



Journal of Environmental Science and Technology

ISSN 1994-7887

science
alert

ANSI*net*
an open access publisher
<http://ansinet.com>



Research Article

Hydrochemistry and Characterization of Shallow Groundwater of Vogan-Attitogon Plateau Southeastern Part of Coastal Sedimentary Basin (Togo)

^{1,3}Gbati Napo, ^{1,2}Kossitse Venyo Akpataku, ¹Tomkouani Kodom, ¹Masamaéya D.T. Gnazou, ¹Limam Moctar Bawa and ¹Gbandi Djaneye-Boundjou

¹Laboratory of Applied Hydrology and Environment (Ex Laboratory of Water Chemistry), University of Lomé, Lomé, Togo

²Department of Chemistry, Faculty of Sciences and Technologies, University of Kara, Togo

³National Institute of Hygiene, P.O. Box 1396, Lome, Togo

Abstract

Background and Objective: The shallow Continental Terminal aquifer is the primary water resource for drinking purposes in the coastal sedimentary basin of Togo. This study aimed to identify hydrochemical processes and groundwater quality to ensure the sustainable water supply in the basin. **Materials and Methods:** Major chemical parameters of forty-two samples of shallow groundwater and eight samples of surface water collected during march 2019 were analyzed using AFNOR methods. The Piper diagram and Principal Components Analysis of the data were used to determining the factors that control groundwater processes in the aquifer system, based on the ionic constituents, water types and component loadings. **Results:** Groundwater was slightly acid and fresh to brackish. Surface water was circum-neutral and fresh to very saline. For both groundwater and surface water, the cations and anions abundance order was $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ and $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^- > \text{NO}_3^-$, respectively. Thus, water samples were predominantly Na-Cl water type (~88%). Most of the groundwater samples were classified Na-Cl water type with two accessory water types (Ca-Cl and Ca-Mg-Cl). The principal process operating in the shallow groundwater of the Vogan-Attitogon plateau was seawater mixing with fresh water and natural silicate weathering. Carbonaceous debris, limestone weathering, pyrite dissolution, ion exchange, evaporation, anthropogenic activities (farming using fertilizers and industrial activity) also influenced groundwater mineralization. **Conclusion:** The analysis of shallow groundwater shows for some samples high Total Dissolved Solids and ions found in concentrations exceeding thresholds. The shallow aquifer of the Vogan-Attitogon plateau face degradation of water quality and the consumption of this water may affect human health.

Key words: Hydrochemical, groundwater, principal component analysis, water type, loading, water quality

Citation: Napo, G., K.V. Akpataku, T. Kodom, M.D.T. Gnazou, L.M. Bawa and G. Djaneye-Boundjou, 2021. Hydrochemistry and characterization of shallow groundwater of Vogan-Attitogon plateau southeastern part of coastal sedimentary basin (Togo). *J. Environ. Sci. Technol.*, 14: 48-57.

Corresponding Author: Tomkouani Kodom, Laboratory of Applied Hydrology and Environment (Ex Laboratory of Water Chemistry), University of Lomé, Lomé, Togo

Copyright: © 2021 Gbati Napo *et al.* This is an open access article distributed under the terms of the creative commons attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited.

Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

In Africa, groundwater is the major source of drinking water and its use in irrigation is forecast to increase substantially to combat growing food insecurity. Because of its resilience to climate variability in many areas of sub-Saharan Africa, groundwater plays a vital role in providing safe water in pursuit of the United Nations Sustainable Development Goal (SDG) 6-water and sanitation for all by 2030¹.

Coastal aquifers serve as major sources of freshwater supply and they are also heavily impacted by urbanization, industrial activity, irrigation, factors making the need for freshwater even more acute. Climate change and human population growth are expected to have substantial impacts on global water resources throughout the twenty-first century². Consequently, shallow coastal aquifers in some developing countries, particularly in the Gulf of Guinea, face different groundwater quality deterioration challenges. Groundwater is highly vulnerable and subject to high pollution risk in the function of the geology, hydrography other parameters of shallow groundwater systems in Central and West Africa³. Seawater intrusion, mixing with saline lake and lagoon systems increase groundwater salinity, contaminants from fertilizers. Septic and sewerage infiltration is responsible for shallow groundwater quality deterioration⁴⁻⁶. The coastal sedimentary aquifers in Togo are not well documented, the available studies on shallow aquifers focus mainly on the Southeastern part of the country which encompasses the capital Lome and its surrounding areas^{5,7,8}.

The Eastern part of the basin, mainly occupied by the Vogon-Attitogon plateau, has received little attention except the rural water supply projects executed by the Directorate of Water Resources and her partners⁹. This part shelters socio-economic activities, including fishing, agriculture and phosphate mining⁹. The shallow Continental Terminal aquifer is the primary water source exploited by low-cost infrastructures such as wells and boreholes.

This study aimed to determine the factors that control shallow groundwater mineralization of the Vogon-Attitogon plateau, based on water physicochemical parameters. Principal Component Analysis (PCA) and the Piper Diagram were used to classifying water types and to identify the major factors that influenced shallow groundwater chemistry in the area.

MATERIALS AND METHODS

Study area: The study area is located in the coastal sedimentary basin, between 1°15'-1°45'N. Altitude ranges from 20-80 m and the area lies between the Mono river, the Lama depression, the Haho river and Togo lake and the Atlantic Ocean. The study area is drained by the Haho river, the Togo lagoon and the Mono river. All the rivers dry up in the dry season except the Mono which has a perennial flow. The climate is subequatorial Guinean, characterized by two rainy seasons alternating with two dry seasons. The annual rainfall is on average 800 mm. Throughout the year, temperature varies from 24-36°C⁴.

