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Research article

Analysis of the qualitative evolution of groundwater in the Abouabou area in the Port-Bouët municipality (Abidjan, Côte d'Ivoire)

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ABSTRACT

The study aimed to analyze the seasonal qualitative evolution of the Quaternary groundwater in the Abouabou area in order to see the capacity of this water to be used as a water supply by the populations. In-situ measurements (temperature, electrical conductivity, dissolved oxygen, turbidity and pH) and chemical parameter analyses (NH_4^+, Ca^{2+}, Mg^{2+}, K^+, Na^+, NO_3^-, NO_2^-, PO_4^{3-}, SO_4^{2-}, Cl^- and HCO_3^-) were performed on the 24 samples collected during the four (4) seasons of the year. The use of Kruskal-Wallis and ANOVA tests has allowed the monitoring of seasonal variations in hydro-chemical parameters in well and borehole water. Also, the Piper diagram permit to identify the main hydrochemical facies according to the seasons. Finally, the Kohonen Self Organizing Maps (SOM) method was applied to physico-chemical parameters in order to highlight the spatial distribution of groundwater quality in the Abouabou area. The results show that, based on the physico-chemical parameters analysed, the groundwater is of good quality due to meeting WHO standards for drinking water consumption during all seasons of the year. Significant seasonal variations were recorded in the values of the parameters like turbidity, pH and Cl^- for well water and turbidity, PO_4^{3-}, NO_3^-, NH_4^+, K^+, Cl^- for borehole water. The hydrochemical facies shows a seasonal variation. Analysis of Abouabou's water reveals the variation of its hydrochemical facies. Thus, bicarbonate, calcium and magnesium facies during the long dry and rainy seasons move towards the chlorine, calcium and magnesium facies during the short dry and rainy seasons. Four water groups have been identified using SOM method, including heterogeneous groups composed mainly of borehole water (I and III) or of well water (II and IV). Borehole and well water acquire most of their mineralization by the infiltration of surface elements. Drinking water from boreholes is of good quality.

1. Introduction

Groundwater is the main source of water supply for major African cities. It is often more reliable, in closer proximity to users, less vulnerable to pollution, and more resilient to climate variability than surface water [1, 2]. Many expanding urban areas in sub-Saharan Africa are dependent on groundwater for at least some, and many cases the majority, of domestic water supply [3, 4]. Despite the perceived safety associated with groundwater consumption, the expansion of these cities and the growth of their population contribute to the degradation of this groundwater's quality [5, 6]. Indeed, several researches have shown that Groundwater can be contaminated by the grazing of animals, discharge of domestic and industrial wastewater, use of pesticides and fertilizers in agriculture [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. Consequently, the supply of water to the urban and peri-urban population in African countries requires that preliminary studies must be associated.

Abidjan is the economic capital of Côte d'Ivoire, and its groundwater resources have come under heavy pressure in order to meet the population's water requirements. Indeed, several studies have shown that the Continental Terminal water table, currently used for water supply to the city, has recorded several cases of water contamination, due to sanitation systems that are frequently faulty or precarious [18, 19]. Therefore, to meet increasing water requirements while preserving water quality, resource managers often turn to peripheral areas of the city of Abidjan, which are less urbanized, in order to increase the production capacity of the Côte d'Ivoire Water Distribution Company (SODECI). The case of the Abouabou area, where five boreholes were drilled, is an illustration of this. Borehole in the Abouabou area, located in the Port-Bouët municipality, aims to strengthen the drinking water supply of southern Abidjan.

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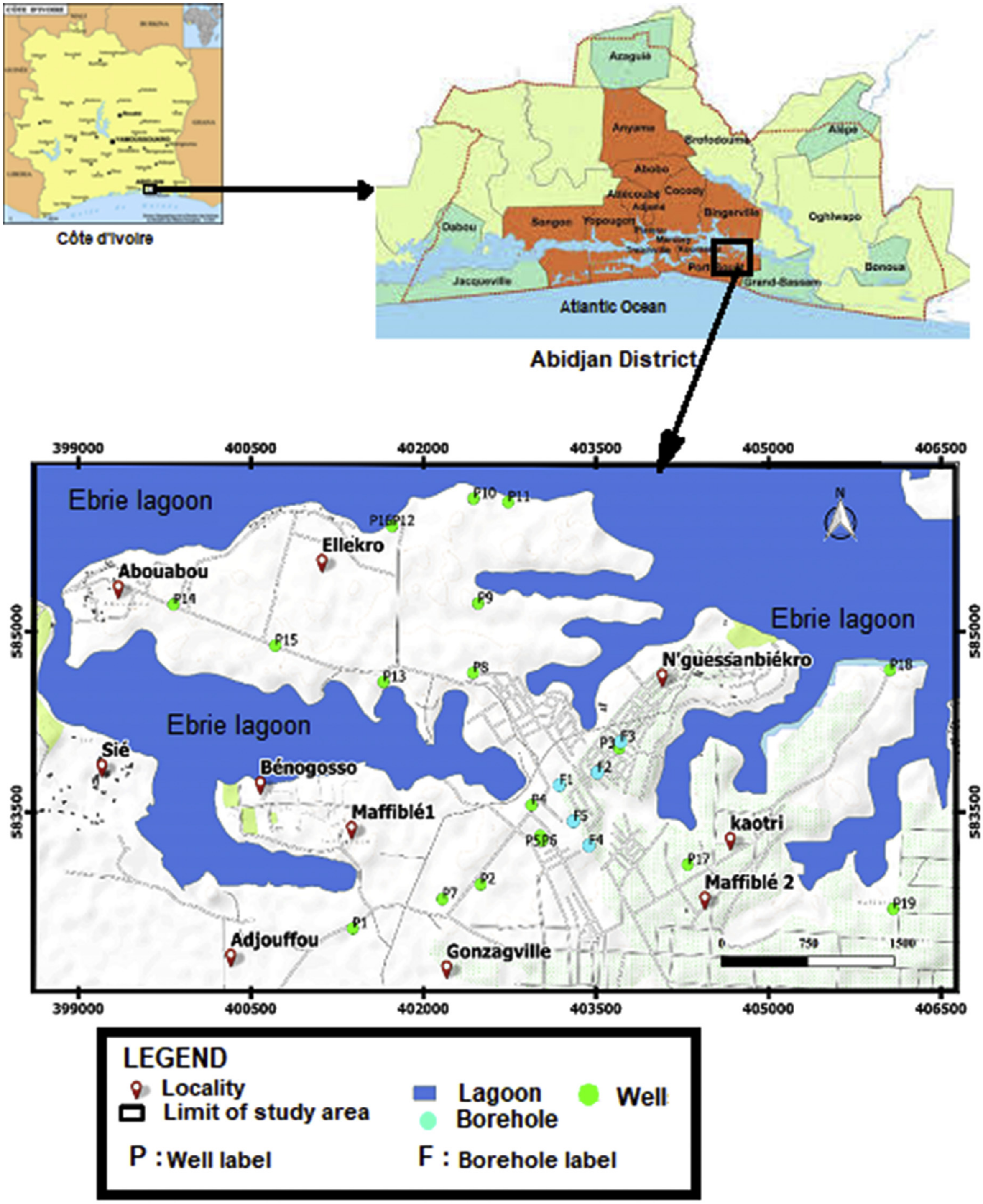

Figure 1. Abouabou area with the location of the sampling sites.

