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Characterization and statistical study of water quality based on physicochemical parameters: Case study of Salamat Province (South Eastern, Chad)

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Abstract

The statistical study and characterization of groundwater quality were calculated based on physicochemical parameters. The objective of this study was to determine the quality of groundwater in the province of Salamat. A total of 25 boreholes were selected. The data used were physicochemical parameters (TDS, EC, T°, Mg^{2+}, Ca^{2+}, K^{+}, Na^{+}, Cl^{-}, HCO_3^{-}, SO_4^{2-}, and NO_3^{-}). Multivariate statistical techniques, including principal component analysis (PCA) and a correlation matrix, were used to define the main parameters controlling the hydrochemistry of groundwater in the province of Salamat. The results showed that the water is within the range recommended by the World Health Organization (WHO). Principal component analysis yielded three significant factors, accounting for 47.22% of the total variance and highlighting the primary processes governing groundwater chemistry. This study will serve as a starting point for an in-depth study of groundwater quality to understand the factors controlling the physicochemical processes of groundwater in the province of Salamat.

Keywords: Water quality; Characterization; Statistical analysis; Salamat; Chad

1. Introduction

Water covers three-quarters of the Earth's surface (1). The availability of high-quality water resources is crucial for life and socio-economic development (2). There are two primary types of water resources: surface water and groundwater (3,4). Unfortunately, in many countries around the world, including Chad, access to drinking water is a real problem in most rural areas (5,6). Indeed, in the province of Salamat, the rate of access to drinking water remains low. For two decades, the province of Salamat has been one of the provinces where agricultural activities have experienced significant growth. As a result, water resources in the province of Salamat include surface water, groundwater, and rainwater. However, population growth and intensive agricultural activities have a direct impact on groundwater. Various health problems related to water resources, such as cancer, hypertension, hyperkeratosis, peripheral vascular diseases, restrictive lung diseases, and gangrene, occur as a result of consuming contaminated water (7). Groundwater is an important natural resource in various daily activities (8,9). It is considered to be relatively cleaner and less polluted than surface water (10,11). The quality of groundwater depends on the aquifer through which it flows (12,13). The chemical composition of groundwater determines its suitability for use as a source of water for human consumption, animal consumption, and irrigation (14,15). Water resources are limited and are increasingly subject to qualitative and quantitative degradation because of natural effects such as climate change, but also anthropogenic activities (16,17). Access to drinking water is a major problem facing several developing countries (18). As a result, many researchers have used geostatistical methods and quality indices in several different geological and environmental contexts to assess water quality (19,20). It serves as a necessary tool for studying the spatial distribution between different sampling points. Physicochemical parameters have been studied by many researchers to assess groundwater quality

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(21,22). In Salamat Province, little research has been conducted on groundwater quality. Given this lack of research, Salamat Province was chosen to determine the types of groundwater quality. The objective of this study is to evaluate the physicochemical and statistical characteristics of groundwater quality for domestic use in the province of Salamat.

1.1. Study area

1.1.1. Geographical context

The province of Salamat is located in southeastern Chad between 19° and 22.5° east longitude and 09° and 12° north latitude (Figure 1). It lies in a vast plain and features a Sahelo-Sudanese climate. The topography is fairly flat. From a hydro-climatic perspective, it falls under the influence of a dry tropical climate, with a rainy season from March to October lasting 7 to 8 months and a dry season from November to March lasting 4 to 5 months.

The average annual temperature ranges from 50°C to 25.41°C, with an interannual average of 35.19°C. The lowest temperatures occur in December and January, around 19°C.

