HYDROGEOCHEMICAL CHARACTERISATION AND EVALUATION OF THE SUITABILITY OF GROUNDWATER FOR CONSUMPTION AND IRRIGATION IN THE RURAL COMMUNE OF GOUNA, ZINDER-NIGER REGION.

SUMMARY

The rural Commune of Gouna is located in the south of the department of Mirriah between latitudes 13°17' and 13°43' North and between longitudes 9°08' and 9°19' East. From a hydrogeological point of view the municipality is underlain by groundwater aquifers formed by formations of recent Korama sands and discontinuous formations of the Damagaram. These aquifers are much in demand for drinking water supply, animal watering and irrigation, which is booming in the commune. Because of their shallow aquifers are very sensitive to anthropogenic pollution. The aim of this study is to characterise these aquifers from a hydrogeochemical and assess the suitability of these waters for human consumption and irrigation. The methodology applied involves conventional hydrochemical approaches the use of Piper diagrams and the correlation matrix, Principal Component Analysis and techniques for assessing the quality of water (SAR, USSL, %Na, Wilcox). Thus, it emerges that 54.76% of the water is of calcic bicarbonate facies, 26.19% calcic chloride facies and magnesian facies, 14.29% sodium and potassium bicarbonate facies and 4.76% sodium chloride facies. Principal Component shows that mineralisation of the water in the study area is mainly controlled by the hydrolysis of silicate minerals due to the presence of presence of CO_2 in the soil, water-rock interactions due to residence time leaching from ferruginous soils and human activities. Comparison of the analytical results with standards (2017) indicates that the majority of groundwater in the study area is fit for human consumption. However, some sampleshave NO_3^-, FeT, $K^+$and Ca^{2+} exceeding the WHO standard. The percentage values for Na (%Na), SAR and the positioning of samples on the Wilcox indicate that the water is of excellent quality for irrigation.

Key words: Damagaram bedrock, PCA, Wilcox, chemical facies, Piper

I. INTRODUCTION

Groundwater is of vital importance in most parts of the world. However, this resource, which was once of good quality, is now under threat from a variety of point and diffuse sources of contamination. Despite the many efforts made since 1973 by governments to provide water to urban, peri-urban and rural centres (Margat, 1996), a third of the world's population does not have access to a source of drinking water, half of whom live in Africa (UNICEF, 2019).

Drinking poor-quality water can cause illness in humans. According to the WHO, nearly 500 million people suffer from waterborne infectious diseases every year (Kouamé et al., 2013). Moreover, in developing countries, 80% of illnesses and more than a third of deaths are attributable to water-borne diseases (Atidelga et al., 2010).

What's more, access to drinking water is at the root of most of the problems faced by developing countries (Hounsou et al., 2010). In Niger, access to drinking water has been a major concern for both the population and politicians for decades. However, coverage in terms of access to this rare commodity remains relatively low. Only 49.93% of Nigeriens have access to drinking water (MHA, 2023). In rural areas, where more than 82% of the national population live, the rate of access to drinking water is 49.12% (WHO, 2014).

The commune of Gouna, located in the Korama basin in the south of the Zinder region, in the centre-east of the country, has significant surface and groundwater potential (Issa Malam S. Souleymane, 2018). For several years, this region has been affected by recurrent droughts that have had negative impacts on its ecosystem (Issa Malam S. Souleymane et al., 2018). In addition, the region has experienced galloping demographic growth, resulting in the expansion of cultivated areas and settlements. All these actions are devastating for the ecosystem (Issa Malam S. Souleymane et al., 2018). They also have an impact on groundwater resources in terms of quantity and quality (Issa Malam S. Souleymane et al., 2020).

Protecting these waters from contamination therefore remains a major challenge (Abdou Babaye et al., 2018). Given the significant costs involved in restoring aquifers, it is important, in the current environmental context, that appropriate measures are taken to protect these aquifers from pollution, while bearing in mind that human activities are a necessity for society (Valérie Murat, 2000).

The general objective of this study is to ~~characterise the hydrogeochemistry and~~assess the quality of groundwater in the rural commune of Gouna.

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The specific objectives are :

- Identify the chemical facies of groundwater in the rural commune of Gouna
- Analyse the phenomena responsible for the mineralisation of this water;
- Estimate the quality of water for human consumption, with reference to WHO standards.
- To determine the suitability of the water for irrigation.

