Multivariate statistical analysis of the hydrochemical characteristics of a sedimentary aquifer: the case of Pala (Burkina Faso)

ABSTRACT

The quality of groundwater and spring water in the Pala locality, influenced by both natural processes and human activities, is a major issue in the supply of drinking water to the city of Bobo Dioulasso. The geological context is mainly composed of Sotouba sandstone. This influences the chemical composition of the aquifers through water-rock interaction. This study examines the hydrogeochemical characteristics of the region's water resources in order to shed light on sustainable management strategies. For this fact, physico-chemical parameters of rainwater, and existing springs and boreholes were analysed in accordance with current standards. Statistical methods including correlation analysis, principal component analysis (PCA), factor analysis (FA) and hierarchical clustering (HCA) were used for interpretation. The results indicate that spring water is less mineralised than borehole water, which shows greater variability in physical and chemical parameters such as pH, electrical conductivity (EC) and turbidity. Major ions, dominated by bicarbonates and calcium, influence the main water facies, which are calcic bicarbonate and calcic and magnesian bicarbonate. Analysis of heavy metals reveals concentrations below WHO standards. The PCA identifies the dominant factors influencing water chemistry. Factor analysis highlights the significant contributions of ions and the importance of understanding hydrogeochemical processes. At present, the spring and borehole water in the study area is fit for drinking in terms of physico-chemical properties and metals in the parameters analysed. Recommendations include the establishment of monitoring frameworks to protect water quality from potential sources of pollution, underlining the need for proactive management strategies in the region.

Keywords: Hydrochemical, PC, HCA, FA, pollution, spring, groundwater

1. INTRODUCTION

The quality of groundwater and surface water, influenced by a variety of natural and anthropogenic factors, is one of the most sensitive issues in the world. It is generally governed by the nature of geochemical reactions, the solubility of salts, the weathering of rocks, the speed and quantity of surface and groundwater flow, crystallisation by water evaporation and the input of atmospheric precipitation materials, and anthropogenic activities. [1], [2], [3], [4], [5].

The interaction between water, atmospheric carbon dioxide and continental rocks leads to the dissolution of minerals that are transported by surface water. [6]. The quality of these waters is a critical factor influencing human health and agro-pastoral production. [7].

Interactions between groundwater and surface water are fairly common in catchment areas. [8], [9]. It is therefore necessary to understand the relationship between groundwater and surface water as well as the mechanisms of mineralisation for better use and sustainable management of precious water resources, especially in arid and semi-arid zones. [10], [11]. The content of the main ions in water is widely used to identify the processes that control its mineralisation. [3], [12], [12], [13], [14], [15], [16], [17], [18], [19], [20].

Piper's trilinear diagram is a widely used tool for assessing hydrogeochemical types and quality control mechanisms in groundwater [16], [21], [22].

Statistical analysis (regression analysis, correlation coefficient) is used to establish the relationship between two variables, test significant hypotheses and study the distribution of the population. [23], [24], [25].

Chemometric analysis such as principal component analysis and hierarchical cluster analysis can help to reduce the number of chemical variables in a dataset to a small number without losing important information, and to divide a large dataset into clusters of similar characteristics [17], [26], [27], [28], [29].

These approaches are crucial for a more in-depth understanding of the hydrogeochemical mechanisms and their controlling factors in groundwater chemistry with a view to proactive management measures. These tools are therefore used in the present study.

The city of Bobo Dioulasso is supplied with drinking water from spring exsurgences and boreholes, including those at Pala. The city's demographic explosion has led to its expansion and to strong pressure on these water resources. This is the case around the boreholes supplying drinking water to the Office National de l'Eau et de l'Assainissement (ONEA) in Pala, where housing, industry and agro-pastoral farms have sprung up. This poses a threat to the quality of the water that will be extracted [30]. Unfortunately, very few studies cover the catchment area. It is therefore necessary to determine the physico-chemical quality of the water and the processes that govern its mineralisation. It is with this in mind that this study was carried out. Its objectives were (a) to assess the quality of groundwater for domestic and industrial uses, (b) to identify the types of groundwater and the mechanisms that control groundwater chemistry, and (c) to determine the origin of the main springs.

This comprehensive study fills a gap in knowledge of water resources and can serve as a data base for decision-making on sustainable groundwater management systems in the region.

2. GEOGRAPHY AND GEOLOGICAL CONTEXT

2.1. GEOGRAPHY OF STUDY AREA

Our study area is located in the rural commune of Pala at the southeast entrance of Bobo Dioulasso, the second largest city in Burkina Faso (Fig.1). The climate is of Sudanian type characterized by alternating dry and rainy seasons. Average temperatures range between 25 and 31 °C. The hottest months are October, March, and April, while August and December are the coldest. Potential evapotranspiration is significant, ranging between 1800 and 2150 mm/year [31]Topographically, it lies on the watershed line of two sub-basins of the Mouhoun River at an altitude of around 400 meters.

2.2. GEOLOGICAL CONTEXT

From geological standpoint, Pala is part of the south eastern Taoudéni Sedimentary Basin (Fig. 1) of the upper Precambrian to Palaeozoic age [32], [33], [34]. The local lithology is mainly composed of a mixture of sandstones, fine glauconitic sandstone (also known as Sotouba sandstone), sandstone with quartz grains, siltstones [35].

Hydrogeological studies have indicated that the hydraulic gradient of the aquifers is relatively low (less than 0.3% in the east-west direction), and their transmissivity is about $3.10\ 10^{-4}\ m^2/s$ [36]. Conversely, the permeability of these sandstone aquifers is high ($1.8\ 10^{-6}$ m/s), and their storage coefficient is approximately $1\ 10^{-4}$ [37]. Overall, groundwater flows from north to south along numerous faults, facilitating the infiltration of rainwater into the aquifer.

3. MATERIAL AND METHODS

A total of 13 water samples, including one from rain, three from springs and nine from underground existing boreholes, were taken between 6 and 7 October 2022 (Fig. 2). It is important to note that there are not enough boreholes in the study area.

