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Assessment of Groundwater Physico-Chemical Quality in the Ouémé Delta (Southern-Benin)

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Abstract

Groundwater resources are the main sources of water used to supply drinking water to the population of the Ouémé Delta via the Continental Terminal aquifer. Urbanization, population growth, and agricultural and industrial activities have resulted in a deterioration in the quality of these resources. To assess the quality of the delta's groundwater and its suitability for human consumption and irrigation, a total of fourteen (14) physico-chemical parameters were analyzed in some forty existing water points between September 2020 and March 2021, using standard water analysis techniques. The values obtained were compared with the potability standards recommended by the World Health Organization (WHO) and the Republic of Benin and were subjected to statistical analysis (principal component analysis (PCA)). In addition, methods for determining the suitability of water for irrigation were used. The results showed that the waters are acidic to slightly neutral and influenced by ambient temperature. In addition, the waters are moderately mineralized, with conductivities (24 - 1205 µS/cm) in line with WHO standards. A comparison of the analytical results of the WHO (2017) and Benin (2001) standards indicates that the majority of the waters studied are of good quality for all the chemical parameters considered. Nevertheless, some samples show levels of nitrates (21%), potassium (14% to 16%), calcium (13%), ammonium (12%), nitrites (8%) and bicarbonates (10%) over their respective standards. The Wilcox and Riverside diagrams indicate that the majority of waters (90%) have excellent suitability for irrigation and no negative effect on soil fertilization.

Keywords

Benin, Ouémé Delta, Groundwater, Physico-Chemical Quality, Consumption, Irrigation

1. Introduction

In Benin, available water for consumption is increasingly polluted by household and industrial waste, as well as fertilizer and pesticide residues in high-risk areas such as water catchment points, riverbanks, deltas, etc. [1]. Sanitation is still almost entirely a problem. Waste management is almost limited in urban agglomerations, where it is struggling to become more widespread, while wastewater management remains unresolved. The threat is real and the challenges are great [1]. Around 34% of households in urban areas have no toilets and they use open defecation as a mode of ease [1]. In addition, 93% of wastewater and 74.9% of solid waste are discharged into the environment [2]. These situations coupled with pollution of agricultural and industrial origin pose a serious threat to the quality of water and ecosystems, with major social, health, and environmental risks as a corollary.

In the Lower Ouémé Valley, agriculture takes place in the riverbed during dry seasons [3]. Mineral and organic fertilizers and plant protection products are used to fertilize the soil and combat insects and weeds. The use of these agricultural inputs can pollute the river and groundwater with nutrients, pesticides, and microorganisms [4]. The valley, and particularly the Delta, is subject to major disruption of land use and land cover, due to anthropogenic and climatic factors [5]. Thus, human activities have become the main factor in the disturbance of plant formations in the classified areas [6]. Also, the significant drop, irregularity, and poor distribution of rainfall experienced by Benin in recent years, particularly in its southern part, have caused environmental degradation in the Ouémé delta [7] [8]. In addition, the populations of the Ouémé Delta engage in several activities that are likely to pollute the waters in the short, medium, and long term. The aquifers likely to be contaminated by these various activities are those of the Mio-Pliocene and Quaternary. These are the two aquifers most frequently used for consumption and multiple purposes (domestic, agricultural, industrial).

This study aims to assess the physico-chemical quality of groundwater in the Ouémé delta, for efficient and sustainable management of this resource. The different parameters analyzed were selected based on their potential impact on human health, on the one hand, and on the other, on the assessment of irrigation efficiency.

2. Materials and Methods

2.1. Study Area

With an area of around 3200 km^2, or 2.8% of Benin's surface area [9], the Ouémé delta is part of the southern part of Benin's coastal sedimentary basin and is located between 06˚20' and 07˚00' North latitude and between 02˚00' and 02˚50' East longitude (**Figure 1**).

The climate of the Ouémé Delta is sub-equatorial, with a bimodal rainfall regime [10] with two rainy seasons (from mid-March to mid to August and from mid-September to November) and two dry seasons (from mid-August to mid-September and December to mid-March). Average annual precipitation increases from the west (900 mm/year) to the east (1400 mm/year) [11]. The average annual temperature is 27˚C and evapotranspiration is about 1300 mm/year. Geologically, stratigraphic units have been identified based on lithological and sedimentary indices, ranging from the Upper Cretaceous (Turonian-Coniacian) to the Quaternary (IRB, 1). The thickness and lithology of these formations vary significantly from north to south and east to west. They consist of detrital formations (sand, gravel, and clay), marl, and limestone [12]. From a hydrogeological point of view, the coastal sedimentary deposits consist of four aquifers (Turonian-Coniacian - Lower Unit I, Paleocene - Lower Unit II, Continental Terminal - Units V, VI, and VII and Quaternary - Unit VIII). Separated between them by layers of clay and marl ([12] [13] [14]). The main aquifers are the Turonian-Koniac Terminal and the Continental Terminal. This study focuses on the continental terminal aquifer, which lies within the Miocene, Pliocene, and Pleistocene continental deposits, and on the Quaternary aquifer on which the major cities of Benin are located and which is undergoing intense urbanization [12] [15] [16]. In this region, farmers make up more than 90% of the population. To improve crops, these populations use agrochemicals (chemical fertilizers, pesticides), organic matter (manure, animal feces), and saline solutions, which are then released into water bodies that, in their tower, recharge the aquifers. These fertilizers can vary from farmer to farmer depending on the crop. For example, 97% of farmers use NPK, KCl, and K_2SO_4, and 68% use triphosphates [17].

2.2. Sample Collection and Analysis

Two major sampling campaigns were carried out, one from September to October 2020 (rainy season) and the other in March 2021 (dry season). These two campaigns involved a total of 40 water points, including 31 wells and 09 boreholes (**Figure 1**). These sites have been selected to spatially represent the study area on the one hand and to sample wells located near likely sources of water contamination on the other. During these campaigns, physical parameters were measured in situ. Prewashed and sterilized 0.5 L polyethylene bottles were used to collect samples after rinsing. A WTW 3110 SET pH meter with Sentix 21 electrodes was used for in-situ measurement of water pH. Electrical conductivity (EC) and total dissolved solids (TDS) were measured using a WTW 340i SET conductivity meter. Chemical ions, including cations (Ca^{2+}, Mg^{2+}, Na^+ et K^+, NH_4^+) and anions (SO_4^{2-}, NO_3^- et Cl, PO_4^{3-} et NO_2^-) were determined by ion chromatography (Dionex ICS-1000) at the Laboratoire d'Hydrologie Appliquée, Université d'Abomey-Calavi, Benin.