II. MATERIALS AND METHODS

II.1 Presentation of the study area

II.1.1. Geographical location

The rural commune of Gouna is located in the south of the department of Mirriah between latitudes 13°17 and 13°43 North and longitudes 9°08 and 9°19 East. It covers an area of 501 km2, or 0.3% of the area of the Zinder region. It is bounded to the east by the communes of Mirriah and Wacha, to the west by the commune of Dogo and the 5th Communal District of the town of Zinder, to the north by the communes of Mirriah and Koléram and to the south by the communes of Bandé and Wacha. Its population was estimated at 81,600 in 2010 (INS, 2010). Applying an intercensal growth rate of 4.5% for the department of Mirriah, the population at the end of 2024 is estimated at 651,153, with a density of 139.22 inhabitants/km².

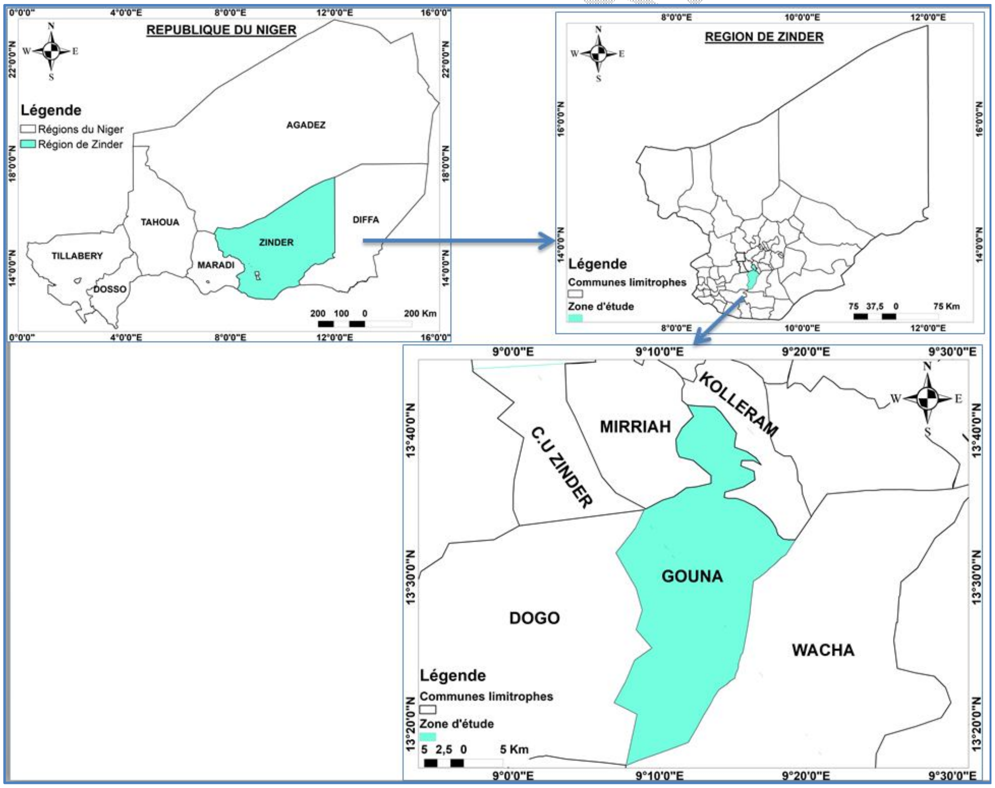

Figure 1: Location of the rural commune of Gouna

II.1.2. Geological and hydrogeological context

From a geological point of view, the commune of Gouna is essentially underlain by sedimentary formations from the Quaternary period, made up of dune sands and recent alluvial deposits from the Korama and granitic formations from the Precambrian basement (fig. 2).

From a hydrogeological point of view, two main aquifers are thus encountered: the recent sand aquifer and the discontinuous granite basement aquifer.

- Discontinuous basement aquifers: These are located to the north and east of the commune. Water can only exist in the cracks, fractures and alterites formed by these formations. This makes it very difficult to supply water to localities in this ~~zone~~area. They are characterised by very low flow rates (less than 5 m3/h). Exceptionally, it can reach a flow rate of up to 14 m3/h, for structures with an average depth of 70 m (PLEA, 2017). It should also be noted that the drilling failure rate is very high - 50%, and as high as 85% in young granite areas (PLEA, 2017). The static level ranges from 10 m to 56 m and the thickness of the alteration can reach up to 59 m (PLEA, 2017). This water table is fed by rainwater through its network of fractures, the sandy overburden of which forms a real passoir for infiltration. Chemically, the water is sodium bicarbonate and moderately charged, with a conductivity of less than 1,350 µS/cm (PLEA, 2017).

