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Hydrochemical Characterization of Groundwater in the Sub-Prefecture of Kokumbo (Ivory Coast)

Armel Kouadio Koblan[1*], Affoué Bénédicte Koffi[1], Aminata Diomandé[1], Deh Serges Kouakou[1], Kan Jean Kouamé[1,2], Jean Patrice Jourda[1,2]

[1]Laboratory of Soil, Water and Geomaterials Sciences (LSEG), U.F.R. Earth Sciences and Mining Resources (STRM), University of Felix Houphouët-Boigny, Abidjan, Ivory Coast
[2]University Center for Research and Application in Remote Sensing (CURAT), University of Félix Houphouët-Boigny, Abidjan, Ivory Coast
Email: *armelkoblan2@gmail.com, benedicteka@gmail.com, amiii072013@gmail.com, deh.serge@yahoo.fr, jeankkan@yahoo.fr, jourda_patrice@yahoo.fr

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Abstract

In the Kokumbo sub-prefecture, groundwater extraction related to gold panning remains a major concern, not to mention the deterioration of its quality. Among the work carried out on water resources, no scientific interest has been shown in groundwater to characterise it. The objective of this study is to contribute to the knowledge of its physico-chemical quality. *In situ* measurements and physico-chemical analyses using an inductively coupled plasma optical emission spectrometer (ICP-OES) were carried out on five (5) human-powered pump (HPP) water samples and six (6) well water samples collected during low and high water seasons. The results show that the physico-chemical quality of the water, which is sometimes turbid, is satisfactory in terms of the mineralization of the borehole and well water, and the pH of the boreholes, while the temperatures of the two waters and the pH of the wells do not comply with WHO standards. The levels of major ions are recommended for consumption. The waters are classified as predominantly bicarbonate-calcium and magnesium (73%) in the dry season and in the flood season, with an equal split between bicarbonate-calcium and magnesium (45.5%) and chloride-calcium and magnesium (45.5%). The elimination of materials responsible for the turbidity of certain waters by managers or populations is essential for drinking water use. The risk linked to this element means that these turbid waters are not recommended for drinking water.

Keywords

Groundwater, Physico-Chemical Parameter, Hydrochemical Facies, Kokumbo

1. Introduction

In the sub-prefecture of Kokumbo, groundwater is found in geological formations that harbour gold mineralization. This essential resource, whose value is not well understood or appreciated by gold miners, is subject to the phenomenon of dewatering. The situation may become a matter of concern if the reasoning is done in terms of renewable groundwater resources. The predominant use of surface water for drinking water supply in the Kokumbo sub-prefecture obscures the management of this groundwater resource. It is important to know certain parameters, in this case the physicochemical quality of groundwater, because the poor quality of this water could be the cause of many public health problems in the localities of the sub-prefecture where its use predominates due to the non-existence of a water distribution network. This approach is essential for aquifer management. Indeed, the natural quality of groundwater can be altered by human activity or by the various elements that the water comes into contact with (Mahamane & Boubié, 2015). The sub-prefecture of Kokumbo is subject to heavy anthropization, including gold panning, and the pressures exerted on the water result not only in the depletion of water resources but also in the deterioration of water quality. It is, therefore, necessary to characterize the quality of this resource used in certain areas of the sub-prefecture for water consumption and for certain domestic uses. The determination of water quality is assessed by measuring physicochemical parameters. The interest of this work is the study of the physicochemical quality of water from boreholes and wells as well as the determination of the main chemical facies of water in the sub-prefecture of Kokumbo.

2. Materials and Methods

2.1. Description of the Study Area

The sub-prefecture of Kokumbo, located in the center of Côte d'Ivoire between latitudes 6˚22N and 6˚40N and longitudes 5˚18W and 5˚06W, belongs to the department of Toumodi (**Figure 1**). The area is characterized by an equatorial climate with four (4) seasons, including two rainy seasons from March to June (long season) and September to October (short season), and two dry seasons from November to February for the long season and the short season from July to August. The average monthly rainfall is between 23.8 and 199.9 mm over the period 2001-2011 with an average temperature of about 25˚C. Water supply is from the surface water of the Bandama River and boreholes. Modern or traditional wells are used for domestic purposes or for watering livestock.

2.2. Sampling and Analysis Techniques

Water samples were collected in plastic bottles from eleven (11) water points, including five (5) boreholes and six (6) wells during the dry and rainy seasons (**Figure 2**). For each water point, two samples were taken. One bottle containing non-acidified water was used to measure the physicochemical parameters

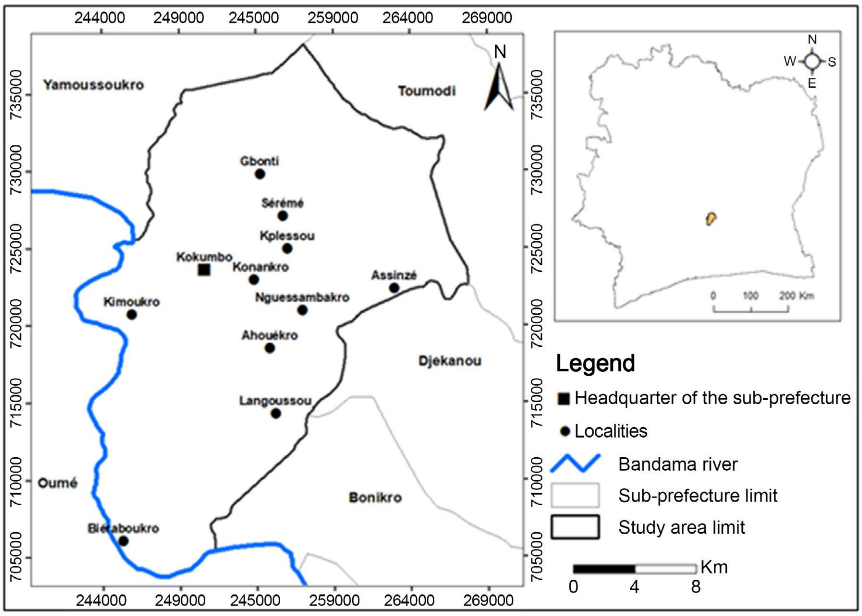

Figure 1. Location of the study area.