The coastal basin of Togo is made of four major lithological formations depending on constitution, from Maastrichtian to Quaternary. The Cretaceous formation is made of detrital rocks with clay or carbonate episodes and the Maastrichtian is formed by deposits dominated by a combination of detrital quartz and clay facies with organic matter. The Paleocene formation is characterized by the predominance of biochemical material and the Eocene is made of clay with detrital quartz inputs. The Oligocene formation includes nummulitic limestone and sandy clay. The Continental Terminal is characterized by a continental mega-sequence and sandy clays dated from the Mio-Pliocene to Quaternary¹⁰.

The coastal sedimentary basin consists of four main aquifers, each with its specific geology and hydraulic head. They are, from bottom to top of the stratigraphic series: A confined aquifer in Cretaceous sands, a confined aquifer in Eo-Paleocene sands and limestones, unconfined sands of the Continental Terminal aquifer and an unconfined recent sandy aquifer^{4,11}. The Continental Terminal aquifer is the most accessible and easily exploitable¹¹. Its productivity is estimated at 32,715 m³ d⁻¹. This aquifer contributes more than 70% of the water supply in Lome. The depth and thickness of the Continental Terminal generally increase from north to south. Depth ranges from 22 m near the Lama depression in the north to 97 m in the south of the study area.

Sampling and analytical procedure: Ground water samples were collected during the dry season (March, 2019) from 37 boreholes and 5 wells used for domestic and agricultural purposes, in addition to 8 surface water samples. The Global Positioning System (GPS: Garmin Montana 680) was used to record sampling point locations. Cleaned polyethylene bottles were used for sampling. The polyethylene bottles were

washed and rinsed several times using the water to be sampled, before collecting samples for physicochemical analysis. The bottles allowed to avoid unpredictable changes in water characteristics.

Physicochemical parameters such as temperature, pH, TDS and Electrical Conductivity (EC) were measured in the field at each sampling point using HANNA portable equipment. Samples were kept at a temperature of 4°C and transported to the laboratory for testing. Major cations (Na^+ , Ca^{2+} , Mg^{2+} , K^+ , HCO_3^- , Cl^- , SO_4^{2-} and NO_3^-) were measured in the laboratory after filtration of the water using a 0.45 μm size filter. Chemical analysis of major cations and anions was carried out using standard methods^{12,13}. The determination of parameters was made at the latest, two days after sampling. Ca^{2+} , Mg^{2+} , HCO_3^- , CO_3^{2-} were analyzed by titration, Na^+ , K^+ by flame photometry and NO_3^- , SO_4^{2-} , PO_4^{2-} , NH_4^+ , F^- and arsenic with a UV spectrophotometer HACH LANGE DR 9000¹⁴. Samples for determining trace elements such as cadmium, chromium were acidified and analyzed using an atomic absorption spectrometer.

Methods

Water classification: Several diagrams are often used for comparing the results of analyses of water types. The Piper diagram is a graphic representation allowing a global visualization of water with different parameters. It is commonly employed for hydrochemical characterization of groundwater^{13,14}.

Principal component analysis (PCA): Multivariate techniques are used for data analysis in several fields, especially in hydrochemistry. Principal Component Analysis (PCA) is one of the best multivariate statistical techniques for extracting linear relationships from a set of variables¹⁵. PCA is widely used as an analytical technique for studying complex data sets⁷. Variables are transformed to a smaller set of new variables, called Principal Components (PCs), which are weighted linear combinations of the original variables. The variance of the original dataset is maximized¹⁶.

PCA provides information on the significant parameters with minimum loss of original information¹⁷. This is achieved by transforming to a new set of variables that are uncorrelated and are ordered so that the first few retain most of the variation present in the original variables. Therefore, standardization (z scale) was done on each chemical parameter before statistical analysis, to eliminate biases caused by the different units in which parameters are

expressed (e.g. mg L^{-1} , °C, dimensionless pH,) and high concentration of parameters¹⁸. The principal components are generated in a sequentially ordered manner with decreasing contributions to variance. The first Principal Component (PC1) explains most of the variations present in the original data and successive principal components account for decreasing proportions of the variance^{19,20}. Principal components corresponding to absolute loading values "strong", "moderate" and "weak", correspond to absolute loading values of >0.75 , 0.75-0.50 and 0.50-0.30, respectively²¹.

An eigenvalue gives a measure of the significance of the factor and the sum of eigenvalues coincides with the total number of variables. According to the Kaiser criterion, only factors with eigenvalues greater than or equal to 1 are considered significant and are possible sources of variance in the data^{22,23}.

RESULTS AND DISCUSSION

Trends of variation: A statistical summary of hydrochemical parameters of groundwater samples of the study area is presented in Table 1.

The temperature of groundwater in the study area varies from 29.4°C (P2) to 32.6°C (F6) with a mean of 31°C. The pH ranges from 4.83-7.63 with a mean of 5.63 and 86% of samples have pH under 6.5. The pH value shows that the groundwater was slightly acidic ($\text{pH} < 7.0$). The partial pressure of CO_2 ranging from 10^{-2} to $10^{-0.097}$ atm was high, showing that the acidity of groundwater was mainly due to CO_2 in the soil surface layers, produced by biological activity or infiltration of precipitation. The acidity of groundwater may result from a co-factor interplay, including atmospheric acid deposition, municipal solid waste incineration, urbanization-induced deforestation, acid-rain gas emissions, loads of organic matter and ammonium and a low proportion of acid-consuming minerals such as carbonates in the aquifer matrix⁵. The acidity could also come from the oxidation of iron minerals (pyrite), which provides H^+ ions that play a key role in the alteration of minerals. Previous studies show similar values of groundwater pH in the coastal basin^{4,5}. The shallow groundwater in the coastal aquifers in Benin, Ivory Coast and Nigeria have also been found acidic^{6,24,25}.