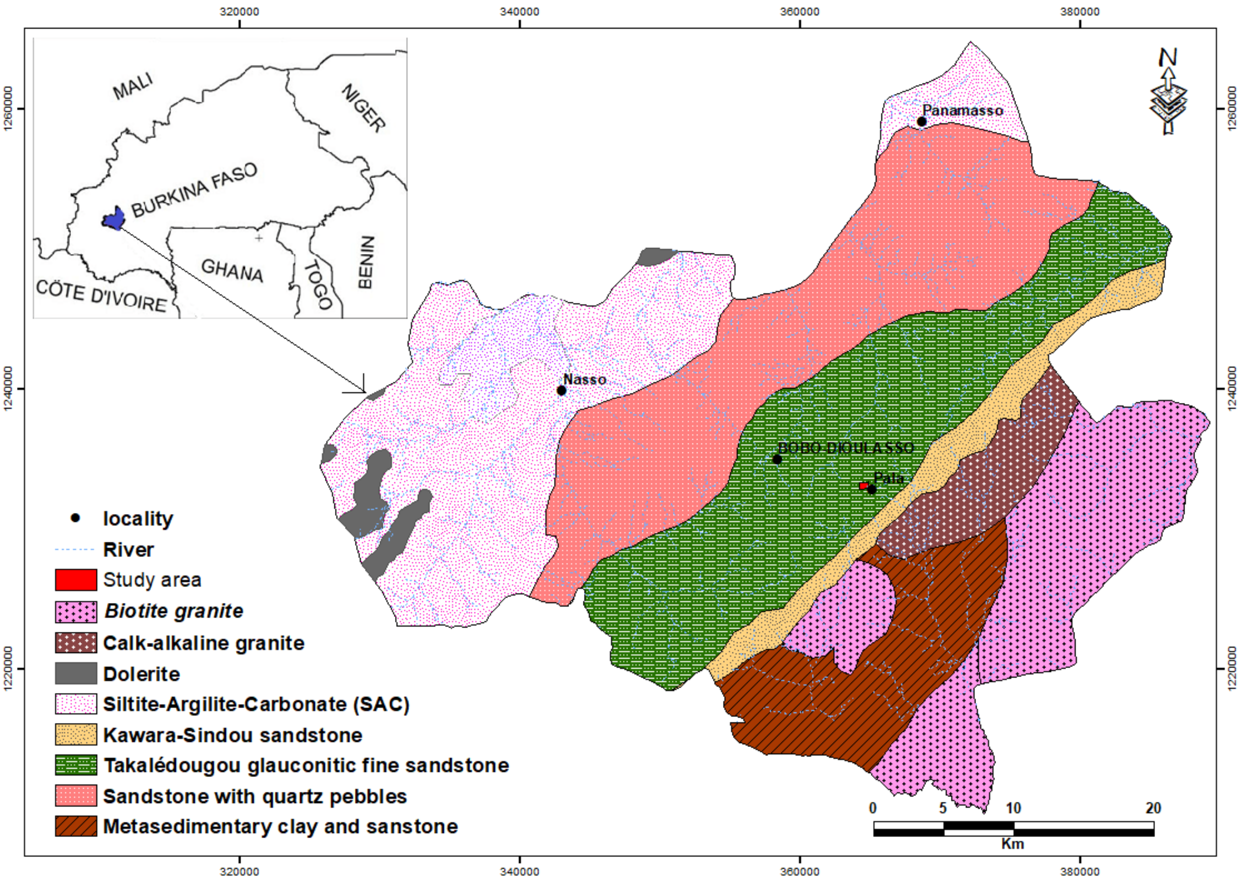

Figure 1: Geological map

To ensure that the borehole samples were indeed representative of groundwater and not of water that had been in the boreholes for some time, we put the boreholes into production for a few minutes (10-15 minutes) before the samples were taken. All of the samples were collected in 1L polyethylene bottles and were acidified by chloride acid for the analysis.

The physical parameters such as pH, Temperature, electrical conductivity (EC) and turbidity were measured in field under minimum atmospheric contact, using a calibrated meter.

Majors cations and anions were analysed at the hydrochemistry laboratory SENEXEL in Ouagadougou/Burkina Faso by ion chromatography using standard procedures (American Public Health Association [38]. The other metallic elements such as Ba, CN-, As, Cd, Co, Cr, Cu, Hg, Ni, Pb, V and Zn were analysed using inductively coupled plasma mass spectrometry (ICP-MS). The analytical accuracy was cross-checked by calculating ionic balance error as follows (Eq. 1):

$$\text{IBE}\ (\%) = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} x100 \quad (1)$$

In general, the value of IBE should be less than ± 5%, and certainly less than ± 10% [39]. In this study, all samples were IBE values less than ± 5% (Fig. 3).

To understand the chemistry of water samples, the approach is to study the statistical relationships between their dissolved constituents and environmental parameters, such as lithology, using multivariate statistics [40]. Multivariate statistical techniques which include HCA, FA and PC are effective means of manipulating, interpreting and representing data concerning groundwater pollutants and geochemistry [41], [42], [43].