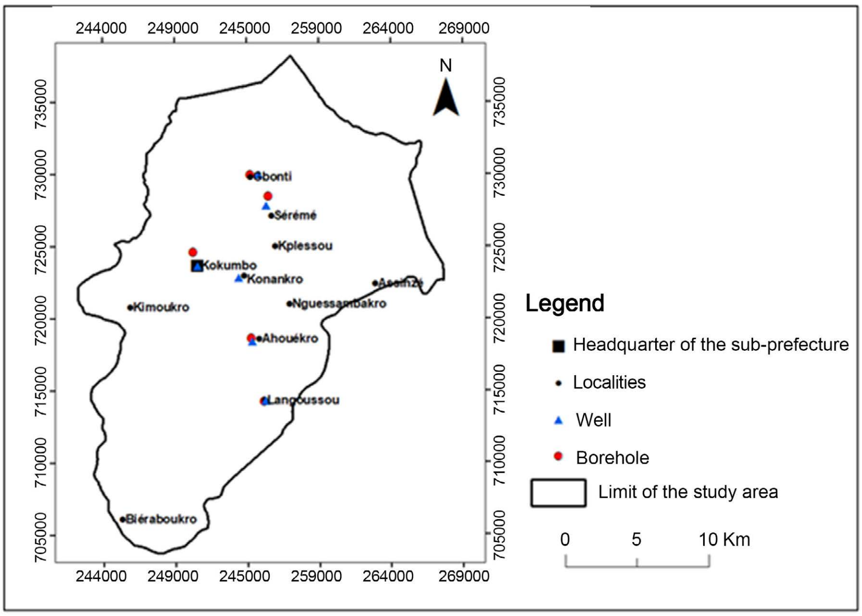

Figure 2. Borehole and well water sampling points in the Kokumbo sub-prefecture.

in-situ, namely hydrogen potential, temperature, electrical conductivity, and turbidity using a multi-parameter toledo device for temperature and pH, a Hach conductivity meter and a Hach 2100 turbidity meter for turbidity. The other bottle of water containing nitric acid was used for major ion analysis. The carefully collected and labeled samples were stored in coolers at 4˚C and transported to the laboratory for analysis.

The analysis of major ions in groundwater was carried out at the Enval laboratory using an inductively coupled plasma optical emission spectrometer (ICP-OES). This is a classical multi elemental analysis technique. In liquid form, the sample is introduced into the plasma where it undergoes vaporization and ionisation. The role of the plasma is to break down molecular bonds to produce ions to be excited. As the sample is ionized in the plasma, the ions emit light lines at different wavelengths specific to the elements being measured. The emitted radiation is separated by a dispersive grating and detected by a charge coupled device called a CCD detector. These rays are converted into information that is fed into a computer which then calculates the concentration of the element in question using a previously established calibration line. The software then provides the results. The ion balance (IB) was calculated to validate the results obtained according to the following formula:

$$BI = \frac{\sum[\text{cations}] - \sum[\text{anions}]}{\sum[\text{cations}] + \sum[\text{anions}]} \times 100$$

BI = Ionic Balance in %.

[ ] = Concentration expressed in meq/l.

It is based on the principle:

- excellent when BI < 5%;
- acceptable when 5% < BI < 10%;
- doubtful when BI ≥ 10%.

Correct (representative and acceptable) chemical analyses are considered when the ion balance is less than or equal to 10%. The determination of the chemical facies of our water samples was done by the Piper diagram. This diagram uses major ions to represent the chemical facies of a set of water samples. It is composed of two triangles (one triangle representing the cationic facies and the other the anionic facies) and a rhombus synthesising the overall facies. This graphic approach is a widely used method.

3. Results

3.1. Physico-Chemical Parameters

The *in-situ* measurements provided the following statistical values for the physico-chemical parameters of the boreholes and wells in the Kokumbo sub-prefecture (Table 1).

Table 1. Statistics of physico-chemical parameters of boreholes and wells in the subprefecture of Kokumbo.

	Parameters *in situ*	Dry season				Rainy season				WHO standards 2017
		Min	Max	Moy	Standard deviation	Min	Max	Moy	Standard deviation	
Boreholes	pH	6.8	7.4	7.1	0.3	6.5	7.4	6.8	0.4	6.5 - 9.5
	T (˚C)	27.8	30.8	29.2	1.1	27.8	30.1	28.9	0.8	22 - 25
	CE (µS/cm)	340	515	410	68.6	306	508	388.8	75.5	1000 - 1400
	Turb (NTU)	1.16	42.2	19.0	18.8	1.1	185	40.5	80.8	≤5
Wells	pH	5.6	7.2	6.3	0.6	5.1	6.8	5.9	0.6	6.5 - 9.5
	T (˚C)	28.4	30.4	29.2	0.7	27.9	29.8	28.8	0.7	22 - 25
	CE (µS/cm)	19.3	290.0	178.4	102.3	25.4	376.0	202.7	145.9	1000 - 1400
	Turb (NTU)	3.5	15.9	8.4	5.3	4.5	161.0	45.9	60.0	≤5

3.1.1. Hydrogen Potential (pH)

Borehole water has on average a higher pH than well water (**Figure 3**). The pH of the boreholes is slightly acidic to neutral in the dry season (6.8 - 7.4) and in the rainy season (6.5 - 7.4). The values are in line with WHO standards. The well water is acidic in the dry season (5.6 - 6.6) and in the rainy season (5.1 - 6.3), except for well P1 in the dry season, which has a neutral pH of 7.2. The pH is in line with WHO standards except for wells P4 (6.3), P5 (5.7), P6 (5.6) in the dry season and wells P3 (5.3), P4 (5.7), P5 (5.1), P6 (5.9) in the wet season.