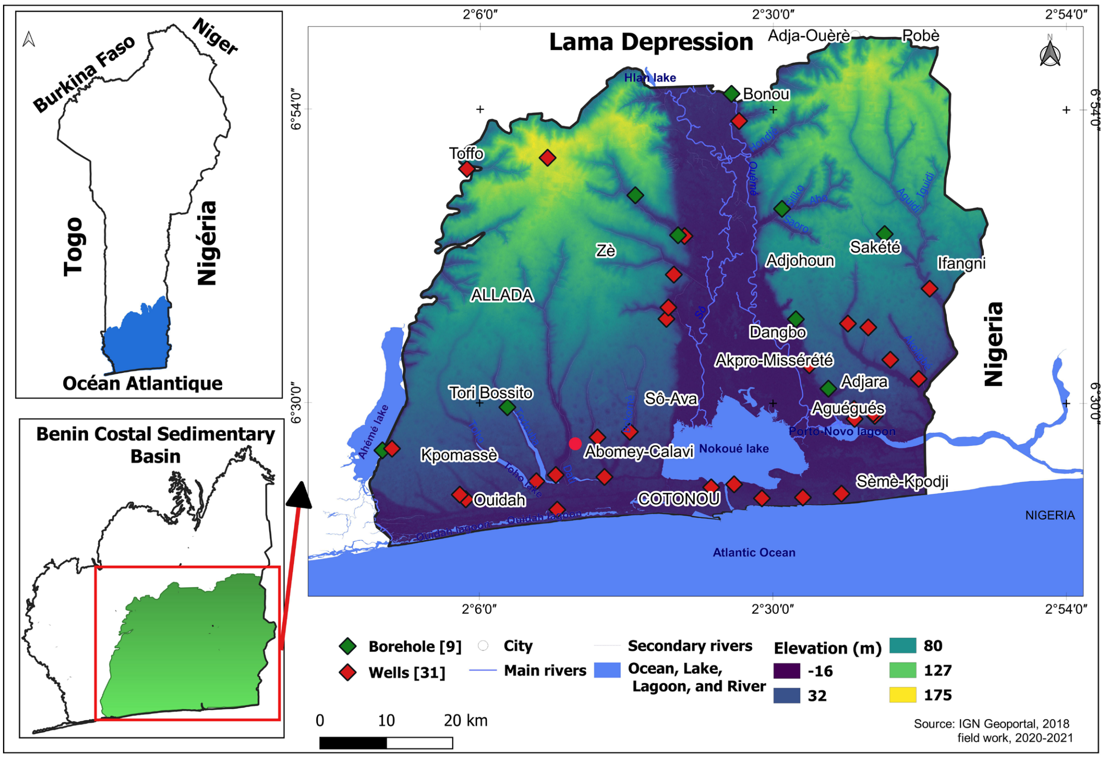


Figure 1. Location, and sampling points map.

2.3. Data Processing

Total hardness (TH) was calculated from the following Equation (1), in which Ca^{2+} and Mg^{2+} concentrations are expressed in mg/L.

$$TH = 2.5 \times Ca^{2+} + 4.1 \times Mg^{2+} \quad [18]\ [19] \qquad (1)$$

R software was used for static data processing. It enabled us to highlight the correlation between the various parameters analyzed and to perform a principal component analysis (PCA).

To assess the suitability for irrigation of groundwater in the Ouémé delta aquifer system, three (3) approaches were used:

- *Sodium Adsorption Rate (SAR) and Salinity Diagram (USSL)*

Sodium risk assessment in irrigation water was carried out by determining the sodium absorption ratio (SAR) according to Equation (2) of Richards (1954) (Table 1). The results were tabulated to produce a Riverside diagram, known as Richard's diagram, as a function of electrical conductivity. This diagram is used to determine the water's suitability for irrigation.

- *Percentage of Sodium (% Na) and Wilcox Diagram*

Calculating the percentage of sodium using the formula in Equation (3) [20] (Table 1) and drawing up the Wilcox diagram (1955) enables us to classify waters according to their suitability for irrigation.

- *Residual Sodium Carbonate*

The residual sodium carbonate (RSC) index is determined from the following expression of Equation (4) [21] (Table 1). Ions are expressed in meq/L.

Table 1. Equations used to calculate sodium adsorption rate (SAR), %Na, and residual sodium carbonate (RSC).

Equation	Equation	Range	Water class	Reference
2	$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}}$	<10 10 - 18 18 - 26 >26	Excellent Good Doubtful Unsuitable	[21]
3	$\%Na = \frac{Na^{+}+K^{+}}{Ca^{2+}+Mg^{2+}+Na^{+}+K^{+}} \times 100$	<20 20 - 40 40 - 60 60 - 80 >80	Excellent Good Permissible Doubtful Unsuitable	[21]
4	$RSC = \left[\left(CO_3^{2-}+HCO_3^{-}\right)-\left(Ca^{2+}+Mg^{2+}\right)\right]$	<1.25 1.25 - 2.50 >2.50	Good Doubtful Unsuitable	[21]

3. Results and Discussion

3.1. General Assessment of Groundwater Suitability for Human Consumption Based on Physicochemical Characteristics and Major Ion Chemistry

Assessing the suitability of water for human consumption is very important because of the critical role it plays in human health. Univariate statistical analyses of the analytical data are presented in Tables 2-4 below. Analytical data for each parameter were compared with WHO standard limits (2017) and the Benin standard

3.1.1. Physical Parameters

The statistics of the physical parameters analyzed are presented in Table 2.

The concentration of H+ protons in the water is measured by the pH of the water, which recapitulates the stability of the equilibrium between the forms of carbonic acid and is linked to the buffer system developed by carbonates and bicarbonates [22]. pH values range from 3.71 to 7.72 with an average of 5.89 in rainy seasons and from 4.01 to 7.47 with an average of 5.68 in dry seasons. It was noted that 71% and 94% of samples in the rainy season and dry season respectively had pH values outside the [26] and Benin standard norms, which range from 6.5 to 8.5. These recorded pH values indicate that the waters are generally acidic to slightly neutral. This means they could have a corrosive tendency on metals and distribution channels [23] [24]. In addition, acidic waters can cause certain adverse health effects, such as gastrointestinal disorders [25] and mucosal deterioration in humans. The acidity of water can be attributed to humic acid from organic or plant decomposition and possibly other geochemical processes [24].

The temperature of the water sampled ranges from 26˚C to 31.8˚C, with an average of 29.08˚C, and from 26˚C to 33.9˚C, with an average of 29.23˚C for high and low-water periods respectively. It is close to the average atmospheric temperature. This indicates a thermal equilibrium between well water and the

Table 2. Statistical values for physical parameters of water.

	Rainy Season (October 2020)					Dry Season (March 2021)					Standard Limit	
Parameters	Min	Max	Mean	Med	SD	Min	Max	Mean	Med	SD	WHO Standard (2017)	Benin Standard (2001)
EC (µS/cm)	24.00	920	333.25	295.00	244.90	27.00	1 205	320.46	266.00	288.78	ND	ND
T (˚C)	26.00	31.80	29.08	29.20	0.96	26.00	33.90	29.23	29.00	1.21	25	ND
TDS (mg/L)	12.00	470.00	165.54	144.00	121.60	13.00	604.00	159.95	133.00	144.07	1000	ND
pH	3.71	7.72	5.89	6.20	1.06	4.01	7.47	5.68	5.66	0.64	6.5 - 8.5	6.5 - 8.5
TDS/EC	0.46	0.51	0.50	0.50	0.01	0.48	0.51	0.50	0.50	0.00	_	_

Table 3. Statistical values for major ions in water.