The EC of groundwater samples ranges from 108.5 $\mu\text{S cm}^{-1}$ (F4) to 8720 $\mu\text{S cm}^{-1}$ (F19) with a mean of 859.08 $\mu\text{S cm}^{-1}$. The TDS ranging from 82,40-6610 mg L^{-1} with a mean of 651.44 mg L^{-1} and a standard deviation of 1165 mg L^{-1} was higher than the limit of WHO standard

Table 1: Statistical summary of hydrochemical parameters of groundwater and surface water samples

Parameters	Groundwater				Surface water			
	Mean	Min	Max	SD	Mean	Min	Max	SD
TDS (mg L ⁻¹)	651.44	82.4	6610	1164.91	9579.88	134	33915	13179.39
T (°C)	31.08	29.4	32.6	0.63	30.29	28.5	31.5	1.03
EC (µS cm ⁻¹)	859.08	108.5	8720	1535.29	11348.68	141.4	39900	15453.16
pH	5.63	4.83	7.63	0.6	6.91	6.24	7.8	0.46
Ca ²⁺ (mg L ⁻¹)	33.69	0.3	400	√62.84	5.08	0.2	11.2	4.24
Mg ²⁺ (mg L ⁻¹)	21.69	0.5	384	59.21	127.51	4.8	638.4	226.06
Na ⁺ (mg L ⁻¹)	105.92	16.8	1002.5	189.75	1054.65	30.2	3014.9	1302.63
K ⁺ (mg L ⁻¹)	2.96	0.47	19.8	3.59	59.95	1.2	184.7	77.55
Fe total (mg L ⁻¹)	0.36	0.02	5.35	0.81	0.69	0.2	1.51	0.59
Mn ²⁺ (mg L ⁻¹)	0.46	0.01	14.88	2.29	0.16	0.02	0.37	0.13
NH ₄ ⁺ (mg L ⁻¹)	0.26	0.01	2	0.42	0.86	0.17	1.44	0.46
HCO ₃ ⁻ (mg L ⁻¹)	34.42	6.1	280.6	44.39	127.34	61	280.6	74.53
Cl ⁻ (mg L ⁻¹)	232.24	10.65	2250.4	467.17	2344.53	38	9514	3394.20
SO ₄ ²⁻ (mg L ⁻¹)	25.71	0.5	221	47.43	44.22	2.6	112	46.47
PO ₄ ²⁻ (mg L ⁻¹)	0.34	0.01	5.23	0.95	0.46	0.14	0.9	0.31
NO ₃ ⁻ (mg L ⁻¹)	18.21	0.5	103.4	21.99	1.67	0.2	3.5	1.26
NO ₂ ⁻ (mg L ⁻¹)	0.05	0.01	0.97	0.15	0.09	0.02	0.3	0.10
SiO ₂ (mg L ⁻¹)	19.12	9.48	41	7.67	20.04	7.6	35.5	9.62
F ⁻ (µg L ⁻¹)	0.23	0.01	1.69	0.32	0.05	0.01	0.1	0.04
As (µg L ⁻¹)	5	5	5		0.01	0.005	0.005	
Cd ²⁺ (µg L ⁻¹)	1.51	0.19	7.2	1.6	5.27	4.1	8.16	1.40
Cr ⁶⁺ (µg L ⁻¹)	0.03	0	1	0.15	0.00	0.002	0.002	
O ₂ -dis (mg L ⁻¹)	5.72	3.7	7.01	0.8	5.24	1.99	6.93	1.97
KMnO ₄ (mg L ⁻¹)	0.78	0.2	1.85	0.42	5.29	2.55	8.85	2.49
RPmV	89.17	-17	140.9	36.02	-3.99	-40.00	68.40	33.74

Min: Minimum, Max: Maximum, SD: Standard deviation, RP: Redox potential and O₂-dis: Dissolved oxygen

(500 mg L⁻¹) for fresh drinking water. The high standard deviation of TDS indicates that the groundwater may be influenced by diverse hydrochemical processes related to natural and anthropogenic factors. Seawater intrusion, mixing of freshwater with saline water and evaporation influence groundwater in coastal aquifers²⁶.

The mean value of groundwater TDS in the present study is smaller than the mean value (1113 mg L⁻¹) of the shallow groundwater in Grand Lome⁵. The high value of TDS in Grand Lome could be related to the over exploitation of CT groundwater⁸. Coastal aquifers in the Gulf of Guinea are characterized by shallow groundwater varying from freshwater to brackish waters depending on the location of the sample. The significant variation in shallow groundwater mineralization in this region was related mainly to local processes^{24,27,28}.

Bicarbonate varies from 6-281 mg L⁻¹ with a standard deviation of 44 mg L⁻¹. Nitrate ranges from 1-103 mg L⁻¹ with a mean of 18 mg L⁻¹ and a standard deviation of 44 mg L⁻¹.

Cations were largely dominated by Na⁺ ranging from 17-103 mg L⁻¹ with a mean of 106 mg L⁻¹. K⁺ ranges from 0.5-20 mg L⁻¹ with a mean of 3 mg L⁻¹. Ca²⁺ and Mg²⁺ range, respectively from 0.3-400 and 0.5-384 mg L⁻¹ with means

of 34 and 22 mg L⁻¹. Cation abundance was Na⁺>Ca²⁺>Mg²⁺>K⁺. Chloride in groundwater ranges from 11-2250 mg L⁻¹ with a mean of 232 mg L⁻¹ and a standard deviation of 467 mg L⁻¹. Bicarbonate concentration varies from 6 to 281 mg L⁻¹ and nitrates from 0.5-104 mg L⁻¹. The abundance of anions was Cl⁻>SO₄²⁻>HCO₃⁻>NO₃⁻. The high salinity is determined by the predominance of the major ions Cl⁻ and Na⁺.

The pH of surface water ranges from 6.2-7.8 with a mean of 6.9 and TDS from 134-33915 mg L⁻¹. Na⁺ ranges from 30-3014.9 mg L⁻¹ with a mean of 1054.7 mg L⁻¹. Ca²⁺ and Mg²⁺ range, respectively from 0.2 and 11.2 mg L⁻¹ with a mean of 5 and 4.8-638.4 mg L⁻¹ with a mean of 127.5 mg L⁻¹. Chloride ranges from 38-9014 mg L⁻¹ with a mean of 2344.5 mg L⁻¹. Na⁺ and Cl⁻ were the major ions in surface water. In surface water, the order of ion abundance was Na⁺>Ca²⁺>Mg²⁺>K⁺ for cations and Cl⁻>SO₄²⁻>HCO₃⁻>NO₃⁻ for anions.

