

Hydrogeochemical and Statistical Characterization of Groundwater in the Lakes Region (Central Côte d'Ivoire)

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Abstract Rural inhabitants depend on groundwater for their drinking water in the Lakes region of central Côte d'Ivoire. The aim of this study is to identify the factors responsible of the water mineralisation and the sources of major ions in groundwater within the area. 123 groundwater samples were collected and analysed for various physico-chemical parameters. Multivariate statistical techniques including Principal Component Analysis (PCA) and Cluster Analysis (CA) were applied on the dataset to evaluate the geochemical processes that control the hydrogeochemistry of groundwater. Ca-HCO₃ and Mg-Ca-HCO₃ hydrochemical facies predominate the groundwater samples. The first 4 factors explain 79.139% of the total variance, their loading allowing the interpretation of hydrogeochemical processes in the area. The sources of ions in the groundwater are due to two main factors: natural mineralisation and anthropogenic activities. The silicates mineral weathering such as acid hydrolysis of silicates provide the major part of the ions in groundwater such as Ca²⁺, Mg²⁺, and HCO₃⁻. The concentrations of NO₃⁻ and Cl⁻ in groundwater were due to anthropogenic activities such as farming. Reduction-oxidation process produced Mn and Fe. The results of this study show the usefulness of multivariate statistical techniques in hydrochemical studies.

Keywords: PCA, CA, groundwater, hydrogeochemical, Lakes region, Côte d'Ivoire

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1. Introduction

In the most parts of the world, groundwater resources are very important to development. According to [1], groundwater resources play a very important role in the socio-economic development of the rural populations. In Côte d'Ivoire, groundwater resources supply virtually all rural communities. Groundwater resources are stored in aquifers that are able to offer natural protection from contamination, reliability of supply, and buffer against drought [2]. Surface water, in contrast to groundwater, used for agriculture, fishing, and hydropower. Groundwater provided the main source of potable water supply in the Lakes region of central Côte d'Ivoire. Generally, groundwater is exempt of contamination compared to surface water. Nevertheless, groundwater quality may deteriorate in some cases due to many factors influencing its chemical composition. Once precipitation reaches the

ground, it reacts with soil, rock and organic debris and dissolves chemical materials besides from any pollution generated by human activities [3]. According to [4], the weathering of silicate rocks and anthropogenic activities are major sources of ions in groundwater. Beyond these factors, we can cite lithology, residence time of water with rocks, ambient temperature and pH, aquifer chemical composition, climatic conditions during the aquifer formation, water quantity available in the aquifer and its circulation rate [5]. The combination of all these factors in a complex system creates many types of water that evolve in the time and in the space and influences the water quality. Hydrochemistry constitutes then an excellent investigation tool of the structure and the functioning of the aquifers systems. In this case, physico-chemical and chemical parameters were used as natural tracers to reveal the organization and the functioning of the hydrogeological system [6]. The processes influencing groundwater hydrochemistry are varied. Understanding these processes required the application of multivariate statistical

techniques. In the literature, these techniques generally applied to make easy the resolution of geo-environmental problems and to understand groundwater system flow in previous cases [7]. These techniques have also previously helped to understand the processes influencing groundwater hydrochemistry on the watershed scale and the regional scale [8,9,10]. Multivariate statistical techniques used again to identify and highlight major sources of anthropogenic effects on groundwater and surface water quality [7,11,12,13]. The understanding of aquifer layers hydraulic properties and water hydrochemical characterization that they contain were necessary for groundwater resources management. In addition, water quality must be a consideration when evaluating water supplies to domestic, irrigation and industrial purposes [3]. Otherwise, in this area, the population due to water taste and hardness problems abandons some boreholes to get supplies in the backwaters and the wells. These waters are often of doubtful quality and sources of disease. Therefore, it is important to assess the processes of mineralization of groundwater in this area. The aim of this study is to determine the main mechanisms that govern the groundwater hydrogeochemistry in the Lakes region of central Côte d'Ivoire using multivariate statistical techniques such as Principal Components Analysis (PCA) and Cluster Analysis (CA).

2. Materials and Methods

2.1. Presentation of the Study Area

The study area is located in the Lakes region of central Côte d'Ivoire, between 6° 30' and 7° 35' north latitudes and 4° 40' and 5° 40' west longitudes (Figure 1). According to the administration plan, the Lakes region principal city is Yamoussoukro, the political capital of the country. It covers an area of about 6,000 km² and contains an estimated population of 502,489 inhabitants [14]. The principal activity is agriculture. The area is drained by the Bandama river and the N'zi tributaries and has several reservoirs for agriculture.