Period	Rainy Season (October 2020)					Dry Season (March 2021)					Standard Limit	
Parameters	Min	Max	Mean	Med	SD	Min	Max	Mean	Med	SD	WHO Standard (2017)	Benin Standard (2001)
Cl^- (mg/L)	5.01	156.05	26.25	13.51	29.88	2.30	152.30	34.64	29.75	32.51	250	250
HCO_3^- (mg/L)	6.10	294.50	66.93	26.20	80.27	2	565.80	74.03	25.43	117.09	250	ND
NO_3^- (mg/L)	0	85.35	21.74	10.81	25.76	0	80.58	22.52	8.13	27.02	50	45
SO_4^{2-} (mg/L)	0	93.60	10.27	3.48	17.51	0	85.80	10.02	5.38	15.44	250	500
Ca^{2+} (mg/L)	0.71	107.26	25.21	9.28	31.36	2.01	187.80	31.54	10.33	47.70	75	100
Mg^{2+} (mg/L)	0.44	29.79	7.16	4.36	6.67	0.49	35.21	6.26	4.32	6.72	50	50
K^+ (mg/L)	0.01	26.32	4.17	1.02	6.56	0.24	49.42	5.60	2.03	9.62	12	ND
Na^+ (mg/L)	0.07	96.20	15.04	8.90	18.43	1.30	95.53	19.24	17.91	17.15	200	ND
Mg^{2+}/Ca^{2+}	0.06	2.73	0.62	0.48	0.52	0.03	1.42	0.43	0.37	0.33	_	_
Dureté totale	5.36	358.20	88.81	39.55	96.51	9.01	613.87	104.88	44.65	136.48	_	_

Table 4. Univariate statistics of nitrogen and phosphorus in water.

	Rainy Season (October 2020)					Dry Season (March 2021)					Standard Limit	
Parameters	Min	Max	Mean	Med	SD	Min	Max	Mean	Med	SD	WHO Standard (2017)	Benin Standard (2001)
NO_3^- (mg/L)	0	85.35	23.17	10.81	27.47	0	80.58	23.29	8.25	27.10	50	45
NO_2^- (mg/L)	0.00	8.76	0.39	0.04	1.61	0	31.08	1.46	0.07	5.49	3	3
NH_4^+ (mg/L)	0	0.42	0.06	0.00	0.11	0	5.85	0.51	0.04	1.27	ND	0.9
PO_4^{3-} (mg/L)	0	2.12	0.19	0.02	0.45	0	0.07	0.02	0.02	0.02	10	ND

atmosphere. It is possible that hot water influences the dissolution rate of minerals and promotes the proliferation of potentially harmful microbes, which may, in turn, influence the taste, color, odor, and corrosive tendency of water [26]. In addition, studies have shown that warmer waters generally contain less oxygen [24] [27], indicating that they are anaerobic [28]. Such a situation could lead to 1) the reduction of nitrates to nitrites by reducing microbes, 2) an increase in the concentration of iron (Fe) in the water, and 3) subsequent discoloration of water transported through pipes when aerated [24] [27].

The electrical conductivity (EC) of water is generally an indicator of the presence of ions and dissolved solids [24]. Conductivity ranges from 24 μS/cm to 920 μS/cm, with an average of 333.25 μS/cm in rainy seasons, and from 27 μS/cm to 1205 μS/cm, with an average of 320.46 in dry seasons. A median of around 266 (dry season) and 295 μS/cm (rainy season) indicates moderately mineralized water (**Table 2**).

We note that almost all the samples analyzed comply with the WHO standard of 1000 mg/L for dry residue (TDS). The waters analyzed are therefore low in mineral content and, on the whole, soft (TDS < 1000 mg/L).

The average TDS/CE ratio is 0.5. This suggests a high mineralization of the sampled waters [29]. Generally, this ratio should be close to 0.7 for waters with low mineralization. However, these ratios do not agree with the conductivity values obtained, which indicate weakly to moderately mineralized waters. This discrepancy between TDS/EC ratios and conductivity classes is thought to be due to the existence of unmeasured minor ions [29] [30].

3.1.2. Chemical Parameters

1) Major ions

The statistical description of major ions in groundwater is presented in **Table 3**. Overall, average concentrations of major ions in 2021 groundwater samples were higher than in 2020, except for SO_4^{2-}, PO_4^{3-}, and Mg^{2+}.

The average concentration of cations in groundwater samples is in the order of $Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$ for both sampling periods. Ca^{2+} is the dominant cation present in the water samples collected. Ca^{2+} concentrations ranged from 0.71 to 107.26 mg/L in the rainy season and from 2.01 to 197.8 mg/L in the dry season. Most of the water analyzed had Ca^{2+} concentrations within the WHO acceptable limit of 75 mg/L and the Benin limit of 100 mg/L, except at five wells (Abattoir (P13), Agongbomè (P15), Tohouikamè (P8), Ouinda (P25) and Topkota (P26)) in the dry season and four wells (Agongbomè (P15), Abattoir (P13), Topkota (P26) and Gbedjromede (P14)) in rainy These high calcium levels could cause intestinal diseases, kidney or bladder stones, and urinary irritation [31].

Mg^{2+} ranged from 0.44 to 29.79 mg/L and from 0.49 to 35. 21 mg/L in high and dry seasons respectively. Mean Ca^{2+} and Mg^{2+} concentrations are 25.21 and 31.54 mg/L, and 7.16 mg/L and 6.26 mg/L at high and low water respectively. Carbonate dissolution is an important origin of Ca^{2+} and Mg^{2+} in water, but as the aquifer system has no carbonate minerals, the contribution of Mg^{2+} ions would probably be due to the dissolution of silicate minerals and cation exchange processes [9]. Mg^{2+} concentrations were observed to be within the [26] and Benin standard of 50 mg/L.

Total hardness recorded values ranging from 5.36 mg/L to 358.20 mg/L and from 9.01 to 613.87 mg/L in wet and dry seasons respectively. The maximum total hardness value for drinking water is 600 mg/L [32]. However, hardness above 300 mg/L could lead to kidney and heart problems [32]. Concerning total hardness results, all water samples were identified as suitable for human consumption except those from P26 (613.87), P25 (485.60), and P8 (373.13) in the dry season and those from P14 (358.20), P15 (304.35) and P22 (Avlékété) (307.05) in the rainy season. Almost all samples therefore comply with the potability standard.

Mg^{2+}/Ca^{2+} ratios ranged from 0.06 to 2.73 in rainy seasons and from 0.03 to 1.42 in dry seasons. They illustrate the relative proportions of these two chemical elements in a solution of water. Thus, hardness is more strongly influenced by fluctuating quantities of magnesium than by variations in calcium.