However, the borehole has not yet been sompleted because of the doubt which hangs over the quality of the water in these boreholes. Indeed, the geological structure of the Port-Bouët area is made up of Quaternary sands, which are quite vulnerable to pollution [20]. In addition, the Abouabou area is surrounded by the Ebrié lagoon, which has brackish water and is subject to urban pollution. This study was therefore initiated to evaluate the suitability of the boreholes in Abouabou area, for exploitation as sources of drinking water. It aims to characterize the variability of the water quality of the Abouabou aquifer. Specifically, the aim is to evaluate the seasonal variability of water quality, to understand the mechanism of the water's acquisition of minerals from the spatio-temporal distribution of physicochemical parameters.

2. Material and methods

2.1. Presentation of the study area

The Abouabou area is in Port-Bouët municipality in the south of Abidjan District between latitudes 582 000 and 586 000 North and longitudes 399 000 and 406 500 West (Figure 1). It includes the villages

Table 1. Characteristics of wells and boreholes in the Abouabou zone.

	Sample Codes	Position UTM, 30N			Depths below the top soil (m)
		X (m)	Y (m)	Z (m) relative to sea level	
Wells	P1	401387	582534	9	4
	P2	402498	582900	11	6.5
	P3	403703	584029	10	6
	P4	402941	583557	6	5
	P5	403017	583304	11	4.5
	P6	403032	583265	12	4
	P7	402166	582777	7	6
	P8	402433	584656	16	4
	P9	402476	585233	14	6
	P10	402437	586103	6	6
	P11	402738	586074	17	4
	P12	401730	585874	6	4
	P13	401653	584581	10	3.5
	P14	401315	583201	11	3.5
	P15	400584	585917	14	6
	P16	401728	585875	12	3
	P17	404299	583064	16	4
	P18	406058	584660	9	5
	P19	406085	582696	9	5
Boreholes	F1	403183	583723	6	60
	F2	403513	583828	8	34
	F3	403716	584082	8	34
	F4	403440	583222	8	30
	F5	403305	583424	10	34

Table 2. Chemical parameters analyzed with the LANG HACH DR6000.

Parameters	Reagents	Wavelength
PO_4^{3-}	Ammonium molybdate reagent	880 nm
NH_4^+	Nessler reagent	425 nm
NO_3^-	Nitraver 3 (sulfanilic acid)	500 nm
NO_2^-	Nitriver 3 (chromotropic acid)	507 nm
K^+	Tetraphenyl-borate	650 nm
SO_4^{2-}	Sulfaver 4	450 nm
Cl^-	Mercuric thiocyanate	455 nm
Mn^{2+}	Ascorbic acid cyanide alkaline solution PAN indicator	560 nm

of Bénégosso, Maffiblé 2, Kaotri, N'guessanblékro, Ellokro and Abouabou. It covers an area of about 16 km^2 with a population of more than 4000 inhabitants who form a part of the 419 033 inhabitants of Port-Bouët municipality [21]. The climate is that of Abidjan District which is equatorial in transition type, marked by four seasons: the long rainy season (April to July), the short dry season (August to September) the short rainy season (October to November) and the long dry season (December to March) [22].

The Abouabou area is located on quaternary rock, composed of clay sands from the low plateaux, mud and sand from fluvio-lagunar depressions and marine sand. The hydrogeological unit of the Abouabou zone is essentially contained in formations 3 and 4, consisting of fine to coarse, highly homogeneous sand [23].

2.2. Materials and methods

The study was carried out at 24 water supply points composed of 19 traditional wells and 5 boreholes (Table 1). The hydrogeologic log of the water supply points is shown by Figure 2.

A GARMIN e-trex 30 GPS system was used to record the geographical coordinates of these water supply points. Sampling expeditions to collect water samples associated with in-situ parameter measurements were carried out over a period from July 2018 to March 2019. Samples were taken in July, September and November 2018 and in March 2019. These months represent respectively the long rainy season (LRS), the short dry season (SDS), the short rainy season (SRS) and the long dry season (LDS). In situ measurements were taken by HACH Lange HQ40 multiparameter

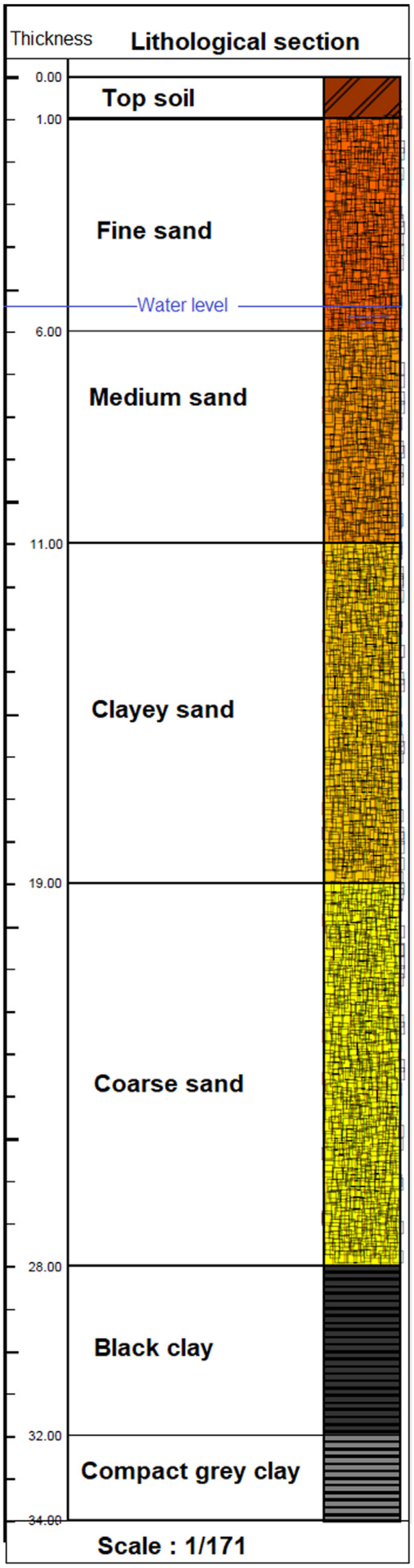

Figure 2. Hydrogeological section in the Abouabou area.

for pH, dissolved oxygen (DO), electrical conductivity, turbidity and temperature. A total of 24 water samples were collected each season in 1-litre polyethylene bottles and stored at 4°C in a cooler. Ca^{2+} and Mg^{2+} were analyzed by complexometry with an EDTA solution according to the NFT 90-003 standard. As for HCO_3^-, it was determined by titration with sulfiric acid reagent and with bromocresol as indicator. Other chemical parameters (Na^+, K^+, NO_2^-, NH_4^+, SO_4^{2-}, PO_4^{3-}, NO_3^-, Cl^-, HCO_3^-) were measured by using a Hach Lange DR 6000 Spectrophotometer (Table 2).

