



Hydrogeochemical Characterization and Multivariate Analysis of Groundwater in Pala, Burkina Faso: Implications for Sustainable Water Management

**Césard Millogo^{a,b*}, Corneille Bakouan^{c,d},
Aboubakar Sako^{a,b} and Samuel Nakolendoussé^b**

^a UFR/Sciences Appliquées et Technologies, Université Daniel OUEZZIN-COULIBALY, BP 139,
Dédougou, Burkina Faso.

^b Laboratoire Géosciences et Environnement (LaGE), Département des Sciences de la Terre,
Université Joseph KI-ZERBO, Ouagadougou, Burkina Faso.

^c UFR/Sciences et Technologies, université Bernard Lédéa OUEDRAOGO, 01 BP 346 Ouahigouya
01, Burkina Faso.

^d Université Joseph KI-ZERBO, Unité de Formation et de Recherche en Sciences Exactes et
Appliquées, Laboratoire de Chimie Moléculaire et des Matériaux, 03 BP 7021 Ouagadougou 03,
Burkina Faso.

Authors' contributions

This work was carried out in collaboration among all authors. Author CM conceptualized the study, did data curation, formal analysis, investigation, performed the methodology, searched for resources, wrote and prepared the original draft of the manuscript, wrote, reviewed and edited the manuscript, did software and data visualization. Author CB wrote, reviewed and edited the manuscript, did data curation and software analysis. Author AS did data visualization, wrote, reviewed and edited the manuscript, did data curation and software analysis. Author SN supervised the experiments, helped in project administration and did data validation. All authors read and approved the final manuscript.

Article Information

DOI: <https://doi.org/10.9734/irjpac/2024/v25i5872>

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://www.sdiarticle5.com/review-history/121921>

*Corresponding author: E-mail: cesardmillogo@yahoo.com;

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 [1-5].

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 [3,12-24].

Piper's trilinear diagram is a widely used tool for assessing hydrogeochemical types and quality control mechanisms in groundwater [16,25,26].

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 [27-29].

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 [17,30-33].

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 [34]. 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, whereas August and December are the coldest. Potential evapotranspiration is significant, ranging between 1800 and 2150 mm/year [35]. Topographically, it lies on the watershed line of two sub-basins of the Mouhoun River at an altitude of around 400 meters.

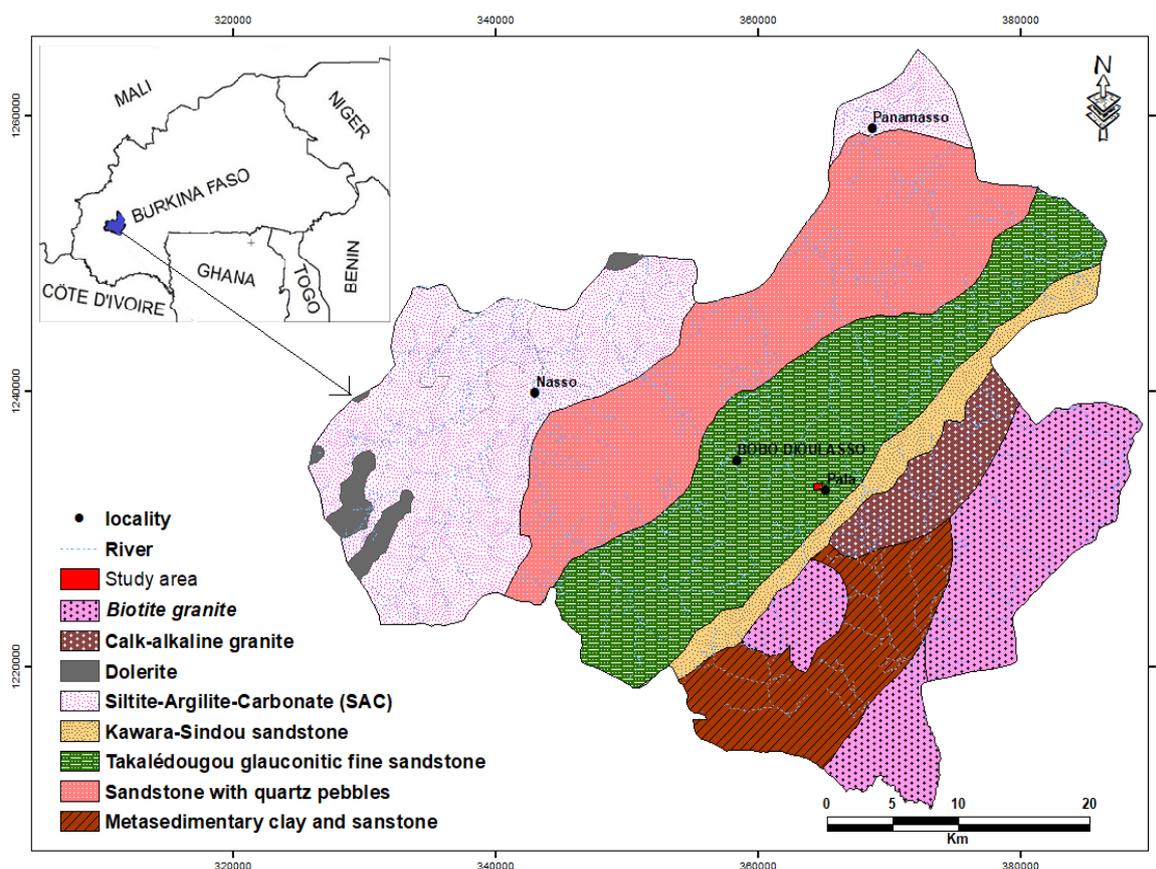


Fig. 1. Geological map

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 [36-38]. The local lithology is mainly composed of a mixture of sandstones, fine glauconitic sandstone (also known as Sotouba sandstone), sandstone with quartz grains, siltstones [39].