Na^+ concentration varied from 0.07 to 96.20 mg/L in the rainy season and from 1.30 to 95.53 mg/L in the dry season, with an average of 15.04 and 19.24 mg/L, respectively. Silicate dissolution can increase Na^+ concentration in samples. In addition, Na^+ can also result from cation exchange [33]. Na concentrations comply with the [26] guideline value of 200 mg/L. The dominant processes in the contribution of sodium and chloride ions to the Continental Terminal aquifer would therefore be leaching, by rainwater, of soils salinized by the deposition of sea spray, dilution/concentration phenomena linked to recharge/evaporation processes and mixing with salt and brackish water [9].

Average K^+ concentrations were 4.17 and 5.60 mg/L in 2020 and 2021, respectively. Maximum K^+ concentrations (12.38; 12.86; 13.59; 17.53; 22.98; 26.32 mg/L) were observed in Takon (P29), Agongbomè (P15), Gbèdjromèdé (P14), Sedjè-Denou (P31), Avlékété (P22) and Tchakpè-codji (P21) wells in the rainy season, and (12.86; 20.58; 22.93; 25.64; 49. 41) in wells P13, P21, P31, P26, P22 in the dry season. It was observed that 16% and 14% of samples in rainy and dry seasons respectively recorded an excessive K+ concentration above the acceptable limit set by [26], which is 12 mg/L. It should be noted that in these areas, the water table is shallow (less than 5 m) and mostly collects the Quaternary aquifer, except at P31 and P29, where it is the border of the Continental Terminal aquifer. In addition, these wells are less than 5 m from sources of contamination, such as crop fields where fertilizers are used, and garbage dumps in densely urbanized areas. This means that these waters are subject to the effects of human activity. Most of the potassium in groundwater comes from human activities and surface salt and brackish water. A significant fraction of this potassium is involved in basic exchange phenomena (fixation by clay and organic matter) [9]. These water samples are considered to present a risk of hyperkalemia to their consumers [34]. Excess potassium can cause severe cardiac disorders, up to and including cardiac arrest and death in the absence of urgent chelator treatment.

HCO_3^- is the dominant anion in groundwater samples, with average concentrations in the order of $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-}$ in the rainy and dry seasons. HCO_3^- ranged from 6.10 to 294. 50 mg/L in the rainy season and from 2 to 565.80 mg/L in the dry season, with an average of 66.93 and 74.03 mg/L, respectively. In addition, 5% and 10% of samples had HCO_3^- levels exceeding the [26] guide value of 250 mg/L in rainy and dry seasons respectively.

The presence of sulfates in groundwater may be due to natural or anthropogenic causes. Sulfate levels in the water varied from 0 to 93.6 in the rainy season and from 0 to 85.8 mg/L in the dry season, with an average of 10.27 and 10.02 mg/L, respectively. SO_4^{2-} concentrations were within the [26] guideline value of 250 mg/L and the Benin (2001) guideline value of 500 mg/L.

Chloride levels ranged from 5.01 mg/L to 156.05 mg/L in the rainy season and from 2.30 mg/L to 152.30 mg/L in the dry season, with an average of 26.25 and 34.64 mg/L, respectively. All the groundwaters studied had chloride concentrations below the WHO and Benin permissible limit (250 mg/L), indicating low chloride contamination. Consequently, consumers of these waters are not exposed to health risks due to the ingestion of excess Cl.

2) Nitrogen and phosphorus

Anthropogenic inputs, such as industrial and agricultural activities, are a major source of NO_3^- in groundwater [35]. NO_3^- concentration in the study area ranged from 0 to 85.35 mg/L in 2020 and from 0 to 140.88 mg/L in 2021. Overall, in both rainy and dry seasons, 21% of samples had the highest NO_3^- concentration exceeding the guide values set by [26] and the Republic of Benin (2001), which are 50 mg/L and 45 mg/L respectively. These nitrate-rich waters are likely to cause diseases such as colon and rectal cancers, methemoglobinemia in infants, and non-Hodgkin's lymphoma [36].

NH_4^+ varies between 0 and 0.42 with an average of 0.06 and between 0 and 5.85 with an average of 0.51 in rainy and dry seasons respectively. Approximately 12% of the samples (P29, P26, P14, and P13) analyzed had ammonium levels exceeding the Benin standard for drinking water in dry seasons. According to [37], depending on the duration of exposure and the dose ingested, ammonium salt can cause human health problems such as pulmonary edema, dysfunction of the nervous and renal systems, and increased blood pressure.

Nitrite NO_2^- or nitrous nitrogen is a less oxygenated and less stable form, representing the transition between nitrate and ammonium. It is a toxic form and its origin is linked to agriculture or urban and industrial discharges [30]. Maximum concentrations are observed at P13 (6.17 mg/L), P14 (31.08 mg/L), and P15 (9.51 mg/L) in the dry season and P14 (8.76 mg/L) in the rainy season. These values exceed the guide value (3 mg/L) set by [26] and Benin (2001) for water intended for human consumption. This situation could have adverse effects on human health. According to [30], excessive nitrite levels in drinking water can cause methemoglobinemia, leading to asphyxia in bottle-fed newborns, and cancer in humans. These high levels are probably due to the progressive accumulation of organic pollutants contained in urban wastewater. They are also due to the effect of oxidation of the ammonium form.

Orthophosphate concentrations recorded at the sampling point ranged from 0 to 2.12 mg/L and 0 to 0.07 mg/L, with an average of 0.19 and 0.02 mg/L in rainy and dry seasons respectively (**Table 4**). They are well below the permissible orthophosphate limit of 10 mg/L. Therefore, this parameter does not represent a major pollution risk for the waters studied and poses no danger for consumers.

3.2. Chemometric Analysis

3.2.1. Pearson Correlation Analysis (CA)

The correlation matrices for the current study are shown in Figure 2 and Figure 3 for the rainy and dry seasons respectively. The following inter-parameter associations observed were: pH and Ca, pH and Mg, pH and HCO_3; EC and Ca, Mg, Na, K, HCO_3, Cl, SO4, and NO_3 in the rainy season. Whereas in the dry season, the inter-parameter associations observed are: CE and Mg, Na, K, Cl, SO_4. Based on the information provided, it can be deduced that alkaline earth metals contribute significantly to the pH and EC of the samples. In addition, the discrete correlation between Cl-NO_3 (r = 0.49), Na-NO_3 (r = 0.55), and K-NO_3 (r = 0.56) in the rainy season confirms that their origins are also linked to anthropogenic activities. Furthermore, the correlation between Mg-Ca (r = 0.70), Mg-Cl (r = 0.77), Mg-SO_4 (r = 0.75), Mg-HCO_3 (r = 0.74) Mg-K (r = 0.68) and Mg-Na (r = 0.67) in the rainy season and between Mg-Ca (r = 0.66), Mg-Cl (r = 0.74), Mg-SO_4 (r = 0.69), Mg-K (r = 0.73) and Mg-Na (r = 0.50) in dry season indicates that their presence in groundwater is influenced by the same source ([31]). The same observation applies to the high correlation between SO4-Na (r = 0.81) and SO_4-K (r = 0.81), SO_4-Cl (r = 0.84), K-Cl (r = 0.83), Na-Cl (r = 0.87), Mg-Cl (r = 0.77). The correlation matrices also reveal strong correlations between EC-Na (r = 74) and EC-Cl (r = 0.85) in the rainy season and between EC-Na (r = 80) and EC-Cl (r = 0.90) in the dry season, testifying to the influence of brackish and salt