3.1.2. Temperature (T)

The temperatures of the borehole and well water are almost identical, less sensitive to seasonal variations and from one point to another (**Figure 4**). For the boreholes, it varies in the dry season from 27.8˚C to 30.8˚C with an average of 29.2˚C and in the rainy season from 27.8˚C to 30.1˚C with an average of 28.9˚C. For the wells, the values are between 28.4˚C and 30.4˚C in the dry season and between 27.9˚C and 29.8˚C in the flood season with respective averages of 29.2˚C and 28.8˚C. The water temperatures are higher than the WHO guidelines.

3.1.3. Electrical Conductivity (EC)

Borehole water is more mineralised than well water (**Figure 5**). In the dry season, the conductivity varies for boreholes from 340 µS/cm to 515 µS/cm and for wells from 19.3 µS/cm to 290 µS/cm. The average in the dry season for the boreholes is 410 µS/cm compared to 178.4 µS/cm for the wells. In the rainy season, it ranges from 306 µS/cm to 508 µS/cm for boreholes and from 25.4 µS/cm to 376 µS/cm for wells. The average is 388.8 µS/cm for the boreholes and 202.8 µS/cm for the wells. Well P5 has the lowest conductivity (19.3 µS/cm) in the dry season and in the rainy season (25.4 µS/cm). The conductivities of the boreholes and wells do not exceed WHO standards.

3.1.4. Turbidity (Tur)

The turbidity of borehole water is high in the dry season compared to well water, while in the flood season the turbidity of well water is high compared to borehole water (**Figure 6**). From the dry to the wet season, the turbidities of the borehole water decrease, except for borehole F5, while those of the well water increase. Turbidities vary during the dry season from 1.16 NTU to 42.2 NTU with an average of 19.1 NTU for boreholes and from 3.48 NTU to 15.9 NTU with an average of 8.42 NTU for wells. During the flood season, they vary from 1.1 NTU to 185 NTU with an average of 40.5 NTU for boreholes and from 4.48 NTU to 161 NTU with an average of 45.9 NTU for wells. The water points generally have high turbidities above the WHO value, except for the water points F1, F4 and P2 which meet the standards in both seasons and P3 and P6 in the dry season only.

3.2. Chemical Composition of Water

The concentrations of the major ions show heterogeneity in both campaigns. The statistical values of the concentrations are presented in **Table 2**.

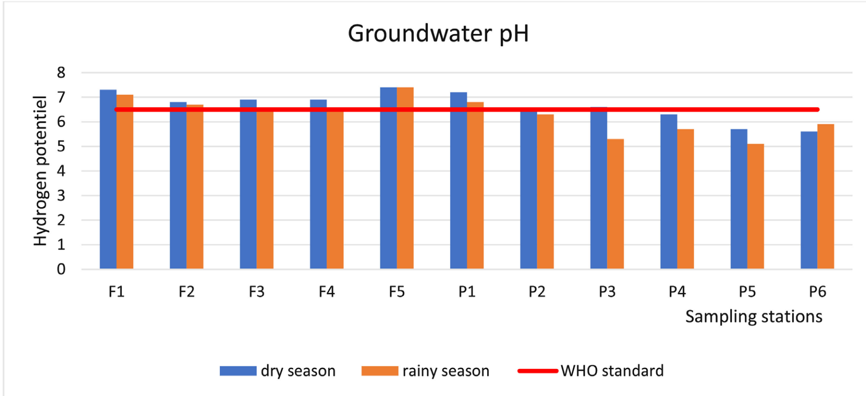

Figure 3. Variation of groundwater pH in Kokumbo sub-prefecture.

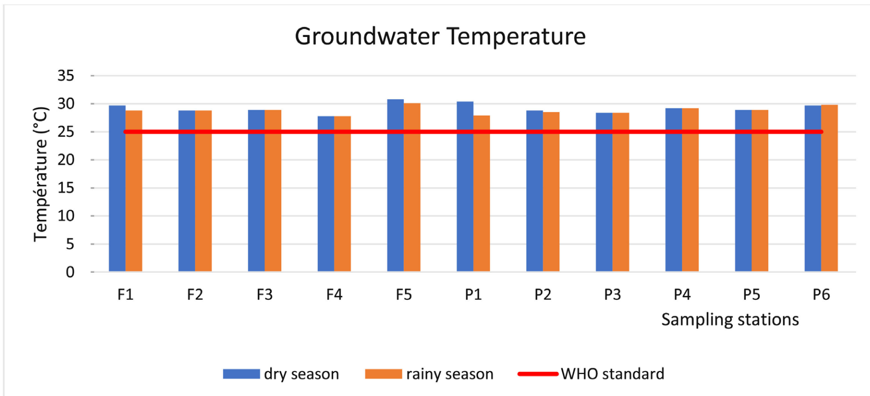

Figure 4. Variation in groundwater temperature in the Kokumbo sub-prefecture.