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- Recent Quaternary formations, mainly aeolian and fluvial in origin, reveal only a few granit basement outcrops in the area. This recent deposit consists of fluvial and eolian sands with gravel levels and well-rounded pebbles becoming increasingly clayey towards the bottom. The recent fine to medium sands are highly permeable, and their thickness can reach several dozen meters in the center of the basin [10]. These formations form the Korama recent sand aquifer (**Issa Malam Salmanou et al., 2023)**.

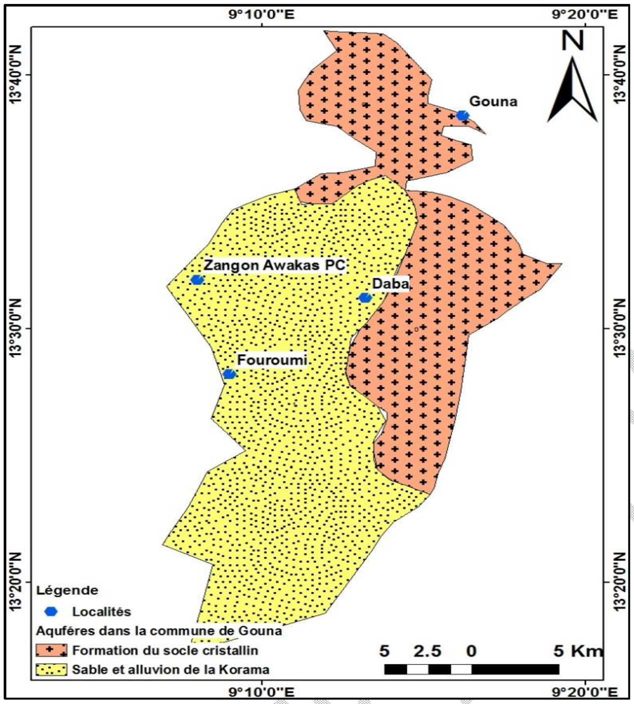

Figure 2: Geological map of the commune of Gouna

II.2 Materials

The materials used in this study include: data and tools.

II.2.1. Data

The data mainly concerned

- the physical parameters of the water (temperature; conductivity; pH and TAC);
- major chemical parameters (Ca2+, Mg2+, Na+, K+, HCO3-, SO42-, Cl-, NO3-) and minor water parameters (NO2-, F-, Fe2+, Fe3+).

II.2.2. Tools

The tools used consisted of :

- Sampling network ;
- Small hydrogeological equipment: electric probe, pH-meter, conductivity meter for water analysis, etc.
- A GPS for taking the coordinates of the water points;
- Bottles and pillboxes for taking water samples.
- Software consisting of : ArcGis, diagram, Xlstat ;
- Water chemical analysis laboratory.

II.3 Methodology

II.3.1. Sampling and in situ measurement

Comment [U4]: The sampling map showing the location of each boreholes and wells is missing.

The water samples for the chemical analyses were taken using 750 ml bottles that had been rinsed with distilled water and then washed three times with water taken from the structure. The vials were filled to the brim to avoid any gas exchange with the atmosphere. The samples were kept in a thermos during transport to the laboratory of the Direction Régionale d'Hydraulique et de l'Assainissement de Zinder (DRH/A) for analysis. A total of 42 boreholes and wells were sampled during the campaign (November to December).

The physical parameters of the water - temperature, electrical conductivity and pH - were measured in situ.

II.3.2. Analytical techniques for chemical parameters

The major chemical parameters (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{2-}, Cl^{-}, NO_3^{-}) and minor water parameters (NO_2^{-}, F^{-}, Fe^{2+}, Fe^{3+}) were determined in the laboratory using the following techniques:

- Ca^{2+} and Mg^{2+} ions were determined by titrimetry using the specific reagents Calver 2 for calcium and Hard 9 for magnesium. The calcium and magnesium values are then verified by determining total hardness, calcium hardness and magnesium hardness;
- K^{+} and Na^{+} ions were obtained by flame photometry using a JENWAY PFP7 type spectrophotometer;
- the spectrophometric method was used for total iron (Fe^{2+}, Fe^{3+}), nitrate, fluoride, sulphate and chloride ions. The apparatus used was the DR 2800 spectrophotometer and the reagents were: iron rover, nitraver 5, nitriver 3, SPDNS, sulfaver, mercuric thiocyanate + ferric ion solution.

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II.4. Data processing

Several methods were used to process and analyse the data on the physico-chemical parameters of the groundwater in the study area.

- **Calculation of the ionic balance**

Firstly, the reliability of the analytical results for the chemical parameters was checked. This is based on the calculation of the ionic balance, given by expression (1).

$$\boldsymbol{BI = \frac{\sum cations - \sum anions}{\sum cations + \sum anions} \times 100 \qquad (1)}$$

Cations and anions are given in milliequivalents per litre (meq/l).

