAIGANE, J. C. D. (2020). Contribution to the hydrochemical study of water resources in the city of Sarh, Southeast Chad. Afrique SCIENCE, 16(2), 177-191.

[16] KOUADRI, S. (2022). Hydrochemical study and modeling of groundwater quality (Case of the Wilaya of Illizi) (Doctoral dissertation, Kasdi-Merbah University of Ouargla).

[17] Karroum, L. A. (2021). Evaluation of surface water and sediment quality: Hydrogeochemistry, mineralization processes, and trace metals. Case of the Oued El Abid, Oued Ahançal, and Oued Srou watersheds (High and Middle Atlas Mountains, Morocco).

[18] Yao, K. S. A., & Ahoussi, K. E. (2021). Application of multivariate statistical methods to the hydrochemical study of groundwater in a mining environment in the Central-West region of Côte d'Ivoire: the case of the Divo Department. Afrique Science, 18(4), 53-68.

[19] Mebarki, M. (2020). Evaluation of the degradability rate of schistose rocks under the effect of weathering (Doctoral dissertation, Mouloud Mammeri University of Tizi Ouzou).

[20] KERBOUSSA, F. Evaluation of groundwater quality and hydrogeochemical characteristics of groundwater in Oued Righ (Algerian Sahara) (Doctoral dissertation).

[21] KADRI, A. (2023). Representation of hydrochemical analyses and fluoride adsorption of groundwater in southern Algeria: The case of the Touggourt basin (Doctoral dissertation, Kasdi Merbah University of Ouargla).

[22] Desoteux, M. (2025). Influence of calcium carbonate equilibria on the chemical characteristics of drinking water in contact with a cementitious material (Doctoral dissertation, University of Toulouse).

[23] Faye, M. D. (2022). Characterization and modeling of pollutant transfer in a fractured aquifer in a basement rock environment (Sissili sub-basin, Burkina Faso) (Doctoral dissertation, International Institute for Water and Environmental Engineering (2iE Institute)).

[24] Adjeffar, E., Adeline, K., & Koutimma, A. (2022). Drinking water quality in the city of Mao, Kanem province, Chad: Findings and perspectives. International Journal of Innovation and Applied Studies, 36(3), 904-916.

[25] BROUYERE, S., DASSARGUES, A., FAYE, S., ORBAN, P., TYCHON, B., LAIGNEL, B., & DELIEGE, J. F. Study of the surface water-groundwater relationship in a context of climate change in the southern zone of the Saloum basin (Senegal).

[26] ALIA SARA, L. A. K. H. D. A. R. I. Hydrogeochemical characterization and nitrate pollution of the Continental Intercalaire aquifer of Adrar (Doctoral dissertation, KASDI MERBAH UNIVERSITY OF OUARGLA).