Assessment of Groundwater Mineralization Processes in Mbakaou Area (Adamawa Plateau – Cameroon), by Using Conventional Diagrams and Multivariate Statistical Analysis

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ABSTRACT

Management of groundwater require knowing their qualities and hydrogeochemical processes whereby these waters acquire their mineralization. The population of Mbakaou in Adamawa Plateau consumes groundwater from a doubtful quality water supply structures (wells, boreholes and catchments). This study was carried out to highlight groundwater quality and processes that govern water mineralization. So, to achieve this, 11 water samples were analyzed (1 rain water, 1 well, 3 springs and 6 boreholes). After analyzing the samples and comparing the obtained values to World Health Organization (WHO) standards, multivariate statistical analysis including Principal Component Analysis (PCA) were applied. Results show that these waters samples are fresh, generally of good quality compared to WHO standards and weakly mineralized (35 to 247.9 mg/l), due to the short residence time. Calcium and magnesium bicarbonate facies is the main water type. Nitrates are the most common pollutants and reveal high vulnerability of saprolite aquifer than fractured aquifer. The groundwater mineralization is influenced by precipitation, base ion exchange process, anthropogenic activities and water-rock interaction through silicate weathering. The PCA analysis yielded three factors that explained 89.33 % of the total variance. Factor 1 (62.60 %), factor 2 (15.54 %) and factor 3 (11.19 %) made respectively the difference between water samples influenced by precipitation or water rock interaction from those influenced by both water-rock interaction with precipitation or anthropogenic activities and those for water rock interaction with ion exchange process.

Keywords: Aquifer vulnerability, Hydrogeochemistry, Principal Component Analysis, Adamawa.

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I. INTRODUCTION

Groundwaters are generally the primary source of water supply for the population of rural area in sub-Saharan countries in general and particularly in Cameroon. These waters are widely used as drinking potable water and for irrigational purposes, due to their relatively good quality in general [1], [2]. According to [3], groundwaters does not require rigorous treatment processes to make it suitable for usage. For this reason, many rural hydraulic programs such as the one in Mbakaou, have enabled the realization of several boreholes to facilitate access to potable water generally without chemical analyses. The lack of knowledge

about groundwater quality in terms of physico-chemical properties does not facilitate water management. To manage groundwater resources and promote the development of rural areas, it is important to know the quality and hydrogeochemical processes that influence water mineralization from the atmosphere to aquifers. Generally, groundwaters comes from rainwater infiltration. As it moves, this water passes through unsaturated to saturated zones and its quality changes due to various processes, including leaching, precipitation, ion exchange, water-rock interaction and anthropogenic activities [4]-[7]. When the natural recharge of aquifers by rain occurs rapidly, the transport of given pollutants from the surface to unconfined

aquifers is eased, causing the deterioration of the groundwater quality. However, this can also affect confined aquifers if its structure allows communication with unconfined aquifers. This context therefore justify why it is important to know the rainwater quality and also why it should be compared to the groundwater in an area where the recharge is made by infiltration. This helps to understand and better explain processes controlling the geochemical evolution of the groundwater in Mbakaou. To achieved this, combination of conventional diagrams (bivariate, Piper, Chadha's and Gibbs) and multivariate statistical analysis through the principal component analysis (PCA) is a useful tool that have been successfully used by many authors [3], [5], [8]-[10] to define and understand the hydrogeochemical processes that influence groundwater quality and sources of pollution. PCA enables to show the differences among physico-chemical parameters at different poles that explains mineralization processes. This study is the first in this locality that intends to assess water evolution from rain to aquifer and proposed mechanism by which water mineralization occurs using both conventional diagrams and multivariate statistical analysis.

II. MATERIALS AND METHODS

A. Study Area

Mbakaou which is located in the Adamawa Region, about 33 km from the southeast of the Tibati city, is well known for its reservoir dam built on the *Djerem* river in 1969. The study area (Fig. 1) extends between latitudes 6°15'N to 6°23'N, and longitudes 12°44'30''E to 12°50'E. The altitudes of the area vary between 800 and 880 m with an average of 840 m. Some permanent or intermittent rivers flow in the large and flat slightly incised valleys. The presence of the Mbakaou dam with a size of about 189.48 Km² has modified the former hydrographic regime of the area. The hydrographic network is very dense, subdendritic, and is made of streams from order 1 to order 4. It is marked at some places by straight portions and numerous waterfalls, which indicate a structural control in the study area. The area has a humid tropical climate, hot and humid, with two distinct seasons. The average annual rainfall is 1908 mm with an average temperature of about 23 °C. The vegetation consists mainly of shrub savannah, which is evolving towards grasslands under the action of bushfires and overgrazing. Some gallery forests remain along rivers. Economically, there is no manufactory industry and income generating activities are farming, fishing and business. Field observations show that there are poor sanitation systems with construction of single pit toilet (with depth of about 5 m) by the population who are the ones in charge of waste management [11].