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 $3.10 \cdot 10^{-4} \text{ m}^2/\text{s}$ [40]. Conversely, the permeability of these sandstone aquifers is high ($1.8 \cdot 10^{-6} \text{ m/s}$), and their storage coefficient is approximately $1 \cdot 10^{-4}$ [41]. Overall, groundwater flows from north to south along numerous faults, facilitating the infiltration of rainwater into the aquifer.

3. MATERIALS 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.

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 [42]). 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):

$$\text{IBE (\%)} = \frac{\sum \text{Cations} - \sum \text{Anions}}{\sum \text{Cations} + \sum \text{Anions}} \times 100 \quad (1)$$



Fig. 2. Geographical location of the groundwater and springs sampling sites and land occupation

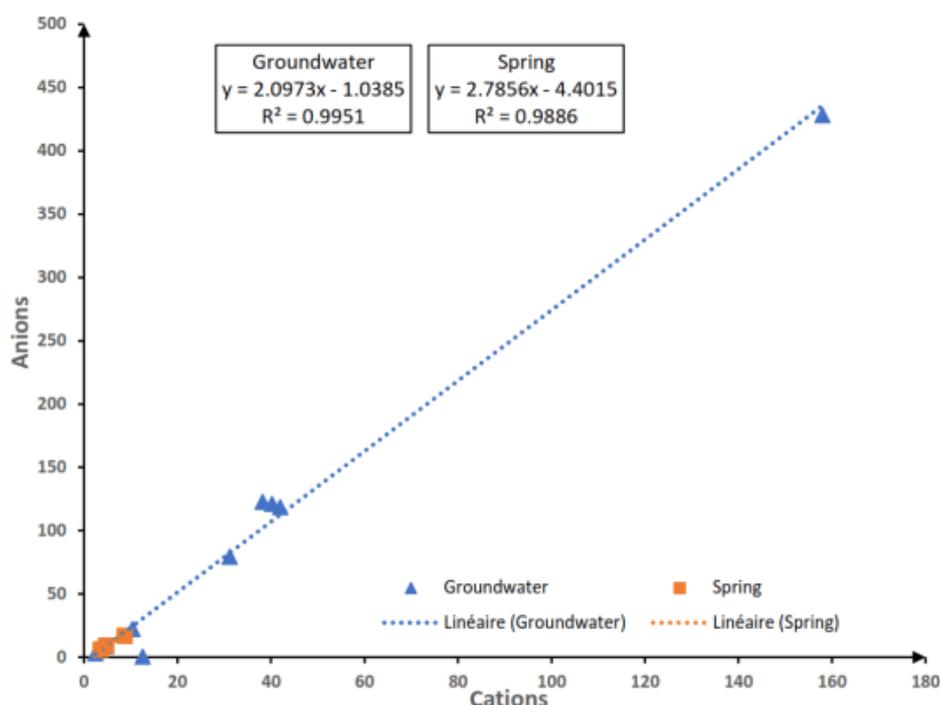


Fig. 3. Ionic balance of major elements

In general, the value of IBE should be less than $\pm 5\%$, and certainly less than $\pm 10\%$ [43]. In this study, all samples were IBE values less than $\pm 5\%$ (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 [44]. Multivariate statistical techniques which include HCA, FA and PC are effective means of manipulating, interpreting and representing data concerning groundwater pollutants and geochemistry [45-47].

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 $\mu\text{S}/\text{cm}$), Turb (120 NTU) and HCO_3^- (135.37 mg/L).

The pH values were 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 [26,48,49] 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 [50] and also indicates the growth of pathogenic microorganisms in water [51] 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 [52,53]. Acidic nature encourages rock-groundwater interactions that result in increased water turbidity due to rock weathering [54]. The total hardness of the water from the springs and boreholes varies from 0.07 to 3 $^\circ\text{f}$, 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 [55]. 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 $\text{HCO}_3^- > \text{NO}_3^- > \text{SO}_4^{2-} > \text{Cl}^-$ 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.

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).

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).