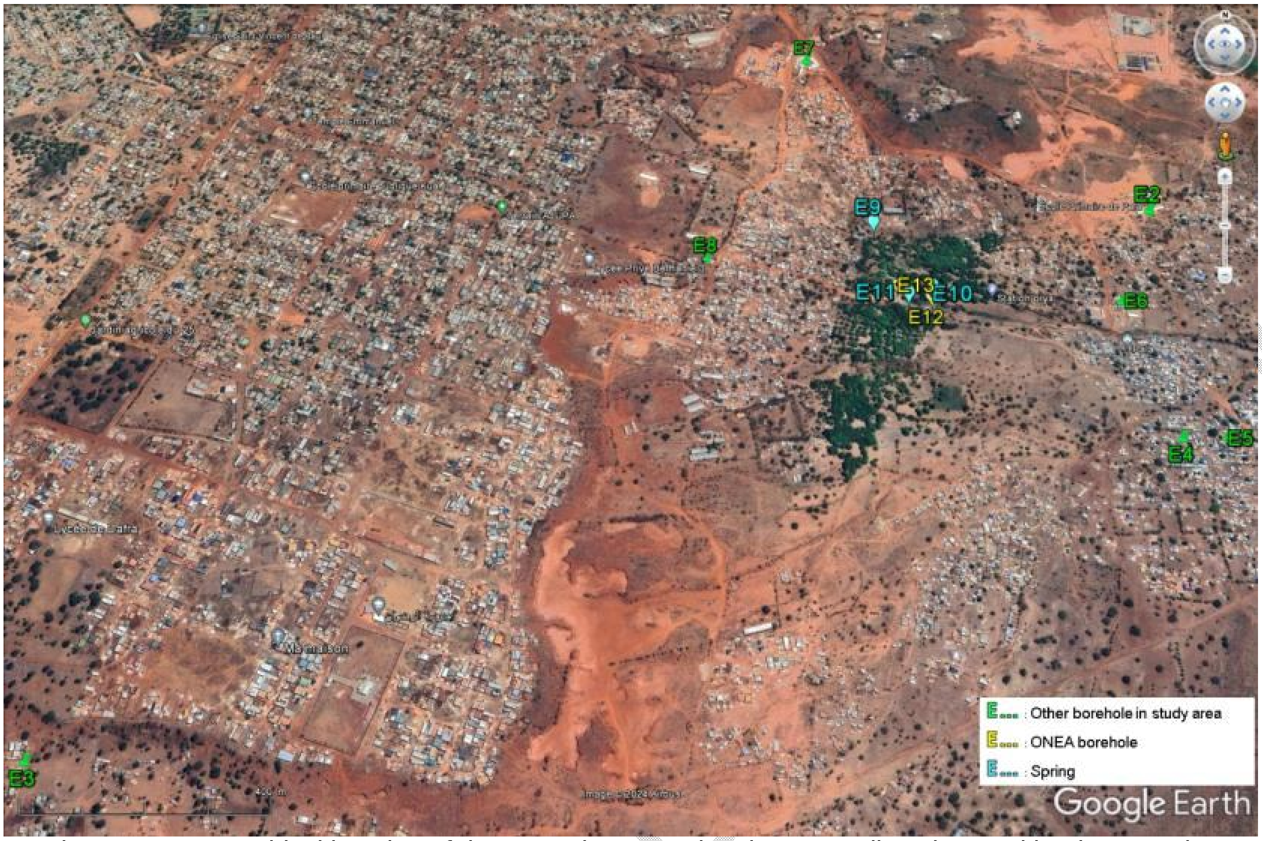

Figure 2 : Geographical location of the groundwater and springs sampling sites and land occupation

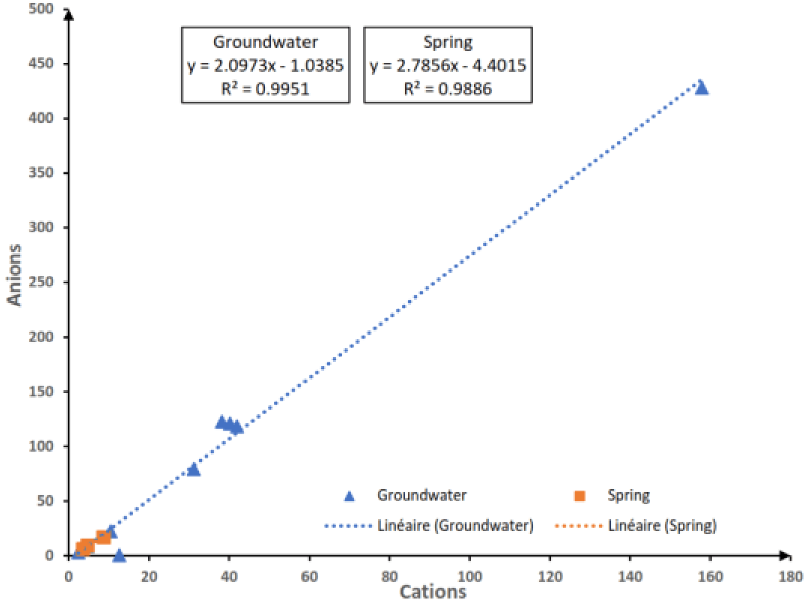

Figure 3 :Ionic balance of major elements

4. RESULTS AND DISCUSSION

4.1. HYDROCHEMICAL CHARACTERISTICS

4.1.1. PHYSICO-CHEMICAL PARAMETERS

The results of physical parameters measured in the groundwater samples are presented in Table 1. On the whole, spring water is less mineralised than groundwater. Some values of physical and chemical parameters in borehole water vary considerably from one borehole to another. This is illustrated by the standard deviation values, which are variables such as EC (194.65 µS/cm), Turb (120 NTU) and HCO3- (135.37 mg/L).

Table 1 : The analytical value on the total hydrochemical parameters in the study area

Type		**Springs**			**Boreholes**			
Variable	**Unit**	**Min**	**Max**	**Number of samples >WHO 2008 value**	**Min**	**Max**	**Number of samples >WHO 2008 value**	**WHO (2008)**
pH		5.01	5.60	0	5.62	6.62	0	6.5-9.2
EC	µS/cm	24.10	49.40	0	9.90	611.00	0	400-500
TAC	meq/L	0.07	0.26	0	0.04	6.92	0	25
TH	mmol/L	0.09	0.12	0	0.03	3.03	0	50°f
Turb	NTU	1.50	6.98	0	0.39	344.40	2	5
Ca^{++}	mg/L	2.24	3.12	0	0.64	117.20	0	100
Mg^{++}	mg/L	0.77	1.06	0	0.38	10.90	0	200
Na^{+}	mg/L	0.36	2.82	0	0.43	4.77	0	200
K^{+}	mg/L	0.13	1.68	0	0.98	33.55	2	12
Fe_T	mg/L	0.02	0.45	1	0.00	0.12	0	0.3
F-	mg/L	0.00	0.16	0	0.00	0.17	0	1.5
HCO_3^{-}	mg/L	4.27	15.86	0	2.68	422.12	3	100
Cl^{-}	mg/L	0.80	1.20	0	0.60	1.20	0	250
SO_4^{--}	mg/L	0.00	1.00	0	0.00	5.00	0	250
NO_2^{-}	mg/L	0.01	0.02	0	0.01	0.01	0	0.1
NO_3^{-}	mg/L	6.10	7.60	0	2.60	6.50	0	45
PO_4^{---}	mg/L	0.03	0.04	0	0.03	0.24	0	0.5
NH_4^{+}	mg/L	0.00	0.11	0	0.00	0.16	0	0.4
Al^{++}	mg/L	0.04	0.36	---	0.00	0.09	---	---
Ba	mg/L	0.03	0.03	0	0.00	0.40	0	0.7
Mn^{++}	mg/L	0.00	0.02	0	0.00	0.60	2	0.4
CN^{-}	µg/L	0.00	0.00	0.00	0.00	0.01	0.00	10

The pH valueswere acid from groundwater indicate a variance of 5.1 to 5.6 in spring values, and from 5.62 to 6.62 in borehole. As for EC, it varied between 24.10 and 49.40 in springs, then 9.90 and 611 in boreholes. These low pH and EC values agreed with those presented by [22], [44], [45] for groundwater samples from the Southwestern border of Taoudéni sedimentary sandstone aquifers. Turbidity value in 2 borehole and 1 spring are higher than the recommended value of 5 NTU (WHO 2008). Water turbidity is usually associated with suspended matter [46] and also indicates the growth of pathogenic microorganisms in water [47]because suspended particles can protect microbes. The higher values can be caused by clay, organic particles (decaying plants or animals), and inorganic particles by natural geological factors [48], [49]. Acidic nature encourages rock-groundwater interactions that result in increased water turbidity due to rock weathering [50]. The total hardness of the water from the springs and boreholes varies from 0.07 to 3°f, indicating that all the water is soft.