Fig. 1. Location of study area (A) on geological map of Cameroon and (B) on geological map of study area with different sampling points. (Redrawn from [12] and [13]).

Geologically, this area is located on the central domain of Panafrican fold belt in Cameroon (Fig. 1) and characterized structurally by the presence of a megastructure called the Tibati Shear Zone (TSZ), known as the southern extension of the Central Cameroon Shear Zone (CCSZ, [14]). Depending on the stage of deformation, the rocks of the study area can be classified as pre-tectonic, syn-tectonic or post-tectonic granitoids [12], [15]. The rocks found on the field are fine grain granite, medium grain granite, and porphyroid granite. All these samples outcrops in slabs and blocks next to the Mekay river bridge, in form of blocks in the Djerem river bed, precisely next to the Mbakaou quarry (located southwest of the study area). The mineralogical composition of these granite include quartz, plagioclase, megacrysts of K-feldspar, hornblende, biotite, and accessory minerals such as sphene and oxides. The textures of these rocks are magmatic heterogranular to granoblastic. [16] and [17] shows that plagioclases are zoned in ranged an 15-23; K-feldspar are rich in Or89; Hornblende and biotite with XMg ranging from 0.47 to 0.58. Mineral chemistry of the whole rocks shows that the proportion of K₂O is greater than that of Na₂O, also the proportion of CaO is greater than that of MgO [16], [17].

Adamawa plateau is stretching in predominantly N70°E direction [13], [16]. Some significant fracturing with variable directions and extensions are observed on the rocks. In the field, these formations are highly altered and, in some places, slightly covered by thick banks of alluviums drained by the *Djerem* river. The outcrops are located in the watercourse bed. There are also some rare preferential orientations of feldspar mega-crystals. Three different types of soils developed over granite and orthogneiss are generally

found in the Adamawa plateau: evolved soils, indurated lateritic soils and hydromorphic soils [18], [19]. Lateritic soils (most represented) are rich in residual clays represented in order of abundance by kaolinite, phlogopite, goethite, hematite, halloysite, illite and smectite [18], [19]. Kaolinites are more present on top of the soil profile while illite and smectite are more present at the bottom. According to [19], alkaline and alkaline earths contents are completely leached from bottom to surface in Adamawa plateau rocks weathered products.

Geomorphological context of Mbakaou area shows a plain with a gentle landscape and a slight dissection model known as the Djerem plain. The course of the great collector *Djerem* river and its tributaries follows in most cases the major tectonic features. The Adamawa Plateau is known as the main water tower of Cameroon, particularly due to the abundance of streams and rivers in the region, as observed at Mbakaou. The most important factor that promotes infiltration and groundwater recharge is the peneplain relief. The thickness of the weathered layer is on average of 15 m and represents an important source of alimentation for the deep aquifers of the area [11], [20]. The fact that springs, wells and boreholes are found in the area are evidences of the availability of groundwater resources [20]. Finally, the Mbakaou artificial lake itself constitutes a big reservoir for groundwater supply in the whole region [11]. Hydrogeological studies carried out by [11], [20] and [21], highlight superficial aquifers located between 2 and 17 m and fractured aquifers located between 11 and 74 m, with resistivity ranged from 50 to 671 Ω .m. The boreholes have yields varying between 2.80 and 5.14 m³/h. Transmissivity and permeability range from 10⁻⁶ to 10⁻⁵ m²/s and from 10⁻⁷ to 10⁻⁶ m/s respectively, indicating that aquifers are semi-permeable. The waters are of good quality compared to WHO standards [22], and weakly mineralized (35 to 247.9 mg/l) with calcium and magnesium bicarbonate facies. According to these authors, water mineralization is influenced by water-rock interaction through silicate weathering [21].