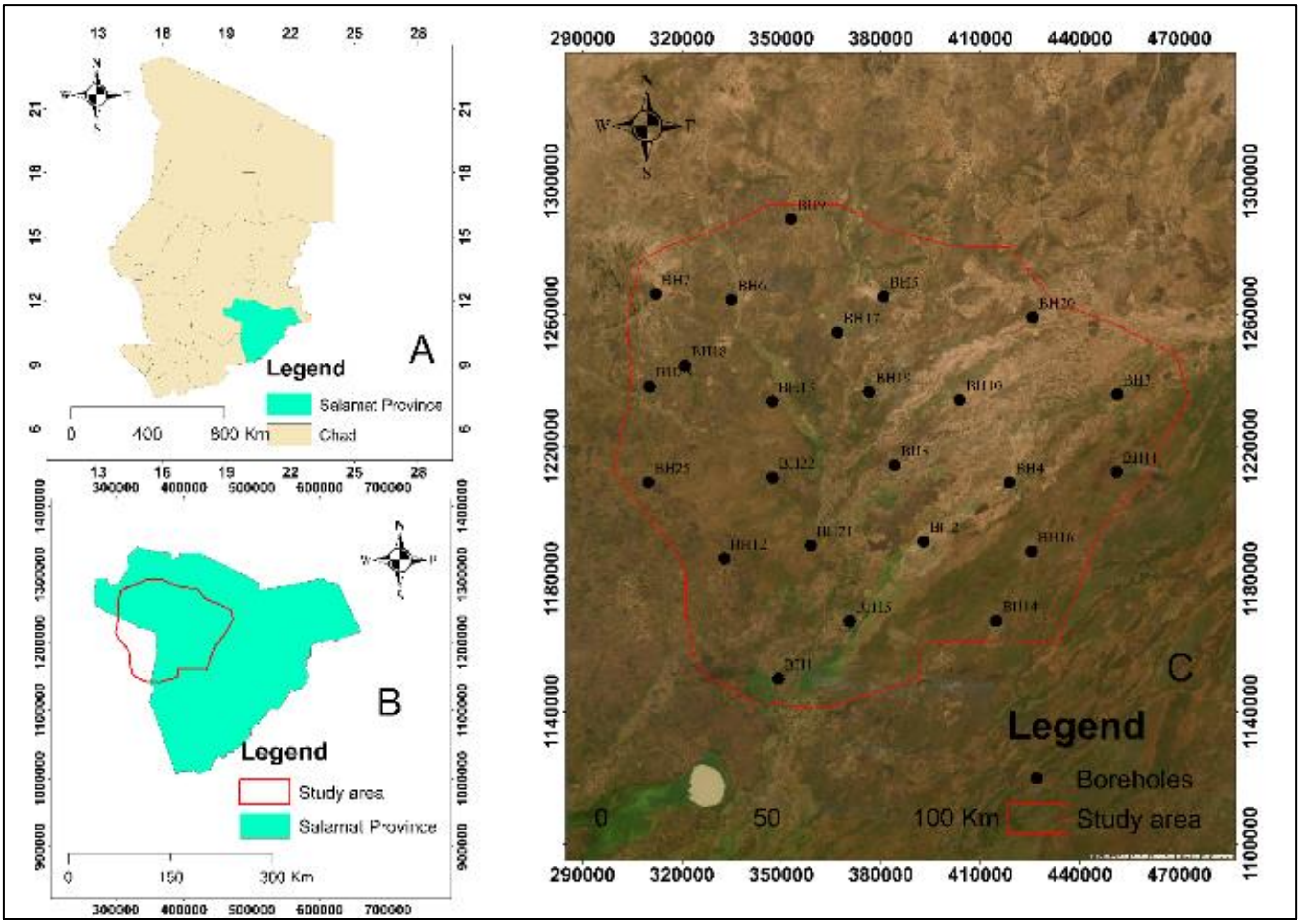

Figure 1 Location map

1.2. Geological and hydrogeological context

The geology of Salamat province features a granite bedrock outcrop beneath a sedimentary cover. To the north, northeast, and northwest, there are various Precambrian bedrock formations, especially around Aboudeïa. This bedrock extends from the Guéra and Ouaddai massifs. In the central and southern areas, sedimentary cover formations are present, including the Continental Terminal and recent and current fluvial alluvium. Quaternary formations cover most of the province and mainly consist of ancient and recent alluvium (Fig. 2). According to the Islamic Development Bank project survey (1987), the water table in Am-Timan ranges from 21 m to 32 m deep. In the sandy aquifer, the depth varies from 5 m to 15 m.