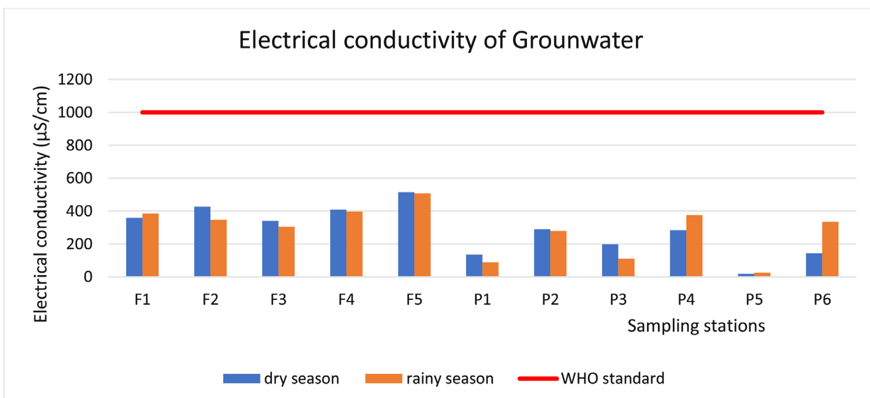

Figure 5. Variation of groundwater electrical conductivity in Kokumbo sub-prefecture.

3.2.1. Calcium (Ca^{2+})

Calcium is the most abundant cation. Calcium levels in boreholes are higher than in wells in both seasons (Figure 7). For the boreholes, they vary in the dry season from 32.8 mg/l to 68.5 mg/l and in the wet season from 8.89 mg/l to 86.6 mg/l. Borehole F5 has the highest concentrations in both seasons. Calcium levels in the wells vary in the dry season between 1.4 mg/l and 30.2 mg/l, and in the wet season between 0.88 mg/l and 32.54 mg/l. The amounts of calcium in the water are low and respect the WHO (2017) standard of 200 mg/l.

3.2.2. Magnesium (Mg^{2+})

Magnesium concentrations in the boreholes are higher than in the wells in both seasons (Figure 8). The boreholes have concentrations ranging from 13.1 mg/l to 25.5 mg/l in the dry season and from 4.5 mg/l to 3.46 mg/l in the wet season. The wells have concentrations ranging from 0.6 mg/l to 13.7 mg/l in the dry season and from 0.89 mg/l to 17.38 mg/l. Well P5 has no concentrations in the wet season.

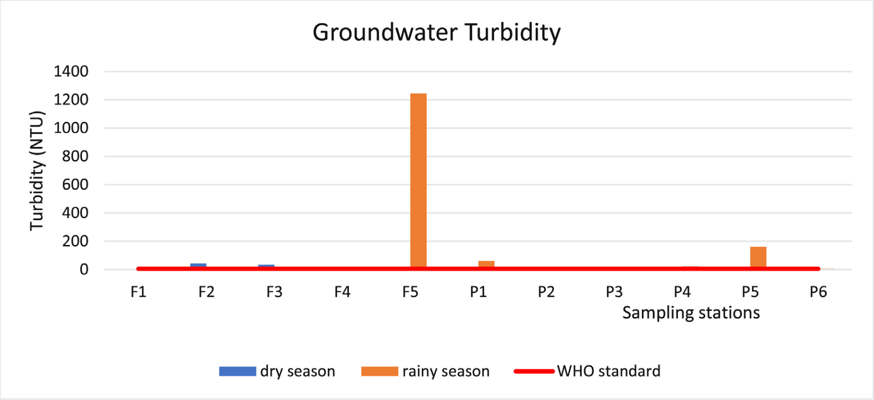

Figure 6. Variation in groundwater turbidity in the Kokumbo sub-prefecture.

Table 2. Cation and anion concentration statistics for water samples from the Kokumbo sub-prefecture.

		boreholes							
	Ions (mg/l)	Ca^{2+}	Mg^{2+}	K^+	Na^+	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-
Dry season	Min	32.6	13.1	0.6	3.9	55.0	0.0	5.8	0.4
	Max	68.5	25.5	4.4	22.5	197.0	0.0	8.5	15.4
	Moy	45.5	19.4	2.5	10.8	163.8	0.0	7.1	4.2
	Standard deviation	13.8	4.5	1.6	8.7	61.2	0.0	1.9	6.3
Wet season	Min	8.89	3.46	0.53	4.94	24.00	26.00	9.12	11.10
	Max	86.60	22.38	2.89	28.86	278.00	26.00	11.14	18.30
	Moy	45.68	14.35	1.18	13.47	177.40	26.00	10.13	14.48
	Standard deviation	27.70	7.18	1.14	9.70	94.23	-	1.43	2.96
		Well							
	Ions (mg/l)	Ca^{2+}	Mg^{2+}	K^+	Na^+	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-
Dry season	Min	1.4	0.6	1.0	0.8	19.0	0.0	10.5	1.2
	Max	30.2	13.7	9.1	26.8	135.0	0.0	32.8	21.5
	Moy	14.6	6.2	4.1	13.4	65.3	0.0	20.7	6.0
	Standard deviation	10.4	4.9	3.2	9.3	48.0	0.0	11.3	8.0
Wet season	Min	0.88	0.89	1.08	1.34	3.00	7.00	26.00	5.30
	Max	32.54	17.38	13.14	27.03	183.00	8.00	34.10	22.60
	Moy	18.41	10.10	6.71	15.25	56.00	7.50	30.05	13.92
	Standard deviation	11.89	6.05	5.70	11.77	67.38	0.71	4.05	6.71