B. Sampling and Analytical Methods

A total of eleven water samples (1 from rain water, 1 open well, 3 springs and 6 boreholes) were collected and analyzed in collaboration with three laboratories (Centre Pasteur of Yaoundé, Laboratory of water analysis at geological research and mining institute of Yaoundé and laboratory of soil analysis and environmental chemistry of the faculty of agronomy and agricultural science of University of Dschang). Two samples per point were collected into 500 ml of polyethylene bottles after rinsing at least three times with water to be sampled. Concerning water samples from boreholes, it was pumped up to 5 min to purge aquifers before the sampling operation. During sample collection, care was taken, and standard procedure was applied to avoid contamination. Sampling points were recorded by means of GPS (Garmin etrex-30) and plotted on a map (Fig. 1). Samples locations with aquifer characteristics are resumed in Table 1. The first sample at each point was used for cations analysis and preserved with acid (2 ml of HNO₃), while second sample was used for anions analysis, with no acid. These samples were then

stored and refrigerated in the laboratory until analyses were conducted.

Physicochemical parameters of water including pH, conductivity, temperature and dissolved oxygen were determined in situ using a portable multiparameter (Waterproof-test) probe calibrated with standard solutions.

TABLE 1: LOCATION AND AQUIFER CHARACTERISTICS OF SAMPLING POINTS

Samples	Coordinates		Alt. (m)	Type of aquifer	Water Depth (m)
	Longitude	Latitude			
Springs	S ₁	12°48'23.00''	06°17'51.33''	Unconfined and Saporite aquifer	-
	S ₂	12°49'43.49''	06°18'00.31''		-
	S ₃	12°44'56.43''	06°15'09.20''		-
Well	Pt	12°45'52.38''	06°21'24.73''		12
Boreholes	F ₆	12°47'49.30''	06°18'06.55''	Confined and Fractured aquifer	15-21
	F ₅	12°46'15.38''	06°21'29.63''		35-38
	F ₄	12°48'03.78''	06°17'46.45''		-
	F ₃	12°48'58.44''	06°17'50.52''		48-51
	F ₂	12°47'26.10''	06°18'49.64''		55-60
	F ₁	12°47'21.39''	06°18'28.50''		-
					11-14
					41-53
					56-61
					67-74

Hydrochemical composition of water samples concerning major elements like cations (Ca²⁺, Mg²⁺, Na⁺, K⁺ and Fe²⁺) and anions (Cl⁻, NO₃⁻, SO₄²⁻ and HCO₃⁻) were determined in the laboratory and table 2 summarizes different methods and indicators used for their determination.

TABLE 2: DIFFERENT METHODS USED FOR PHYSICOCHEMICAL PARAMETER ANALYSIS OF WATER SAMPLE

Indicator	Methods	Parameter designation
Systronic-371	Water analyzer	Total Dissolved Solids
Eriochrome black-T	Complexometric EDTA	Total hardness
Eriochrome murexide		Calcium hardness
Methyl-orange	Titrimetric method	Carbonate and Bicarbonate
K ₂ CrO ₄	Argentometric method	Chloride concentration
Brucine	Atomic	
Turbidimetric	Absorption Spectrophotometry	Nitrate (NO ₃)
	Flame photometry	Sulfate (SO ₄)
		Sodium Potassium
	Calculated from total hardness and Calcium hardness	Magnesium

The quality of the investigated water samples for drinking purposes was assessed in comparison with the WHO standards. In order to perform the chemical analyses and some graphical representation (Piper and Gibbs diagrams), open software such as "DIAGRAMMES" version 5.3 were used. To identify different water types and hydrochemical processes, Chadha's diagram was used and created by Ms Excel spreadsheet. To represent this diagram, data was converted to percentage values (milli-equivalent percentages) and expressed as the difference between

alkaline earths (Ca+Mg) and alkali metals (Na+K) for cations plotted on X-axis, and the difference between weak acidic anions ($\text{HCO}_3^- + \text{CO}_3^{2-}$) and strong acidic anions ($\text{Cl}^- + \text{SO}_4^{2-}$) plotted on Y-axis. The resulting field of study is a square or a rectangle that indicated in each of the four quadrants of the graph, the hydrochemical processes [23]. These are broadly brief as: recharging water (Ca–Mg– HCO_3^- -type), reverse ion exchange water (Ca–Mg–Cl-type), seawater/end-member waters (Na–Cl-type), and base ion exchange water (Na– HCO_3^- -type).