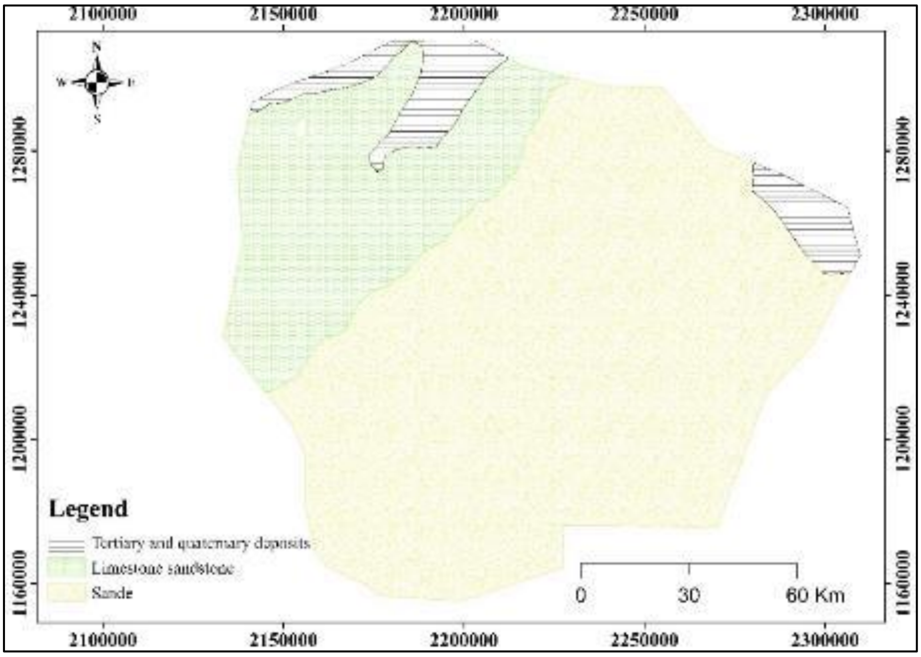

Figure 2 Hydrogeological map of area

2. Materials and Methods

The equipment and methods used for acquiring and processing physicochemical data.

2.1. Materials

Samples were taken from twenty-five (25) boreholes, and in situ analyses were performed. Temperature (T°), electrical conductivity (EC), and hydrogen potential (pH) were measured using a portable multi-parameter device. The locations of the various boreholes were recorded using a Garmin Global Positioning System (GPS) device to obtain geographical coordinates.

2.2. Sampling

For laboratory analysis of major elements, water was pumped from the borehole. The water sample is collected in 100 ml bottles, which are acidified beforehand with nitric acid to prevent precipitation. The physicochemical analyses from different boreholes. They are used to determine the chemical quality of the water. Their contents are measured in milligrams per liter (mg/l) in this study.

2.3. Groundwater quality

To determine groundwater quality, the physicochemical elements presented below in Table 1 were used in this study.

Table 1 Information on the study area

Name	Longitude	Latitude	Mg^{2+}	Ca^{2+}	K^+	Na^+	Cl^-	HCO^{3-}	SO_4^{2-}	$NO3^-$	EC	T°	pH
BH1	349090,2	1149855,6	2.2	7.78	3.5	22.1	0.59	91.8	1.64	0.21	161	31.3	6.8
BH2	392977,3	1191302,9	2.09	6.93	7.5	12.4	1.09	68.5	1.23	0	124	32.2	6.48
BH3	451202,9	1235612	3.68	26.4	3.8	45.7	7	193	9.52	0.921	352	29.3	7.59
BH4	418696,5	1209076,1	4.69	18.3	3.8	16.3	3.57	99.6	2.23	15.6	210	30	6.8
BH5	380875,1	1265164,9	3.91	17.3	4.2	24.1	4.52	98.7	2.7	28.7	240	29.5	6.9
BH6	334913,3	1264195,3	3.61	14.8	4.5	8.4	6.49	46.9	1.4	29.4	161	30.8	6.9
BH7	312142,5	1265926,8	11.7	64.3	2.3	58	23	244	29.2	84	666	32.7	6.74
BH8	384125,1	1214263,2	7.43	55.7	25.5	6.2	3.83	220	8.55	21.8	420	29.5	7.32