The Piper diagram allowed the classification of waters into six fields: Ca-HCO₃ type, Na-Cl type, Ca-Mg-Cl type, Ca-Na-HCO₃ type, Ca-Cl type and Na-HCO₃ type. A Piper diagram was created for the Vogon-Attitogon plateau area groundwater and surface water using the analytical data

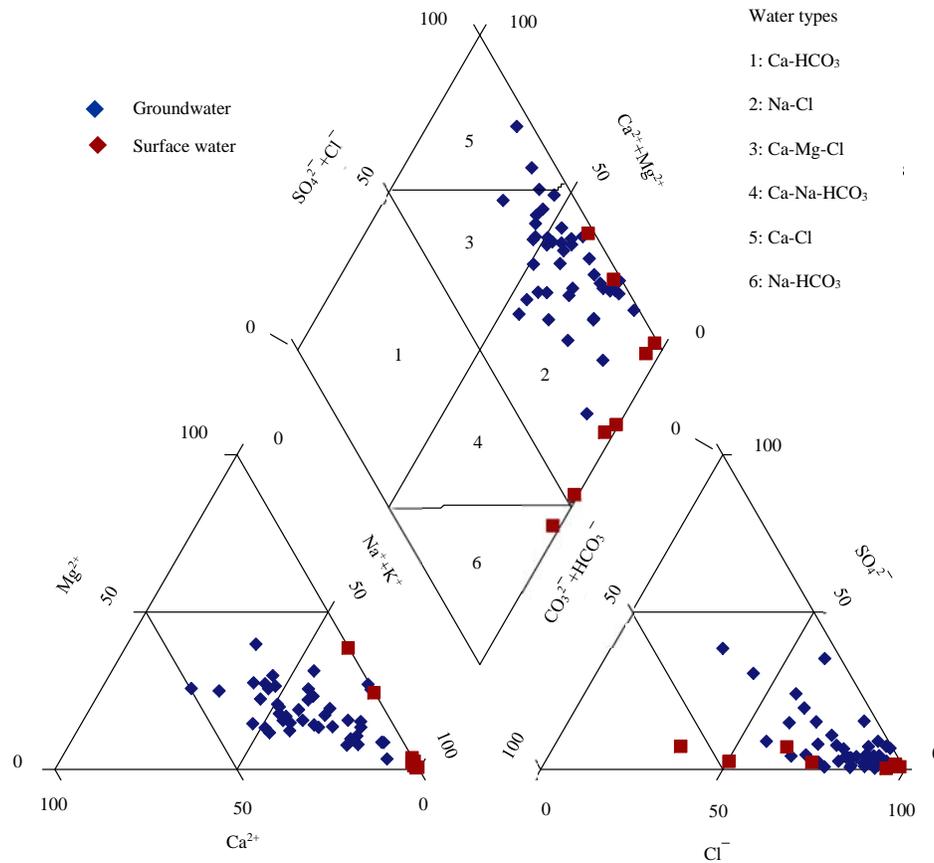


Fig. 1: Piper classification diagram

obtained from the hydrochemical analysis in Fig. 1. The water types found were confined to the first three types. The majority of the samples (81%) are plotted in the Na-Cl field followed by Ca-Cl (12%) and Ca-Mg-Cl (7%).

In the triangle of cations, the diagram shows samples dominated by sodium and potassium with a tendency to mixing with calcium and in the triangle of anions, samples show a predominance of chloride with a slight tendency toward the sulfate pole. Higher TDS values characterize samples with Na-Cl groundwater in the CT aquifer of the Vogon-Attitogon plateau.

The Na-Cl water type of groundwater was found everywhere in the study area, mainly toward the coast, near the Togo Lake, the Zowla Lake and the Mono river. Na-Cl water type was also found to be very dominant (88%) in surface water followed by the Ca-Na-HCO₃ water type (12%).

The predominance of Na-Cl water type was also found in groundwater by other studies of the coastal shallow aquifers in the Gulf of Guinea. These studies explained the predominance of Na-Cl water type by processes such as the strong influence of coastal sea aerosol spray, atmospheric deposition and saline water intrusion from seawater and

lagoon systems^{5,24,27}. The presence of accessory water types indicates the influence of carbonaceous debris, gypsum and concrete material dissolution⁵. The proportion of the calcic and bicarbonate water types increases at greater and greater distances from the coastline because of the decreasing impact of saltwater^{4,24}. The proportion of chlorinated facies waters of the CT of the Vogon-Attitogon plateau is comparable to that of the Sakete plateau in Benin. The CT groundwater of the Sakiete plateau was characterized predominantly by the Na-Cl water type (80%). The predominance of this water type was related to marine water effects, lake and lagoon waters which have more impact on the mineralization of the water table than other processes⁶.

Principal component analysis observation: In this study, PCA was performed on the standardized dataset to determine the factors that influence the hydrochemistry of groundwater. Fifteen variables were considered in this analysis.