4.1.3 Heavy metal chemistry

Concentrations of Al (<0.36 mg/L), Mn (<0.6 mg/L), Ba (<0.4mg/L), CN^- (<0.04mg/L) are very low and variable and well below 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

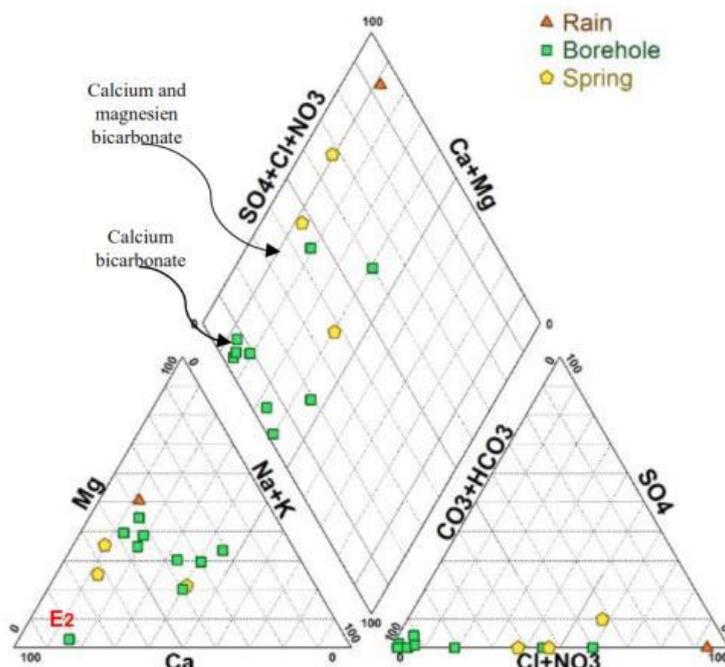


Fig. 4. Piper's Trilinear plot diagram on hydrochemical facies for the major ions of water samples

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

Type Variable	Unit	Springs			Boreholes			WHO (2008)
		Min	Max	Number of samples >WHO 2008 value	Min	Max	Number of samples >WHO 2008 value	
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

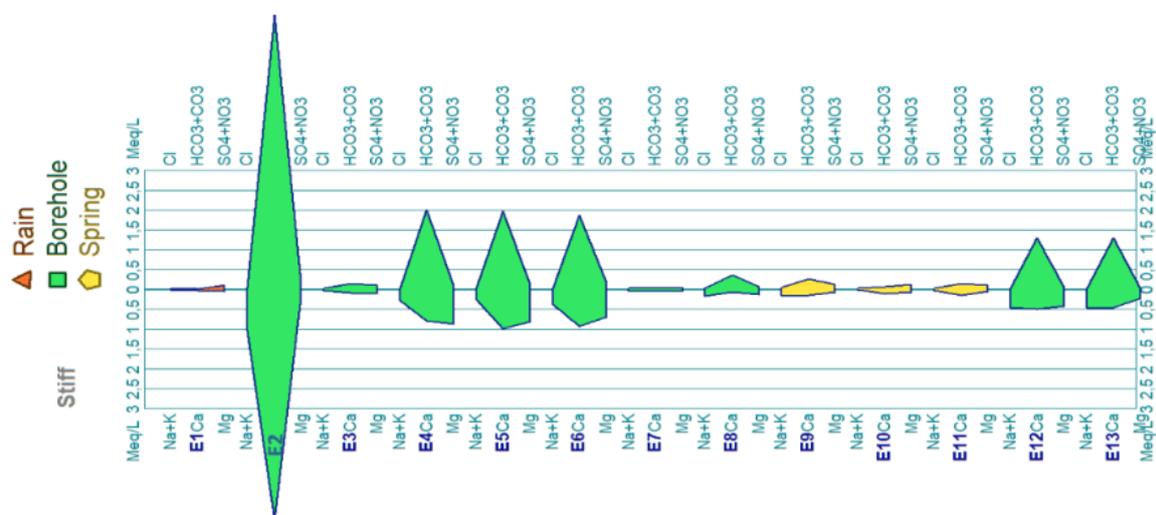


Fig. 5. Water classification on the Stiff diagram

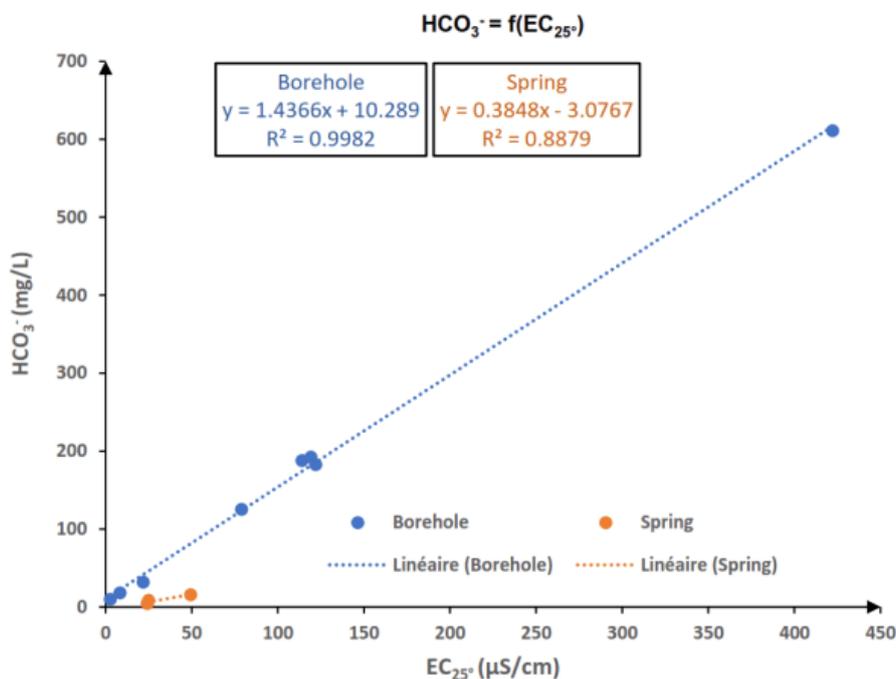


Fig. 6. Correlation between HCO₃⁻ content and EC

potential pollution sources around the spring. According to [56], 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 Analyze

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 [57]. 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^- ($r=0.99$), SO_4^{2-} ($r=0.82$), 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.