The analytical results can be considered reliable for an ion balance value of ± 10%.

Next, the statics (mean; maximum; minimum; median and standard deviation) of the physicochemical parameters of the water are determined in order to compare the different waters.

To determine the suitability of these waters for human consumption, the maximum values of these physico-chemical parameters were compared with the WHO standard (2017) and that of Niger (2010).

- **Graphical representation of physico-chemical parameters**

Piper diagrams, correlation matrices and PCA were used to characterise the hydrochemistry of the aquifers in the study area. In this study, the PCA was applied to 14 variables: electrical conductivity (EC), temperature, pH, Ca^{2+}, Mg^{2+}, K^+, Na^+, HCO_3^-, NO_3^-, NO_2^-, Cl^-, SO_4^{2-}, F^- and total iron.

- **Suitability of water for irrigation**

In this work, several methods are used to assess the quality of water intended for irrigation:

- **Sodium Adsorption Rate (SAR) and Salinity Diagram (USSL)**

The Sodium Adsorption Ratio (SAR) is a measure of the risk of alkalinity in water (Alagbe 2006 in Balaji et al., 2016). It reflects the replacement of Ca^{2+} and Mg^{2+} by Na^+ in the soil through a cation exchange process. SAR is calculated from the following formula (Todd 1980):

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

The United State of Salinity diagram (USSL) is based on the sodium adsorption rate (SAR) on the ordinate and the TDS or conductivity of the water on the abscissa. It is also used to classify water intended for irrigation.

- **Percentage of Sodium (% Na) and Wilcox diagram**

The evolution of the quantity of sodium (%Na) in water intended for irrigation is very necessary. In large quantities, sodium reacts with the soil to clog pores, thus reducing water permeability and plant respiration (Todd and Mays 2005; Srinivasamoorty et al. 2011; Balaji et al., 2016 in Issa Malam Salmanou et al., 2020). The %Na is determined by the following formula (Todd, 1980):

$$\%\boldsymbol{Na} = \frac{(\boldsymbol{Na^+} + \boldsymbol{K^+}) \times \mathbf{100}}{(\boldsymbol{Ca^{2+}} + \boldsymbol{Mg^{2+}} + \boldsymbol{Na^+} + \boldsymbol{K^+})} \quad (3)$$

Ion concentrations are expressed in mg/l.

The Wilcox Diagram (Wilcox, 1955) is drawn up from %Na values plotted on the ordinate and electrical conductivity or TDS values plotted on the abscissa. It is used to classify water samples into five (5) categories of water intended for irrigation: Excellent, Good, Acceptable, Poor and Bad (Issa Malam Salmanou, 2018).

III. RESULTS AND DISCUSSION

III.1 Results

Table 1 presents the results of classical statistics of physicochemical parameters of groundwater in the study area.

Table 1: Descriptive statistics for water physicochemical parameters

Variable	Unit	WHO standard (2017)	Minimum	Maximum	Mean	Standard deviation
pH	-	6,5-8,5	5,62	8	6,69	0,49
CE	µs/cm	1200	21	618	206,55	133,45
T°	°C	-	22,30	36,20	30,35	1,93
HCO_3^-	mg/lCaCO$_3$	-	0,33	484,08	121,32	111,89
Cl-	mg/l	250	3,80	60	22,85	15,07
SO4--	mg/l	400	0	68	12,63	15,62
F-	mg/l	1,5	0	1,26	0,25	0,29
NO3-	mg/l	50	0	69,08	14,26	18,78
NO2-	mg/l	3	0	1,24	0,06	0,19
Na+	mg/l	200	3	60	20,02	11,94
K+	mg/l	12	0	20	3,78	4,19
FeT	mg/l	0,3	0	2,63	0,67	0,75
Ca++	mg/l	-	8	80	25,36	18,55
Mg++	mg/l	-	0	48,88	10,69	12,49

III.1.1. Physical parameters of the water

The water temperature varies between 22.30°C (at Kalgo tchama borehole 1) and 36.20°C (at Burbaram borehole 1) for a mean of 30.35°C and a standard deviation of 1.93 over 42 samples. The electrical conductivity of the water ranged from 21 µs/cm (Garmaki) to 618 µs/cm (Houroumi borehole 2), with an average of 206.55 µs/cm and a standard deviation of 133.45 over 42 samples. The pH values ranged from 5.62 (Barago cemented well 1) to 8 (Zongon Awakass) with an average of 6.69 (Table 1).