Correlation analysis: A correlation analysis is a bivariate method that shows how well one variable predicts the other. The analysis of Pearson's correlation matrix is a useful

Table 2: Correlation coefficient among groundwater parameters

	TDS	T	EC	pH	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Fe total	Mn ²⁺	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	PO ₄ ²⁻	NO ₃ ⁻
TDS	1.000														
T	-0.109	1.000													
EC	0.999	-0.100	1.000												
pH	0.030	-0.404	0.030	1.000											
Ca ²⁺	0.901	-0.260	0.902	0.179	1.000										
Mg ²⁺	0.921	-0.225	0.922	0.103	0.974	1.000									
Na ⁺	0.877	0.086	0.877	-0.098	0.605	0.628	1.000								
K ⁺	0.861	-0.111	0.869	0.112	0.868	0.836	0.694	1.000							
Fe total	0.850	-0.195	0.851	0.088	0.917	0.962	0.534	0.802	1.000						
Mn ²⁺	0.812	-0.257	0.812	0.106	0.918	0.963	0.455	0.734	0.972	1.000					
HCO ₃ ⁻	0.756	-0.340	0.746	0.197	0.864	0.868	0.427	0.680	0.850	0.893	1.000				
Cl ⁻	0.961	-0.037	0.963	-0.036	0.777	0.799	0.961	0.785	0.697	0.647	0.585	1.000			
SO ₄ ²⁻	0.732	-0.122	0.722	0.158	0.588	0.525	0.800	0.609	0.423	0.368	0.447	0.773	1.000		
PO ₄ ²⁻	0.624	-0.173	0.625	0.078	0.724	0.768	0.327	0.536	0.772	0.800	0.685	0.491	0.235	1.000	
NO ₃ ⁻	-0.136	0.245	-0.126	-0.030	-0.030	-0.085	-0.181	0.128	-0.128	-0.131	-0.118	-0.161	-0.285	-0.129	1.000

Table 3: Principal component loadings

Variables	PC 1	PC 2	PC 3	PC 4
TDS	0.977	-0.190	0.029	-0.019
T (°C)	-0.206	-0.642	-0.498	0.060
EC	0.976	-0.194	0.018	-0.025
pH	0.110	0.529	0.445	-0.563
Ca ²⁺	0.960	0.157	-0.087	-0.085
Mg ²⁺	0.972	0.144	-0.132	0.039
Na ⁺	0.766	-0.578	0.197	-0.047
K ⁺	0.880	-0.087	-0.131	-0.284
Fe total	0.923	0.214	-0.184	0.125
Mn ²⁺	0.901	0.315	-0.191	0.159
HCO ₃ ⁻	0.846	0.345	-0.057	0.046
Cl ⁻	0.891	-0.389	0.124	-0.033
SO ₄ ²⁻	0.679	-0.382	0.489	-0.172
PO ₄ ²⁻	0.724	0.335	-0.239	0.271
NO ₃ ⁻	-0.145	-0.033	-0.679	-0.678
Eigen value	9.368	1.828	1.374	1.020
Total variance (%)	62.453	12.187	9.160	6.803
Cumul (%)	62.453	74.640	83.801	90.604

tool to indicate the origins and associations between hydrogeochemical parameters. In this study, the relationships between various elements have been studied.

The correlation matrix shows a strong correlation between EC and TDS, strong correlations between TDS and Ca²⁺, Mg²⁺, Na⁺, K⁺, Cl⁻, Fe, Mn²⁺ (>0.75) and moderate correlations with HCO₃⁻, SO₄²⁻ and PO₄²⁻ (between 0.75 and 0.50). Chloride shows strong correlations with sodium, potassium, calcium, magnesium and moderate correlations with manganese and iron. It shows that chloride was the principal constituent of the TDS. Nitrate shows weak negative correlations with most of the variables (>-0.50). Iron shows strong correlations with calcium, magnesium, potassium and a moderate correlation with sodium. Bicarbonate shows a strong correlation with calcium and magnesium. Sulfates show a strong correlation with sodium, chloride and a moderate correlation with calcium, magnesium and potassium. Phosphates show a strong correlation with

iron, magnesium, manganese and a moderate correlation with calcium, potassium, bicarbonate. pH exhibited a smaller positive correlation with most of the variables and temperature weak negative correlation with most of the variables in the matrix. The weak positive associations between parameters suggest that many factors could be influencing their occurrence in the groundwater samples. Table 2 showed negative and negligible relationships between temperature and other parameters. This indicates that temperature has little or no control over the presence of cations and anions in the study area. Table 2 showed that Na⁺, Cl⁻ and Mg²⁺ were the major products of shallow groundwater mineralization. Temperature and pH were not the principal factors influencing the CT groundwater mineralization.

Components analysis: The PCA approach considers only the first two factors that have the most important loadings and excludes the less important ones²⁹. The calculated component loadings, eigenvalue, percentages of variance, cumulative percentage explained by each factor are listed in Table 3.

An initial run using the Kaiser criterion²² resulted in fifteen principal components. However, it was observed that the last eleven factors would not each constitute a unique source of variance in the hydrochemistry since each factor had an Eigenvalue less than 1. The first four factors were chosen for varimax rotation. The results show that the first four PCs account for 90.6% of the total variance of parameters, which is quite good and can be relied upon to identify the main sources of variation in the hydrochemistry of groundwater in the study area.

PC1 represents about 62.45% of the total variance with strong positive loadings in EC, Ca²⁺, Mg²⁺, Na⁺, K⁺, Fe total, Mn²⁺, HCO₃⁻, Cl⁻ (>0.75), moderate positive loading in SO₄²⁻ and PO₄²⁻ (between 0.75 and 0.50) and is associated with

Table 4: Number and percentage of samples with values of parameters exceeding the WHO standard

Chemical parameters (mg L ⁻¹)	Standard	No samples exceed	Samples exceed (%)
pH	6.5-8.5	36	86
TDS	500	30	71
Ca ²⁺	75	3	7
Mg ²⁺	50	2	5
Na ⁺	200	3	7
K ⁺	12	1	2
HCO ₃ ⁻	120	2	5
Cl ⁻	250	7	17
SO ₄ ²⁻	250	0	0
NO ₃ ⁻	50	4	10
Fe	0.3	10	24
Mn ²⁺	0.5	3	7
Cd ²⁺	0.003	8	19
As	0.010	17	40
Cr ⁶⁺	0.050	1	2

various hydrogeochemical processes resulting in high TDS (mineralized water). PC1 with a lower loading in pH, temperature and nitrate, indicates that these parameters were not associated with groundwater mineralization. The high loadings in EC, TDS, Na⁺, Cl⁻ reflect seawater intrusion influencing groundwater mineralization^{4,30}. This result explained the predominance of the Na-Cl water type. The groundwater characteristics can be associated with silicate natural weathering, limestone, pyrite dissolution and various ion exchange processes in the groundwater system⁵. The moderate loading of Mg²⁺ in SO₄²⁻ indicates a moderate non-permanent hardness of groundwater in this area. This is confirmed by the moderate linear correlation between Ca²⁺, Mg²⁺ and HCO₃⁻ (Table 2).