For this analysis, only two principal components (PCs) with eigenvalues greater than 1 were retained, as suggested by the Kaiser criterion [58,59].

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.

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

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.

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

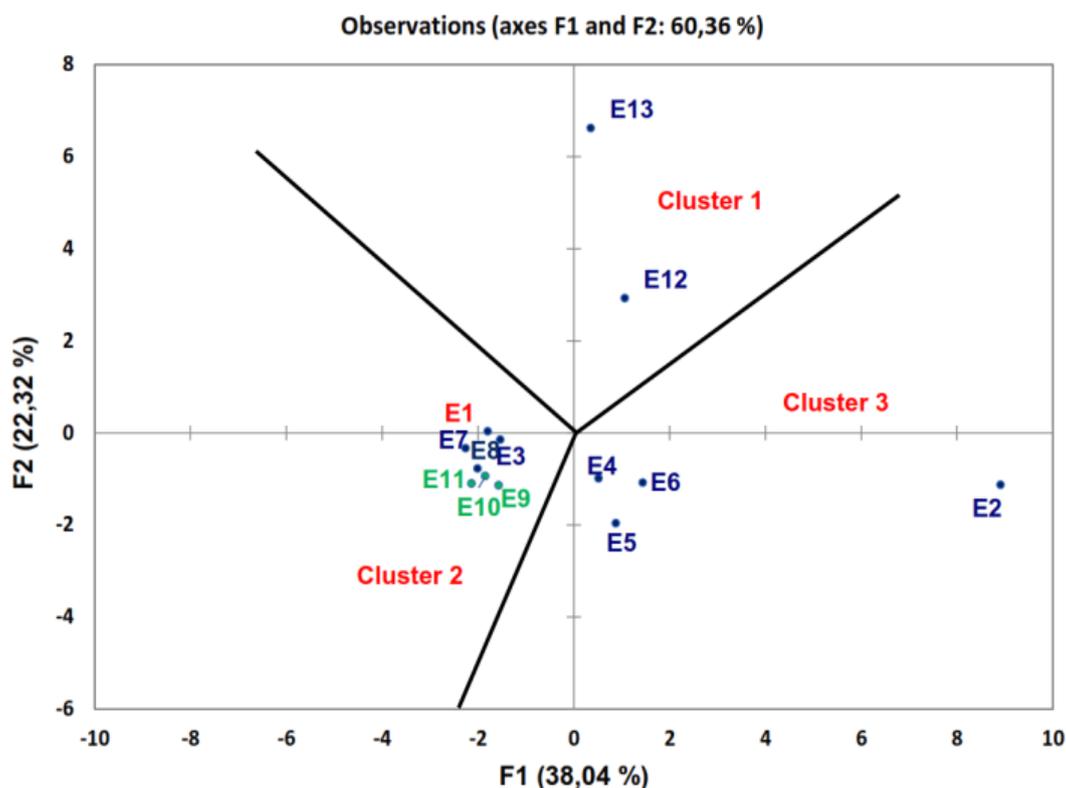


Fig. 7. Scores in PC1 and PC2 for all the water analyses

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) [32,60-62] across a dendrogram at a linkage distance of about 35% (Fig. 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^+ 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).

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.