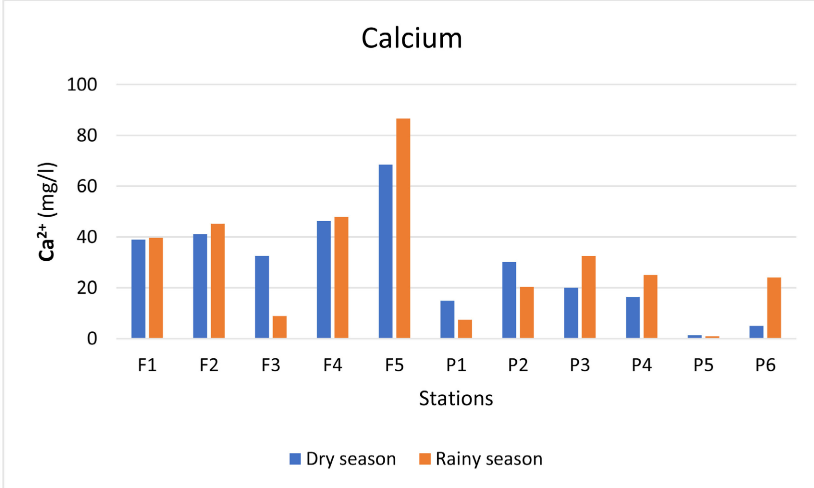

Figure 7. Calcium concentrations in boreholes and wells in different seasons.

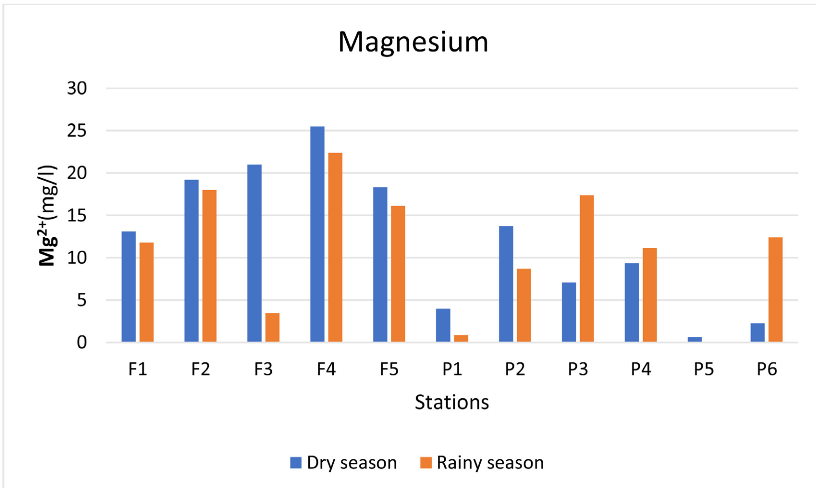

Figure 8. Magnesium concentrations in boreholes and wells in different seasons.

3.2.3. Sodium (Na^+)

The sodium concentrations of the water bodies are heterogeneous (**Figure 9**). The levels in the boreholes range from 3.9 mg/l to 22.5 mg/l in the dry season and from 4.94 mg/l to 28.86 mg/l in the wet season. The wells have levels ranging from 0.8 mg/l to 26.8 mg/l in the dry season and from 1.34 mg/l to 27.03 mg/l. Sodium levels in the water bodies are below the WHO standard (2017) of 200 mg/l.

3.2.4. Potassium (K^+)

The potassium content of the water bodies is heterogeneous (**Figure 10**). The concentrations in the boreholes vary in the dry season between 0.6 mg/l and 4.4 mg/l and in the flood season between 0.53 mg/l and 2.89 mg/l. The values measured in the wells vary from 1 mg/l to 9.1 mg/l in the dry season and from 1.08 mg/l to 13.14 mg/l. The water points F2 and P2 do not show any concentrations in the dry season, whereas in the wet season the water points F2, P1 and P5.

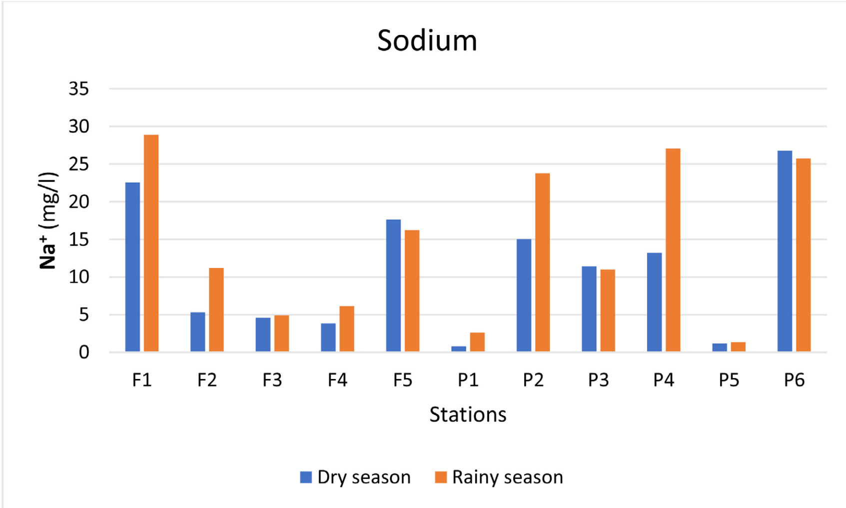

Figure 9. Sodium concentrations in boreholes and wells in different seasons.