4.1.2. MAJOR ION CHEMISTRY

The major cations (Ca^{2+}, Mg^{2+}, Na^{+} et K^{+}) concentrations in spring water were low and were under WHO values. The low concentrations of base cations in spring water can be attributed not only to the short residence time of the groundwater but also to the high resistance of the local bedrock, which is mainly sand, to chemical alteration [51]. In the borehole water, the main cations (Ca^{2+}, Mg^{2+}, Na^{+} et K^{+}) have concentrations higher than those in the springs but also lower than WHO values, with the exception of potassium in two samples.

We can therefore deduce that certain aquifers exploited by borehole have a longer residence time than that of springs.

Anion concentrations are below WHO standards for both spring and borehole water. Thus, the overall order of abundance is $HCO_3^- > NO_3^- > SO_4^{2-} > Cl^-$ in both spring and borehole waters. The nitrite ion (NO_2^-) is also present but in very low concentrations. No water has a nitrate concentration higher than the World Health Organisation (WHO) standard of 50 mg/L. Ammonia (NH^{4+}) is found in all the surface waters at very low and variable concentrations (0 mg/L to 0.11 mg/L). Analysis of PO_4^{3-} ions did not reveal any significant variations in content in the various waters.All waters have levels below 0.24 mg/L.

The representation of all the waters analysed on the Piper diagram (Fig. 4) shows a certain balance of cations, with the exception of borehole sample E2.

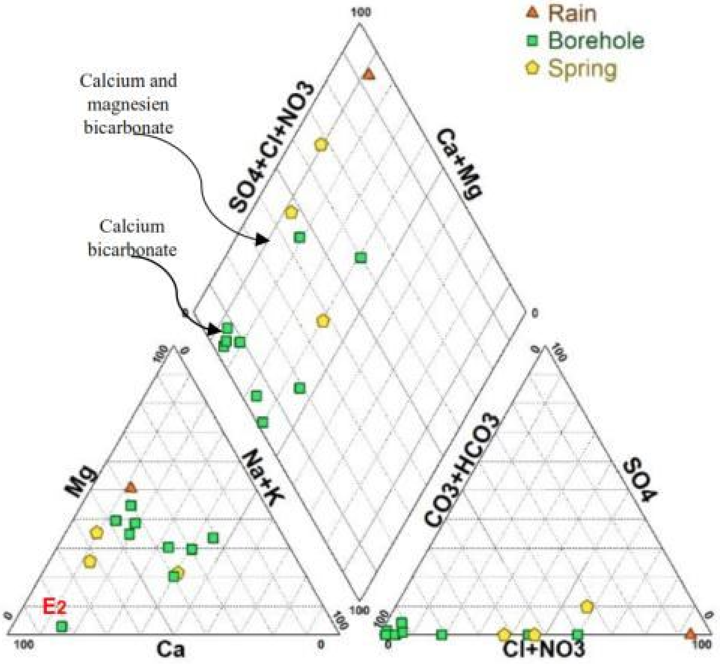

Figure 4 : Piper'sTrilinearplotdiagramonhydrochemicalfaciesforthemajorionsof water samples

In the anion triangle, the majority of waters are grouped in the bicarbonate pole, which belongs to groundwater. Spring waters tend towards the chloride + nitrate pole (dashed arrow). These waters have high nitrate levels, often associated with chloride, but well below the WHO standard for drinking water. Borehole water is predominantly calcium bicarbonate, unlike spring water, which is calcium and magnesium bicarbonate. This predominance is confirmed by the Stiff diagram (Fig. 5).

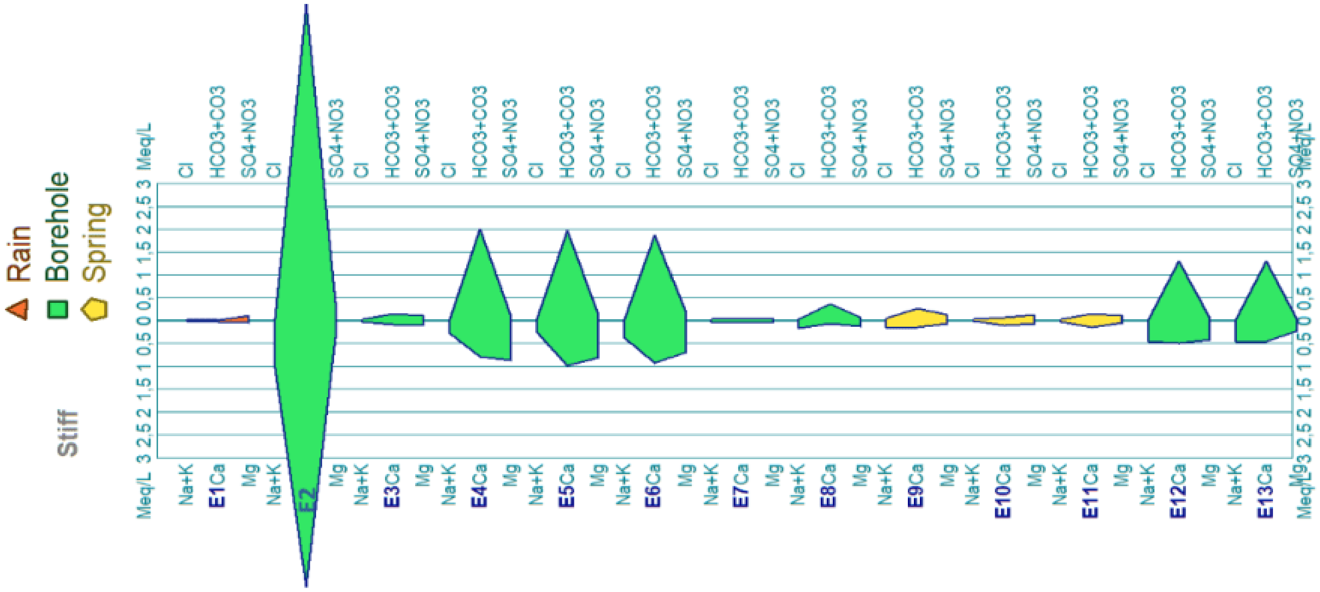

Figure 5: Water classification on the Stiff diagram

There is a strong correlation between the electrical conductivity of borehole water and bicarbonate content, with a coefficient of determination of 0.99 (Fig. 6).