Data processing was initially performed by statistical descriptive analyses to assess the water quality of the Abouabou area. To evaluate the variability of well and borehole parameters, non-parametric tests (Kruskal-Wallis and Mann-Whitney) and parametric tests (ANOVA test) were conducted using software R version 3.6. These analyses were carried out using the "vegan" package.

The Kruskal-Wallis test was used to test the variability of the parameters at different seasons (LDS, SDS, LRS, SRS). The significance of the results is assessed based on the probability p-value. When p is greater than 0.05, there is no significant variation in the parameter under study. Otherwise ($p < 0.05$), a significant difference is inferred, and the analysis continues with the Mann-Whitney test to locate this difference.

The Bartlett test was used to evaluate the homogeneity of the variance of the parameters according to the normal distribution. At the end of this test ($p > 0.05$), the ANOVA test was performed to evaluate the variation of these parameters. The significance of the results is assessed based on the probability p value. When the p value is greater than 5%, there is no significant variation in the parameter studied. Otherwise, the Tukey HSD test, which is a multiple comparison test, was used to locate this difference.

The significant difference is translated by different letters a, b or c. When the same letter a, b or c is repeated on the boxplots, it means that there is no significant difference between the values of the observed parameters.

The choice of these tests is supported by the distribution of data previously evaluated using Kolmogorov-Smirnov normality tests (sample size >50) at the wells and Shapiro-Wilkinson (sample size <50) at the borehole.

Subsequently, the Piper diagram allowed to determine the hydrochemical facies. Finally, the Kohonen Self Organizing Maps (SOM) method was used to investigate the mechanisms of mineral acquisition based on the spatio-temporal distribution of the physico-chemical parameters of water in the area.

3. Results

3.1. *Quality of quaternary groundwater in the Abouabou area*

Table 3 shows that well water has an acidic character ($pH < 6.5$) during all seasons while borehole water has this acidic character during the long dry season, the short dry season and the short rainy season with average pH values of 6.1 ± 0.83, 6.1 ± 0.40 and 6.2 ± 0.70 respectively. Except for the pH, all other physico-chemical parameters analyzed respect the WHO guideline values for all seasons.

Figure 3 shows the seasonal minimum and maximum values of the physico-chemical parameters at the wells in the Abouabou zone. Thus, the statistical treatments based on the Kruskal-Wallis test show that for parameters such as EC, DO, NO_3^-, NO_2^-, NH_4^+, PO_4^{3-}, Ca^{2+}, Mg^{2+}, K^+, SO_4^{2-}, Na^+, HCO_3^-, with a probability $p > 0.05$, reflecting a non-significant difference in the values of these parameters between the different seasons. On the other hand, for the other parameters (turbidity, pH and temperature), there is a significant variation ($p < 0.05$) in the values of these parameters between the different seasons. Thus, for turbidity, the Kruskal-Wallis test shows that the LDS (b) has values that differ significantly from those of the LRS (a), SDS (a) and SRS (c) seasons. Therefore, the variation in turbidity is significant between SRS and the other seasons SDS and LRS. At the level of pH, the values obtained during LDS(b) and SDS(a) are statistically different. Therefore, the variation in temperature is significantly different between LDS (a) and SDS (b), and between

Table 3. Seasonal variation in the values of the physico-chemical parameters of groundwater in the Abouabou area.

Parameters	Units	WHO Guidelines (2011)	Dry seasons				Rainy seasons			
			LDS		SDS		SRS		LRS	
			Wells	boreholes	Wells	boreholes	Wells	boreholes	Wells	boreholes
			Avge±SD	*Avge±SD*	*Avge±SD*	*Avge±SD*	*Avge± SD*	*Avge± SD*	*Avge±SD*	*Avge± SD*
Temp	(°C)	<25	29.0 ± 0.40	30.0 ± 0.23	29.1 ± 0.50	30.2 ± 0.10	28.5 ± 0.50	29.3 ± 0.40	28.5 ± 0.50	30.2 ± 0.20
EC	µS/cm	<400	173.3 ± 92.20	61.6 ± 4.70	149.7 ± 81.40	58.2 ± 7.70	130.4 ± 70.00	52.7 ± 7.70	162.4 ± 82.80	52.8 ± 9.20
Turb	UNT	5	4.1 ± 2.50	3.5 ± 0.90	6.4 ± 3.80	1.7 ± 0.50	7.9 ± 2.80	1.8 ± 0.57	5.3 ± 2.80	2.3 ± 0.20
pH		6.50–8.50	5.8 ± 0.30	6.10 ± 0.83	6.3 ± 0.30	6.6 ± 0.24	6.1 ± 0.40	6.8 ± 0.24	6.2 ± 0.70	6.7 ± 0.20
DO	% of 1L of water		51.6 ± 5.30	95.3 ± 11.20	52 ± 9.20	94.1 ± 11.20	53.7 ± 60	98.8 ± 7.00	53.1 ± 5.90	89.9 ± 7.20
NO_3^-	mg/L	≤50	26.5 ± 1.70	2.6 ± 0.06	21.1 ± 8.60	10.8 ± 2.00	18.2 ± 10.30	8.4 ± 3.20	30.3 ± 17.00	3.2 ± 0.00
NO_2^-	mg/L	≤0.1	0.027 ± 0.02	0.023 ± 0.01	0.029 ± 0.01	0.02 ± 0.02	0.035 ± 0.01	0.022 ± 0.00	0.031 ± 0.01	0.024 ± 0.00
NH_4^+	mg/L	≤0.5	0.14 ± 0.00	0.16 ± 0.00	0.13 ± 0.10	0.12 ± 0.40	0.14 ± 0.00	0.16 ± 0.00	0.15 ± 0.00	0.17 ± 0.00
PO_4^{3-}	mg/L	≤1.08	0.17 ± 0.10	0.12 ± 0.10	0.44 ± 0.40	1.08 ± 0.80	0.26 ± 0.20	0.08 ± 0.00	0.17 ± 0.10	0.14 ± 0.10
Ca^{2+}	mg/L	≤100	32.3 ± 17.20	7.8 ± 1.70	29.7 ± 12.20	8.1 ± 2.30	26 ± 13.80	9.1 ± 2.40	29.4 ± 15.00	8.3 ± 2.70
Mg^{2+}	mg/L	≤50	6.8 ± 3.10	2.2 ± 0.60	3.5 ± 1.60	2.6 ± 0.47	3.0 ± 1.60	3.2 ± 0.29	3.4 ± 1.50	2.2 ± 0.60
K^+	mg/L	-	13.5 ± 8.10	2.8 ± 0.40	12.3 ± 7.00	1.5 ± 0.61	8.4 ± 4.60	2.1 ± 2.80	10.8 ± 7.30	2 ± 0.50
SO_4^{2-}	mg/L	≤250	11.8 ± 1.10	3.4 ± 1.60	6.4 ± 5.30	1.8 ± 0.64	7.9 ± 6.60	2.6 ± 0.36	7.6 ± 5.10	2.6 ± 1.90
Na^+	mg/L	≤150	20.3 ± 10.70	11.1 ± 3.20	18.8 ± 9.50	9.58 ± 1.90	17.18 ± 8.90	7.02 ± 1.40	18.6 ± 7.20	8.7 ± 1.20
Cl^-	mg/L	≤200	27.0 ± 11.40	7.5 ± 1.00	13.4 ± 9.80	2.7 ± 0.30	19.6 ± 9.80	2.8 ± 0.90	19.8 ± 8.80	5.7 ± 1.00
HCO_3^-	mg/L		23.7 ± 2.30	4.9 ± 1.10	19.5 ± 1.90	2.8 ± 0.40	8.8 ± 2.70	3.8 ± 1.10	18.8 ± 14.00	3.4 ± 0.70