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III.1.2. Chemical parameters of the water

III.1.2.1. Distribution of chemical parameters

Among the anions, bicarbonate ions are predominant in the groundwater of the study area with highly variable concentrations (fig.3 ; table 1). They represent more than 60% of the anions in these waters. Chloride ions come secondly with 16.66% of the total anions. Next come nitrate, sulphate, fluoride and nitrite, representing 10.39%, 9.20%, 0.19% and 0.04% respectively.

The order of predominance of the anions can therefore be established as follows: HCO_3^-> Cl^-> NO_3^-> SO_4^{2-}> F^-> NO_2^-.

Calcium is the most abundant cation, accounting for over 40% of the total. Sodium ions come secondly with 32% of the total. Then magnesium ions, potassium ions and total iron with respectively 17.70%, 6.27% and 1.11% of the total cations.

The order of predominance of the canions can be established as follows: **Ca^{2+}> Na^+> Mg^{2+}> K^+> FeT.**

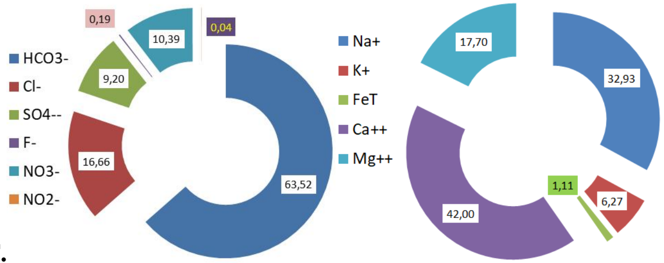

Figure 3: Descriptive statistics for physico-chemical water parameters

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The order of anions can therefore be established as follows: **HCO3- > Cl- > NO3- > SO42- > F- > NO2-.**

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The order of the cations can be established as follows: **Ca2+ > Na+ > Mg2+ > K+ > FeT.**

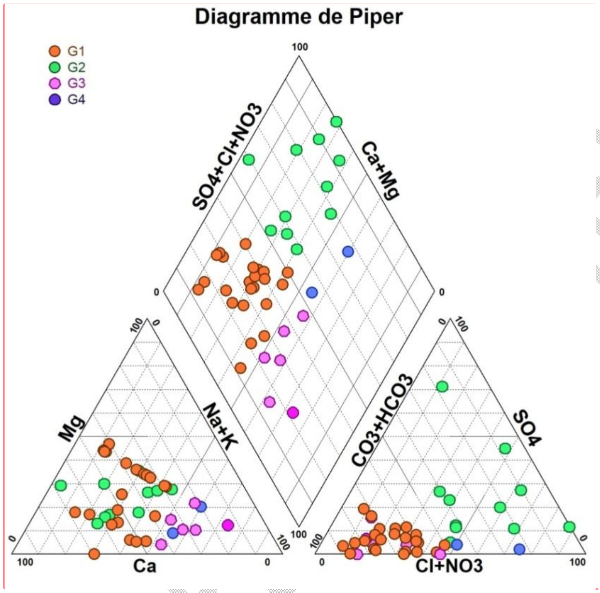

Figure 4: Piper diagram

III.1.4. Study of the processes controlling groundwater mineralisation

In order to study the processes responsible for groundwater mineralisation in the study area, two multivariate statistical analysis approaches are used in this work. These are the correlation matrix and principal component analysis.

III.1.4.1. Bivariate relationship between physico-chemical elements

The correlation between the physico-chemical parameters of the water shows that (table 2):

- pH is moderately correlated with HCO_3^-(r = 0.56) but weakly correlated with Cl^-(r = 0.47), - Na^+(r = 0.48), Ca^{2+}(r = 0.43) and Mg^{2+} (r = 0.46).
- C.E is moderately correlated with SO_4^{2-}(r = 0.53) and weakly correlated with K^+ (r = 0.42).
- HCO_3^- is strongly correlated with Ca^{2+} (r = 0.88), Mg^{2+} (r = 0.91) but weakly correlated with Cl^- (r = 0.44), F^- (r = 0.42) and Na^+ (r = 0.47).
- Cl^- is moderately correlated with Mg^{2+} (r = 0.54) and Na^+ (r = 0.50).
- Na^+ is weakly correlated with K^+(r = 0.44).
- Ca^{2+} is strongly correlated with Mg^{2+} (r = 0.87) but moderately correlated with pH and F^-.

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- Mg^{2+} correlates strongly with HCO_3^- and FeT but moderately with pH and Cl^-.