The Lakes region is a large peneplain surrounded by Yaouré mountains in the North-West and the Fetékro chain in the South-East [15]. The mean altitude of the region between these two mountains is 200 m, thus placing it at the meridional limit of the area named plateau (200 and 500 m). The highest altitudes are near 240 m. The climate of the area is equatorial transition attenuated, between the Guinean and Sudanese climates types [15,16]. Four seasons with two dry seasons and two wet seasons are characterised the study area.

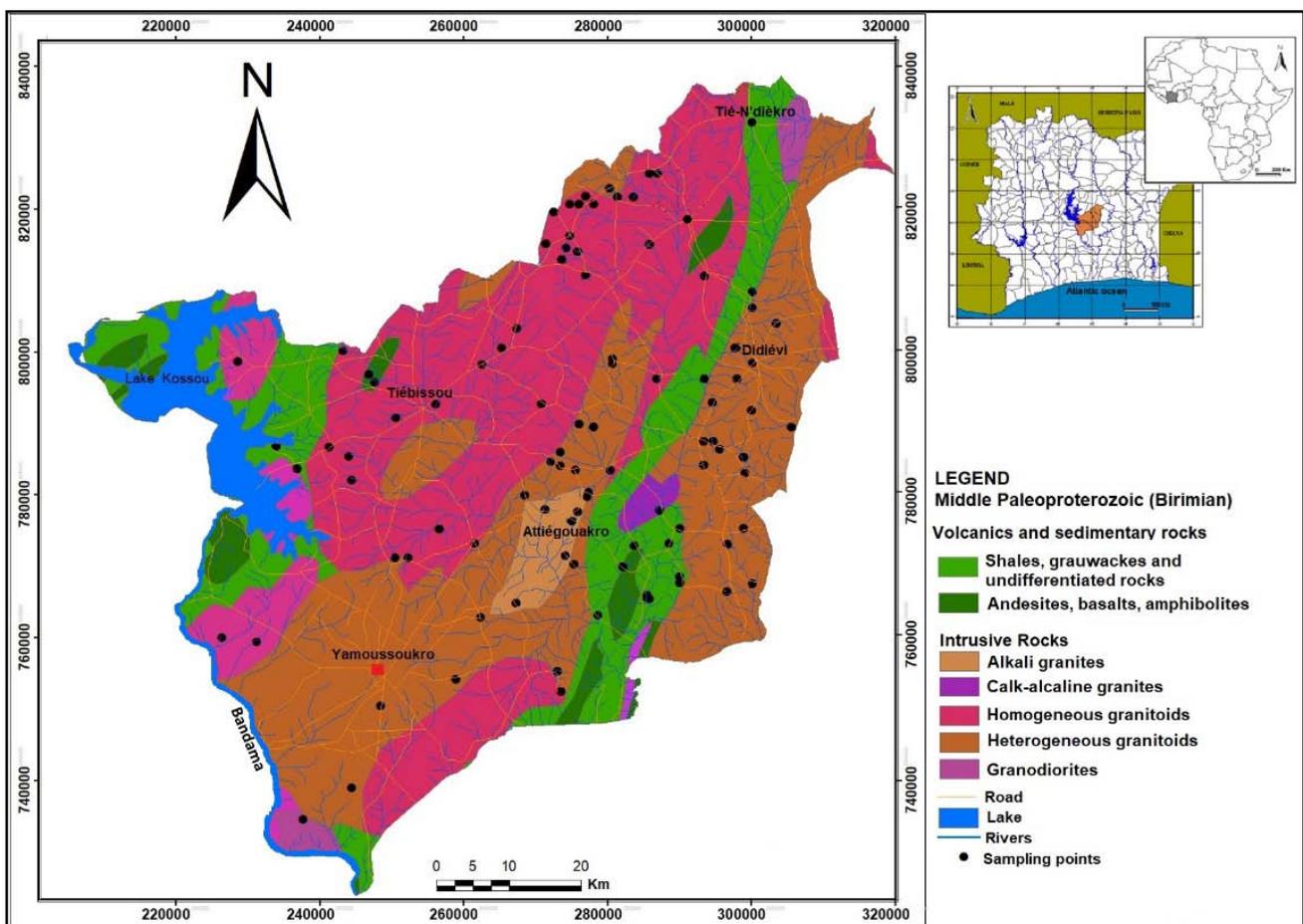


Figure 1. Map of location, geological and sampling points from the Lakes region

On geological plan, the Lakes region is a part of the Proterozoic domain of LEO dorsal (Figure 1) located in the Birimian of the Côte d'Ivoire that is part of the Baoulé-Mossi domain of West African craton. The main geological formations are magmatic and metamorphic rocks [15,17,18]. The magmatic rocks are part of the Eburnean complex and included in Eburnean granitoids. They are biotit granits, two micas granits, the migmatits, the concordant granodiorites, and the pegmatits. The volcano-sedimentaries are represented by the schists (green and shale), the quartzites, the metasediments and birimian green rocks. They are schistoids characterized by slight schistosity and granoblastic structure. They are not breakable or crackable but behave like schists [19]. The green color with which they emerge confers them this generic name of green rock. Thus, this group includes metabasalts, metaandesits, metadolerites, and metagabbros. In the field, they appeared in elongated form. The main aquifer unit is the fractured or fissured basement rocks. The mean depth of the water table is 60 m. A second aquifer less important is the weathering one. The local population accesses the aquifers with hand-dug wells. The wells have a depth of at least 20 m and the level of the water table found within 2 m. The water of this aquifer is unsuitable for drinking because the well is not protected from pollutants. However, a part of the population uses this water for various purposes needs such as laundry and bath.

2.2. Sampling and Analytical Methods

The Hydraulic Territorial Direction (DTH) of Yamoussoukro obtained the data of this study. The sampling made on boreholes waters realised in the area in the setting of the phase 3 of the project funded by the French Development Fund/Entente Council (*Caisse Française de Développement / Conseil de l'Entente phase 3 (CFD/CE3)*) between 1998 and 2000. Its concerned 123 groundwater samples collected from boreholes in the study area. The chemical analyses were determined using a portable spectrophotometer (HACH, DR 3000). The major elements analysed are bicarbonates (HCO_3^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), chlorides (Cl^-), iron (Fe), manganese (Mn), nitrates (NO_3^-), and sulfate (SO_4^{2-}). In the field, temperature, pH and electrical conductivity (EC) were measured using a multiparameter portable meter (HANNA, HI 9033 Multi-range) after pumping water sufficiently in the boreholes to obtain a stable temperature.