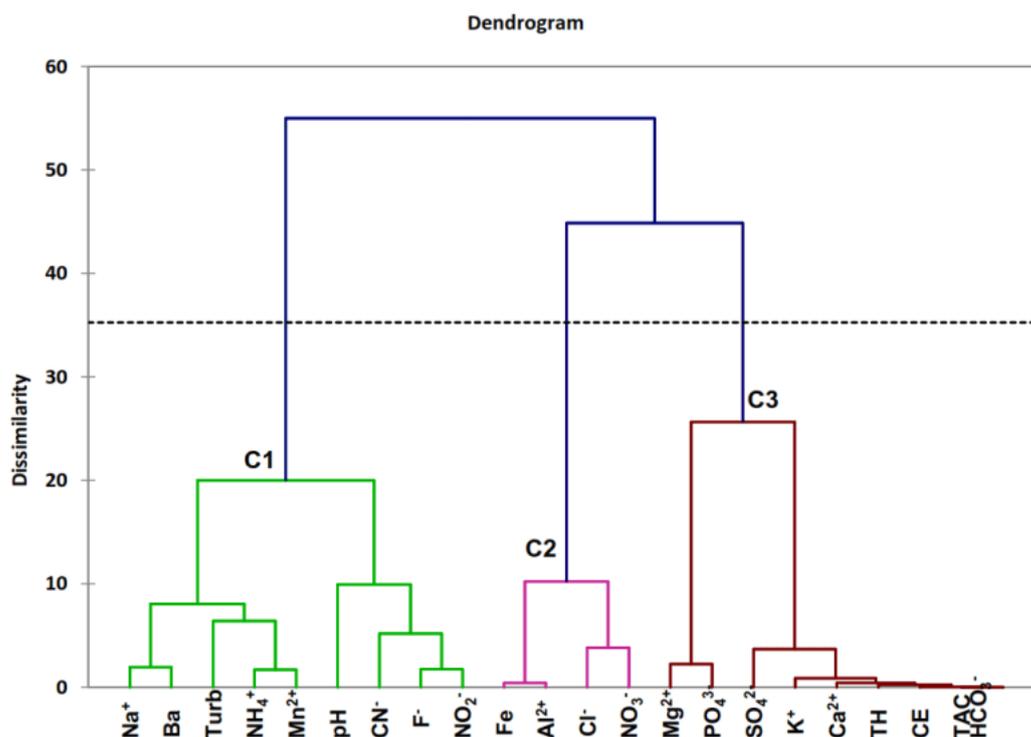


Fig. 8. Dendrogram of HCA for water quality parameters

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.

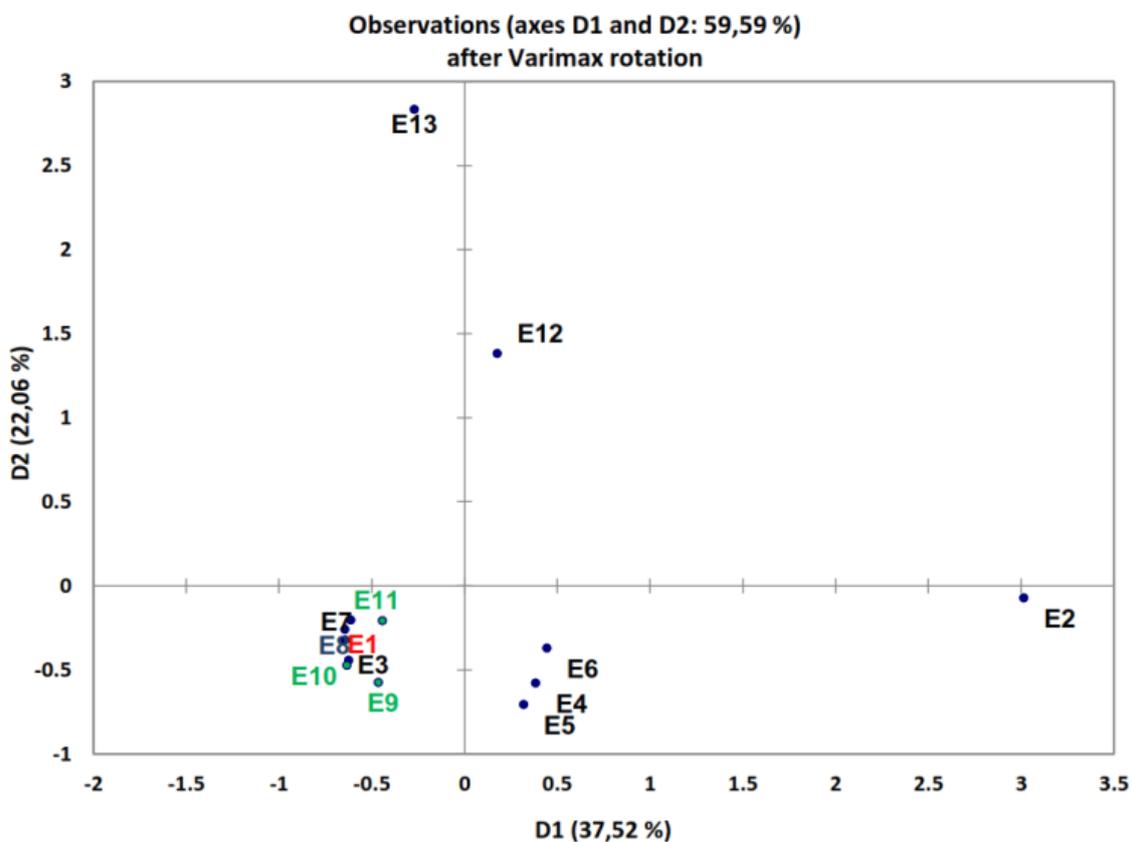


Fig. 9. Observation of individuals after using varimax rotation





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

Factor 3 explains 13.06% of the total variance with strong negative loadings on Fe and Al²⁺. 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).

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).

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.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

ACKNOWLEDGEMENTS

The authors would like to thank all those who contributed in any way to the success of this work.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Grimaldi C, Grimaldi C. Hydrochimie de petits bassins versants Apports à la connaissance du fonctionnement géochimique du sol et de la qualité de