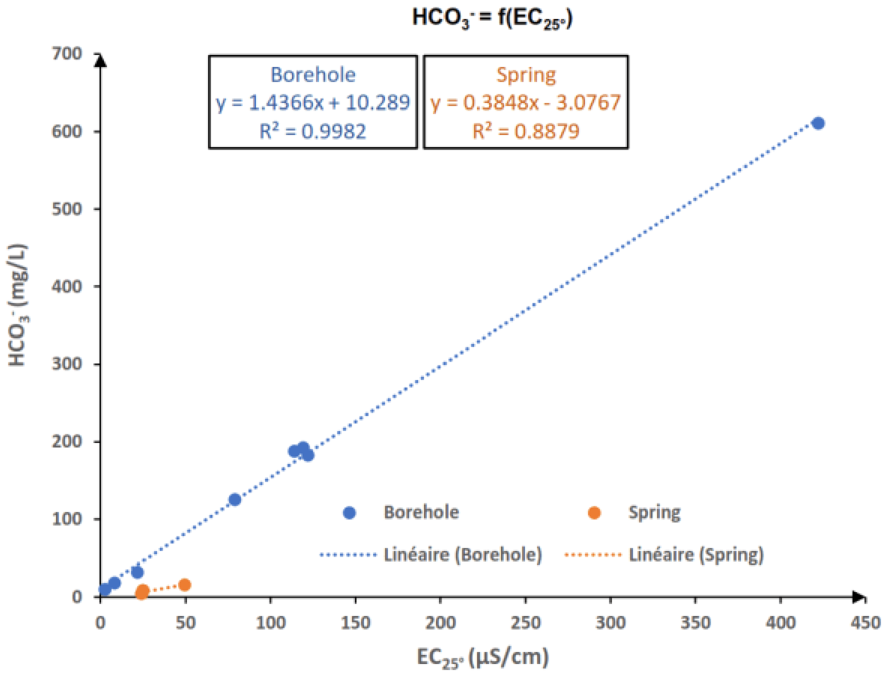

Figure 6 :Correlation between HCO3- content and EC

4.1.3. HEAVY METAL CHEMISTRY

Concentrations of Al, Mn, Ba, CN^- are very low and variable and well above WHO standards. Other metals such as As, Cd, Co, Cr, Cu, Hg, Ni, Pb, V and Zn were analysed, but their values were above the instrumental detection limits. Fe_T concentrations in the springs vary from 0.02 to 0.45mg/L. This concentration decreases in the borehole water, ranging from 0 to 0.12 mg/L. Only the E9 sample has a Fe_T content above the WHO standard. This high level could be linked to anthropogenic pollution due to the presence of potential pollution sources around the spring. According to [52], groundwater with an Fe concentration greater than 0.12 mg/L gives water an unpleasant metallic taste, and a concentration greater than 0.3 mg/L stains clothes.

4.2. STATISTICAL ANALYSE

Correlation coefficient is commonly used to measure and establish the relationship between two variables. It is a simplified statistical tool to show the degree of dependency of one variable to the other.A negative r value indicates an inverse relationship and a positive r value indicates a direct relationship [53]. The results of Pearson's correlation matrix in Table 2 show that the electrical conductivity has high correlations with K^{+} (r=0.97), HCO$_{3}^{-}$ (r=0.99), SO42- (r=0.82), Ba (r=0.77) indicating the contribution of major ions to the salinity of groundwater in the area. Other weak, moderate, and strong correlations have been established between different parameters.

4.2.1. PRINCIPAL COMPONENT ANALYSIS

For this analysis, only two principal components (PCs) with eigenvalues greater than 1 were retained, as suggested by the Kaiser criterion [54], [55].

PC1 represents 38.04% of the total variance within the data (Table 3); it shows positive weightings of all the variables. In particular, the highest weightings in PC1 are Ca$^{2+,}$ K^{+}, HCO$_{3}^{-}$, TAC, TH and electrical conductivity, which control mineralisation in this component, showing the dominance of these ions in water.

CP2 accounts for 22.32% of the total variance in the data (Table 3); it is associated on the one hand with the negative weights of Mn^{2+}, NO$_{3}^{-}$, NO$_{2}^{-}$, NH^{4+} and F^{-}, and on the other hand with positive weights for NO$_{3}^{-}$ even though the levels are below the WHO standard. The first two components account for approximately 60.36% of the variability in the data.

Figure 7 is a projection of the scores in PC1 and PC2 for all the water analyses, separated by the cluster to which they belong.

Table 2 : Table of component weightings principal component Eigenvalues and variance of principal components

	F1	F2
TAC	**0.9758**	0.0128
TH	**0.9233**	0.0687
Turb	0.0086	0.1621
CE	**0.9756**	0.0164
pH	0.1254	0.1838
Ca^{2+}	**0.9242**	0.0209
Mg^{2+}	0.0962	0.0126
Na^{+}	**0.5359**	0.0451
K^{+}	**0.9720**	0.0002
Fe	0.0259	0.0092
F^{-}	0.0417	**0.7074**
HCO$_{3}^{-}$	**0.9798**	0.0065
Cl^{-}	0.2247	**0.3019**
SO$_{4}^{2-}$	**0.6631**	0.0768
NO$_{2}^{-}$	0.0063	**0.5437**
NO$_{3}^{-}$	0.0109	**0.7048**
PO$_{4}^{3-}$	0.0235	0.0595
NH$_{4}^{+}$	0.0666	**0.6953**
Al^{2+}	0.0644	0.0715
Ba	**0.6974**	0.1372
Mn^{2+}	0.0261	**0.8352**
CN^{-}	0.0014	0.2396
Eigenvalue	8.3689	4.9113
Variability (%)	38.0405	22.3240

Cumulative %	38.0405	60.3645

Table 3: Pearson correlation for the physicochemical parameters for wet season samples