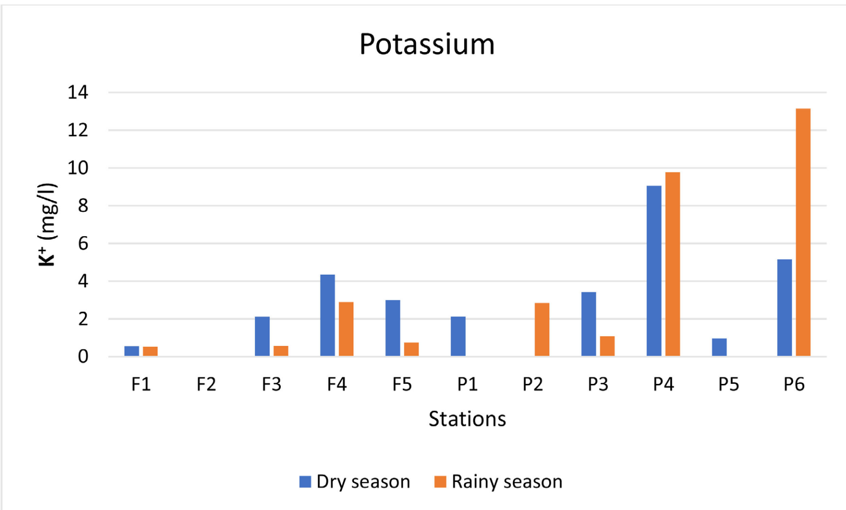

Figure 10. Potassium concentrations in boreholes and wells in different seasons.

3.2.5. Bicarbonates (HCO_3^-)

Bicarbonates are the predominant anions in the water, with concentrations in the boreholes being higher than in the wells (Figure 11). The concentrations measured in the boreholes range from 55 mg/l to 197 mg/l in the dry season and in the flood season from 24 mg/l to 278 mg/l. Concentrations in wells range from 19 mg/l to 135 mg/l in the dry season and from 3 mg/l to 183 mg/l in the wet season.

3.2.6. Sulphates (SO_4^{2-})

The water from the boreholes and wells is characterised by an absence of sulphate ions in the dry season (Figure 12). In the rainy season, only the water points F5, P4 and P6 show concentrations. The sulphate concentration of the borehole is higher than both concentrations of the wells. The measured values are below the WHO (2017) standards of 250 mg/l.

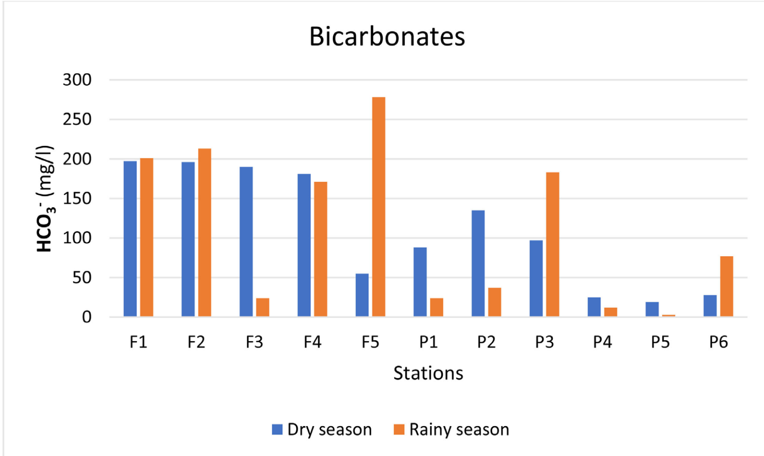

Figure 11. Bicarbonate concentrations in boreholes and wells in different seasons.

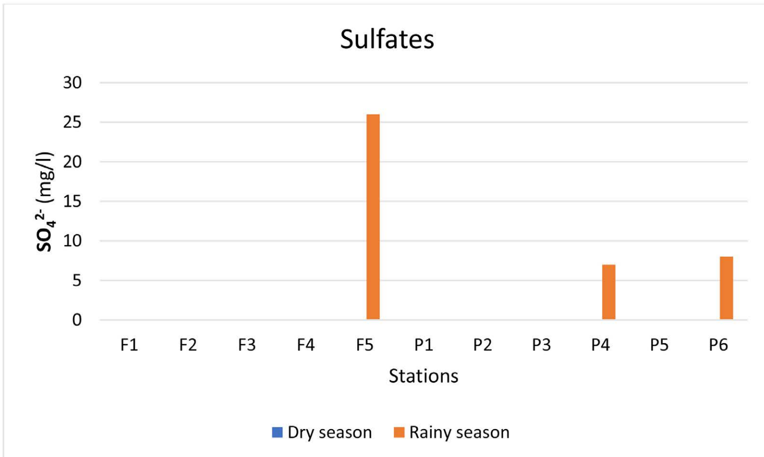

Figure 12. Sulphate concentrations in boreholes and wells in different seasons.

3.2.7. Chlorides (Cl^-)

Chlorides in boreholes vary from 5.8 mg/l to 8.5 mg/l in the dry season and from 9.12 mg/l to 11.14 mg/l in the rainy season. In the wells, concentrations vary between 10.5 mg/l and 32.8 mg/l in the dry season and between 26 mg/l and 34.1 mg/l (Figure 13). Water points F1, F2, F3, P1, P3, P5 do not have chloride levels in either the dry or wet season. The concentrations are below the WHO (2017) standards of 250 mg/l.

3.2.8. Nitrates (NO_3^-)

Nitrate levels vary little from one point to another within a season and increase from the dry season to the flood season (Figure 14). Borehole water levels vary from 0.4 mg/l to 15.4 mg/l in the dry season and from 11.1 mg/l to 18.3 mg/l. The concentration in borehole F4 is much higher than in the others in the dry season. The wells have concentrations between 1.2 mg/l and 21.5 mg/l in the dry season and between 5.3 mg/l and 22.6 mg/l in the wet season. Well F6 has a high concentration in the dry season. The measured values are below the WHO (2017) threshold value of 50 mg/l.