- l'eau des cours d'eau, in: UMR INRA-Agrocampus « Sol Agronomie Spatialisation » Rennes, Université de Rennes. 2004;1.
2. Liu W, Sha JB. Failure mode transition of Nb phase from cleavage to dimple/tear in Nb-16Si-based alloys prepared via spark plasma sintering, *Materials & Design*. Dec. 2016;111:301–311.
DOI: 10.1016/j.matdes.2016.08.087.
 3. Pant RR, et al. Spatiotemporal variations of hydrogeochemistry and its controlling factors in the Gandaki River Basin, Central Himalaya Nepal, *Science of The Total Environment*. May 2018;622–623:770–782.
DOI: 10.1016/j.scitotenv.2017.12.063.
 4. Zong-Jie L, Zong-Xing L, Ling-Ling S, Jin-Zhu M, Yong S. Environment significance and hydrochemical characteristics of supra-permafrost water in the source region of the Yangtze River, *Science of The Total Environment*. Dec. 2018;644: 1141–1151.
DOI: 10.1016/j.scitotenv.2018.07.029
 5. Zong-Jie L, Ling-Ling S, Jin-Zhu M. Hydrochemical characteristics and environmental significance in different ablation period in Hulugou River Basin in Qilian Mountain, *Environ Earth Sci*. Sep 2017;76(17):606.
DOI: 10.1007/s12665-017-6911-3
 6. Gurumurthy GP, et al. Controls on intense silicate weathering in a tropical river, southwestern India, *Chemical Geology*. Mar. 2012;300–301:61–69.
DOI: 10.1016/j.chemgeo.2012.01.016
 7. Zheng Q, Ma T, Wang Y, Yan Y, Liu L, Liu L. Hydrochemical characteristics and quality assessment of shallow groundwater in Xincai River Basin, Northern China, *Procedia Earth and Planetary Science*. 2017;17:368–371.
DOI: 10.1016/j.proeps.2016.12.093
 8. Coffie-Anum E, Kuma JSY, Ewusi A, Ganyaglo SY. Hydrogeochemical evolution and isotopic characteristics of groundwater-surface water interaction processes within the Kawere Catchment and its hydrogeotechnical implication on pit slope stability at the Nsuta Mine, Ghana, *Groundwater for Sustainable Development*. 2024;101246.
DOI: <https://doi.org/10.1016/j.gsd.2024.101246>
 9. Kalbus E, Reinstorf F, Schirmer M. Measuring methods for groundwater – surface water interactions: A review, *Hydrol. Earth Syst. Sci*. Nov. 2006;10(6): 873–887.
DOI: 10.5194/hess-10-873-2006
 10. Souid F, Agoubi B, Telahigue F, Chahlaoui A, Kharroubi A. Groundwater salinization and seawater intrusion tracing based on Lithium concentration in the shallow aquifer of Jerba Island, southeastern Tunisia, *Journal of African Earth Sciences*. Feb. 2018;138:233–246.
DOI: 10.1016/j.jafrearsci.2017.11.013
 11. Zhao D, et al. Groundwater-surface water interactions derived by hydrochemical and isotopic (²²²Rn, deuterium, oxygen-18) tracers in the Nomhon area, Qaidam Basin, NW China, *Journal of Hydrology*. Oct. 2018;565:650–661.
DOI: 10.1016/j.jhydrol.2018.08.066
 12. Badeenezhad A, et al. Estimation of the groundwater quality index and investigation of the affecting factors their changes in Shiraz drinking groundwater, Iran, *Groundwater for Sustainable Development*. Oct. 2020;11:100435.
DOI: 10.1016/j.gsd.2020.100435
 13. Bakouan C, Guel B, Hantson A-L, Caractérisation physico-chimique des eaux des forages des villages de Tanlili et Lilgomdé dans la région Nord du Burkina Faso - Corrélation entre les paramètres physico-chimiques, *Afrique Science*. 2017;13(6):325–337.
 14. Diamantini E, Lutz SR, Mallucci S, Majone B, Merz R, Bellin A. Driver detection of water quality trends in three large European river basins, *Science of the Total Environment*. Jan. 2018;612:49–62.
DOI: 10.1016/j.scitotenv.2017.08.172
 15. Gautam A, Rai SC, Rai SP, Ram K, Sanny, Impact of anthropogenic and geological factors on groundwater hydrochemistry in the unconfined aquifers of Indo-Gangetic plain, *Physics and Chemistry of the Earth, Parts A/B/C*. 2022;126:103109.
DOI: <https://doi.org/10.1016/j.pce.2022.103109>
 16. Millogo C, Bakouan C, Sawadogo S. Caractérisation physico-chimique des eaux de surface et des altérites du bassin versant du lac Bam, Centre Nord du Burkina Faso, *Afrique Science*. 2020; 5(17):137–150.
 17. Subba Rao N, Das R, Sahoo HK, Gugulothu S. Hydrochemical