Table 2: Correlation matrix for physico-chemical water parameters

Variables	pH	CE	T°	HCO_3^-	Cl^-	SO_4^{2-}	F	NO_3^-	NO_2^-	Na^+	K+	FeT	Ca^{2+}	Mg^{2+}
pH	1													
CE	0,076	1												
T°	0,012	-0,315	1											
HCO_3^-	0,559	0,238	-0,311	1										
Cl^-	0,472	-0,261	-0,102	0,438	1									
SO_4^{2-}	-0,099	0,530	-0,312	0,130	-0,156	1								
F	0,377	-0,057	-0,001	0,418	0,120	-0,127	1							
NO_3^-	-0,087	0,155	0,055	-0,177	-0,209	0,170	0,016	1						
NO_2^-	0,017	-0,036	-0,067	-0,037	0,140	0,034	-0,033	0,046	1					
Na^+	0,481	0,318	-0,154	0,474	0,496	-0,092	0,035	-0,277	0,043	1				
K^+	0,322	0,417	-0,128	0,041	0,010	0,088	0,077	0,082	-0,094	0,440	1			
FeT	0,016	-0,087	0,033	0,022	-0,178	-0,219	0,149	-0,302	0,167	-0,046	-0,294	1		
Ca^{2+}	0,434	0,280	-0,256	0,879	0,317	0,332	0,446	0,135	-0,007	0,153	-0,114	-0,039	1	
Mg^{2+}	0,462	0,073	-0,353	0,906	0,538	0,269	0,328	-0,044	0,011	0,249	-0,094	-0,103	0,867	1

III.1.4.2. Principal Component Analysis

Table 3 shows the eigenvalues, the variances expressed for each factor and their totals. The first three (03) factors, F1, F2 and F3, are selected for this study because they represent more than 56% of the total variance. The F1 factor is the most important, expressing 28.91% of the variance, followed by the F2 and F3 factors with 15.22% and 12.56% of the total inertia respectively.

Table 3: Eigenvalues and percentages expressed for the principal axes.

	F_1	F_2	F_3
Eigenvalue	4,048	2,164	1,759
Variability (%)	28,915	15,457	12,566
Cumulative	28,915	44,372	56,938

III.1.4.3. Distribution of variables on the factorial plane

The F1 axis, with 28.91% of the total inertia and grouping together the following elements (Figure): pH, HCO_3^-, Cl-, Mg2+ and Ca2+ could control the major process of mineralisation of the water in these aquifers.

Component F2, with 15.46% of the total inertia, includes the following elements (Figure 5): EC, SO42-, NO3-, FeT and NO2-.

Axis F3 expresses 12.57% of the total inertia of water mineralisation. It includes Na+ and K+.

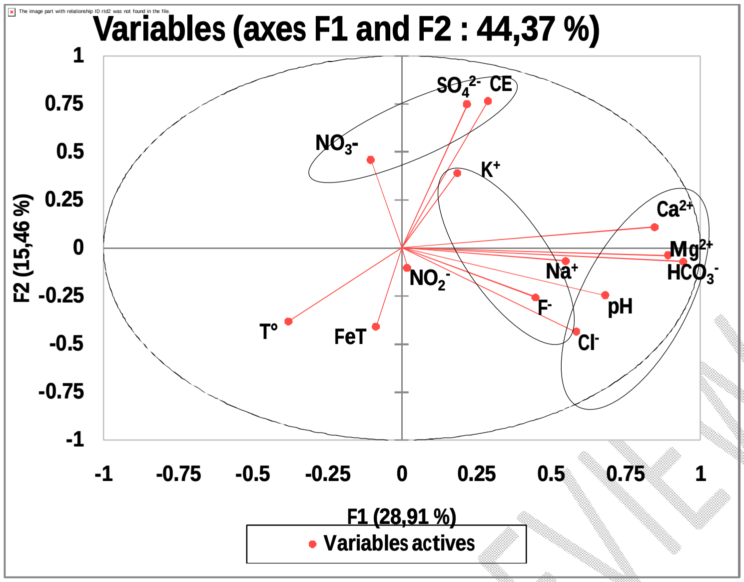

Figure 5: Analysis of the statistical units of the F1XF2 factorial design.

III.1.5. Suitability for irrigation

Several approaches are used to assess the suitability of water for irrigation.

III.1.5.1 Sodium Adsorption Rate (SAR) and Richard's diagram

The classification of groundwater according to SAR shows that of the 42 samples, 29, 08 and 05 are respectively of excellent, good and admissible quality for irrigation (table 4). The Richard diagrams show that all the samples are divided into two classes: C1-S1 represented by 74.41%, and C2-S1 with 25.58% of the total samples. (fig. 6).