PC2 which accounts for 12.2% of the total variance has positive moderate loadings in pH and moderate negative scores with temperature and sodium. The moderate negative loading in sodium associated with a high value of Ca²⁺ reflects the inverse cations exchange reactions leading to adsorption of Na⁺ on clay minerals and a simultaneous release of Ca²⁺ during the dry season²⁹. The moderate negative loading in temperature indicates that evaporation is playing a role in groundwater mineralization, although the samples were taken in the dry season. The negative loading in pH is associated with organic matter oxidation related to anthropogenic activities³¹.

PC3 with 9.2% of the total variance has a moderate negative score with temperature and nitrate and suggests evaporation and anthropogenic activities as factors influencing groundwater mineralization.

PC4 accounts for 6.8% of the total variance explained by moderate loadings in pH and nitrate. This condition may be attributed to anthropogenic factors like agricultural and industrial activities and acid rainfall. It indicates the leaching

of agricultural runoff (NPK fertilizer) and seepage of wastewater caused by the lack of a proper sewerage system. Previous studies show that downstream site waters of the Zio river were degraded by human activities and record lower levels of dissolved oxygen⁷. The use of fertilizers and pesticides in agriculture was caused by the high concentration of nitrate in the groundwater of the study region. In shallow groundwater in Grand Lome, 50.0% of the collected samples, contain nitrate higher than the guideline values for drinking⁵. The loading in pH also reflects anthropogenic factors. The acidic water results from co-factors, including atmospheric acid deposition from industries, municipal solid waste incineration, urbanization, induced deforestation and acid-rain gas emissions, loads of organic matter, ammonium and a low proportion of acid-consuming minerals such as carbonates in the aquifer matrix⁵.

Water quality: The Drinking Water Quality Index (DWQI) and other methods are usually used to assess water quality^{26,32}. The analytical results of the physical and chemical parameters of groundwater were compared to WHO standard guideline values.

The shallow groundwater of the Vogan-Attitogon plateau reveals high values of TDS during the dry season making it unsuitable for drinking purposes regarding WHO guidelines for drinking water in Table 4. Almost 71% of groundwater samples contain over 500 mg L⁻¹ of TDS. The 13% of samples have TDS higher than 1,000 mg L⁻¹. WHO suggests a threshold limit of 1,000 mg L⁻¹ for TDS, which should correspond to about 1,380 µS cm⁻¹. TDS content can affect the taste of water especially when ion concentrations exceed threshold values. 7% of the samples exceed the required limit for Ca²⁺ (75 mg L⁻¹) and the limit for Na⁺ (200 mg L⁻¹) for drinking water. About 19% of groundwater samples exceed the

suitable limit for chloride (250 mg L^{-1}). In groundwater, nitrate varies from 0-2 times the WHO standard and 10% of samples contain nitrate exceeding the guideline value for drinking (50 mg L^{-1}) fixed by the World Health Organization. The 24 and 7% of samples contain respectively iron and manganese, exceeding WHO guidelines (respectively 0,2 and $0,5 \text{ mg L}^{-1}$). Trace elements such as cadmium and arsenic were found in 19 and 40% of samples, respectively exceeding WHO guidelines (respectively 0.003 and 0.01 mg L^{-1}).

The degradation of groundwater quality in this area is due to high values of TDS and high content of nitrate, iron, manganese, chloride, sodium and trace elements in shallow groundwater. High TDS in groundwater is generally not harmful to human beings but a high concentration of these elements may affect persons who are suffering from kidney and heart diseases^{33,34}. Water high in solids may cause laxative or constipation effects. Sulfate ions associated with high concentrations of Mg^{2+} and Na^+ act as a laxative and may cause gastric disorders^{34,35}. Ingestion of nitrate in drinking water and dietary sources may cause cancer, birth defects, infant methemoglobinemia or other adverse health effects³⁶. Manganese causes non-carcinogenic health risks to the human body. The interaction between metabolic genes and manganese and iron in drinking water, even at low levels, could lead to an elevated risk of fetal growth retardation³⁷. A high level of cadmium was reported by Tanouayi *et al.*³⁸, (2016) in groundwater around the phosphorite treatment plant at Kpeme and fluoride present in the water was responsible for the discolouration of the teeth of many children and adults living there³⁹.

CONCLUSION

Statistical analysis was applied to the hydrochemical data set of samples of the shallow groundwater of the Vogon-Attitogon plateau to identify geochemical processes and their relation to groundwater quality. The Piper diagram and Principal Component Analysis have been used to determine the factors that control groundwater processes in the aquifer system based on the ionic constituents, water types and component loadings. The Piper diagram has given three water types. The predominant water type found was Na-Cl water type with two accessory water types (Ca-Cl and Ca-Mg-Cl). The principal process operating in the shallow groundwater of the Vogon-Attitogon plateau was seawater mixing with fresh water. Natural silicate weathering, limestone and pyrite dissolution and ion exchange, evaporation, anthropogenic activities such as farming using fertilizers, industrial activity

and waste incineration were also identified to influence groundwater mineralization. The shallow groundwater quality of the Vogon-Attitogon plateau was affected by high TDS, nitrate, whereas iron, manganese, cadmium and arsenic were found in concentrations exceeding their threshold for drinking purposes. The consumption of the shallow groundwater of the Vogon-Attitogon plateau may affect human health. Therefore, understanding the environmental consequences of agricultural practices is essential to minimize unexpected problems. Water resource management and conservation policy can improve the application of best practices.