Variables	TAC	TH	Turb	CE	pH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Fe	F^{-}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	NO_2^{-}	NO_3^{-}	PO_4^{3-}	NH_4^{+}	Al^{2+}	Ba	Mn^{2+}	CN^{-}
TAC	**1.00**																					
TH	**0.99**	**1.00**																				
Turb	0.00	-0.03	**1.00**																			
CE	**1.00**	**0.99**	0.00	**1.00**																		
pH	0.30	0.22	-0.09	0.28	**1.00**																	
Ca^{2+}	**0.98**	**0.97**	-0.06	**0.97**	0.25	**1.00**																
Mg^{2+}	0.32	0.32	0.11	0.34	0.22	0.12	**1.00**															
Na^{+}	**0.67**	**0.63**	**0.60**	**0.68**	0.10	**0.65**	0.10	**1.00**														
K^{+}	**0.98**	**0.95**	0.10	**0.97**	0.31	**0.94**	0.35	**0.71**	**1.00**													
Fe	-0.16	-0.15	-0.11	-0.13	-0.19	-0.11	-0.28	0.22	-0.20	**1.00**												
F^{-}	0.12	-0.03	-0.01	0.11	0.48	0.10	-0.04	0.13	0.16	-0.05	**1.00**											
HCO_3^{-}	**1.00**	**0.98**	-0.01	**1.00**	0.31	**0.98**	0.32	**0.67**	**0.98**	-0.16	0.15	**1.00**										
Cl^{-}	0.53	**0.59**	-0.34	**0.56**	-0.02	0.54	0.20	0.34	0.42	0.46	-0.24	0.52	**1.00**									
SO_4^{2-}	**0.81**	**0.83**	-0.17	**0.82**	0.24	**0.81**	0.23	0.42	**0.81**	-0.16	0.07	**0.80**	0.46	**1.00**								
NO_2^{-}	-0.14	-0.27	-0.17	-0.14	0.42	-0.13	-0.20	-0.01	-0.14	0.33	**0.86**	-0.11	-0.09	-0.25	**1.00**							
NO_3^{-}	-0.02	0.11	-0.38	0.00	-0.36	0.04	-0.04	-0.14	-0.15	0.33	**-0.68**	-0.05	**0.68**	0.10	-0.43	**1.00**						
PO_4^{3-}	0.21	0.22	-0.26	0.22	0.17	0.06	**0.82**	-0.23	0.17	-0.25	-0.04	0.21	0.15	0.17	-0.14	0.04	**1.00**					
NH_4^{+}	0.14	0.01	0.44	0.14	0.53	0.12	-0.08	**0.57**	0.20	0.24	**0.72**	0.17	-0.09	-0.06	**0.72**	-0.53	-0.31	**1.00**				
Al^{2+}	-0.23	-0.20	-0.14	-0.20	-0.32	-0.19	-0.21	0.12	-0.29	**0.95**	-0.23	-0.24	0.51	-0.21	0.19	0.52	-0.14	0.08	**1.00**			
Ba	**0.78**	**0.71**	0.29	**0.77**	0.26	**0.82**	-0.11	**0.80**	**0.81**	-0.10	0.44	**0.79**	0.17	0.55	0.18	-0.36	-0.27	0.53	-0.25	**1.00**		
Mn^{2+}	0.04	-0.09	**0.69**	0.03	0.30	-0.02	0.04	0.49	0.14	-0.09	**0.70**	0.06	-0.43	-0.18	0.54	**-0.75**	-0.20	**0.86**	-0.22	0.49	**1.00**	
CN^{-}	-0.03	-0.14	-0.29	-0.04	0.15	-0.11	0.24	-0.19	-0.01	-0.05	**0.63**	0.00	-0.11	-0.26	**0.65**	-0.40	0.26	0.27	-0.12	0.05	0.30	**1.00**

Table 4: Principal Component Factor Analysis completed using the varimax rotation

	F1	F2	F3

TAC	**0.9902**	0.1133	0.0217
TH	**0.9637**	0.2633	0.0193
Turb	0.0939	-0.4168	-0.0548
CE	**0.9898**	0.1278	0.0028
pH	0.3260	**-0.3731**	0.1677
Ca^{2+}	**0.9633**	0.1430	-0.0805
Mg^{2+}	0.3081	0.1212	0.5067
Na^+	**0.7345**	-0.2276	-0.4398
K^+	**0.9858**	0.0143	0.0675
Fe	-0.1577	0.0859	**-0.8590**
F^-	0.2011	**-0.8351**	0.0248
HCO_3^-	**0.9922**	0.0809	0.0226
Cl^-	0.4686	**0.5376**	-0.4685
SO_4^{2-}	**0.7893**	0.2639	0.0640
NO_2^-	-0.0807	**-0.7348**	-0.3010
NO_3^-	-0.1008	**0.8082**	-0.3322
PO_4^{3-}	0.1491	0.2486	**0.5282**
NH_4^+	0.2552	**-0.8349**	-0.3705
Al^{2+}	-0.2526	0.2607	**-0.8525**
Ba	**0.8340**	-0.3787	-0.1875
Mn^{2+}	0.1613	**-0.9273**	-0.0399
CN^-	-0.0363	-0.4427	0.1699
Eigenvalue	8.3254	4.8014	2.8753
Variability (%)	37.8428	21.8246	13.0695
Cumulative %	37.8428	59.6674	72.7369

Groups 1 and 3 are the only clusters with positive weightings in PC1 and correspond to the most mineralised clusters in the dataset. These two groups were very rich in HCO_3^-, Ca^{2+} and K^+.

Conversely, group 2 samples have a negative weighting in PC1 and correspond to the most recent groundwater. This is evidenced by their proximity to the rainwater sample in red (E1).

As far as PC2 is concerned, group 1 shows positive weightings, these samples having a fluoride, nitrate and manganese character even though these levels are well below the WHO standard.

Groups 2 and 3 only show negative weightings in PC2; group 2 samples are dominated by nitrate and have high concentrations of iron and aluminium (Table 4). Group 3 samples are dominated by HCO_3^-, Ca^{2+} and K^+.

A clear differentiation between the scores of each group can be seen in Fig. 7, which shows no overlap, making it possible to define group zones (separated by black lines in Fig. 7) in the graph of scores.