***DO**: dissolved oxygen; **EC**: electrical conductivity; **Turb**: turbidity; **Temp**: temperature; Avge ± SD: average ± standard deviation; LRS: long rainy season; SDS: short dry season; SRS: short rainy season; LDS: long dry season.*

SDS(b) and SRS(a). Finally, the change in Cl^- is statistically different between LDS(a) and SDS(b), and between LDS(a) and SRS(b).

Figure 4 also shows the boxplots generated from the Kruskal-Wallis and ANOVA tests. These Boxplots make it possible to know the minimum and maximum values obtained at the level of the boreholes, during the seasons and to appreciate the significance of the variation of the values of the parameters between different seasons. Thus, according to these tests, the variations of the parameters with a probability $p >$

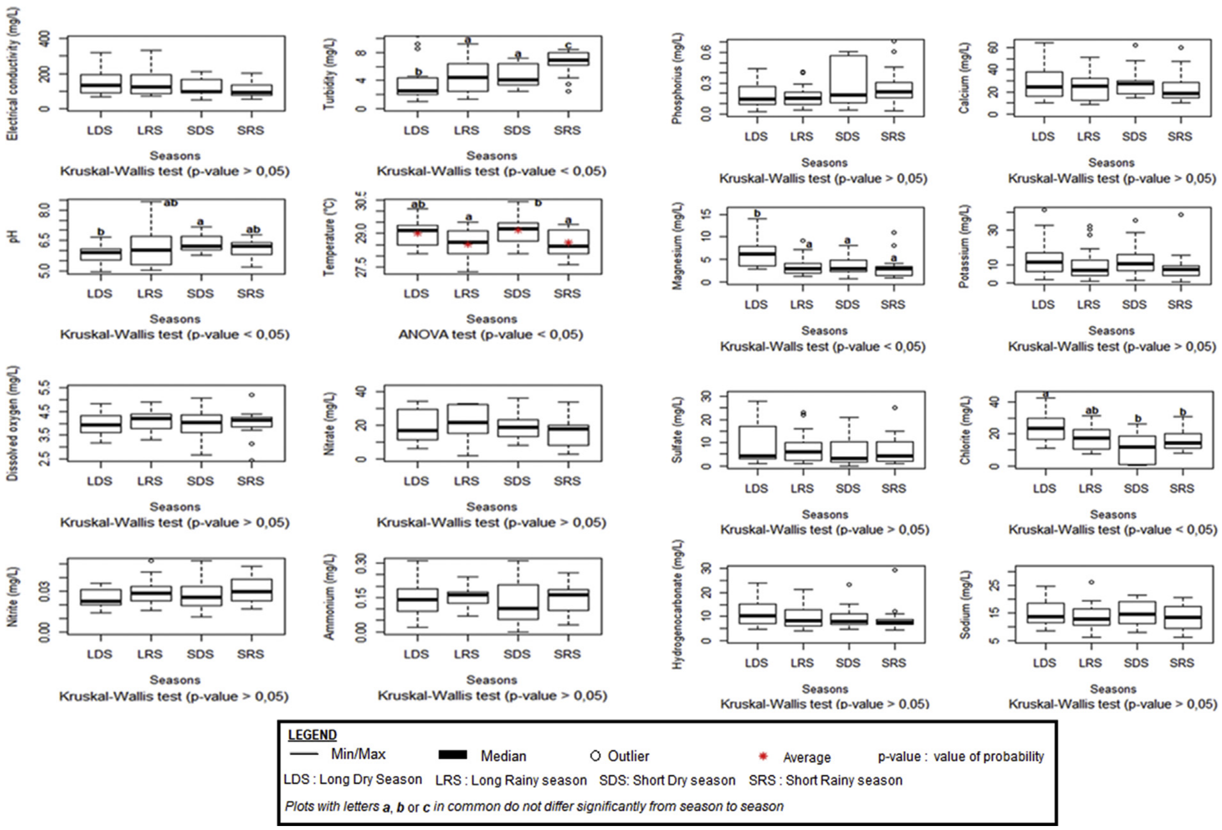

Figure 3. Seasonal variation in the physico-chemical parameters of wells in the Abouabou area.