Multivariate statistical analyses were performed using Statistica 7.0 software to make a correlation between chemical parameters and determine the principal component analysis (PCA). PCA is important to display a complex relationship among many variables and their hydrogeochemistry roles [1], [4], [5]. It is also used to distinguish different groups of samples in terms of similarities of their origin and processes that govern their mineralogy. This technique was applied on 13 variables and 11 observations. Data have been standardized as required for statistical procedures and different variables were reduced and centred to a few factors that could be interpreted as new variables. Before obtaining these factors, we extracted eigenvalues and eigenvectors of the correlation matrix [1], [6], [10], [24]. The eigenvalues are a key to choose the number of factors used to explain hydrochemical processes that define groundwater quality. Then, an eigenvalue equal or greater than 1 indicates all principal components to adopt according to Kaiser criterion [1], [6], [10], [24]. We also add another criterion to the latter that consisted of conserving all factors with total sums of variance equal or greater than 70% [3], [9].

III. RESULTS AND DISCUSSION

A. Hydrogeochemical Characterization

Analytical results of rain, springs, well and boreholes waters have been summarized in Table 3. In general, the

Electrical Conductivity (EC), increases from rain (6.20 $\mu\text{S}/\text{cm}$) to boreholes (249.2 $\mu\text{S}/\text{cm}$). The pH level of rainwater to groundwater ranges from 5.3 (acidic) to 7.3 (neutral). Cations concentrations in all water samples (comprise between 0.1 and 36 mg/l), are below the WHO standards. Ca^{2+} (in Pt, S₃, F₁, F₂ and F₃) and Na^+ (in Pt, S₁, S₂, and F₅) are the most abundant cations. In many cases, the highest values were obtained in boreholes samples. The order of abundance is as follows: $\text{Ca}^{2+} > \text{Na}^+ > \text{Mg}^{2+} > \text{K}^+$. Anions concentrations in most water samples (0.02 to 195.2 mg/l), are dominated by HCO_3^- which are low (13.4 to 20.7 mg/l) in the well and springs, but high (41.5 to 195.2 mg/l) in boreholes. The order of abundance of other anions were NO_3^- (0.0–13.7 mg/l), SO_4^{2-} (0.52–9.7 mg/l) and Cl^- (0.02–0.56 mg/l). Nitrates (NO_3^-) are present in the well, springs and some boreholes (F₄, F₅ and F₆) but relatively absent in others (F₁, F₂ and F₃). All anions concentrations values (excepted nitrates) are higher in boreholes than in water samples from springs and well. These anions concentration values are lower than the WHO standard limits. These results confirm the evolution of the water mineralization which is function of the residence time, lithological nature of the aquifer and human activities [9], [25]. Comparison between mineralization value of rainwater with springs or well on the one hand and rainwater with boreholes on the other hand, shows that the residence time of the groundwater in boreholes is greater than groundwater of springs or well.

This result is in agreement with those along the Cameroon Line where many authors [26]–[28] argue that low mineralization of groundwaters (less than 500 mg/l) is due to the short residence time and fast flowing water. The fact that the contents of alkalis and alkaline earths metals increase from groundwater of saprolite aquifers to groundwater of fractured aquifers in general, reveal the intense leaching that occurs and confirms the previous study made by [18] and [19].