- characterization and water quality perspectives for groundwater management for urban development, *Groundwater for Sustainable Development*. 2024;24:101071.
DOI:
<https://doi.org/10.1016/j.gsd.2023.101071>
18. Rezaei A, Hassani H, Tziritis E, Fard Mousavi SB, Jabbari N. Hydrochemical characterization and evaluation of groundwater quality in Dalgan basin, SE Iran, *Groundwater for Sustainable Development*. Apr. 2020;10:100353.
DOI: 10.1016/j.gsd.2020.100353
 19. Sako A, Semdé S, Wenmenga U. Geochemical evaluation of soil, surface water and groundwater around the Tongon gold mining area, northern Côte d'Ivoire, West Africa, *Journal of African Earth Sciences*. Sep. 2018;145:297–316.
DOI: 10.1016/j.jafrearsci.2018.05.016
 20. Sako A, Bamba O, Gordio A. Hydrogeochemical processes controlling groundwater quality around Bomboré gold mineralized zone, Central Burkina Faso, *Journal of Geochemical Exploration*. Nov. 2016;170:58–71.
DOI: 10.1016/j.gexplo.2016.08.009
 21. Moayedi H, Salari M, Dehrashid AA, Le BN. Groundwater quality evaluation using hybrid model of the multi-layer perceptron combined with neural-evolutionary regression techniques: case study of Shiraz plain, *Stochastic Environmental Research and Risk Assessment*. Aug. 2023;37(8):2961–2976.
DOI: 10.1007/s00477-023-02429-w.
 22. Moayedi H, Canatalay PJ, Dehrashid AA, Cifci M, Salari M, Le BN. Multilayer perceptron and their comparison with two nature-inspired hybrid techniques of biogeography-based Optimization (BBO) and Backtracking Search Algorithm (BSA) for Assessment of Landslide Susceptibility, Land; 2023, [Online]. Available:<https://api.semanticscholar.org/CorpusID:255920800>
 23. Khorasani M, Ehteshami M, Ghadimi H, Salari M. Simulation and analysis of temporal changes of groundwater depth using time series modeling. *Modeling Earth Systems and Environment*. 2016;2:1-10.
 24. Salari M. Investigating the spatial variability of some important groundwater quality factors based on the geostatistical simulation (case study: Shiraz plain), *Desalination and Water Treatment*; 2017.
 25. Chen L, Wang G. Hydrochemical changes of a spring due to the May 30, 2014 Ms 6.1 Yingjiang earthquake, southwest China, *Environmental Pollution*. Sep. 2021; 284:117125.
DOI: 10.1016/j.envpol.2021.117125.
 26. Sako A, Kafando S. Hydrogeochemical and spatial assessment of groundwater quality from basement aquifers in the Central Plateau Region of Burkina Faso, West Africa, *Environ Earth Sci*. May 2021;809:358.
DOI: 10.1007/s12665-021-09668-6
 27. Aladejana JA, Kalin RM, Sentenac P, Hassan I. Groundwater quality index as a hydrochemical tool for monitoring saltwater intrusion into coastal freshwater aquifer of Eastern Dahomey Basin, Southwestern Nigeria, *Groundwater for Sustainable Development*. May 2021;13:100568.
DOI: 10.1016/j.gsd.2021.100568.
 28. Dlamini AE, Demlie M. Integrated hydrogeological, hydrochemical and environmental isotope investigation of the area around the Kusile Power Station, Mpumalanga, South Africa, *Journal of African Earth Sciences*. Dec. 2020;172:103958.
DOI: 10.1016/j.jafrearsci.2020.103958
 29. Saikrishna K, et al. Deciphering groundwater quality, mechanisms controlling groundwater chemistry in and around Suryapet, Telangana, South India, *Total Environment Research Themes*. Jun. 2023;6:100035.
DOI: 10.1016/j.totert.2023.100035
 30. Jang C-S. Applying scores of multivariate statistical analyses to characterize relationships between hydrochemical properties and geological origins of springs in Taiwan, *Journal of Geochemical Exploration*. Apr. 2010;105(1–2):11–18.
DOI: 10.1016/j.gexplo.2010.02.001.
 31. Li M, Liu Z, Zhang M, Chen Y. A workflow for spatio-seasonal hydro-chemical analysis using multivariate statistical techniques, *Water Research*. Jan. 2021; 188:116550.
DOI: 10.1016/j.watres.2020.116550
 32. Yang J, et al. Using cluster analysis for understanding spatial and temporal patterns and controlling factors of groundwater geochemistry in a regional aquifer, *Journal of Hydrology*. Apr. 2020; 583:124594.
DOI: 10.1016/j.jhydrol.2020.124594