2.3. Principal Components Analysis (PCA) and Cluster Analysis (CA)

The Principal Components Analysis (PCA) is a multidimensionnal statistical method that allows to synthetize information and compare systems. The PCA is particularly used and adapted [1,20,21,22,23] to explain in another part the chemical resemblances between different waters and/or the different acquisition poles of mineralization. In previous studies, Cluster Analysis (CA) and PCA were applied on a major ion dataset and indicated the major hydro-geochemical processes that govern the spatial variation in groundwater chemistry

[23], [24]. Furthermore, PCA technique was applied to chemical data to extract the principal factors corresponding to the different natural and anthropogenic processes that exert control on the chemical composition of groundwater [25,26,27]. In fact, it's a method allowing to take into account a large variables and samples. To avoid mis-classifications arising from the different orders of magnitude of variables or from the effect of parameters with the highest variances on the calculation of Euclidean distances [28], the variance for each variable is standardized to their corresponding Z scores, which are calculated by Eq. (1).

$$Z_i = (x_i - \mu) / \sigma \quad (1)$$

where Z_i is the standardized Z scores; X_i is the value of each variable; μ is the mean value of the normal distribution from each datum, and σ is the standard deviation of the distribution. Thus, Kaiser-Meyer-Olkin (KMO) test of sampling adequacy was used to study the fit degree of the data to factor analysis, and Barlett's test of sphericity to examine the null hypothesis that the resulting correlation matrix is an identity matrix [29]. The sample is adequate if KMO value is more than 0.7, and is inadequate if less than 0.50. [30]. The value of 0.50 is considered suitable for factor analysis [31]. The factor extraction was based on the Kaiser's criteria (eigenvalue>1). An exploratory HCA was carried out on 11 variables of water quality using Ward's method and the Euclidean distance as a measure of dissimilarity. In this study, cluster analysis has been used to determine group associations and to assess the affinity among variables ([29,32]. The IBM® SPSS v.22 software was used to analyse the data of samples. In this study, 123 samples and 11 variables (T°C , Electrical Conductivity, pH, Ca^{2+} , Mg^{2+} , HCO_3^- , NO_3^- , Cl^- , SO_4^{2-} , Mn et Fe) were processed using PCA and HCA.

3. Results and Discussion

3.1. Groundwater Types

The piper diagram indicates that the facies type $\text{HCO}_3\text{-Ca}$ recorded in the majority of boreholes (Figure 2). Only a few samples are Mg-Ca-HCO_3 facies. In West Africa, several studies indicated that the dominants water types' groundwater within the fractured aquifers is Ca-HCO_3 [33,34]. This results imply the dominance of alkaline earth over alkali ($\text{Ca}^{2+} + \text{Mg}^{2+} > \text{Na}^+ + \text{K}^+$).