TABLE 3: PHYSICOCHEMICAL ANALYSIS AND CHLORO-ALKALINE INDEX (CAI) OF WATER SAMPLE IN THE STUDY AREA

Sample	pH	EC $\mu\text{S}/\text{cm}$	Temp (°C)	Na^+	K^+	Mg^{2+}	Ca^{2+}	Fe^{2+}	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	TDS	CAI1	CAI2
mg/l															
meq/l															
R	5.60	6.20	20.30	0.40	0.20	0.03	0.10	0.00	7.00	0.00	0.01	0.00	7.74	-38.97	-0.19
Pt	5.50	13.50	25.20	2.06	1.40	1.20	2.10	0.35	15.80	1.40	0.06	11.20	35.60	-73.23	-0.43
S ₃	5.55	10.50	25.10	1.00	0.90	0.40	1.20	0.31	14.80	0.82	0.03	13.10	32.56	-77.76	-0.25
S ₂	5.71	11.60	25.60	0.98	0.50	0.10	0.10	0.47	20.70	0.00	0.14	0.00	23.10	-13.06	-0.15
S ₁	5.60	15.30	25.90	2.66	1.40	1.30	1.80	0.73	13.40	1.19	0.04	10.90	33.50	-133.50	-0.62
F ₆	5.65	43.00	27.40	1.84	4.30	1.30	2.30	0.56	41.50	1.23	0.02	13.70	66.80	-336.71	-0.27
F ₅	5.25	35.60	27.90	3.88	0.40	0.10	0.50	0.09	36.60	0.00	0.11	9.98	51.60	-56.75	-0.29
F ₄	5.78	61.50	26.30	1.84	5.50	2.60	1.70	0.15	61.00	0.66	0.07	10.90	84.50	-111.09	-0.22
F ₃	7.22	214.00	27.40	10.60	3.80	9.20	18.60	0.30	185.10	0.52	0.56	0.00	228.80	-34.39	-0.18
F ₂	7.31	249.20	27.20	3.48	4.20	1.10	36.00	0.00	195.20	7.70	0.20	0.00	247.90	-44.97	-0.08
F ₁	7.23	244.70	27.50	3.50	5.00	1.10	36.00	0.10	189.10	9.70	0.40	0.00	244.90	-23.88	-0.08
WHO (2006)	6,5 - 8,5	750	/	200	100	30	75	<0,3	200	250	200	10			

Two groups of facies ([29]) were identified in the Mbakaou area (Fig. 2a):

- Calci-magnesian bicarbonate (Ca-(Mg)- HCO_3^-) facies which grouped majority of water samples from springs and well (Pt, S₁, and S₃) and those from boreholes (F₁, F₂, F₃, F₄, and F₆);

- Sodid and potassic bicarbonate (Na-(K)- HCO_3^-) facies which are represented by water from rain (R), spring (S₂) and borehole (F₅).

The first water facies indicates that the mineralization process is mainly influenced by the weathering of silicate [7], [26]–[28], which produces mostly Ca^{2+} and HCO_3^- and influences the water type. The second water facies influenced by Na^+ , is due to the cation exchange process [7],

[25] which indicates the exchange of Ca^{2+} by Na^+ . Variation of facies from the atmosphere to the surface and subsurface suggests that different processes took place when rain fell, and these processes modify water composition and their mineralization.

Fig. 2. Samples grouped in term of Chemical facies A) on the Piper diagram [29] and B) on the Chadha's diagram.

To confirm the results obtained from the Piper diagram, the hydrochemical diagram proposed by [23] was also applied (Fig. 2b) to identify different water types and hydrochemical processes. From this diagram, two types of waters are distinguished: the most dominant Ca – Mg – HCO_3 water type belong to the 5th field and corresponds to recharging waters, followed by Na - HCO_3 water type in field 8 which is less represented and corresponds to the base ion exchange water.

These two types of waters confirm results obtained from the Piper diagram. The most dominant facies observed in this area shows that alkaline earths metals and weak acidic anions in water samples exceed alkali metals and strong acidic anions (Pt, S₁, S₃, F₁, F₂, F₃, F₄ and F₆) respectively. The second facies shows that alkali metals and weak acidic anions in water samples exceed alkaline earths and strong acidic anions respectively (R, S₂ and F₅). Recharging waters are formed when water that enters into the ground from the surface, carries dissolved minerals that contains calcium in

the form of HCO_3 and the geochemically mobile Ca.

Base ion exchange waters are less prominent in the study area, due to the normal ion exchange processes [30], [31]. This result was confirmed by the chloro-alkaline index (CAI) which is computed using the following formula (1) and (2) ([32]):

$$\text{CAI 1} = [\text{Cl}^- - (\text{Na}^+ + \text{K}^+)] / \text{Cl}^- \quad (1)$$

$$\text{CAI 2} = [\text{Cl}^- - (\text{Na}^+ + \text{K}^+)] / (\text{SO}_4^{2-} + \text{HCO}_3^- + \text{NO}_3^-) \quad (2)$$

where all values are expressed in meq/l.