III.5.1.2. Percentage of sodium (%Na) and Wilcox diagram

The %Na values for the 42 groundwater samples show that only 05 samples are of excellent quality, 14 are of good quality, 17 are of acceptable quality and 6 are of poor quality. From the Wilcox point of view, all the water samples analysed are excellent for irrigation, with the exception of a single sample belonging to the admissible class out of the 42 (fig.6).

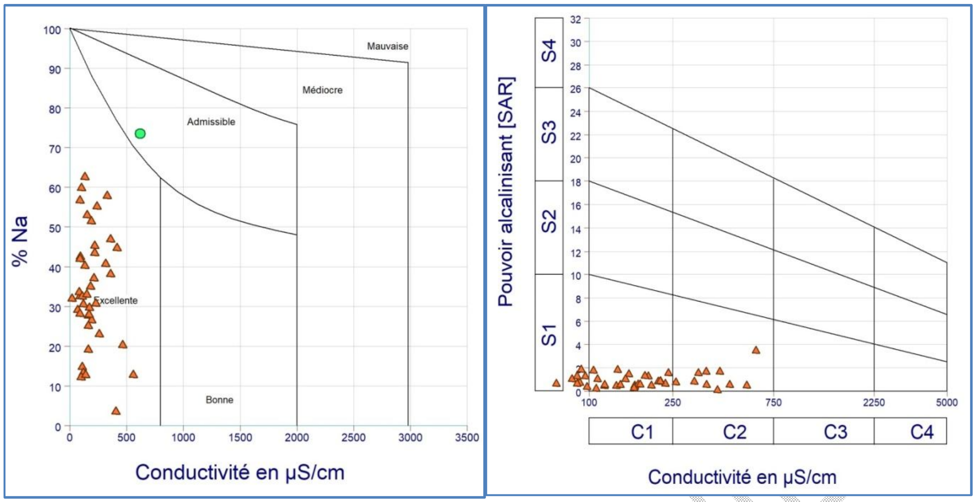

Figure 6: Wilcox diagram (left) and Richards diagram (right)

Table 4: Summary of groundwater classification results for irrigation.

Parameter	Category		
		Nombre n=42	**Proportion**
SAR mg/l (Richards, 1954)			
0-6	Excellent	29	69%
6-9	Good	8	19%
>9	Admissible	5	12%
% Na mg/l (Wilcox., 1955)			
< 20	Excellent	5	12%
20-40	Good	14	33%
40-60	Admissible	17	40%
60-80	Uncertain	6	14%
> 80	Poor	-	-

III.2. Discussions

III.2.1. Physical parameters of the water

The temperature values of the groundwater in the study area reflect those of the atmospheric air, which means that these aquifers are open (Issa Malam Salmanou et al., 2023). In addition, conductivity values are generally low, which could be attributed to the shallow depth of the water and its short residence time (Issa Malam Salmanou, 2018). The pH values show a slightly acidic trend overall. This acidity is probably linked to the combination of free CO2 and rainwater, which form carbonic acid, thus lowering the pH of the water (Sethy et al., 2016).

III.2.2. Chemical facies

The hydrochemical study highlighted the predominance of calcic bicarbonate facies in the groundwater in the commune of Gouna. This result is in agreement with those of several authors who have worked in the West African basement and who have revealed that the bicarbonate facies is the typical facies of waters in basement zones (Yao et al., 2012). The predominance of HCO3 ions at the origin of this facies can be explained by the hydrolysis of silicates in the presence of CO2 from the soil and/or the dissolution of carbonates (DJahadi et al., 2021).

III.2.3. Origin and process of water mineralisation

The diversity of groundwater facies in the study area highlights that several processes could be at the origin of the mineralisation processes in these waters. Principal Component Analysis (PCA) shows that the F1 axis, characterised by a strong correlation between pH, HCO3- ions, Mg2+, Ca2+ and Cl-, controls the major water mineralisation process (Issa Malam Salmanou et al., 2020). Most of these ions could therefore come from the acid hydrolysis of silicate minerals due to the presence of CO2 in the soil. The strong correlation between Ca2+, Mg2+ and HCO3- ions (Table 2) highlights the dissolution of carbonate minerals on the one hand and the alteration of ferromagnesium minerals on the other (Djahadi et al., 2021). Mg2+ ions could also be derived from water-rock relations (Abdou Babaye et al., 2016).

Furthermore, the association of these elements : CE, SO42-, NO3-, FeT and NO2- on the F2 axis could reflect the contribution of human activities in controlling the mineralisation of these groundwaters. The presence of iron in these waters is thought to result from the leaching of ferruginous soils.

The association of these ions on the same axis highlights the water-rock relationship characterised by the ion exchange process between the K+ ions in the rocks and the Na+ ions contained in the water (Prasanna et al., 2010 in Issa Malam Salmanou S, 2018).