3.2. Descriptive Statistical of Characteristics of Groundwaters

The charge balance errors of chemical dataset analysed were calculated by electro-neutrality. The results show balance errors less than $\pm 5\%$ for the majority of samples. This value is acceptable error [35,36].

Groundwater geochemistry is affected by many factors such as rock type, residence time in the host rock, original composition of the groundwater, and the other characteristics of the water flow path [4]. The statistical summary of hydrochemical parameters is presented in Table 1. Coefficient of variation (CV) was the most

important factor in describing the variability of groundwater properties. To highlight the homogeneous or heterogeneous distribution of the parameters data was ranked according to amount of variation as low variability ($CV \leq 15\%$), moderate variability ($CV 15-35\%$) or high variability ($CV > 35\%$) [37]. The groundwater from region of lakes shows a high to moderate variability in standard deviation (SD) and coefficient of variation (CV) among the parameters of the samples. The CV values in the groundwater parameters ranged from 3.51 to 463.32%. All the physico-chemical parameters in the study area were found to exhibit high variability. These high values of CV indicate a heterogeneous distribution of the physico-chemical parameters properties in the corresponding sampling points and may reflect a spatial variation of groundwater quality in the area.

The pH values of groundwater range from 5.53 to 8.18 with a mean of 6.70 that is in the range of acidic to slightly alkaline water. The pH values in 13% of the samples are below the guidelines of [38], while 87% of samples have pH within the permitted limit. Electrical conductivity (EC) values range from 77.00 to 1097.00 $\mu\text{S}/\text{cm}$ with an average of 362.29 $\mu\text{S}/\text{cm}$. The gastrointestinal irritation in human being may be due to the higher EC content in groundwater [39,40]. Geochemical processes such as ionic exchange, reverse exchange, evaporation, silicate weathering, rock water interaction, sulfate reduction and oxidation processes, and anthropogenic activities are the factors responsible for large variation in EC [39,40,41]. In the study area, HCO_3^- concentration range from 35.00 to 325.00 mg/L with a mean concentration of 138.51 mg/L. The primary sources of HCO_3^- were weathering of carbonate and alumino-silicate rocks with a contribution of CO_2 gas dissolution. Subsurface lithology of the area is composed of alumino-silicate rocks. The main source of HCO_3^- ions in groundwater arises from the dissolution of secondary

carbonate rocks and silicate minerals dissolution. The soil zone has an elevated CO_2 pressure due to biodegradation of organic matter and root respiration. Carbon dioxide combines with infiltrating rainwater to form HCO_3^- [42]. The Calcium concentration ranges from 4.01 to 106.00 mg/L with an average of 30.24 mg/L. The Mg^{2+} concentrations range from 0.49 to 36.00 mg/L, with an average value of 8.49 mg/L. According to "Reference [4]", the sources of Mg^{2+} in groundwater are dolomite and/or silicate dissolution. The sulfate concentration ranges from 0 to 30 mg/L, averaging 4.99 mg/L. All of the SO_4^{3-} concentrations are within the desirable drinking limit guidelines. A higher sulfate content also may have a laxative effect with excess of magnesium [39,43].

The Cl^- concentration ranges from 1 to 117 mg/L (mean: 15.64 mg/L). The nitrate concentrations range from 0 to 149 mg/L, with an average value of 3.56 mg/L. About two samples have NO_3^- concentration greater than the permissible limit of 50 mg/L [38]. Higher values of nitrate in groundwater may be due to agricultural or other anthropogenic activities in vadose zone because of its large ionic size and flushing during rainfall [36]. Higher concentration of NO_3^- can cause methaemoglobinaemia, gastric cancer, goiter, birth malformation and hypertension [36,40]. The concentration of iron in the groundwater ranges from 0.00 to 16.20 mg/L, with a mean of 0.38 mg/L. The maximum allowable limit of iron concentration in groundwater is 0.3 mg/L as per classification [38]. About 83.74% of the samples were within the permitted limit. According to [37], under reducing conditions, the solubility of Fe-bearing minerals increases in water, leading to the enrichment of dissolved iron in groundwater. Manganese concentration in the groundwater ranges from 0 to 2.70 mg/L with a mean value of 0.07 mg/L. Most of the manganese concentrations (98%) are within the desirable drinking limit of 0.5 mg/L [38].