From these indexes, when there is a normal exchange between Ca^{2+} or Mg^{2+} in water with Na^+ and K^+ in the aquifer material, both the above indices give negative values. If these indexes give positive values, there is a reverse ion exchange i.e., exchange between Na^+ and K^+ in water with Ca^{2+} or Mg^{2+} in the aquifer matrix [32], [33]. All samples had negative CAI 1 and CAI 2 values (Table 3), indicating that the normal ion exchange prevailed over the reverse ion exchange in the aquifer matrix.

The characterization of water samples in function of factors that influence mineralization [34], reveals that we have three groups (Fig. 3).

Fig. 3. Mineralization process of the analyzed waters on the Gibbs diagram.

The first group represented by water samples which are entirely influenced by the water rock interaction (WRI) through silicates weathering (F₁, F₂, F₃, F₄, F₅ and F₆).

The second group represented by water samples influenced by WRI and precipitation (Pt, S₁ and S₃).

The third group represented by water samples moderately or only influenced by precipitation (R and S₂).

Based on the Gibbs diagram we can conclude that water mineralization in the study area, is mainly controlled by the WRI process and precipitation.

B. Correlation among Variables

Relationships between the main hydrochemical variables were evaluated using the Pearson correlation coefficient which should either be positive or negative (Table 4), and correlation diagrams (Fig. 4).

TABLE 4: CORRELATION MATRIX OF PHYSICO-CHEMICAL PARAMETER OF WATER SAMPLE IN THE STUDY AREA

	pH	EC	T°C	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	Fe ²⁺	HCO ₃ ⁻	SO ₄ ²⁻	Cl ⁻	NO ₃ ⁻	TDS
pH	1.000												
EC	0.975	1.000											
T°C	0.378	0.498	1.000										
Na ⁺	0.619	0.630	0.503	1.000									
K ⁺	0.640	0.685	0.537	0.337	1.000								
Mg ²⁺	0.527	0.480	0.312	0.898	0.426	1.000							
Ca ²⁺	0.941	0.961	0.415	0.438	0.603	0.255	1.000						
Fe ²⁺	-0.351	-0.427	0.159	-0.053	-0.153	0.066	-0.433	1.000					
HCO ₃ ⁻	0.973	0.997	0.519	0.670	0.695	0.531	0.939	-0.417	1.000				
SO ₄ ²⁻	0.746	0.788	0.351	0.092	0.557	-0.094	0.914	-0.371	0.744	1.000			
Cl ⁻	0.834	0.818	0.457	0.858	0.445	0.745	0.694	-0.217	0.843	0.421	1.000		
NO ₃ ⁻	-0.677	-0.593	0.159	-0.323	-0.076	-0.230	-0.595	0.460	-0.591	-0.409	-0.622	1.000	
TDS	0.968	0.997	0.546	0.659	0.717	0.520	0.946	-0.390	0.997	0.767	0.825	-0.540	1.000

Based on these correlation values we can distinguish three categories of relationships:

- variables with correlation values greater than 0.70 which indicate a high correlation. Therefore, we have a high and strong positive correlation of pH with EC, Ca²⁺, HCO₃⁻, SO₄²⁻, Cl⁻ and TDS; EC with Ca²⁺, HCO₃⁻, SO₄²⁻, Cl⁻ and TDS; Na⁺ with Mg²⁺ and Cl⁻; K⁺ with TDS; Mg²⁺ with Cl⁻; Ca²⁺ with HCO₃⁻, SO₄²⁻ and TDS; HCO₃⁻ with SO₄²⁻, Cl⁻ and TDS; SO₄²⁻ with TDS and Cl⁻ with TDS;

- variables with correlation values ranging between 0.50 and 0.70, which indicate a moderate correlation. According to table 4, we have a moderate relationship which is positive (between pH with Na⁺, K⁺ and Mg²⁺; EC with Na⁺ and K⁺; Temperature with Na⁺, K⁺, HCO₃⁻, and TDS; HCO₃⁻ with Na⁺, K⁺ and Mg²⁺; SO₄²⁻ with K⁺; Cl⁻ with Ca²⁺) and negative (between NO₃⁻ with pH, EC, Ca²⁺, HCO₃⁻, Cl⁻ and TDS);

- variables with correlation values less than 0.50, which indicate a weak correlation like Fe²⁺ with other variables.