BH9	352872,15	1288544,7	2.98	8.06	1.5	8.2	1.9	60.3	0.606	5.98	117	30	6.2
BH10	403820,7	1233990,8	2.13	8.68	2.7	10.4	0.34	64.4	0.218	0.142	107	29.4	6.66
BH11	451043,13	1212298,6	4.41	19.4	4.1	20.3	3.1	121	2.71	8.76	229	28.5	6.43
BH12	332831	1186101,2	3.28	14.3	3.8	9.9	7.19	61.9	0.661	15.2	345	31	6
BH13	347309,34	1233569	2.39	9.88	2.1	10.6	0.58	65.8	0.311	2.07	116	30	6.34
BH14	414717,8	1167312,5	2.62	9.28	2.2	7.6	0.46	55.7	0.042	3.28	103	30.9	6.4
BH15	370590,6	1167188	2.72	9.41	2.8	6.7	4.1	27.8	0.332	27.2	116	31.1	6.27
BH16	425497,2	1188295,8	2.78	10.3	2.6	8.4	1.39	62.6	0.484	2.22	245	24.3	7.3
BH17	366929,2	1254357,7	3.4	13	2.9	21 .5	1.04	119	0.843	0.125	113	28.5	6.4
BH18	320898,35	1244266,7	4.19	16.4	3.9	9.2	2.46	76.8	3.28	11.4	539	29.2	9.2
BH19	376460,94	1236329,2	6.23	26.4	4.1	17.4	0.69	150	0.322	0.817	197	29.7	6.98
BH20	425739,69	1258818,8	5.95	22.7	5.6	23.7	1.4	157	1.52	0.919	161	25.3	8.02
BH21	358932,26	1190027	6.83	28.5	5.5	39.1	2.4	202	5.27	10.6	167	29.9	7.04
BH22	347356,72	1210532,3	6.25	25.2	4.3	65.3	2.78	157	6.08	14.2	276	30.4	8.04
BH23	310314,98	1237982,9	5.87	25.1	5.3	20.9	2.9	147	3.1	9.97	245	28.7	7.08
BH24	49717,8	1197312,5	2.2	7.78	3.5	22.1	0.59	91.8	1.64	0.21	161	31.3	6.8
BH25	309819,22	1209116,3	5.87	25.1	5.3	20.9	2.9	147	3.1	9.97	245	28.7	7.08

Mg^{2+}, Ca^{2+}, K^+, Na^+, Cl^-, HCO_3^-, SO_4^{2-}, and NO_3^- are expressed in mg/L, EC (µS/cm), temperature (°C), and pH without units.

2.4. Statistical analysis

The spatial distribution of the sampled boreholes is illustrated in Figure 1. Although there are several water quality parameters, only eleven (11) parameters are selected because they were measured in all the selected boreholes. The water quality parameters, their units, and the methods of analysis are summarized in Table 1. Multivariate statistical methodology encompasses a wide variety of statistical techniques that can be used to measure, study, analyze, and group data sets in order to provide meaningful data on the relationships between variables (23,24). The physicochemical parameters were subjected to two multivariate techniques: principal component analysis (PCA) and matrix correlation.

3. Results and discussion

3.1. Ionic balance (IB)

When using hydrochemical data, it is important to verify the analysis results, and an acceptable error of + or – 5% is permitted.

The ion balance (IB) equation is equal to: (∑Anions -∑Cations) / (∑Anions + ∑Cations) (1)

3.2. Physicochemical analyses

The physicochemical data are summarized in Table 2.