SIGNIFICANCE STATEMENT

This study shows shallow groundwater of the Vogon-Attitogon plateau was influenced by the seawater intrusion, the dissolution of evaporites, contamination from fertilisers, industrialization, mining exploitation and can be beneficial for the government et communities to ensure safe water resource management in this area. This study will help researchers to conduct studies to identify the sources of shallow groundwater quality degradation in this area. The theory on the dissolution of evaporites may be developed.

ACKNOWLEDGMENTS

This study was carried out with the technical support of the Laboratory of Applied Hydrology and Environment (Ex Laboratory of Water Chemistry, University of Lomé, Togo) and the National Institute of Hygiene of Lome (Togo). Thanks for the collaboration between the Ministry in charge of water (Togo), the Laboratory of Applied Hydrology and Environment (University of Lomé, Togo) and the National Institute of Hygiene of Lome (Togo).

REFERENCES

1. Diaw, M.T., S. Cissé-Faye, C.B. Gaye, S. Niang, A. Pouye, L.C. Campos and R.G. Taylor, 2020. On-site sanitation density and groundwater quality: Evidence from remote sensing and in situ observations in the Thiaroye aquifer, Senegal. *J. Water Sanitation Hyg. Dev.*, 10: 927-939.
2. Ferguson, G. and T. Gleeson, 2012. Vulnerability of coastal aquifers to groundwater use and climate change. *Nat. Climate Change*, 2: 342-345.
3. Ouedraogo, I., P. Defourny and M. Vanclooster, 2016. Mapping the groundwater vulnerability for pollution at the pan African scale. *Sci. Total Environ.*, 544: 939-953.

4. Akouvi, A., M. Dray, S. Violette, G. de Marsily and G.M. Zuppi, 2008. The sedimentary coastal basin of Togo: Example of a multilayered aquifer still influenced by a palaeo-seawater intrusion. *Hydrogeol. J.*, 16: 419-436.
5. Akpataku, K.V., M.D.T. Gnazou, T.Y.A. Nomesi, P. Nambo, K. Doni, L.M. Bawa and G. Djaneye-Boundjou, 2020. Physicochemical and microbiological quality of shallow groundwater in Lomé, Togo. *J. Geoscience Environ. Prot.*, 08: 162-179.
6. Houéménou, H., S. Tweed, G. Dobigny, D. Mama and A. Alassane *et al.*, 2020. Degradation of groundwater quality in expanding cities in West Africa. A case study of the unregulated shallow aquifer in Cotonou. *J. Hydrol.*, Vol. 582. 10.1016/j.jhydrol.2019.124438.
7. Tampo, L., D.T.M. Gnazou, T. Kodom, A. Oueda and L.M. Bawa, 2015. Suitability of groundwater and surface water for drinking and irrigation purpose in Zio River Basin (Togo). *J. Res. Sci. Univ. Lomé (Togo)*, 17: 35-51.
8. Gnazou, M.D.T., B.E. Sabi, J.L. Lavalade, J. Schwartz, W. Akakpo and A. Tozo, 2017. Multilayered aquifer modeling in the coastal sedimentary basin of Togo. *J. Afr. Earth Sci.*, 125: 42-58.
9. Ouro-Sama, K., H.D. Solitoke, G. Tanouayi, I.M. Lazar and P. Bran *et al.*, 2020. Spatial and seasonal variation of trace elements contamination level of the waters from the Hydrosystem Lake Togo-Lagoon of Aného (South of Togo). *SN Appl. Sci.*, Vol. 2. 10.1007/s42452-020-2593-7.
10. da Costa, P.Y., P. Affaton, J. Salaj, A.K.C. Johnson and K. Seddoh, 2013. Biozonation of the sedimentary formations of the coastal basin of Togo (West Africa), *Rev. Ivoir. Sci. Technol.*, 21-22: 45-73.
11. Gnazou, M.D.T., L.M. Bawa, O. Banton and G. Djanéyé-Boundjou, 2011. Hydrogeochemical characterization of the coastal paleocene aquifer of Togo (West Africa). *Int. J. Water Resour. Environ. Eng.*, 3: 10-29.
12. Barakat, A., A. Hilali, M.E. Baghdadi and F. Touhami, 2019. Assessment of shallow groundwater quality and its suitability for drinking purpose near the Béni-Mellal wastewater treatment lagoon (Morocco). *Hum. Ecol. Risk Assess.: An Int. J.*, 26: 1476-1495.
13. Ahamed, A.J., K. Loganathan and R. Jayakumar, 2015. Hydrochemical characteristics and quality assessment of groundwater in Amaravathi river basin of Karur district, Tamil Nadu, South India. *Sustainable Water Resour. Manage.*, 1: 273-291.
14. Guler, C., G.D. Thyne, J.E. McCray and K.A. Turner, 2002. Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. *Hydrogeol. J.*, 10: 455-474.
15. Cloutier, V., R. Lefebvre, R. Therrien and M.M. Savard, 2008. Multivariate statistical analysis of geochemical data as indicative of the hydrogeochemical evolution of groundwater in a sedimentary rock aquifer system. *J. Hydrol.*, 353: 294-313.
16. Belkhir, L., A. Boudoukha and L. Mouni, 2011. A multivariate statistical analysis of groundwater chemistry data. *Int. J. Environ. Res.*, 5: 537-544.
17. Singh, K.P., A. Malik, D. Mohan and S. Sinha, 2004. Multivariate statistical techniques for the evaluation of spatial and temporal variations in water quality of Gomti River (India)-A case study. *Water Res.*, 38: 3980-3992.
18. Simeonov, V., P. Simeonova and R. Tzimou-Tsitouridou, 2004. Chemometric quality assessment of surface waters: Two case studies. *Chem. Eng. Ecol.*, 11: 449-469.
19. Pires, J.C.M., M.C. Pereira, M.C.M. Alvim-Ferraz and F.G. Martins, 2009. Identification of redundant air quality measurements through the use of principal component analysis. *Atmospheric Environ.*, 43: 3837-3842.
20. Vieira, J.S., J.C.M. Pires, F.G. Martins, V.J.P. Vilar, R.A.R. Boaventura and C.M.S. Botelho, 2012. Surface water quality assessment of Lis river using multivariate statistical methods. *Water Air Soil Pollut.*, 223: 5549-5561.
21. Liu, C.W., K.H. Lin and Y.M. Kuo, 2003. Application of factor analysis in the assessment of groundwater quality in a blackfoot disease area in Taiwan. *Sci. Total Environ.*, 313: 77-89.
22. Monjerezi, M., R.D. Vogt, P. Aagaard and J.D.K. Saka, 2011. Hydro-geochemical processes in an area with saline groundwater in lower Shire River valley, Malawi: An integrated application of hierarchical cluster and principal component analyses. *Applied Geochem.*, 26: 1399-1413.
23. Shrestha, S. and F. Kazama, 2007. Assessment of surface water quality using multivariate statistical techniques: A case study of the Fuji River Basin, Japan. *Environ. Modell. Software*, 22: 464-475.
24. Alassane, A., R. Trabelsi, L.F. Dovonon, D.J. Odeloui, M. Boukari, K. Zouari and D. Mama, 2015. Chemical evolution of the continental terminal shallow aquifer in the south of coastal sedimentary basin of Benin (West-Africa) using multivariate factor analysis. *J. Water Resour. Prot.*, 7: 496-515.
25. Aladejana, J.A., R.M. Kalin, P. Sentenac and I. Hassan, 2020. Assessing the impact of climate change on groundwater quality of the shallow coastal aquifer of eastern Dahomey Basin, Southwestern Nigeria. *Water*, Vol. 12. 10.3390/w12010224.
26. Egbueri, J.C., 2019. Evaluation and characterization of the groundwater quality and hydrogeochemistry of Ogbaru farming district in Southeastern Nigeria. *SN Appl. Sci.*, Vol. 1. 10.1007/s42452-019-0853-1.
27. Yusuf, M.A., T.A. Abiye, M.J. Butler and K.O. Ibrahim, 2018. Origin and residence time of shallow groundwater resources in Lagos coastal basin, South-West Nigeria: An isotopic approach. *Heliyon*, Vol. 4. 10.1016/j.heliyon.2018.e00932.