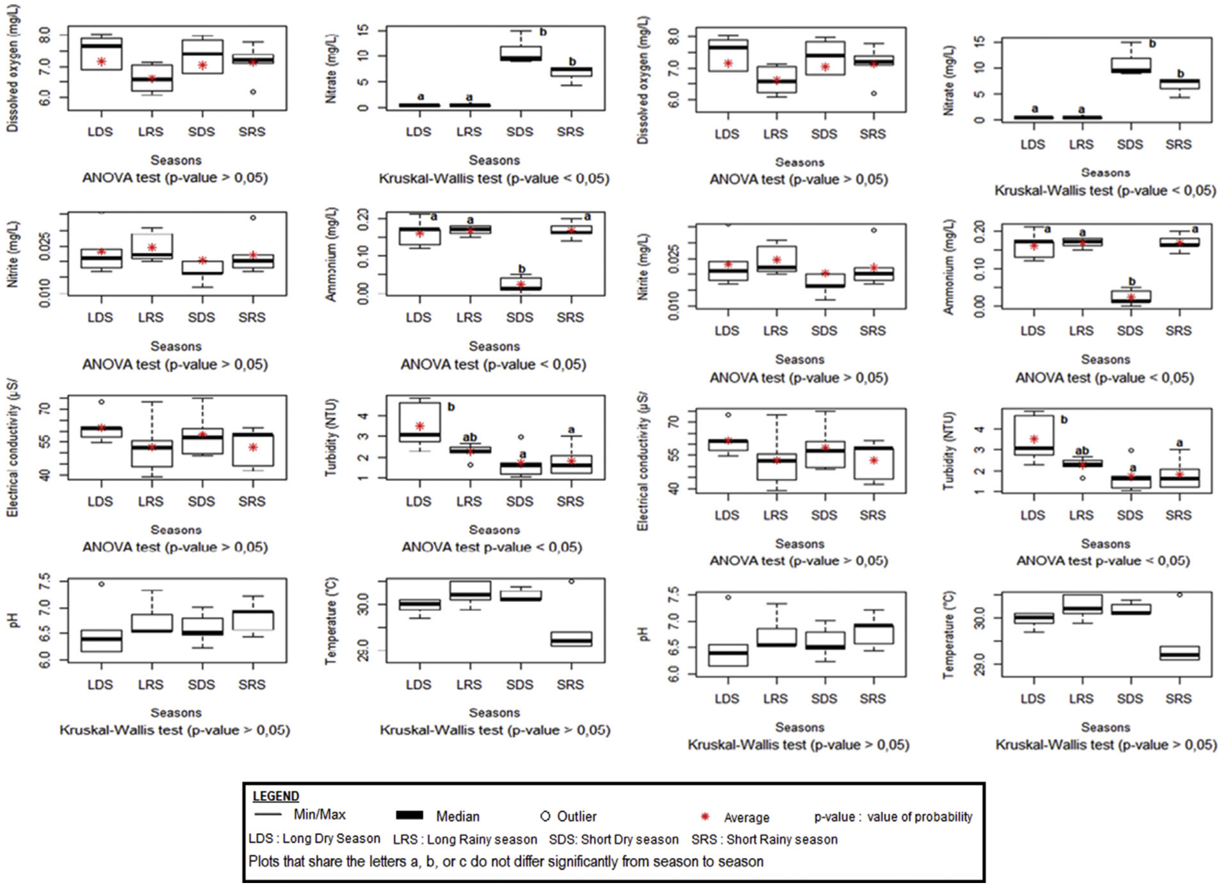

Figure 4. Seasonal variation in the physico-chemical parameters of borholes in the Abouabou area.

0.05, are insignificant between the different seasons for DO, NO_2^-, EC, pH, Temperature, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, Na^+. On the other hand, the probability *p* is less than 0.05 for the other parameters NO_3^-, NH_4^+, Turbidity, PO_4^{3-}, K^+, Cl^- according to the ANOVA and Kruskal Wallis tests. That indicates that there is a significant difference between the observed variations in the values of the measured parameters. Indeed, for nitrate (NO_3^-) this significant difference is observed between the long seasons (LDS, LRS) (a) and the short seasons (SDS, SRS) (b).

For NH_4^+ and phosphorus (PO_4^{3-}), the significant difference is observed between the short dry season (SDS) (b) and the other three seasons (LDS, LRS, SRS) (a). Also, Turbidity during the long dry season (LDS) between 2 and 5 NTU, is significantly different from the Turbidity value of the 2 other seasons (SDS, SRS) whose values are between 1 and 3 NTU.

For potassium K^+, concentrations vary significantly between the LDS, SDS and SRS seasons. Finally, for chlorides (Cl^-), the variations in concentrations are significant between SDS (b) and SRS (c), and between SDS (b), SRS (c) and the other seasons (LDS, LRS) (a).

3.2. Hydrochemical type of the quaternary groundwater in the Abouabou area

The Piper diagram shows the overall hydrochemical type of groundwater in the Abouabou area (Figure 5). The results show that the hydrochemical type of water varies with the seasons. Indeed, during the long rainy season, the boreholes generally have bicarbonate, calcium and magnesium type of water. Thereafter, this type of water changes during the short dry season (SDS) and the short rainy season (SRS) into a chlorinated, calcic and magnesian type. Finally, a bicarbonate, calcium and magnesium type is obtained during the long dry season (LDS) in all boreholes. As for wells, they also have a practically similar evolution of the hydrochemical type of water according to the seasons of the year.

3.3. Spatio-temporal distribution of quaternary groundwater quality in the Abouabou area

The hierarchical classification dendrogram of the cells of the Kohonen map, applied to all the water supply points (wells and boreholes) during the four seasons, highlights 4 groups of water supply points (Figure 6).

Also, Figure 7 shows the physico-chemical characteristics dominant in the waters of each group. Thus, Group I represents the waters of catchment structures. Group I represents water from water supply points characterized by acidic pH and high temperatures, high concentrations of PO_4^{3-}, K^+, O_2 and moderate concentrations of NO_2^-. The Group II water supply points are characterized by high turbidity and moderate electrical conductivity, high NO_3^- and Cl^- concentrations and moderate concentrations of NH_4^+ and K^+. Group III is composed of waters with high temperatures, slightly acidic pH, low chloride concentrations and high concentrations of NH_4^+ and O_2. Finally, group IV characterizes water supply points with slightly acidic waters, low concentrations of K^+, moderate concentrations of NO_2^-, NO_3^-, Cl^- and high concentrations of HCO_3^- and SO_4^{2-}.

Figure 8 illustrates the spatio-temporal distribution of water samples according to their physicochemical characteristics. Thus, out of a total of 96 water samples collected, 20 samples have been identified in group I and represent 20.83% of all data. Group II contains the largest number of samples (41) and represents 42.70% of all data. The mineralization of the waters in this group has been observed in 12 wells P1, P2, P3, P7, P10, P11, P14, P15, P16, P17, P18, P19. This mineralization is acquired over