Table 2 Statistics of physicochemical parameters

	Mg^{2+}	Ca^{2+}	K^+	Na^+	Cl^-	HCO^{3-}	SO_4^{2-}	$NO3^-$	EC	T°	pH
Max	11.7	64.3	25.5	65.3	23	244	29.2	84	666	32.7	9.2
Min	2.09	6.93	1.5	6.2	0.34	27.8	0.042	0.01	103	24.3	6
Average	4.31	19.4	4.66	20.5	3.47	111.77	3.49	12.23	232.1	29.7	6.9

3.3. Physical parameters

3.3.1. Electrical conductivity

EC varies between 103 and 666 µS/cm, with an average of 232.6 µS/cm (Table 2). The highest conductivity values are observed in the BH7 borehole and the lowest in the BH2 borehole. These values range from 103 to 666 µS/cm and remain below the WHO standard of 1000 µs/cm. Values above 500 µs/cm probably indicate alterations in the granite and/or evaporation of surface water. Therefore, it provides information on the degree of water mineralization. In the study area, surface waters are less mineralized.

3.3.2. Temperature

The temperature varies between 24.3°C and 32.7°C, with an average of 29.69°C (Table 2). This value is close to the average ambient air temperature of 29.02°C, suggesting a thermal equilibrium between the aquifer system and the atmosphere.

3.3.3. pH

pH is an important indicator of water quality and depends on the origin of the water, the nature of the lithological formation, and the aquifer from which it is drawn. pH values range from 6 to 9.2, with an average of 7 (Table 2). The pH values show that the water is slightly acidic. This parameter determines a large number of physicochemical balances between water, dissolved carbon dioxide, carbonates, and bicarbonates, which form buffered solutions that provide favorable conditions for aquatic life.

3.4. Chemical parameters

3.4.1. Ions

Ions are chemical elements from various sources. They enable the chemical properties of water to be assessed. Their concentrations are measured in milligrams per liter (mg/l) in this study.

3.4.2. Cations

(Ca^{2+}) range from 64.3 mg/l to 6.93 mg/l, with an average of 19.6 mg/l. The highest value is found in the BH8 borehole (Table 2). The presence of calcium ions indicates that they may originate either from the dissolution of carbonate formations, calcite, dolomite, or from the dissolution of evaporite formations.

(Mg^{2+}) vary between 2.09 mg/l and 11.7 mg/l, with an average of 6.9 mg/l. It is high in the BH7 borehole and low in the BH2 borehole (Table 2). The presence of magnesium remains very low in almost all boreholes, except for BH7, which is characterized by high Mg2+ content.

(K^{+}) are highest in borehole BH7 (25.5 mg/l) and lowest in borehole BH2 (1.5 mg/l). The average content is 4.69 mg/l (Table 2). Potassium levels remain very low in almost all boreholes, with the exception of BH8, which has high K^{+} levels. The increase in potassium ions in this borehole indicates that they originate from water that has passed through evaporite formations rich in sylvite (KCl) or from water in clay formations.

(Na^{+}) vary between 6.2 mg/l and 65 mg/l, with an average of 20.5 mg/l. The lowest value is found in the BH2 borehole and the highest in the BH24 borehole (Table 2). The presence of sodium ions in the boreholes indicates that they may originate from leaching of NaCl-rich formations (clays, marls), sodium-rich domestic wastewater, and/or highly soluble salt deposits such as halite (NaCl) and sylvite (KCl) from granite degradation.

3.4.3. Anions

(Cl^{-}) range from 23 mg/l in the BH7 borehole to 0.34 mg/l in the BH7 borehole, with an average of 3.45 mg/l (Table 2).

(HCO^{3-}) range from 244 mg/l in the BH7 borehole to 27.8 mg/l in the BH2 borehole, with an average of 132.2 mg/l (Table 2).

($SO4^{2-}$) ranged from 29.2 mg/l to 0.042 mg/l, with an average of 3.48 mg/l. They were high in the BH7 borehole and low in the BH2 borehole (Table 2).