28. Emvoutou, H.C., B.K. Tandia, S.N.B. Nkot, R.C.S. Ebonji and Y.B. Nlend *et al*, 2018. Geologic factors controlling groundwater chemistry in the coastal aquifer system of Douala/Cameroon: Implication for groundwater system functioning. *Environ. Earth Sci.*, Vol. 77. 10.1007/s12665-018-7400-z.
29. Kumar, M., A. Ramanathan, M.S. Rao and B. Kumar, 2006. Identification and evaluation of hydrogeochemical processes in the groundwater environment of Delhi, India. *Environ. Geol.*, 50: 1025-1039.
30. Mohamed, M.L., D.M.L. Diongue, H.C. Emvoutou, A.S. Mohamed, M. Jiddou and S. Faye, 2020. Salinization processes in the benichab coastal aquifer-mauritania. *Int. J. Geosci.*, 11: 377-392.
31. Krishnaraj, S., V. Murugesan, K. Vijayaraghavan, C. Sabarathinam, A. Paluchamy and M. Ramachandran, 2011. Use of hydrochemistry and stable isotopes as tools for groundwater evolution and contamination investigations. *J. Geo-Sci.*, 1: 16-25.
32. Nijesh, P., K.V. Akpataku, A. Patel, P. Rai and S.P. Rai, 2021. Spatial variability of hydrochemical characteristics and appraisal of water quality in stressed phreatic aquifer of upper Ganga plain, Uttar Pradesh, India. *Environ. Earth Sci.*, Vol. 80. 10.1007/s12665-021-09410-2.
33. Gupta, S.K. and R.D. Deshpande, 2004. Water for India in 2050: First-order assessment of available options. *Curr. Sci.*, 86: 1216-1224.
34. Ramakrishnaiah, C.R., C. Sadashivaiah and G. Ranganna, 2009. Assessment of water quality index for the groundwater in Tumkur Taluk, Karnataka State, India. *E-J. Chem.*, 6: 523-530.
35. Herojeet, R., M.S. Rishi, R. Lata and R. Sharma, 2016. Application of environmetrics statistical models and water quality index for groundwater quality characterization of alluvial aquifer of Nalagarh Valley, Himachal Pradesh, India. *Sustainable Water Resour. Manage.*, 2: 39-53.
36. Ward, M.H., R.R. Jones, J.D. Brender, T.M. De Kok and P.J. Weyer *et al*, 2018. Drinking water nitrate and human health: An updated review. *Int. J. Environ. Res. Public Health*, Vol. 15. 10.3390/ijerph15071557.
37. Grazuleviciene, R., R. Nadisauskiene, J. Buinauskiene and T. Grazulevicius, 2009. Effects of elevated levels of manganese and iron in drinking water on birth outcomes. *Pol. J. Environ. Stud.*, 18: 819-825.
38. Tanouayi, G., K. Gnandi, K. Ouro-Sama, A.A. Aduayi-Akue, H. Ahoudi, Y. Nyametso and H.D. Solitoke, 2016. Distribution of fluoride in the phosphorite mining area of Hahotoe-Kpogame (Togo). *J. Health Pollut.*, 6: 84-94.
39. Gnandi, K., G. Tchangbedji, K. Killi, G. Baba and K. Abbe, 2006. The impact of phosphate mine tailings on the bioaccumulation of heavy metals in marine fish and crustaceans from the coastal zone of Togo. *Mine Water Environ.*, 25: 56-62.