These correlation values among variables (Table 4) mean that paired variables have a strong to moderate influence on water mineralization [9]. Moreover, these correlations show that the order of contribution in water mineralization by ions is as follow: HCO₃⁻, Ca²⁺, Cl⁻, SO₄²⁻, K⁺, Na⁺, Mg²⁺ and NO₃⁻. Due to low correlation between Fe²⁺ and TDS, Fe²⁺ contributes less than the other variable to the water mineralization. The strong to moderate positive relationship between major ions (excepted nitrate) implies that these ions were derived from the same source. This is supported by the positive correlation between HCO₃⁻ with Mg²⁺, Na⁺, K⁺, SO₄²⁻, Cl⁻, and Ca²⁺ ($r = 0.531$, $r = 0.670$, $r = 0.695$, $r = 0.744$, $r = 0.843$ and $r = 0.939$, respectively) and also between SO₄²⁻ with K⁺, HCO₃⁻, TDS and Ca²⁺ ($r = 0.557$, $r = 0.744$, $r = 0.767$, and $r = 0.914$ respectively, Table 4) which suggests that weathering of rock-forming minerals is the main source that provide these ions concentration in solution [7]. Fig. 4a and 4b show that all sample points are below equiline 1/1. This fact confirms that WRI through silicates weathering is the main source of ions found in groundwater [31].

Fig. 4. Scatter diagram of A) alkaline earths metals (Ca²⁺ + Mg²⁺) versus total cations (TZ⁺) and B) Ca²⁺ + Mg²⁺ versus HCO₃⁻ + SO₄²⁻.

Concerning nitrate, it is a soluble anion found naturally at low concentrations in precipitation, but it can be enriched to high levels in groundwater by anthropogenic activities [7], [25], [28] like agriculture in many cases. To assess the influence of agricultural practices in groundwater contamination by nitrate, a strong positive relationship should be observed between nitrate and potassium. In the present case the correlation coefficient between NO₃⁻ and K⁺ showed no significant correlation ($r = 0.076$, Table 4) indicating that agricultural practices cannot be considered as the major source of NO₃⁻ in the study area. However, the moderate but negative correlation ($r = -0.622$) (Table 4) between NO₃⁻ and Cl⁻ supports input of NO₃⁻ by human-related activities which in this case can be attributed to poor sanitation conditions [6], [10], [26], [35].

C. Principal Component Analysis (PCA)

Analysis of the influence of different parameters in water mineralization, was performed through PCA of a dataset of 11 observations and 13 variables. According to the Kaiser criterion, three Principal Components were extracted with an eigenvalue greater than 1 (Table 5; Fig. 5), accounting

for 89.33% of the total variance in the dataset.

TABLE 5: AMOUNT OF VARIANCE THAT EXPLAIN COMPONENTS CHOSEN

	Eigenvalue	% of variance	Cumul % of variance
PC1	8.14	62.60	62.60
PC2	2.02	15.54	78.13
PC3	1.45	11.19	89.33
PC4	0.61	4.72	94.04
PC5	0.48	3.68	97.72
PC6	0.19	1.47	99.19
PC7	0.08	0.60	99.79
PC8	0.02	0.18	99.97
PC9	0.00	0.03	100.00
PC10	0.00	0.00	100.00

Fig. 5. Eigenvalues of Principal Components.

Component 1 (PC1) explains 62.60% of the total variance (Fig. 6). PC1 is characterized by a high positive loadings on eleven variables (HCO_3^- , Ca^{2+} , Cl^- , SO_4^{2-} , K^+ , Na^+ , Mg^{2+} , TDS, EC pH and Temperature) and negative loadings on two variables (NO_3^- and Fe^{2+}). This shows that chemical parameters correlated positively are those which highly control water mineralization in the study area [9] and concentration of these parameters are linked to the pH and temperature. There is association of Na^+ and Cl^- to this PC1 and a high correlation between them (Table 4); this suggests salinization. Because there is no marine water but a lake in the study area, excess sodium observed in these samples can come from rocks weathering and leaching. Negative loading of nitrate which is on the opposite side of the other ion suggests groundwater pollution by anthropogenic activities. Then the component 1 is defined as mineralization by rock weathering process which is dominant and anthropogenic activities.

Component 2 (PC2) describes 15.54% of total variance. PC2 is characterized by a moderate positive loading of SO_4^{2-} , and negative loading of Na^+ , Mg^{2+} and Fe^{2+} . This fact confirms that these ions which contributes to water mineralization, may have different origins: WRI (by silicate weathering of ferromagnesian minerals and sodic feldspars) and anthropogenic factors [6], [9], [36].