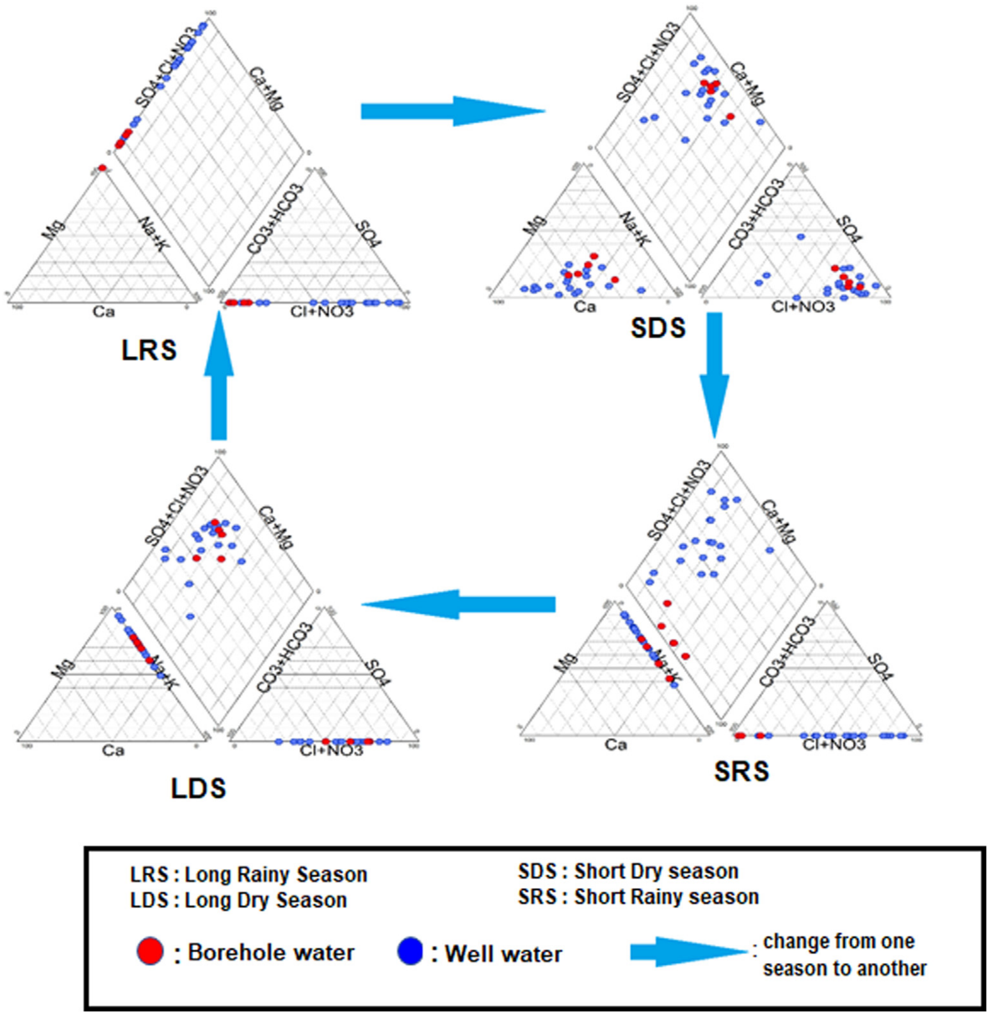

Figure 5. Hydrogeochemical type of Groundwater in the Abouabou area.

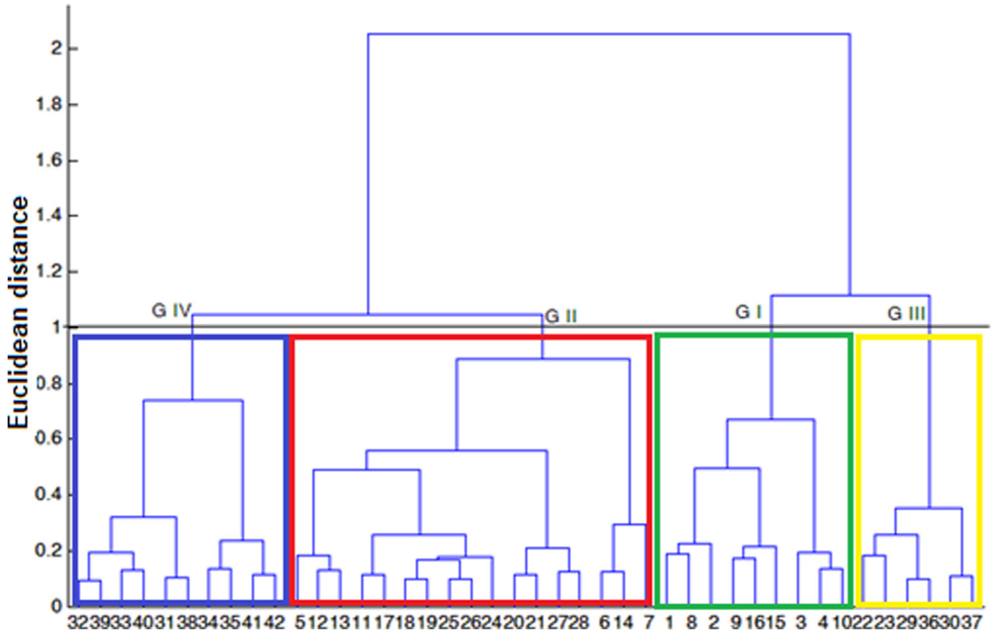

Figure 6. Dendrogram of a hierarchical classification of the cells of the Kohonen map based on the physicochemical parameters of the waters.

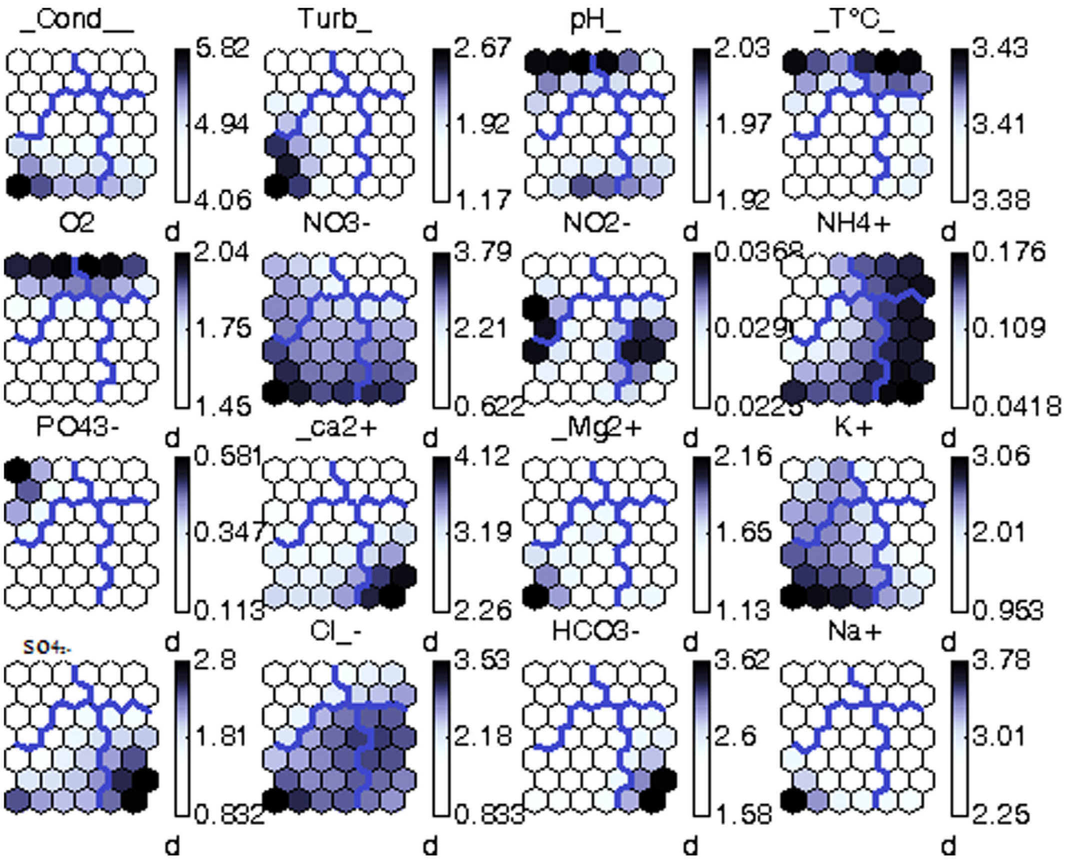

Figure 7. Gradients of the value of individual physicochemical parameters in the definition of groups on the Kohonen map.

all four seasons (A: Long rainy season; b: short dry season; a: Short rainy season; B: Long dry season) of the year. Group III represents 23.95% of all data with 23 samples. The mineralization of this group has been observed in all boreholes (F1 to F5) during the dry (B) and rainy (A) seasons and in the P11 and P13 wells during the short rainy season (a). Group IV is composed of 12 samples representing 12.50% of the water supply points. This group is essentially composed of data according to the seasons (A, B, a, b) of wells P1 (A), P4 (A, B), P5 (A, B), P8 (A, a, B, b). P9 (A, a, B, b), P10 (A, a), P11 (B), P12 (A, a, B, b) and P13 (A, B, b).