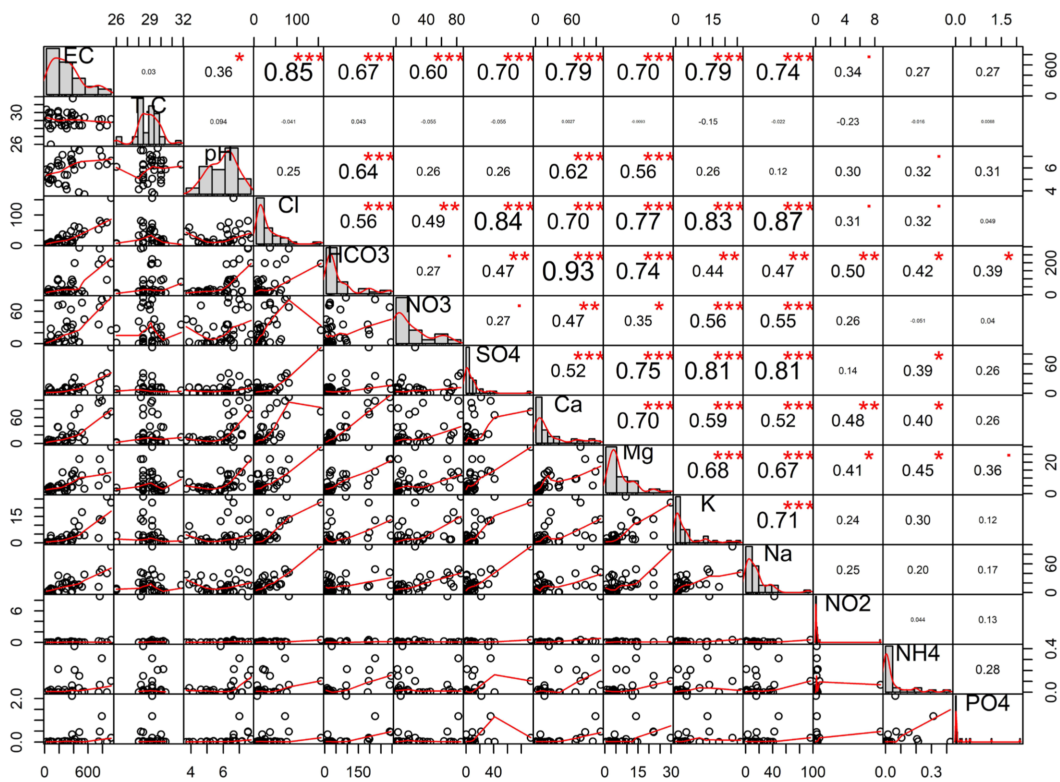


Figure 2. Pearson correlation matrix of rainy season parameters analyzed. *: low correlation; **: medium correlation; ***: high correlation.

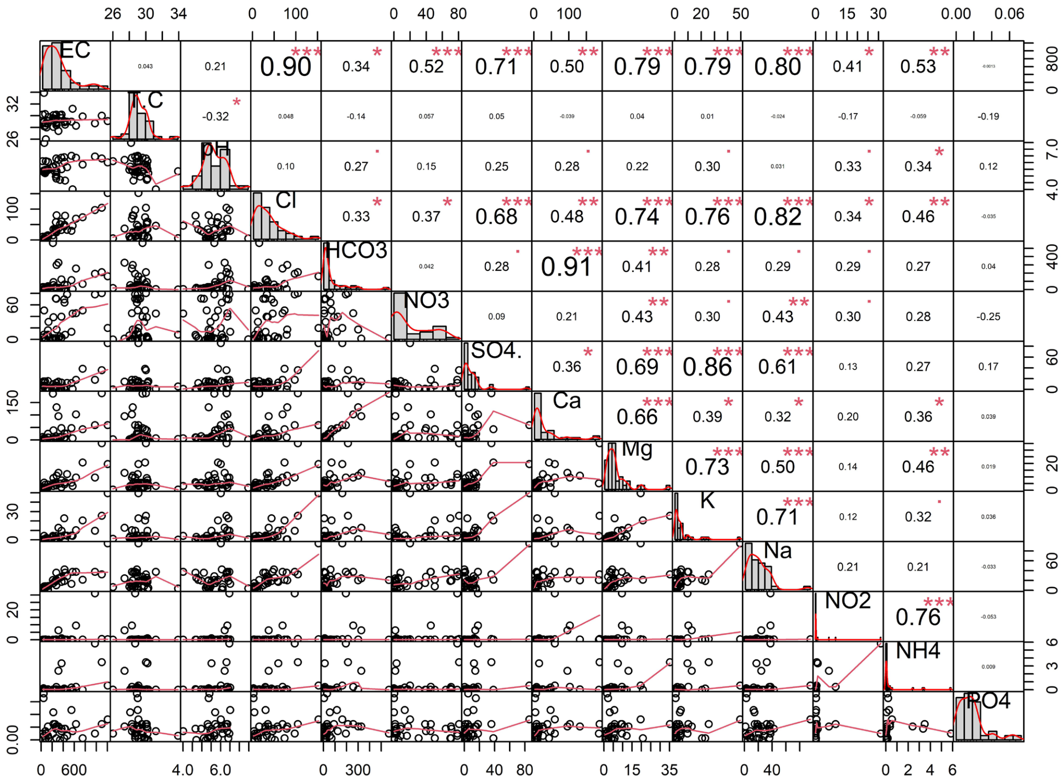


Figure 3. Pearson correlation matrix for the dry season parameters analyzed. *: low correlation; **: medium correlation; ***: high correlation.

water. Lastly, the discrete relationship between EC and NO3 (r = 60) and (r = 0.52) in rainy and dry seasons respectively, confirms that anthropogenic inputs play an important role in defining the hydrogeochemistry of groundwater in the area [28].

3.2.2. Principal Component Analysis (PCA)

For both sampling periods, factor groups with an eigenvalue greater than or equal to 1 were selected for this analysis.