Fig. 6. Hydrochemical variables plotted on the A) F1xF2 and B) F1xF3 axis.

However, the fact that Na^+ with Mg^{2+} are highly correlated and are on opposite side with Fe^{2+} and Ca^{2+} , suggests that PC2 explains the ion exchange process [1]. The origin of Fe^{2+} , Mg^{2+} and Na^+ can be attributed to the hydrolysis of ferromagnesian rich minerals [26], [27] such as hornblende and biotite that are composed of basement rocks [16], [17]. Na^+ and Ca^{2+} can be attributed to the hydrolysis of plagioclase as suggested many authors along the Cameroon Line in the basement area ([26], [27] in Western Highlands of Cameroon; [28] in Mbanga, Njombe and Penja in Mungo Division; [7] in West Cameroon).

Component 3 (PC3) explains 11.19% of the total variance in water chemistry. PC3 has negative loading with NO_3^- and temperature. This implies that the concentration of this ion is also influenced by temperature like others. The fact that PC3 is correlated to nitrate, explains groundwater pollution by anthropogenic activities [1], [10], [24], [35]. The presence of nitrate in some groundwater may be due to leaching of NO_3^- from fertilizers or waste disposal during infiltration [24], [36]. The fact that water from some boreholes (F₄, F₅ and F₆), springs (S₁ and S₃) and well (Pt)

contain nitrate confirms that the water from these structures (boreholes, springs and well) are the mixture of surface water, groundwater from saprolite layer and groundwater from fractured aquifers.

Individual factor maps help to identify the contribution of water samples in the definition of different axes that constitute principal component (Fig. 7) and makes a difference between samples in function of mineralization processes.

Fig. 7. Individual factor map on the A) F1xF2 and B) F1xF3 axis.

According to this individual factor map along the F1 axis, two groups are distinguished between these samples. The first group concerns water from boreholes F₁, F₂ and F₃ with high mineralization and mainly influenced by WRI. Second group corresponds to water samples with low mineralization, influenced by precipitation (R and S₂) and both processes, precipitation with WRI (F₅ Pt, S₃, S₁, F₄, and F₆). Factors 2 and 3 allow distinguishing three groups of water samples. The first group represented by R and S₂ samples are influenced by precipitation. The second group represented by samples F₅, Pt, S₃, S₁, F₄, and F₆, in which mineralization is influenced either by precipitation, WRI or by anthropogenic activities. The fact that water samples from boreholes belong to the same group with those from springs and well suggest the mixing of the good groundwater with the infiltration of poor water quality [10], [24]. This situation can be justified by the presence of nitrate despite the fact that water samples came from fractured aquifer. The third and last group represented by F₁, F₂ and

F₃, corresponds to water samples in which mineralization processes are mainly influenced by WRI through hydrolysis and the ion exchange process [10], [35].

IV. CONCLUSION

Assessment of factors influencing water mineralization through conventional diagrams and statistical analyses in the Mbakaou area revealed that the water sources are slightly acidic to neutral. Piper and Chadha's diagrams show that two facies are represented: Calci-magnesian bicarbonate (Ca-(Mg)-HCO₃) facies and Sodici and potassic bicarbonate (Na-(K)-HCO₃) facies. Mineralization processes according to conventional diagrams and multivariate statistical analysis are influenced by four main processes: precipitation, water rock interaction, base ion exchange processes and anthropogenic activities. The mineralization process of some boreholes and springs are influenced by water rock interaction, mixing of rain with good groundwater which through leaching of infiltration contribute to pollution from nitrates which can be attributed to anthropogenic activities. Leaching contributes to export of alkaline and alkaline earths metals from the top of the soil profiles to the bottom and increases these ions in groundwater from saprolite to fractured aquifer.

To manage groundwater quality efficiency in Cameroon in general and in the Adamawa plateau particularly, the main pollutant which is nitrate should be used as an indicator to assess if waters from realized boreholes coming exclusively from closed fractured aquifers or if these waters are mixed with those coming from saprolite aquifers which are more vulnerable. It results from this study that conventional hydrogeochemical diagrams coupled with multivariate statistical analysis are suitable for better understanding of hydrogeochemical processes which influenced water mineralization.

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