Projection of the samples on the F1XF2 factorial plane (Figure 7) shows that these elements are grouped according to the variation in the electrical conductivity of the water and their pH on either side of the F1 and F2 axes. Highly mineralised samples are placed on the positive pole, while less mineralised samples are placed on the negative pole. Also, individuals with acid pH are grouped together on the positive pole of F2, while individuals with basic pH are found on the negative pole of the F2 axis.

However, the projection of the samples onto the F1xF3 factorial plane (Figure 7) shows that these elements are grouped according to the variation in the electrical conductivity of the water and their pH on either side of the F1 and F3 axes. Highly mineralised samples are placed on the positive pole, while less mineralised samples are placed on the negative pole. Also, individuals with acid pH are grouped together on the negative pole of F3, while individuals with basic pH are found on the positive pole of the F3 axis.

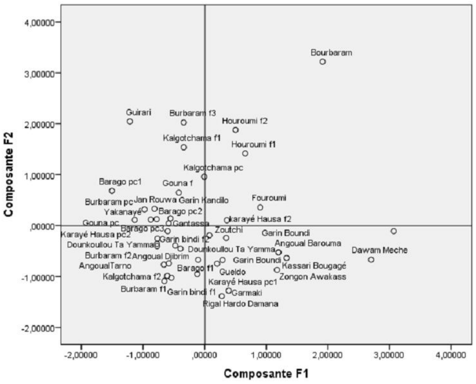

Figure 7: Distribution of samples on the factorial plane F1xF2 (left) and F1xF3 (right)

III.2.4 Suitability of water for irrigation and human consumption

This study also revealed that the groundwater is physico-chemically compliant overall with the standards recommended by the WHO (WHO, 2017) and does not present a major hazard for human consumption. However, total iron, nitrate, calcium and potassium levels in some localities are high.

The high levels of iron in groundwater are attributed to sedimentary formations containing clays. Iron can be in true solution in a colloidal state, more or less combined with organic matter, in the form of organic or mineral complexes or in the form of suspended particles (Amadou et al., 2014).

Although, the nitrate ion analyses were carried out during the high water period, and corresponds to the favourable period for dilution. This probably explains the low levels. Nonetheless, there are high nitrate levels exceeding the WHO standard in the water from certain facilities. These ions ingested when drinking water are reduced to nitrite in the intestines and bind to haemoglobin, reducing its oxygen transfer capacity (WHO, 2017). This condition, known as methaemoglobinaemia, mainly affects young children. It is therefore important that these waters should not be used by the general public.

Nitrate pollution of the groundwater studied is thought to be due to the shallowness of certain structures, the lack of hygiene around them and agricultural activities (return of wastewater and agricultural water), which are thought to be the cause of these high NO_3 levels (Issa Malam Salmanou et al., 2020).

The presence of Na^+ ions could be linked to the ion exchange process, while the presence of K^+ ions could be released from the alteration of potassium feldspar and plagioclase in the environment through water-rock exchanges (Prasanna et al., 2010 in Issa Malam Salmanou, 2018).

For irrigation, calculations of SAR and %Na and the projection of samples onto the Richard and Wilcox diagram classify most of the groundwater in the commune of Gouna as being of good to excellent quality for irrigation and presenting no risk of salinisation for soils. However, some samples are of poor quality for irrigation in terms of SAR and %Na. Sodium reacts with the soil to clog pores, reducing water permeability and plant respiration (Todd and Mays 2005; Srinivasamoorty et al. 2011; Balaji et al., 2016 in Issa Malam Salmanou et al., 2020).

IV. CONCLUSION

The hydrogeochemical characterisation of the commune's groundwater revealed four (4) types of chemical facies: calcic bicarbonate facies (54.76%), calcic chloride facies (26.19%), sodium bicarbonate facies (14.29%) and sodium chloride facies (4.76%).

Principal Component Analysis indicates that the mineralisation of the commune's water is controlled by the acid hydrolysis of silicate minerals due to the presence of CO_2 in the soil, water-rock interactions (mineralisation linked to residence time), the leaching of ferruginous soils, human activity around water points and the nature of the geological formations in the commune.

Analysis of drinking water has shown that the chemical parameters of the water are for the most part below the WHO drinking water standard, except at a few points where nitrate and potassium levels are high and sometimes well above the standard. Trace metal levels in the water are also high, approaching the standard by a factor of two, and sometimes far exceeding it, as in the case of iron. Even if illnesses linked to the consumption of this water do not occur, it is necessary to take preventive measures to avoid a health problem for the population.

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