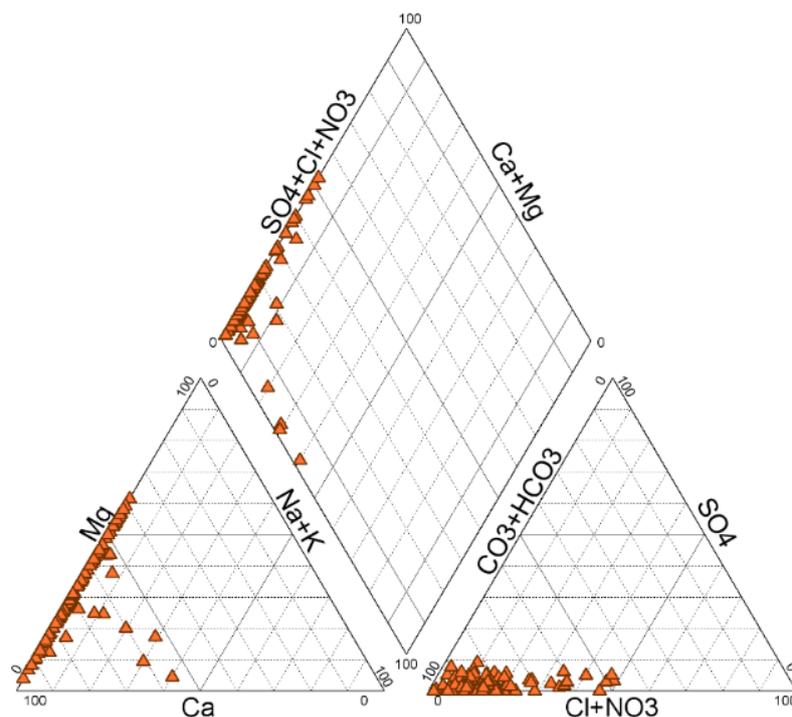


Figure 2. Piper diagram of groundwater in the Lakes region

Table 1. Summary statistics for concentrations of chemical constituents of groundwater from the Lakes region

Parameters	N	Min.	Max.	Mean	SD	CV (%)	WHO limit (2011)
T (°C)	123	25.50	30.10	27.17	0.95	3.51	< 25
pH	123	05.53	08.18	6.70	0.59	8.82	6.5<pH<8.5
EC (µS/cm)	123	77.00	1097.00	362.29	192.57	53.15	<400
HCO ₃ ⁻ (mg/L)	123	35.00	325.00	138.51	71.34	51.51	600
Ca ²⁺ (mg/L)	123	4.01	106.00	30.24	20.83	68.87	200.00
Mg ²⁺ (mg/L)	123	0.49	36.00	8.49	6.99	82.33	150.00
SO ₄ ²⁻ (mg/L)	97	0.00	30.00	4.99	5.68	113.69	200.00
Cl ⁻ (mg/L)	123	1.00	117.00	15.64	15.82	101.15	600.00
NO ₃ ⁻ (mg/L)	123	0.00	149.00	3.56	16.48	463.32	50.00
Mn (mg/L)	122	0.00	02.70	0.07	0.28	409.97	0.50
Fe (mg/L)	123	0.00	16.20	0.38	1.61	427.06	0.30

3.3. Multivariate Statistical Analyses

3.3.1. Correlation Study

Correlation analysis establishes the relationships between physico-chemical parameters of groundwater samples, which can reveal the sources of each ion. High correlation coefficient (near 1 or -1) means a good positive or negative relationship between two variables and its value around zero means no relationship between them at a significant level of $p < 0.05$. More precisely, that parameters showing $r > 0.7$ are considered strongly correlated whereas r between 0.5 and 0.7 shows moderate correlation [44]. The correlation matrix for the 11 variables is presented in Table 2.

The pH shows a moderate positive correlation with Electrical conductivity (EC) ($r = 0.511$), HCO₃⁻ ($r = 0.610$) and Ca ($r = 0.524$). EC-HCO₃⁻ ($r = 0.697$), EC-Mg ($r = 0.659$), EC-SO₄²⁻ ($r = 0.692$) and EC-Cl ($r = 0.651$) show moderate positive relation. Furthermore, EC shows a strong positive correlation with Ca ($r = 0.898$). The moderate and strong correlation between EC and these ions signifies the natural input in providing these ions into groundwater. Natural sources such as mineral weathering, ion exchange, the residence time of water and the interaction water-rock inputs are major solute acquisition

mechanisms that provide these ions in groundwater. Ca shows moderate positive correlation with Mg ($r = 0.667$) and SO₄²⁻ ($r = 0.575$). Generally, the sources of these ions in groundwater are rock weathering, carbonate dissolution and silicates minerals hydrolysis. The dissolution of secondary carbonate process is playing significant part in providing Ca, Mg and SO₄²⁻ in groundwater in the study area. A moderate positive relation of SO₄²⁻-Cl ($r = 0.551$) indicates the same sources input in enrichment of these ions in groundwater. Chloride ions are due to halite dissolution.