33. Yidana SM, Dzikunoo EA, Aliou A-S, Adams RM, Chagbeleh LP, Anani C. The geological and hydrogeological framework of the Panabako, Kodjari, Bimilla formations of the Voltaian supergroup – Revelations from groundwater hydrochemical data, *Applied Geochemistry*. Apr. 2020;115:104533. DOI: 10.1016/j.apgeochem.2020.104533
34. Millogo C. Etude hydrogéologique et géologique pour la délimitation des périmètres de protection des captages de l'ONEA à Pala, BERGEB-AFRIQUE, Ouagadougou, Rapport étude. May 2023;2023–01.
35. Traoré F. Méthodes d'estimation de l'évapotranspiration réelle, Liège, Mémoire de fin d'étude de Diplôme d'Etudes Approfondies (DEA) en Sciences et Gestion de l'Environnement; 2007.
36. Bronner G, Roussel J, Trompette R, Clauer N. Genesis and Geodynamic Evolution of the Taoudeni Cratonic Basin (Upper Precambrian and Paleozoic), Western Africa, in *Geodynamics Series*, A. W. Bally P. L. Bender, T. R. McGetchin, R. I. Walcott, Eds., Washington, D. C.: American Geophysical Union. 2013;81–90. DOI: 10.1029/GD001p0081
37. Giovenazzo D, Ouédraogo A, HIEN KAA, Ouédraogo PI, Dahl R, Sountra Y. Carte de synthèse géologique, structurale et des substances minérales du Burkina Faso à 1/1 000 000; 2018.
38. Moussine-Pouchkine A, Bertrand-Sarfati J. Tectonosedimentary subdivisions in the neoproterozoic to Early Cambrian cover of the taoudenni Basin (Algeria-Mauritania-Mali), *Journal of African Earth Sciences*. 1997;24:425–443.
39. Ouédraogo C. Synthèse géologique de la région ouest du Burkina Faso; 2006.
40. SOGREAH Ingénierie, Etude des ressources en eau souterraines de la région de Bobo Dioulasso, Sogreah; 1994.
41. Gombert P. Synthèse sur la géologie et l'hydrogéologie de la zone sédimentaire RESO, RESO; 1998.
42. APHA, et al. Eds., Standard methods for the examination of water and wastewater. Washington, DC: American Public Health Association; 1995.
43. Domenico PA, Schwartz FW. *Physical and Chemical Hydrogeology*. Wiley; 1990.
44. Drever JI. *Geochemistry of natural waters*, Prentice Hall; 1997;388. [Online]. Available: <https://api.semanticscholar.org/CorpusID:128580356>
45. Hegeu H, Kshetrimayum KS. Hydrochemical characterization of groundwater in geomorphic units using graphical and multivariate statistical methods in the Dimapur valley, Northeast India, *Groundwater for Sustainable Development*. Apr. 2019;8:484–500. DOI: 10.1016/j.gsd.2019.01.004
46. Hota SR, Hota RN, Goswami S. Statistical appraisal of major ion chemistry of Groundwater: A Case Study from a River-Bounded Rural Area, *Journal of the Geological Society of India*. Sep. 2023;99(9):1253–1262. DOI: 10.1007/s12594-023-2459-x
47. Rashid A, et al. Fluoride prevalence in groundwater around a fluorite mining area in the flood plain of the River Swat, Pakistan, *Science of The Total Environment*. Sep. 2018;635:203–215. DOI: 10.1016/j.scitotenv.2018.04.064
48. Taupin MJD, et al. Gestion intégrée et durable des systèmes aquifères et des bassins partagés de la région du Sahel, RAF/7/011; 2017.
49. Huneau F, et al. Flow pattern and residence time of groundwater within the south-eastern Taoudeni sedimentary basin (Burkina Faso, Mali), *Journal of Hydrology*. Oct. 2011;409(1–2):423–439. DOI: 10.1016/j.jhydrol.2011.08.043
50. Bright C, Mager S, Horton S. Response of nephelometric turbidity to hydrodynamic particle size of fine suspended sediment, *International Journal of Sediment Research*. Oct. 2020;35(5):444–454. DOI: 10.1016/j.ijsrc.2020.03.006
51. Putra BTW, Rocelline LA, Syahputra WNH. Embedded system in handheld water turbidity meter for smallholders, *Microprocessors and Microsystems*. 2022; 93:104603. DOI: <https://doi.org/10.1016/j.micpro.2022.104603>
52. Helmy Q, Notodarmojo S. Improvement of the raw drinking water quality from shallow well by ozone treatment, *IOP Conf. Ser.: Mater. Sci. Eng*. Sep. 2019;620(1):012052. DOI: 10.1088/1757-899X/620/1/012052
53. MWSMH, *Turbidity in Manitoba Water Supplies*; 2011.
54. Agyemang VO. Application of GIS technique in suitability assessment of groundwater in the Assin North and South

- municipalities, Ghana, Journal of African Earth Sciences. 2023;197:104778.
DOI: <https://doi.org/10.1016/j.jafrearsci.2022.104778>
55. Elango L, Kannan R. Chapter 11 Rock–water interaction and its control on chemical composition of groundwater, in Developments in Environmental Science, Elsevier. 2007;5:229–243.
DOI: 10.1016/S1474-8177(07)05011-5
56. Dippong T, Mihali C. Hoaghia M-A, Cical E. Cosma A. Chemical modeling of groundwater quality in the aquifer of Seini town – Someș Plain, Northwestern Romania, Ecotoxicology and Environmental Safety. Jan. 2019;168:88–101.
DOI: 10.1016/j.ecoenv.2018.10.030
57. Li Y, Migliaccio K. Water quality concepts, sampling, analyses. CRC Press; 2010.
58. Kaiser HF. The application of electronic computers to factor analysis, Educational and Psychological Measurement. 1960; 20(1):141–151.
DOI: 10.1177/001316446002000116
59. Thyne G, Güler C, Poeter E. Sequential analysis of hydrochemical data for watershed Characterization, Groundwater. Sep. 2004;42(5):711–723.
DOI: 10.1111/j.1745-6584.2004.tb02725.x
60. Corliss JO, Sneath PHA, Sokal RR. Numerical taxonomy: The Principles and Practice of Numerical Classification; 1973. [Online].
Available:<https://api.semanticscholar.org/CorpusID:59744508>
61. Gourdol L, Hissler C, Hoffmann L, Pfister L. On the potential for the partial triadic analysis to grasp the spatio-temporal variability of groundwater hydrochemistry, Applied Geochemistry. Dec. 2013;39:93–107.
DOI: 10.1016/j.apgeochem.2013.10.002.
62. Saravanan K, et al. Geochemical evolution of groundwater along flow path in Upper Vellar sub basin, Tamilnadu, India: An integrated approach using hydrochemistry, modeling and statistical techniques, Modeling Earth Systems and Environment. Jun. 2018;4(2):647–658.
DOI: 10.1007/s40808-017-0400-2

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the publisher and/or the editor(s). This publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© Copyright (2024): Author(s). The licensee is the journal publisher. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:

The peer review history for this paper can be accessed here:
<https://www.sdiarticle5.com/review-history/121921>