4. Discussion

The results of the physico-chemical analysis show that for the parameters measured, borehole water in the Abouabou region complies with WHO recommendations. This water is therefore of high enough quality for human consumption except for the acidity of the water recorded in these boreholes. This acidity is more pronounced during the dry season. These results confirm those of the work conducted on the quaternary groundwater in the southern zone of Abidjan District [24].

At the well level, there is a significant difference in the values of parameters such as pH, turbidity and chlorides (Cl^-) over the seasons. Indeed, during the long rainy season (LRS), the water in wells that are shallow (<10m) is recharged by infiltration water. These infiltration waters, which are generally rich in organic matter of anthropogenic origin, increase the turbidity of the well water.

During the decomposition of this organic matter, carbonic acid is produced which increases the acidity of the well water. This acidity is more pronounced during the major dry seasons (LDS and SDS). Also, for Cl^- ions, the significant variations observed between LDS and the other two seasons (SDS and SRS) can be explained by the intrusion of nearby lagoon water into the quaternary surface water table captured by the wells. This intrusion of lagoon water is more pronounced during the LDS and less pronounced during the SRS and SDS.

For borehole water, the Kruskral-Wallis test and the ANOVA show that significant seasonal variations in the values of the parameters Turbidity, PO_4^{3-}, NH_4^+, NO_3^-, K^+ and Cl^-, can be linked to deep water recharge from the infiltration of rainwater rich in organic matter of surface origin or to the hydrolysis of minerals in the aquifer (K^+, Cl^-). Denitrification may also occur when water reaches the water table, leading to a reduction in nitrate concentrations through dilution or a reduction in nitrates from the consumption of dissolved oxygen. This result agrees with those of [25], who worked on the evolution of nitrates in a system of superimposed aquifers.

The borehole waters of the Abouabou area show a magnesian calcium bicarbonate facies during the long rainy season. This facies evolves towards a chlorinated, calcic and magnesian facies during the short dry season and the short rainy season. The chlorinated nature of the waters during this season could be linked either to the enrichment of the waters by infiltration of water from the main rainy season, which would contain high concentrations of chlorides, or by lateral contamination of the quaternary waters by lagoon water located around the Abouabou area. The same mechanism which occurs during the short dry season would also be maintained during the short rainy season. However, during the long dry season, the evolution of the chemistry of bicarbonate calcium and magnesium in boreholes can be attributed to the presence of thick clay layers that play a fixing role through the adsorption or absorption of elements such as potassium or calcium. Indeed, during the long dry and rainy seasons when the aquifers are not supplied with water, mineralization should essentially come from the host that releases the Ca^{2+} and Mg^{2+} ions into the water, and from the organic matter contained in the aquifer following this almost permanent infiltration of humic acid. The Ca^{2+} and Mg^{2+} ions would then originate from feldspar pebbles

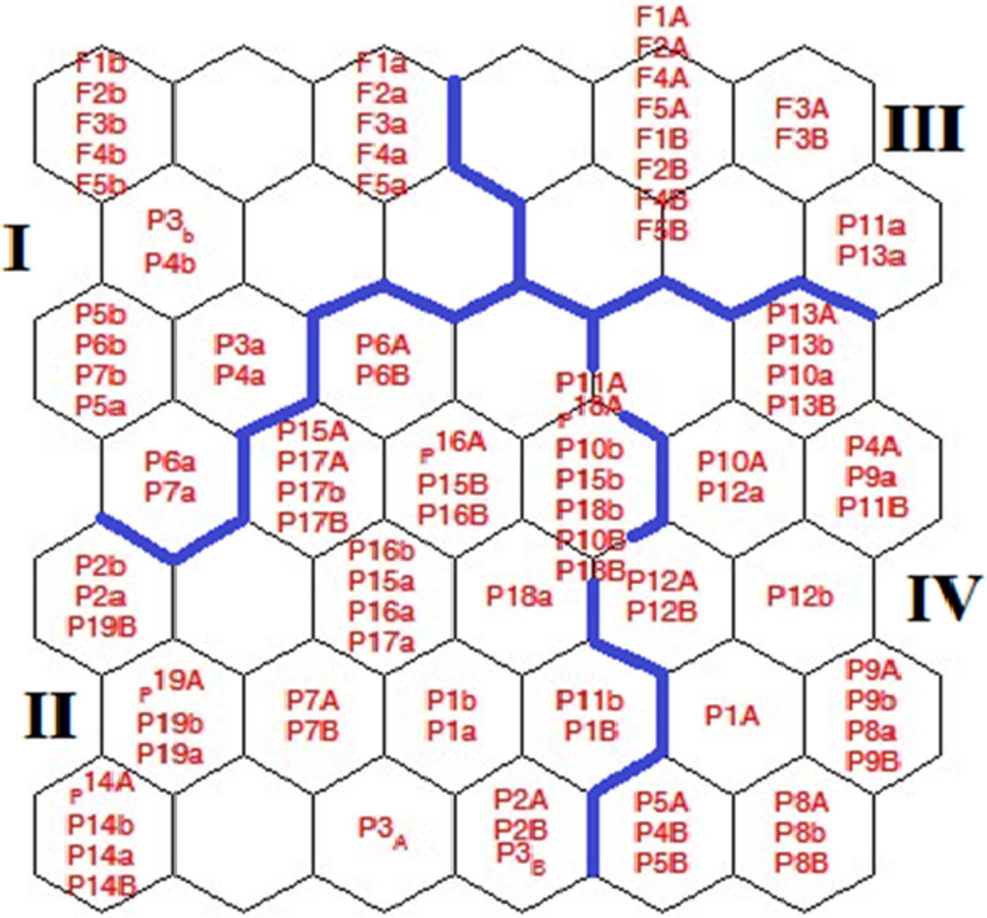

Figure 8. Spatio-temporal distribution of samples according to their physicochemical characteristics.

interspersed in the aquifers as shown by [26] and [27]. Many authors who have studied hydrochemistry in West Africa have concluded that bicarbonate facies is most abundant in groundwater [28, 29, 30]. Elsewhere, these phenomena are also observed in the coastal groundwater of the Trarza aquifer in Mauritania [31].