While sulfates ions in groundwater may be due to dissolution of gypsum-anhydrite and/or potassium sulfates added to the agricultural soil as fertilizers [4]. A good positive relation of NO₃⁻-Fe ($r = 0.778$) signifies the anthropogenic input such as fertilizer use by the farmers in providing these ions into groundwater. This phenomenon is due to the practices of farmers and the soil permeability. The excess fertilizer left after plant uptake, infiltrate while recharging aquifer and increase NO₃⁻ and others ions in groundwater system [36]. In fact, all these correlations between some of the hydrochemical parameters indicate the same input sources and similar geochemical process. The major sources of ions in groundwater of the study area are the weathering of silicate rocks and anthropogenic activities.

Table 2. Correlation matrix of physico-chemical parameters for the groundwater samples from the Lakes region

	T°C	pH	EC	HCO ₃ ⁻	Ca ²⁺	Mg ²⁺	SO ₄ ²⁺	Cl ⁻	NO ₃ ⁻	Mn	Fe
T°C	1.000										
pH	-0.171	1.000									
EC	0.065	0.511	1.000								
HCO ₃ ⁻	-0.083	0.610	0.697	1.000							
Ca ²⁺	-0.024	0.524	0.898	0.752	1.000						
Mg ²⁺	0.024	0.258	0.659	0.572	0.667	1.000					
SO ₄ ²⁺	0.122	0.404	0.692	0.407	0.575	0.367	1.000				
Cl ⁻	0.140	0.066	0.651	0.115	0.469	0.381	0.551	1.000			
NO ₃ ⁻	0.266	0.165	0.310	-0.137	0.187	0.168	0.470	0.419	1.000		
M	0.110	-0.092	0.001	-0.002	0.029	0.037	0.016	-0.003	-0.013	1.000	
Fe	0.231	0.158	0.266	-0.165	0.159	0.123	0.475	0.249	0.778	0.253	1.000

3.3.2. Principal Components Analysis (PCA)

Factor analysis has been performed to understand various sources and geochemical process. Four (04) definite Principal components were obtained with eigenvalues higher than 1. Varimax rotation used to maximize the sum of the variance of the factor coefficients that better explained the possible groups or sources that influences the groundwater geochemistry. Thus to find out the validity of the analysis before conducting the factor analysis, the KMO test and Bartlett's test were carried out. The Table 3 shows that KMO test results were greater than 0.50 which is the minimal value accepted level (KMO = 0.688). This indicates that these data are significant to allow a PCA. Furthermore, the Bartlett test results are highly significant ($p=0.000$).

Thus, the corresponding components, their loading, the variance percentage of each factor, and cumulative percent of variance presented in Table 4 and Table 5. Components loadings are classified according to [45] as "strong", "moderate", and "weak" corresponding to absolute loading values of > 0.75 , $0.75-0.50$, and $0.50-0.30$, respectively. Four (4) principal components (PC) accounted for a cumulative 79.14% of the structure of the parameters analysed (Table 4) with an eigenvalue >1 have been extracted. These components imply that there are four major distinct processes contributing to groundwater chemistry in the study area. The first principal component (PC1) accounting for as much as 35.78 % of total variance, was strongly positive correlated with the EC, HCO_3^- , Ca^{2+} and Mg^{2+} (Table 5).

Then a moderate loading is observed for SO_4^{2-} (0.606) and Cl^- (0.561). The significant high positive loadings of EC, HCO_3^- , Ca^{2+} and Mg^{2+} suggests a natural origin such as mineral weathering in the water of the study area as major geochemical process. These variables in groundwater are usually the result of water-rock interaction and dissolution of secondary carbonates and silicates.

The plot $\text{Ca}^{2+} + \text{Mg}^{2+}$ versus $\text{HCO}_3^- + \text{SO}_4^{2-}$ gives more highlights into the weathering mechanism that provides the ions in solution. Figure 3 showed that, in the study area, the majority of samples falling below the equiline. That means the weathering of silicate minerals is the main process of hydrochemistry groundwater that provides ions in solution. A few samples are above the equiline. Which means that a part of the ions in solution such as cations resulted from carbonate mineral weathering of aragonite, calcite and dolomite.

The HCO_3^- were primarily originate from weathering of carbonate and aluminosilicate rocks with a contribution of CO_2 gas dissolution [42,46]. According to "Reference [47]", the Ca^{2+} , Mg^{2+} and Na^+ concentrations in groundwater may be due to silicate/aluminosilicate weathering processes. The sources of the high SO_4^{2-} in groundwater could possibly be from anthropogenic contamination such as farming and livestock. Sulphate and chloride would have commons sources such as agricultural fertilizers and contribution of rainfall. The influence of both ions is lower than the mineral weathering and water-rock interaction. Thus, this factor explains natural mineralization of groundwater such as water-rock interaction and dissolution of secondary carbonates and silicates.