(NO^{3-}) ranged from 84 mg/l in the BH7 borehole to 0.01 mg/l in the BH2 borehole, with an average of 12.5 mg/l (Table 2).

3.5. Geostatistical Analysis

Geostatistical analysis was performed using Excel-Stat software to reduce and organize data presenting physicochemical characteristics. A total of 11 physicochemical parameters were used for correlation matrix analysis, principal component analysis, and cluster analysis.

3.6. Correlation Matrix

The correlation matrix is used to determine the degree of correlation between the various physicochemical variables influencing groundwater quality in the study area. A strong positive correlation may indicate the same sources of particular ions, which may be of natural or anthropogenic origin and mobility, while a weak correlation suggests that the ion sources are independent of each other (25). Physicochemical analysis of groundwater is used to discover the relationship between variables within the study area. Correlation matrices for eleven (11) physicochemical parameters were prepared and their results are presented in Table 3. Variables with a correlation coefficient (r < -0.10) are considered insignificant, where values between 0.5 and 0.7 indicate a moderate correlation, while values greater than 0.7 are considered strong. This table shows that there is a negative correlation between PH and Cl (r = -0.10) and K (r = - 0.01). Table 3 confirms that there is a weak correlation between TDS and EC (r = 0.23), Ph (r = 0.07), Cl (r = 0.41), SO4 (r = 0.35), HCO3 (r = 0.19), N03 (r = 0.21), Ca (0.46), Mg (0.35), Na (0.37), and K (r = 0.19). As well as EC and pH (r = 0.29), Cl (r = 0.39), Mg (r = 0.46), Na (r = 0.40), HCO3 (r = 0.32), Ca (r = 0.38), K (r = 0.29). As well as between PH and SO4 (r = 0.18), HCO3 (r = 0.10), N03 (r = 0.44), Ca (r = 0.12) and Mg (r= 0.17). We also note that there is a moderate correlation between the physicochemical variables Cl and SO4 (r = 0.55) as well as Cl with HCO3, NO3, Ca, and Mg with r = 0.70, r =0.48, r= 0.71, r= 0.61. We also note that there is another moderate correlation between SO4 and HCO3 (r = 0.65), as well as between SO4 and Ca, Mg, and Na (r = 0.69, r = 0.61, and r = 0.67, respectively). Between HCO3 and Ca (r = 0.62) and also with HCO3 Mg and Na r = 0.55), r = 0.70. Furthermore, between NO3 and Ca (r = 0.52), Mg r= 0.51 and K (r = 0.60). Furthermore, between Ca and Mg (r = 0.62), Na (0.82) and K (r = 0.54). As well as between Mg and Na (r = 0.62) and K (r = 0.51). And finally, between Na and K (r = 0.65). The table showed that Cl- has a strong correlation with Ca (r = 0.71) as well as Cl and Na (r = 0.86) and between Ca and Na (r = 0.82) and K (r = 0.73).

Table 3 Coefficient matrix of physico chemical parameters

	CE	T°C	pH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO^{3-}	$N03^{-}$
CE	1										
T°C	0	1									
pH	0.6	0	1								
Ca^{2+}	0.9	0	0.5	1							
Mg^{2+}	0.9	0	0.4	0.9	1						
Na^{+}	0.8	0	0.4	0.6	0.6	1					
K	0.4	0	0.4	0.5	0.3	0.2	1				
Cl^{-}	0.5	0	0.1	0.7	0.7	0.5	0	1			
SO_4^{2-}	0.8	0	0.3	0.9	0.8	0.8	0.1	0.39	1		
HCO^{3-}	1	0	0.6	0.9	0.9	0.8	0.4	1	0.9	1	
$N03^{-}$	1	0	0.4	0.5	0.9	0.7	0.4	0.39	0.5	0.72	1