In the rainy season (October 2020), the first two (02) dimensions of the analysis express 62.82% of the total dataset inertia (**Figure 4(a)**). This means that 62.82% of the total variability of the cloud of individuals (or variables) is explained by the plane. This is a high percentage, and the first plane therefore represents the variability contained in a very large part of the active dataset. The first factor explained 50.17% of the total variance and is correlated with all parameters (EC, Mg et Ca, Na, K, HCO_3, Cl, SO_4 and NO_3, pH), except T, PO_4, NO_2, and NH_4. Clustering the latest with the other elements suggests an influence of total mineralization by anthropogenic activities. This means that component 1 alone explains the natural and anthropogenic origin of the various elements. Component 2 is positively correlated with pH, highlighting the acidity of the water. In addition, the classification performed on the individuals shows 3 classes (**Figure 4(b)**). Class 1 is made up of P3, P4, P6, P25, P30 and P31. This group is characterized by low values of the variables HCO_3, Ca, Mg, EC, NH_4,

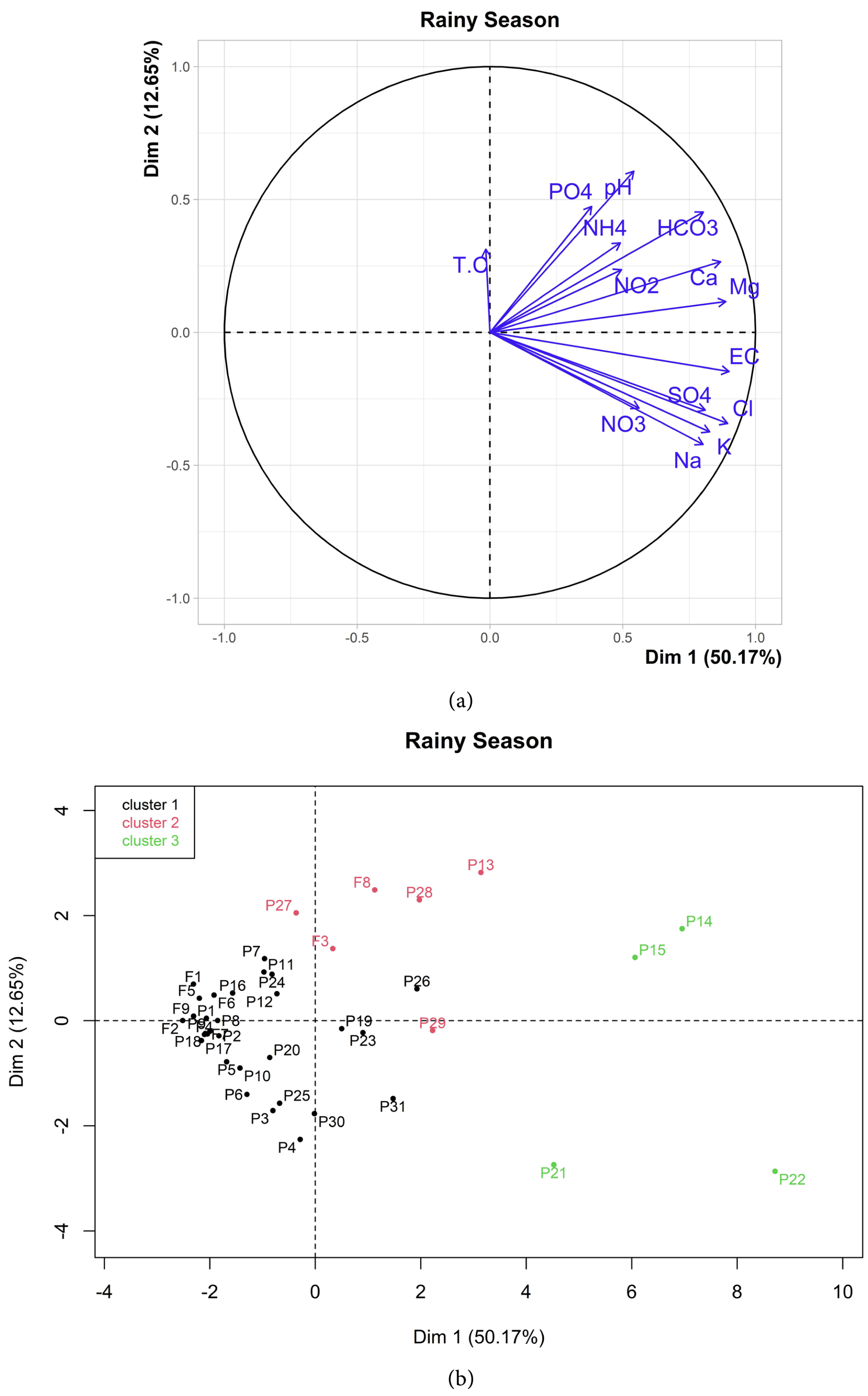
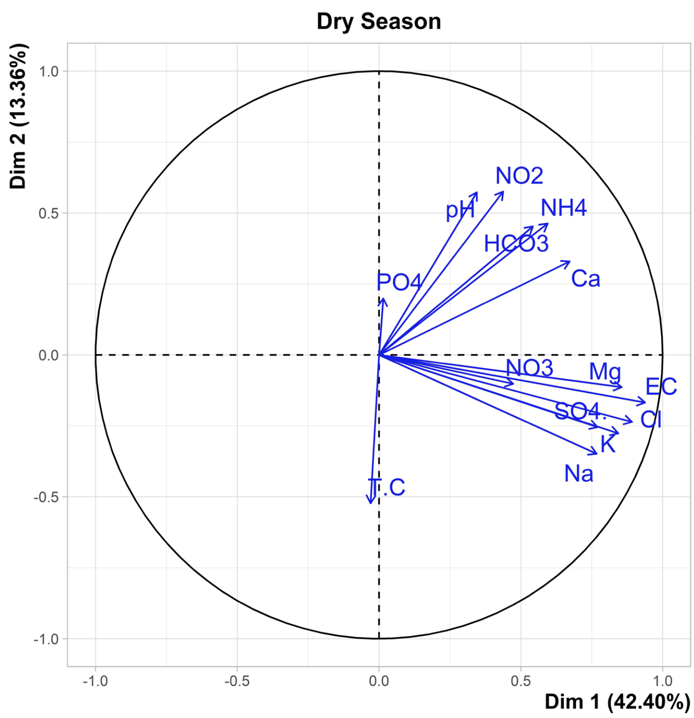


Figure 4. Projection of variables and individuals on the factorial plane (Rainy season).

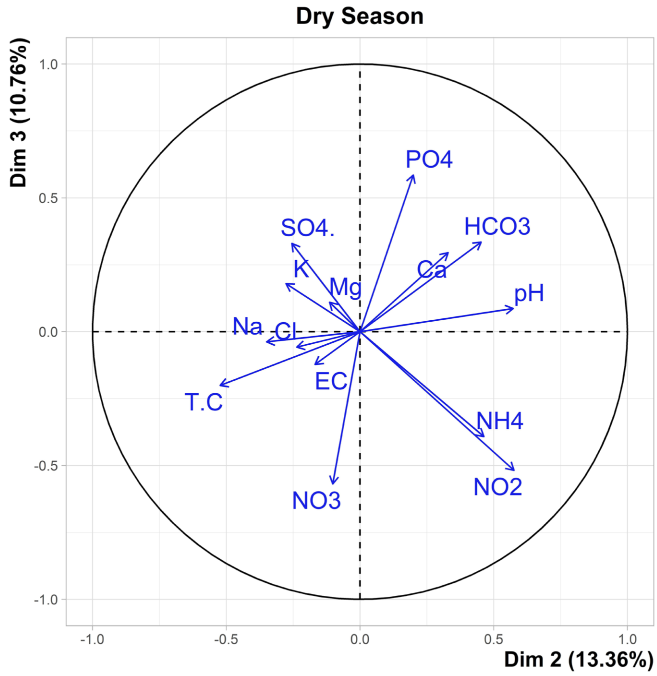
SO_4, pH, Cl, K, and PO_4. Class 2 is made up of F3, P13, P27, P28 and F8. This group is characterized by high values for NH_4, HCO_3, pH, Ca, PO_4, and Mg. Class 3 is made up of P14, P15, P21 and P22. This group is characterized by high values of the variables K, Cl, SO_4, Na, EC, Ca, Mg, HCO_3, NO_3, and NO_2 and is influenced by anthropogenic pollution.