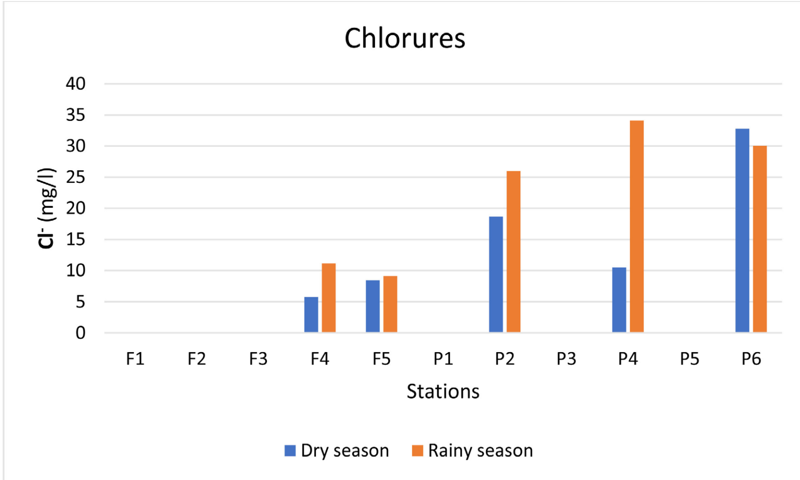

Figure 13. Chloride concentrations in boreholes and wells in different seasons.

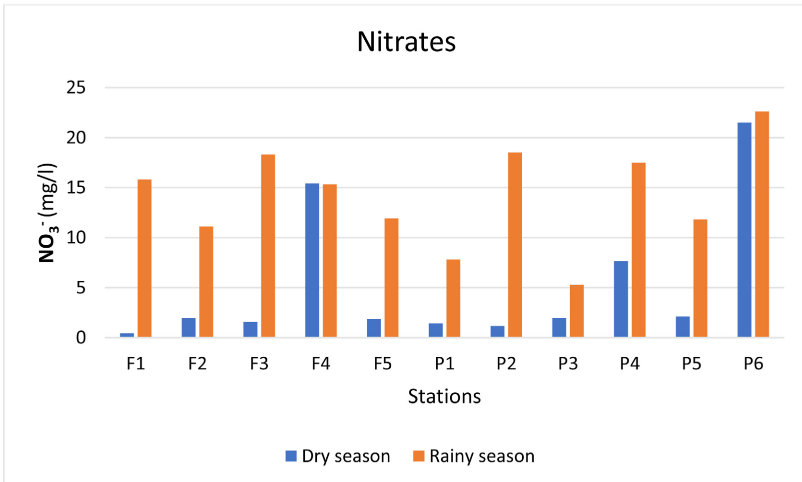

Figure 14. Nitrate concentrations in boreholes and wells in different seasons.

3.3. Chemical Facies of the Waters

3.3.1. Dry Season

The water is distributed over three facies (Figure 15(a)). 73% of the water, i.e. all the borehole water and well water P1, P2 and P3, belongs to the calcic and magnesian bicarbonate facies. Mixed facies are observed for the water sample P5, i.e. 9%, situated between the calcic and magnesian bicarbonate and calcic and magnesian chloride facies. The waters of wells P4 and P6, each representing 9%, are classified respectively in the calcic and magnesian chloride facies and the sodium and potassium chloride facies. The cation triangle shows calcic facies for 27% of the waters (F5, F2, P1) and sodium and potassium facies for the water sample P6, i.e. 9%. There are no dominant cations for 64% of the waters (F1, F3, F4, P2, P3, P4, P5). In the anion triangle, 73% of the waters, i.e. all borehole and well waters P1, P2, P3 are in the carbonate pole and the well water P6, i.e. 9%, in the chloride-nitrate pole. There are no dominant anions for 18% of the waters (P4 and P5).

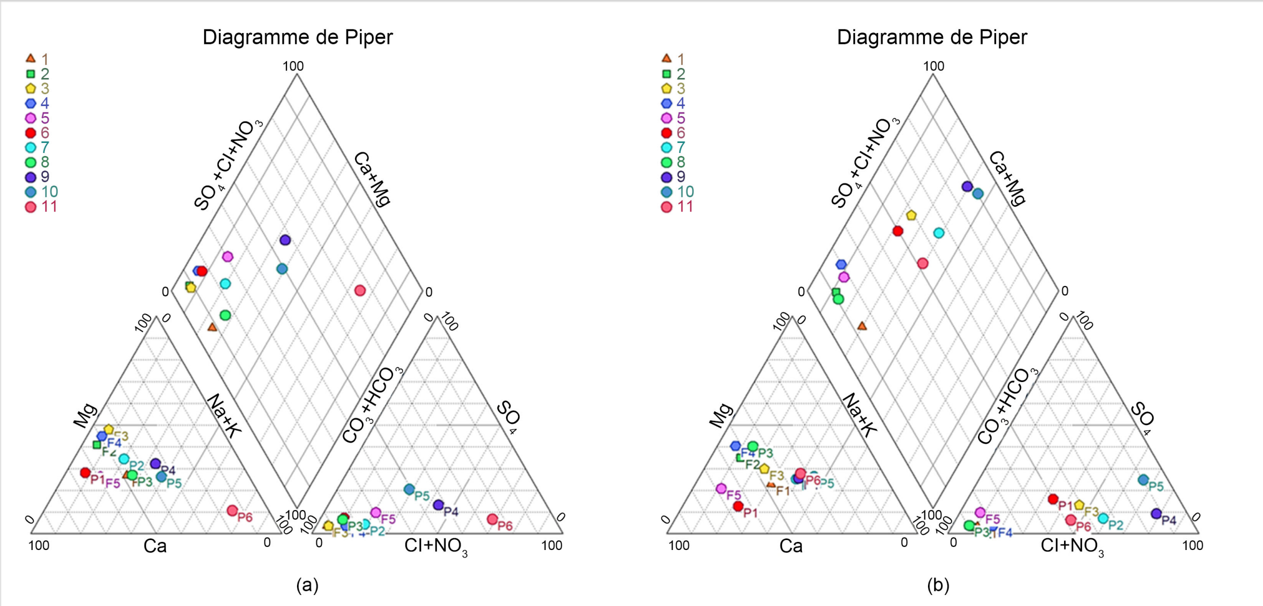

Figure 15. Groundwater piper diagram: (a) dry season, (b) wet season.