Table 3. Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.688
Bartlett's Test of Sphericity	Approx. Chi-Square	714.916
	df	55
	Sig.	0.000

Df : degrees of freedom ; Sig : Significance probability or p-value.

Table 4. Total variance in the data explained by the main components

Total Variance Explained						
Components	Initial Eigenvalues			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	4.429	40.260	40.260	3.936	35.783	35.783
2	2.168	19.710	59.970	2.366	21.508	57.290
3	1.085	9.866	69.837	1.329	12.079	69.369
4	1.023	9.301	79.138	1.075	9.769	79.138
5	.802	7.290	86.428			
6	.573	5.208	91.636			
7	.350	3.181	94.817			
8	.243	2.209	97.026			
9	.174	1.582	98.608			
10	.104	.944	99.552			
11	.049	.448	100.000			

Extraction Method: Principal Component Analysis.

Table 5. Component matrix of groundwater physico-chemical parameters

Rotated Component Matrix ^a				
	Component			
	1	2	3	4
T°C	0.046	0.214	0.638	0.169
pH	0.485	0.258	-0.708	-0.019
EC	0.925	0.270	-0.006	-0.061
HCO ₃ ⁻	0.831	-0.202	-0.367	0.092
Ca ²⁺	0.917	0.128	-0.126	0.019
Mg ²⁺	0.789	0.009	0.109	0.053
SO ₄ ²⁺	0.606	0.573	-0.017	-0.069
Cl ⁻	0.561	0.358	0.469	-0.259
NO ₃ ⁻	0.086	0.908	0.139	-0.098
Mn	0.030	0.070	0.133	0.944
Fe	0.024	0.915	0.040	0.241

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 6 iterations.

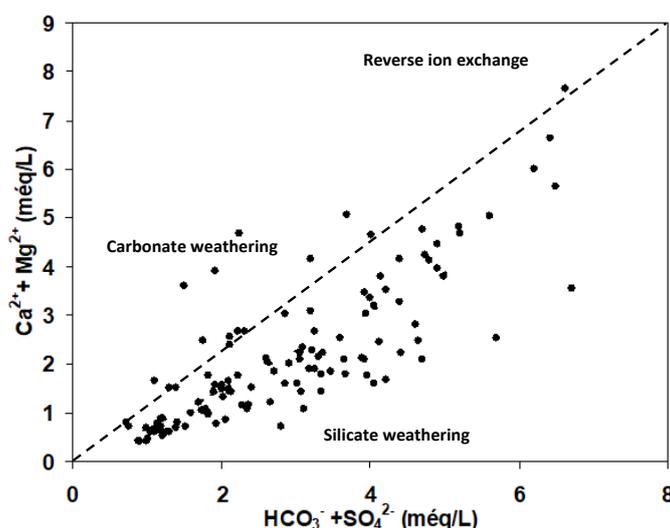


Figure 3. Ca²⁺+Mg²⁺ versus HCO₃⁻+SO₄²⁻ plot showing predominance of silicate hydrolysis in groundwater chemistry

The PC2 explains 21.51% of total variance and shows a significantly high positive loading for NO₃ and Fe. The positive correlation and loading of nitrate gave a good indication of the effect of agricultural fertilizers input in providing this ion into groundwater. Nitrate and sulphate rich fertilizers and manures are extensively used in farming activities. The excess fertilizer washed into the groundwater system, and this has the potential of raising the nitrate and sulphate levels beyond their natural concentrations [48]. The occurrence of iron in groundwater is natural phenomenon such as reduction and oxidation compounds. According to "Reference [49]", iron is usually present in form of inorganic complexes derived from laterites and other soils. In the study area, the values of iron might be provided from water-rock interactions. Moreover, high concentrations of Fe in groundwater could not be due to anthropogenic activities, and as such as the possible source being geogenic, through-rock water interaction [50]. Thus, factor 2 represents both anthropogenic and natural influences on the geochemistry of groundwater.

The PC3, accounting for about 12.08% of total variance, consists of Temperature and pH. The moderate positive

loading of temperature and high negative loading of pH indicated the influence of both variables on the water-rock interaction. According to [51], a negative loading of pH was due to the high concentration of H⁺ that absorbed by the process of water-rock interaction. The pH levels in groundwater is due principally to natural biogeochemical processes and the presence of silicates/ aluminosilicates found may probably be responsible for the acid neutralizing potential of groundwater [47].