In the dry season (March 2021), the first 3 dimensions of the analysis express 66.52% of the total dataset inertia. This means that 66.52% of the total variability of the cloud of individuals (or variables) is explained by the Dim1 Dim2 and Dim2 Dim3 planes. The first factor explained 42.4% of the total variance and is also highly correlated with all parameters (EC, Mg and Ca, Na, K, HCO_3, Cl, SO_4, NH_4). This also means that dimension 1 alone largely explains the natural origin of the various elements, but its correlation with NH_4 indicates a probable influence of anthropogenic activities. The second dimension, which accounts for 13.36% of the total variance, opposes pH and NO_2, which are positively correlated with T (˚C) but negatively correlated (**Figure 5(a)**). Component 3 accounts for 10.76% of the total variance, and opposes PO_4, which contributes positively to this axis, and NO_3, which correlates negatively (**Figure 5(b)**). This shows that components 2 and 3 explain the anthropogenic origin of the variables.

Moreover, for this period, the classification carried out on the individuals reveals 3 classes (**Figure 6**). Class 1 is made up of P3, P4, P6, F2, P17, F6 and P30. This group is characterized by low values of Ca, HCO_3, Mg, EC, SO_4, Cl, K, Na, and pH. Class 2 is made up of P8, P13, P15 and P25. This group is characterized by high values of HCO_3, Ca, pH, and NO_3. Class 3 is made up of P14, P22 and P26. This group is characterized by high values of Mg, SO_4, EC, K, Cl, Na, Ca and NO_3. The high nitrate values in these waters show their anthropogenic influence on groundwater quality and their contribution to mineralization.



(a)



(b)

Figure 5. Projecting variables on the factorial plane (Dry season).

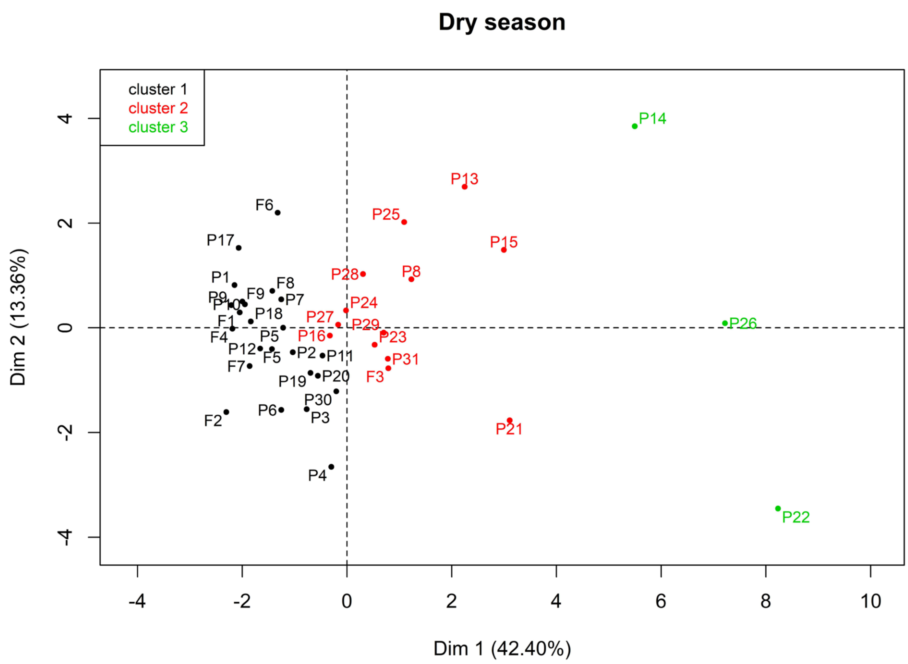
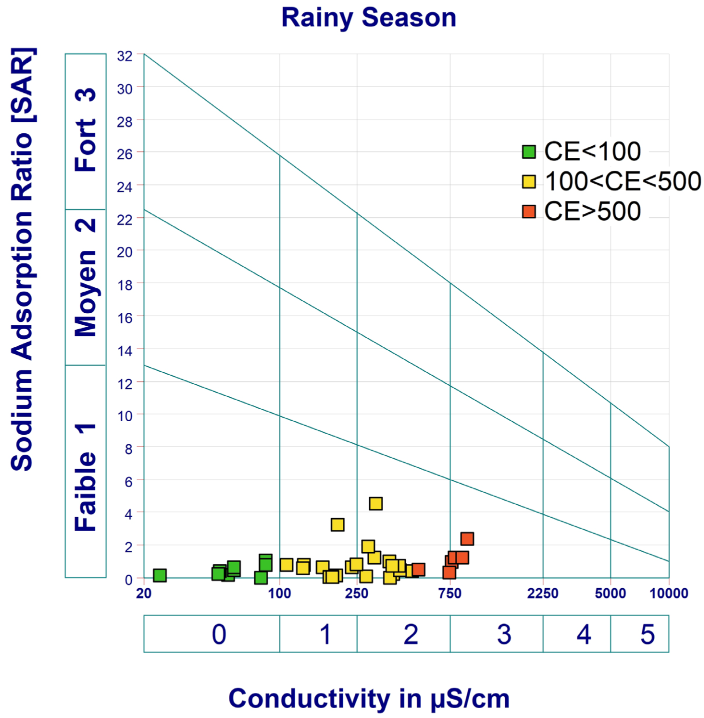


Figure 6. Projection of individuals (Dry season).

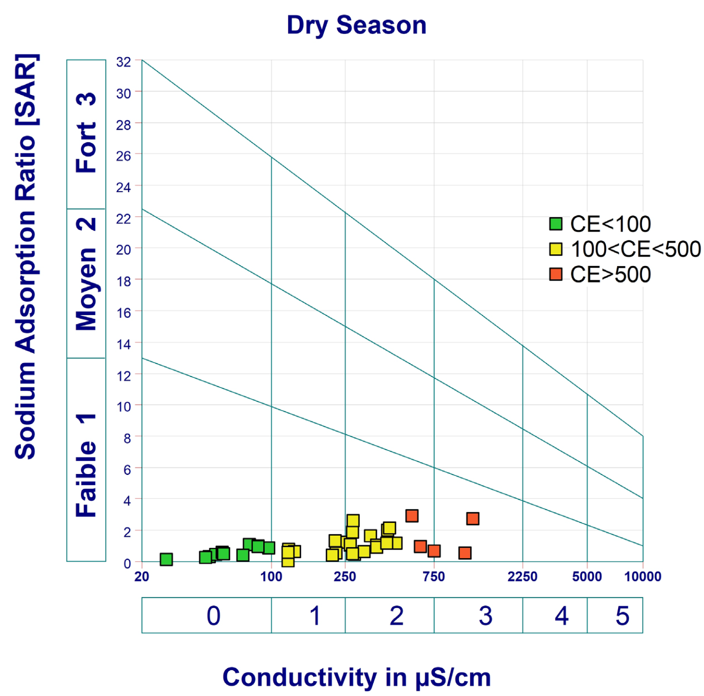
3.3. Assessing Water Suitability for Irrigation

3.3.1. Riverside Method

SAR values calculated from analytical results range from 0.005 to 4.52 meq/L and from 0.06 to 2.94 meq/L in rainy (**Figure 7(a)**) and dry seasons (**Figure 7(b)**) respectively. These values correspond to those of water with a low risk of soil salinization. The SAR and conductivity values at 25˚C show the classes to which the samples belong (Figure 7). Analysis of this figure reveals four classes (4): C0S1, CAS1, C2S1 and C3S1.