3.3.2. Wet Season

Two facies are observed (**Figure 15(b)**). The calcic and magnesian bicarbonate facies covers 45.5% of the water (F1, F2, F4, F5, P3) and the calcic and magnesian chloride facies 45.5% of the water samples (F3, P2, P4, P5, P6). The water from well P1, i.e. 9%, is on a mixed facies between the two above-mentioned facies. In the cation triangle, 36% of the waters (F2, F4, F5, P1) fall into the calcic pole and 64% (F1, F3, P2, P3, P4, P5, P6) have no dominant cations. In the anion triangle, the carbonate pole predominates in 45% of the waters (F1, F2, F4, F5, P3) and the chloride-nitrate pole in 27.5% of the waters (P2, P4, P5). The waters P1, P6 and F3 do not show any dominant anions, i.e. 27.5%.

4. Discussion

The quality of the various groundwater bodies in the Kokumbo sub-prefecture was assessed by means of *in situ* and laboratory measurements. The physico-chemical parameters studied show that some of the values observed do not comply with the standards recommended by the WHO, namely temperature and turbidity for borehole and well water, and pH for wells. Temperatures are above WHO standards. The seasons have a negligible effect on the temperature variation. These results are consistent with Rodier (2009) who states that groundwater is less sensitive to temperature variations. Temperatures obtained above 25˚C are not a danger (Orou et al., 2016). Average groundwater temperatures in West Africa are 30˚C and rarely below 25˚C due to climatic conditions (Rodier, 1996). The measured temperature values are similar to the work on groundwater in West Africa (Yao et al., 2012; Rabilou et al., 2018; Ehoussou, Kouassi, & Kamagaté, 2019). The high turbidities observed in some boreholes and wells belong to the class of non-potable water that requires potabilization treatment. These problems occur in boreholes in the dry season and in wells in the rainy season. Turbidity, a sign of a source of water contamination, has several sources, including meteoric inputs and domestic pollutants. For human powered boreholes, it could be due to domestic pollutants because the insalubrity around the water points is very remarkable with the presence of stagnant water and filth. As for the wells, it is linked to meteoric inputs. The pH of the well water is acidic in the dry season (average pH = 6.32) and in the wet season (average pH = 5.85), and the borehole water is slightly acidic to neutral. The slight acidity of the boreholes could be due to the fissure aquifers which are in contact with the superficial aquifers of the basement whose waters are acidic (Rabilou et al., 2018). Work on groundwater has shown that the pH is between 6 and 8.5 (Kouame & al., 2021). The low mineralized waters are suitable and identical to several works in the basement environment (Mahamane & Boubié, 2015; Kouame et al., 2021). The levels of cations and major anions are below WHO standards without any health hazards. These levels indicate good quality water in terms of ions. The majority of the waters analysed have an ionic balance of less than 10%. This confirms the reliability of the results. However, for some water points, we had ionic balances that did not respect this value due to the absence of certain major ions and minor ions in the water that were not analysed SO_4^{2-}, the least abundant anion in the water in both seasons, is totally absent in the dry season. This characteristic of the Kokumbo basement waters is similar to the basement waters of the Zinder region in Niger in both seasons. The low sulphate values recorded during both seasons are due to a very limited supply of sulphate ions from the oxidation of pyrite in the rocks (Rabilou et al., 2018). The high nitrate levels obtained in the rainy season at all water points, both boreholes and wells, compared to the very low levels in the dry season are very remarkable. This corroborates the studies carried out by some authors who have studied the contribution of NO_3^- ions by rainwater in the basement zone (Faillat & Drogue, 1993). This suggests a vulnerability of the water table to pollution and pollution of anthropic origin. The poor maintenance of the water points, solid residues and anthropic activities present a disadvantage in rainy periods for the boreholes. The waters are classified as calcic and magnesian bicarbonate for the majority of the samples in the dry season and in the flood season a change of facies is observed for certain waters towards the calcic and magnesian chloride pole, thus reflecting chloride inputs. The results from the Piper diagram confirm the predominance of the bicarbonate-calcium-magnesium facies in West African basement groundwater (Oga et al., 2009; Mahamane & Boubié, 2015; Rabilou et al., 2018). This predominance can be justified by the presence of granitoid rocks in the subprefecture which are responsible according to Oga et al. (2009) and Mahamane and Boubié (2015) for the preponderance of bicarbonate calcium and magnesium facies in the waters. The geological substratum of the Kokumbo sub-prefecture is in fact made up of alternating volcanosedimentary and plutonic rocks (granitoids, granites, tonalites) of Birimian age.

5. Conclusion

The present study made it possible to highlight the physico-chemical characteristics of the groundwater in the sub-prefecture of Kokumbo. With the exception of the water temperature, the turbidity of certain water points and the pH of the wells, which do not comply with the WHO guide values, the low mineralization of the water, the pH of the boreholes and the major ion content measured comply with the guidelines for drinking water in both seasons. Analysis of the facies indicates the predominance of calcium and magnesium bicarbonate water (73%) in the dry season and an equitable distribution of facies between calcium and magnesium bicarbonate water (45.5%) and calcium and magnesium chloride water (45.5%) in the flood season. The turbidity of the water at some water points constitutes a risk for use as drinking water.

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Conflicts of Interest

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

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