The PC4 explains 9.77% of total variance and shows higher positive loading for Manganese. Mn is likely to be derived from natural water-rock reaction processes [37]. Therefore, the PC4 is assumed to have less influence of Mn on the overall hydrogeochemistry in the study area because of the lower values of Mn in groundwater. Thus, from the PCA, it can be deduced that, the main natural processes (water-soil-rock interactions) through which groundwater within the study area acquires its chemical characteristics. A second mechanism through which the groundwater acquires its mineralization is the anthropogenic activities such as agricultural fertilizers. At last, we have a third one such as phenomenon of oxidation-reduction.

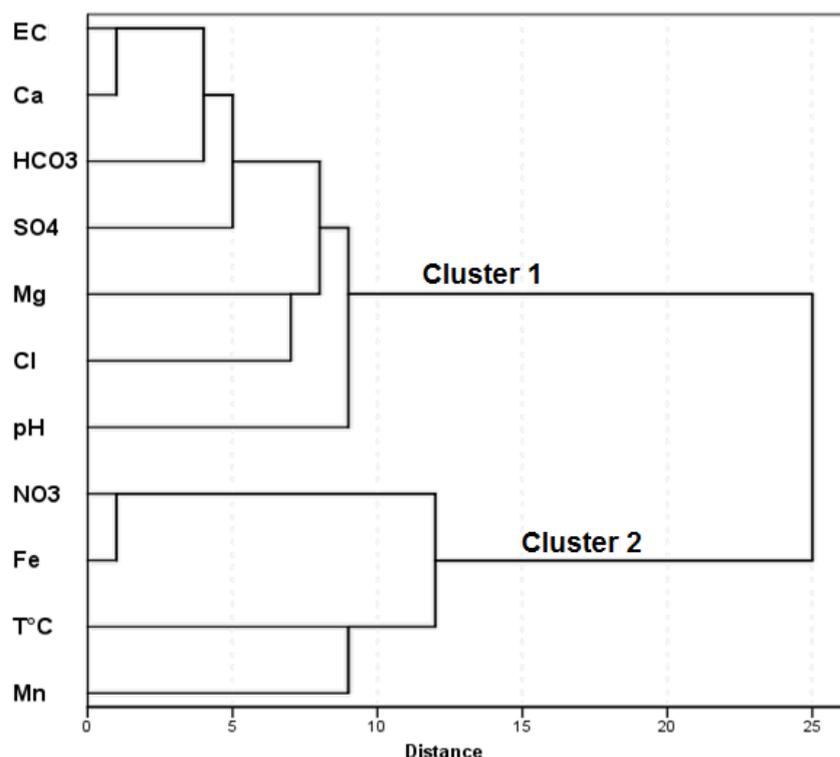


Figure 4. Dendrogram for groundwater parameters in the study area showing two clusters

3.3.3. Cluster Analysis (CA)

The R-mode CA resulted in two main clusters representing two major geochemical processes that influence the groundwater of the study area according to spatial resemblance (Figure 4). The first cluster is determined by HCO_3 , pH, SO_4 , Mg, Ca, Cl and EC. The mechanism that provide these hydrogeochemical parameters in water is mineral weathering such as the silicates hydrolysis. The second cluster is composed of NO_3 , Mn, T°C and Fe. Nitrates were lied to anthropogenic activities such as fertilizers use in agriculture, livestock waste etc. The iron and the manganese come from phenomena of oxidation-reduction that takes places in a confine medium. In consequence, three hydrogeochemical processes are involve the groundwater chemistry in study area. The main phenomenon that is responsible for increasing ions in groundwater is the mineral weathering. Then, oxydo-reduction phenomenon is which lies iron and manganese precipitation in the waters and a last process lied to anthropogenic activities that provide nitrates in water. Thus, the groundwater hydrogeochemistry in the study area is influenced by both natural and anthropogenic mechanisms.

4. Conclusion

The aim of the present study was to understand the mechanisms that control groundwater mineralization in Lakes region of central of Côte d'Ivoire. Multivariate statistical techniques analysis such as PCA and CA used in the purpose to better planification and management of these resources. The mean temperature of waters is 27.21°C . The groundwater samples are acidic with mean pH value of 6.6 and 5.86 respectively for boreholes. The mean electrical conductivity value is $331 \mu\text{S}/\text{cm}$ with

extreme values ranged from 11.2 and $1097 \mu\text{S}/\text{cm}$. Principal component analysis (PCA) and Cluster Analysis (CA) allowed to highlight the mechanisms responsible for ions productions in groundwater within the study area. The main hydrochemistry process that provide ions in solution is mineral weathering such as silicate linked with mineralization-residence time. Then the reduction-oxidation in the aquifer media release iron in solution. These mechanisms are natural and increase the major ions in the water. Anthropogenic activities contribute to the degradation of water quality by carried out the nitrates that is came from fertilizers use in agriculture and livestock waste.

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