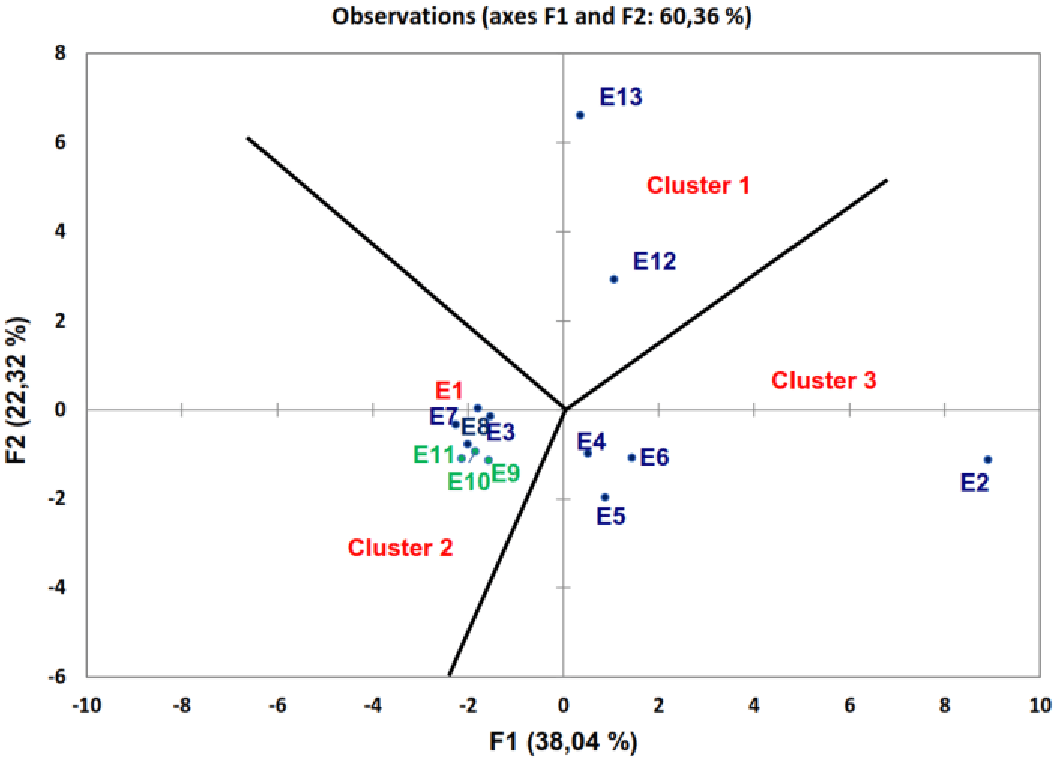

Figure 7 : scores in PC1 and PC2 for all the water analyses

4.2.2. HIERARCHICAL CLUSTER ANALYSIS

HCA is used to classify waters into objective groups. Sample classification into clusters was based on dendrogram visual analysis by drawing the phenon line, and changing the location of the phenon line on the dendrogram changed the number of clusters. A subjective evaluation was made choosing the horizontal line (phenon line) [28], [56], [57], [58] across a dendrogram at a linkage distance of about 35% (Figure 8) based on its visual examination to obtain three clusters (main groups) as it was resulted from the PCA.

Cluster 1 is that of water enriched in NH^{4+}a and Na^{+}. Cluster 2 consists of water whose mineralization is controlled by the infiltration of surface water, hence the presence of nitrates. Cluster 3 is that of hard water rich in major Ca^{2+}, Mg^{2+}, HCO$_3^-$ having acquired their mineralisation following a more or less long residence time in the surrounding soils. The cations Ca^{2+} and Mg^{2+} indicate the hardness (TH) of these waters, while HCO$_3^-$ indicates alkalinity (Fig. 8).

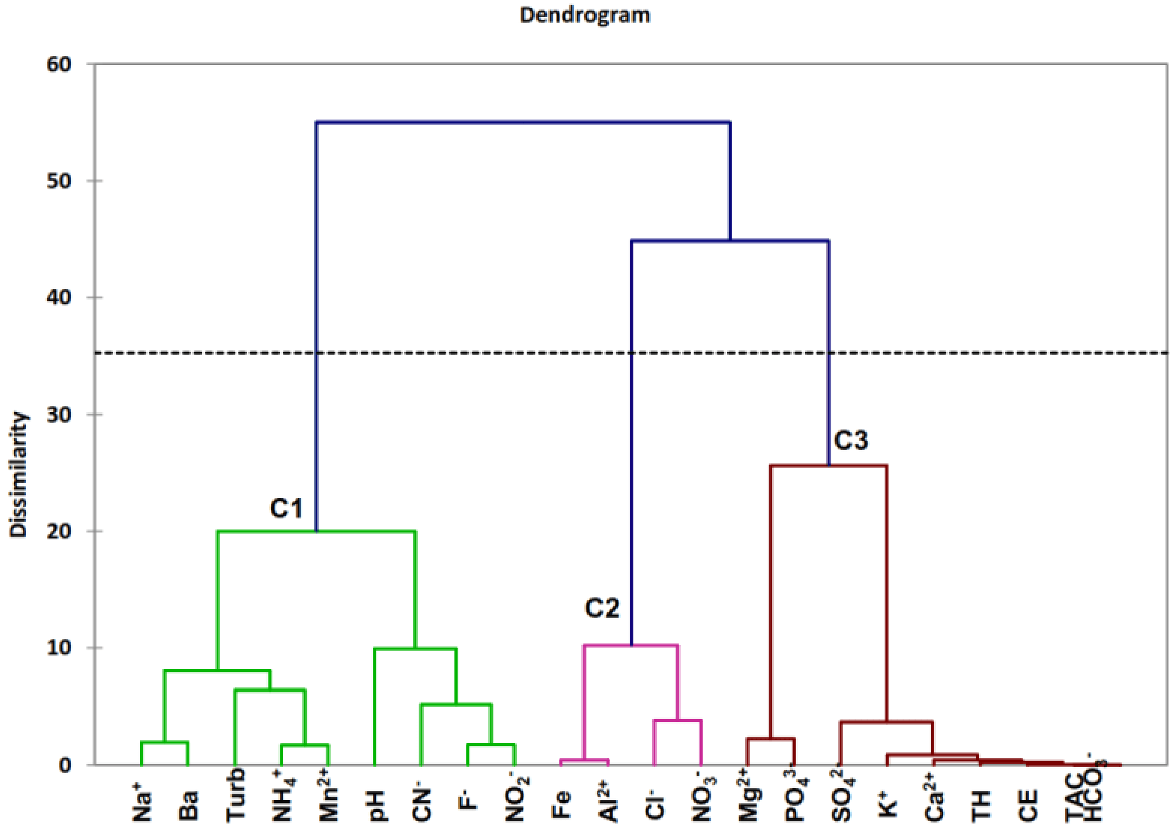

Figure 8 : Dendrogram of HCA for water quality parameters

4.2.3. FACTOR ANALYSIS (FA) ROTATE

To understand the hydrogeochemical processes responsible for the observed hydrochemical data of the water samples, factor analysis was carried out on the selected hydrochemical variables. Table 3 shows the results of the Principal Component Factor Analysis completed using the varimax rotation method in order to maximize the variance. To improve interpretations, a ''strong" loading was defined as >0.75, a "moderate" loading from 0.50 to 0.75 and loadings <0.5 were considered "weak" and they were omitted from being reported and interpreted.