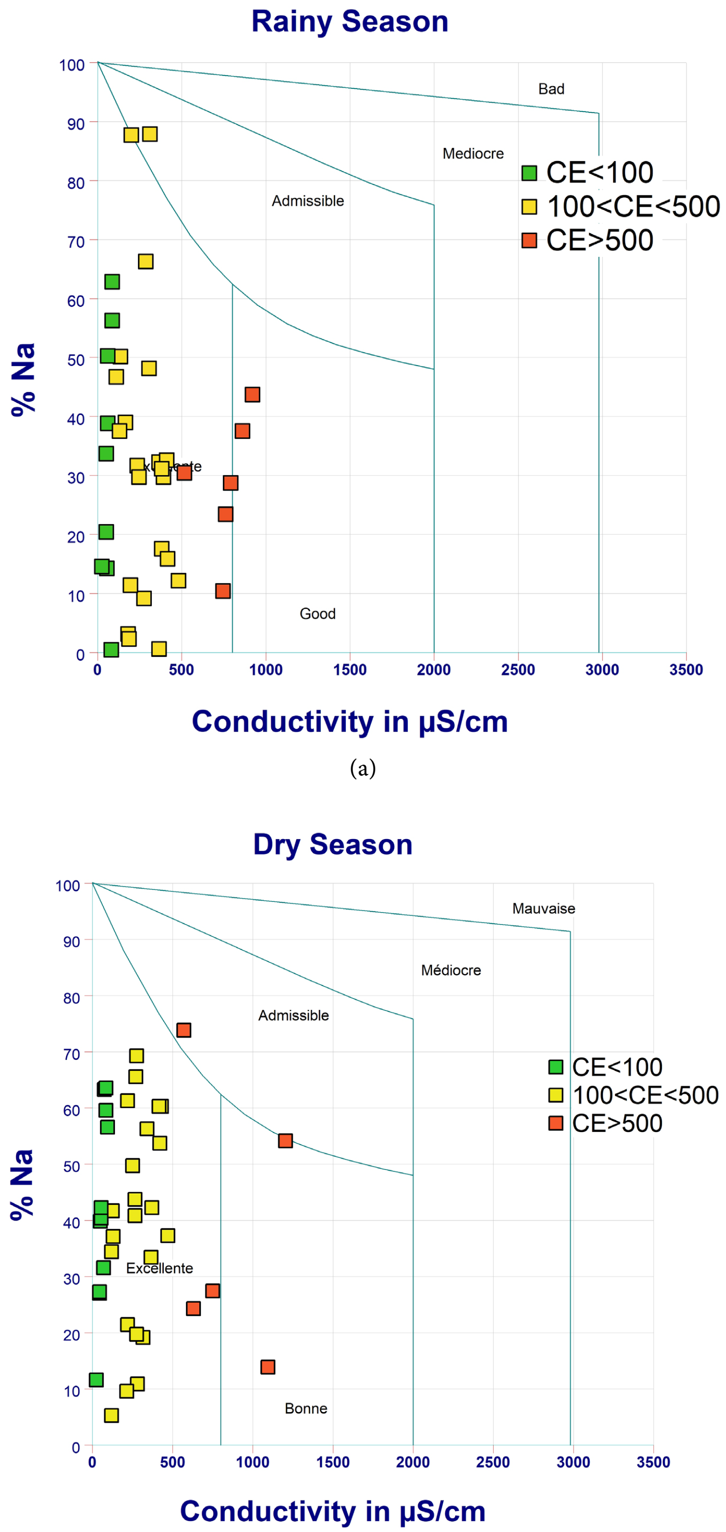


(a)



(b)

Figure 7. Plotting of samples on the USSL salinity diagram for classification of water for irrigation purposes.



(a) (b)

Figure 8. Samples plotted on the Wilcox irrigation water classification chart.

- Classes C0S1 and C1S1 are characteristic of water of excellent quality for irrigation and present no risk to crops or soil. They represent around 60% of samples;

- Class C2S1, which represents good quality water for irrigation, covers around 35% of samples;

- Class C3S1, representing water of acceptable quality for irrigation, covering only 5% of samples.

3.3.2. Wilcox Method

The values expressed as a percentage (%) of sodium content and electrical conductivity (µS/cm) plotted on the Wilcox diagram (**Figure 8(a)** et **Figure 8(b)**), for both rainy and dry seasons, show that the majority of groundwater in the delta belongs to the category of excellent quality water for irrigation, except P26, P4, and P22 in the dry season and P21, P22, P2, P20 in the rainy season, which belongs respectively to the categories of good and admissible quality water for irrigation.

3.3.3. Residual Sodium Carbonate (RSC)

The RSC calculated in this work is between −2.93 and 0.31 and −3.99 and 0.44 meq/L respectively in rainy and dry seasons. These values are all below 1.25 and indicate good water quality for irrigation. Such low levels of RSC in water have no negative effect on soil fertility and plant growth [38] [20].

4. Conclusion

This study successfully used multiple approaches to analyze the quality status of groundwater from wells and boreholes in Ouémé delta districts in southeastern Benin. Based on the results of this research, it was concluded that Thermal equilibrium is established between the water table and the atmosphere, with well and borehole water temperatures ranging from 26˚C to 33.90˚C. Furthermore, the water's pH, which ranges from 3.71 to 7.72, proves that the water is acidic, in keeping with the lithological nature of the aquifer reservoir, which is essentially siliceous and very open to the atmosphere, favoring the exchange of CO_2 with the soil atmosphere. The electrical conductivity of this groundwater varies between 24 and 1205 µS/cm for water samples studied, with around 60% between 100 and 500 µS/cm, reflecting an average mineralization overall. The highest values generally correspond to local groundwater pollution. Parameters such as EC, Mg, Na, Cl, and SO_4 recorded results within their respective [26] and Benin (2001) standard limits. However, K, NO_3, Ca, and HCO_3 pollution was observed in some samples. This pollution is likely to be due to anthropogenic activities. Assessment of the water's suitability for irrigation using the Riverside, Wilco,x, and RSC methods shows that the water is good and admissible for irrigation, and has no effect on soil fertility or plant growth.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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