3.7. Principal component analysis (PCA)

(PCA) was performed on physicochemical data relating to the drill holes. This was done to determine the origins of mineralization and the links between the different elements. The latter takes into account all the analyses carried out by us. The matrix used comprises 25 boreholes and 11 physicochemical elements (T°, EC, pH, nitrates, chlorides, sulfate, bicarbonates, calcium, magnesium, sodium, and potassium). The PCA was performed using Excel-Stat software. The PCA circle Figure 3 formed by the PC1/PC2 axes, providing 47.22% of the information, shows pH, EC, Mg, and Cl located on the positive side (X and Y) of the PC1 axis (25.55%), while TDS, SO4, Ca, HCO3, K, and Na are located on the positive axis of X and the negative axis of Y. We can deduce that highly mineralized waters are located in the positive part of the axes (X and Y), while weakly mineralized waters are characterized by a positive abscissa axis and a negative ordinate axis. Observing the circle along the PC2 axis (21.67%), we notice a contrast between magnesium chloride waters and sodium bicarbonate or calcium sulfate waters. In addition, we find that conductivity and pH accompany magnesium chloride waters.

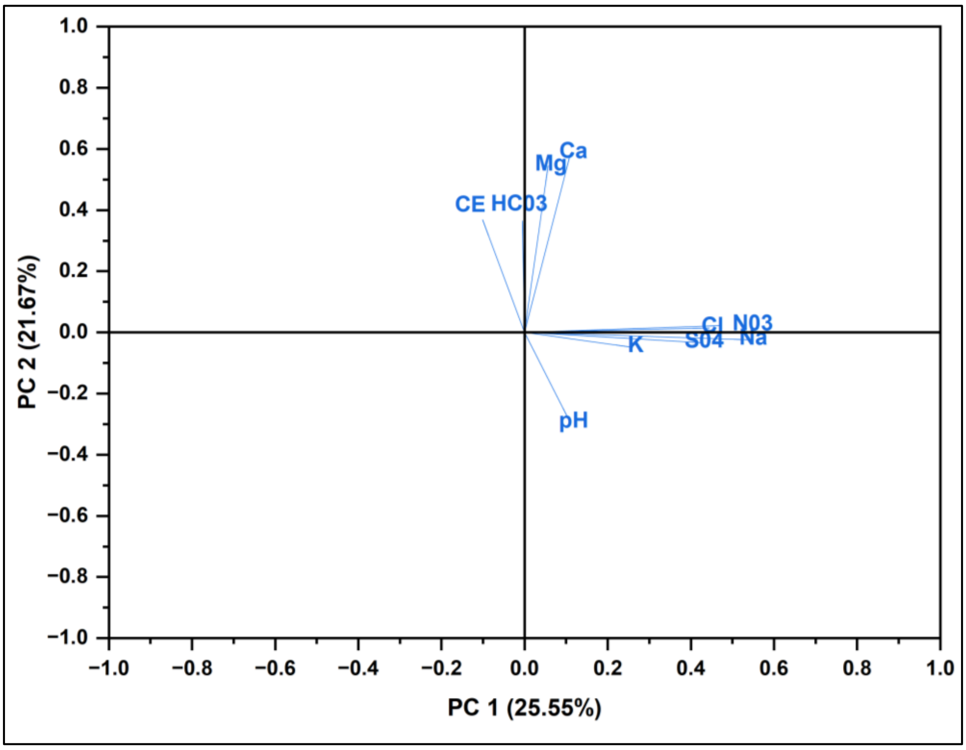

Figure 3 Principal Component

4. Conclusion

This study focused on the characterization and statistical analysis of groundwater quality in the province of Salamat. This relatively flat province consists of a flood zone during the rainy season. The hydrogeochemical study was conducted to characterize groundwater quality. The techniques used included hydrogeochemical studies and multivariate statistical analysis applied to physicochemical data. Subsequently, principal component analysis and multiple variable statistical correlation matrix analysis reduced 11 of the initial variables to two factors that explain the total variance of the data set. In addition, the results of the statistical analyses for the data sets defined two main hydrochemical processes that are similar to each other.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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