Table 3 listed the eigenvalues of the first three factors, their percentage of variance and cumulative percentage of variance. It revealed that the eigenvalues of the three factors, which exceed one, explain 72.73% of the total variance. It's indicating the saturation of the quartimax-rotative factor matrix for the three-factor model. Absolute values of factor loadings greater than 0.7 were considered a strong correlation and marked in bold to elucidate the relationships between the factors and the hydrochemical data.

Factor 1, which explains 37.84% of the total variance, has strong positive loadings on TAC, TH, EC, Ca^{2+}, Na^+, K+, HCO_3^{2-}, SO_4^{2-} and Ba. To compare with data on hydrochemical parameters (Table 1) Ca^{2+}, Na^+, K+, HCO_3^{2-} and SO_4^{2-} items are the dominant solutes in groundwaters. This factor highlights the degree of mineralisation of the water by acid hydrolysis of the minerals during the contact time of the meteoric water with the surrounding rock.

Factor 2 explains 21.82% of the total variance with strong negative loadings on F^-, NO_2^-, NH_4^+, Mn^{2+}, and strong positive one NO_3^-. To compare with hydrochemical data on table 1, NO_3^- item is the dominant solutes in spring waters. The circulation of pollutant-laden meteoric water in contact with the spring water results in a high concentration of NO_3^- ions in the spring water. This factor therefore reflects the mineralisation of water by rainfall.

Factor 3 explains 13.06% of the total variance with strong negative loadings on Fe and Al^{2+}.It reflects the mineralisation of well water through redox.

The observation of individuals after using varimax rotation confirms the division of water into three groups as obtained with the ACP (Fig. 9).

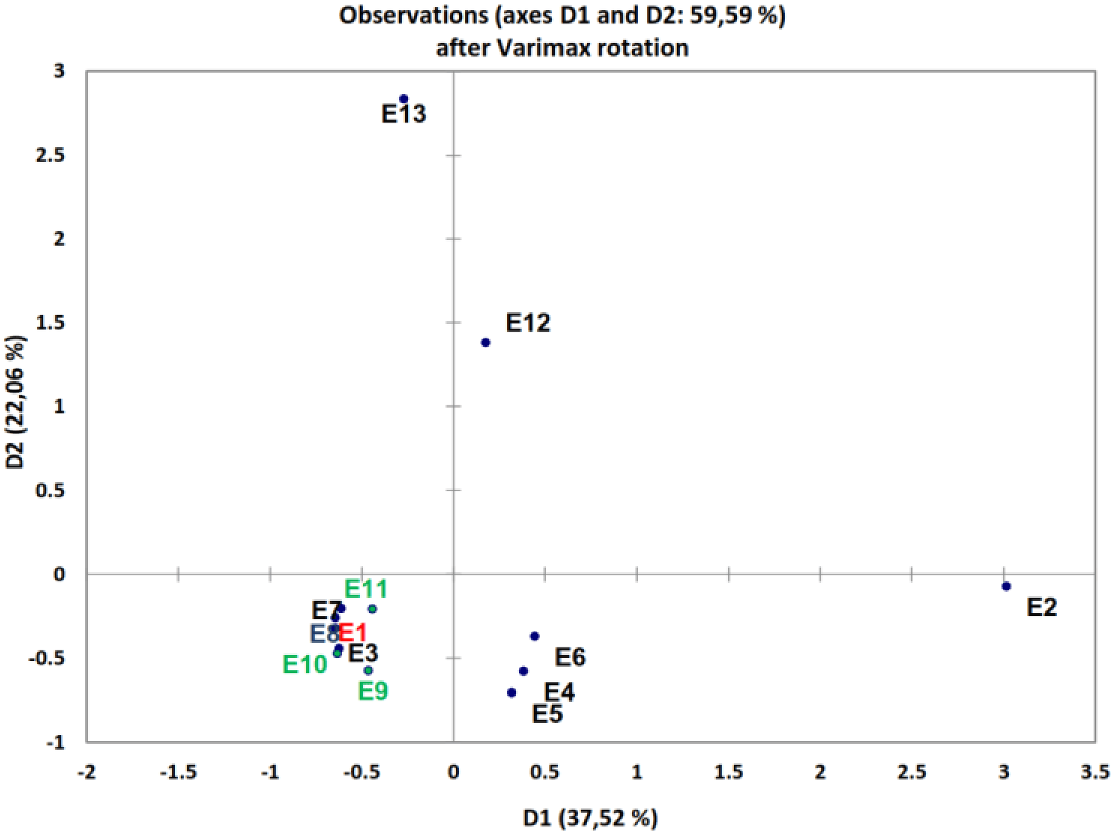

Figure 9 : Observation of individuals after using varimax rotation

4.3. ENVIRONMENTAL SURVEY

However, human activities produce waste that can adversely affect the physical and chemical quality of the water. These include agro-pastoral activities, uncontrolled dumps and the dumping of septic tank sludge into the environment (Fig. 10).

Figure 10 : Dumping of domestic wastewater (a), septic tank sludge (b) and solid waste (c) around springs and boreholes

5. CONCLUSION

The hydrochemical analysis revealed that geological processes have played a significant role in attributing the ionic character to the groundwater in the study area. The analysis methods used have enabled us to understand the nature of the water and the physical and chemical processes that govern its mineralisation. Spring water comes from the geological formation of fine glauconitic sandstone. However, anthropogenic activities have not yet had a significant negative impact on groundwater. It is important to note that anthropogenic activities are potential sources of pollution that could have an impact on groundwater quality in the long term. The same applies to some shallow boreholes. Others exploit only the deeper aquifers known as the Kawara Sindou sandstone. ONEA's boreholes exploit the two superimposed aquifers. It is recommended that a piezometric belt be set up around the catchment area to monitor quality at regular intervals, depending on potential sources of pollution

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