The self-organizing maps of Kohonen, provide an understanding of the mechanism of mineral acquisition by wells and boreholes in the Abouabou area. Indeed, during the short dry and rainy seasons, the surface elements of origin (PO_4^{3-}, K^+, NO_2^-) are drained by infiltration into the wells (P3, P4, P5, P6, P7) and all of the 5 boreholes. However, during the long dry and rainy seasons, NH_4^+ is present in wells P11 and P13 and all the boreholes. The presence of ammonia is attributed to the practice of cattle and poultry production in the Abouabou area, with the permanent presence of manure and excreta on the ground, drained by infiltration water into boreholes and wells. For the rest of the wells represented by Groups II and IV, mineralization seems to be acquired during all seasons of the year either by infiltration of rainwater or by contamination of the structures by nearby lagoon waters.

5. Conclusion

This study provides information on the chemical characteristics of groundwater in the Abouabou area. Physico-chemical analyses show that the water is acidic, both in the rainy and dry seasons. Overall, these waters are generally fresh with low mineralization and moderate electrical conductivity. The hydrochemical facies of the waters of the Abouabou boreholes from the Piper Diagram show an evolution of the facies of the waters of calcium-magnesium bicarbonate type during the LDS and LRS to a calcium-magnesium chloride-type facies in SDS and SRS. The chemical quality parameters measured in the Abouabou area are below the WHO drinking water guidelines. The SOM methods of neural networks have shown that all samples are subdivided into four water groups. They are represented by homogeneous groups (II and IV) composed only of well water with high electrical conductivity and heterogeneous groups (I and III) composed mainly of drilled water with low electrical conductivity.

Declarations

Author contribution statement

H. K. Konan: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

I. K. Kouame: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

A. Dao: Analyzed and interpreted the statistical data; Wrote the paper. D. Noufé, J. T. K. Koffi, B. Kamagate: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] A.M. MacDonald, H.C. Bonsor, B.E.O. O'Dochartaigh, R.G. Taylor, Quantitative maps of groundwater resources in Africa, Environ. Res. Lett. 7 (2012) pp1–7.

[2] D.J. Lapworth, A.M. MacDonald, M.N. Tijani, W.G. Darling, D.C. Gooddy, H.C. Bonsor, L.J. Araguás-Araguás, Residence times of shallow groundwater in West Africa: implications for hydrogeology and resilience to future changes in climate, Hydrogeol. J. 21 (3) (2013) 673–686.

[3] S.M.A. Adelana, T.A. Abiye, D.C.W. Nkhuwa, C. Tindemugaya, M.S. Oga, Urban groundwater management and protection in Sub-Saharan Africa, in: S.M.A. Adelana, A.M. MacDonald (Eds.), Applied Groundwater Studies in Africa, CRC, Boca Raton, FL, 2008, pp. 231–260.

[4] S.S.D. Foster, B.L. Morris, A.R. Lawrence, P.J. Chilton, Groundwater impacts and issues in developing cities: an introductory review, in: P.J. Chilton (Ed.), Groundwater in the Urban Environment: Selected City Profiles, Balkema, Dordrecht, The Netherlands, 1999.

[5] D. Chakraborti, M.M. Rahman, S. Ahamed, R.N. Dutta, S. Pati, S.C. Mukherjee, Arsenic contamination of groundwater and its induced health effects in Shahpur block, Bhojpur district, Bihar state, India: risk evaluation, Environ. Sci. Pollut. Res. 23 (10) (2016) 9492–9504.

[6] S. Indelicato, S. Orecchio, G. Avellone, S. Bellomo, L. Ceraulo, R. Di Leonardo, V. Di Stefano, R. Favara, E.G. Candela, L. La Pica, S. Morici, G. Pecoraino, A. Pisciotta, C. Scaletta, F. Vita, S. Vizzini, D. Bongiorno, Effect of solid waste landfill organic pollutants on groundwater in three areas of Sicily (Italy) characterized by different vulnerability, Environ. Sci. Pollut. Res. 20 (2017) 1–14.

[7] A.O. Majolagbe, A.A. Adeyi, O. Osibanjo, Vulnerability assessment of groundwater pollution in the vicinity of an active dumpsite (Olusosun), Lagos, Nigeria, Chem. Int. 2 (2016) 232–241.

[8] O.B. Yapo, V. Mambo, A. Seka, M.J.A. Ohou, F. Konan, V. Gouzile, A.S. Tidou, K.V. Kouame, P. Houenou, Evaluation de la qualité des eaux de puits à usage domestique dans les quartiers défavorisés de quatre communes d'Abidjan (Côte d'Ivoire) : Koumassi, Marcory, Port-Bouet et Treichville, Int. J. Biol. Chem. Sci. 4 (2) (2010) 289–307.

[9] I.K. Kouame, A.G. Douagui, K. Koffi, B. Dibi, L.K. Kouassi, I. Savane, Modeling of quaternary groundwater pollution risk by GIS and multicriteria analysis in the southern part of Abidjan district (Côte d'Ivoire), J. Environ. Protect. 4 (2013) 1213–1223.

[10] A.G. Douagui, I.K. Kouame, K. Koffi, A.T.B. Goula, B. Dibi, D.L. Gone, K. Coulibaly, A.M. Seka, A.K. Kouassi, J.M. Oi Mangoua, I. Savane, Assessment of the bacteriological quality and nitrate pollution risk of Quaternary groundwater in the southern part of Abidjan District (Côte d'Ivoire), J. Hydro Environ. Res. (2012) 227–238.

[11] I.C. Nnorom, U. Ewuzie, S.O. Eze, Multivariate statistical approach and water quality assessment of natural springs and other drinking water sources in Southeastern Nigeria, Heliyon 5 (2019), e011123.

[12] B. Shaharoona, S. Al-Ismaily, A. Al-Mayahi, N. Al-Harrasi, R. Al-Kindi, A. Al-Sulaimi, H. Al-Busaidi, M. Al-Abri, The role of urbanization in soil and groundwater contamination by heavy metals and pathogenic bacteria: a case study from Oman, Heliyon 5 (2019), e01771.

[13] N. Nouayti, D. Khattach, M. Hilali, Assessment of physico-chemical quality of groundwater of the Jurassic aquifers in high basin of Ziz (Central High Atlas, Morocco), J. Mater. Environ. Sci. 6 (4) (2015) 1068–1081.

[14] C. Defo, B.P.K. Yerima, I.M.K. Noumsi, N. Bemmo, Assessment of heavy metals in soils and groundwater in an urban watershed of Yaoundé (Cameroon-West Africa), Environ. Monit. Assess. 187 (77) (2015) 1–17.

[15] A.O. Fayiga, M.O. Ipinmoroti, T. Chirenje, Environmental pollution in Africa, Environ. Dev. Sustain. 20 (2018) 41–73.

[16] D.J. Lapworth, D.C.W. Nkhuwa, J. Okotto-Okotto, S. Pedley, M.E. Stuart, M.N. Tijani, J. Wright, Urban groundwater quality in sub-Saharan Africa: current status and implications for water security and public health, Hydrogeol. J. 25 (2017) 1093–1116.

[17] K. Masindi, T. Abiye, Assessment of natural and anthropogenic influences on regional groundwater chemistry in a highly industrialized and urbanized region: a case study of the Vaal River Basin, South Africa, Environ. Earth Sci. 77 (722) (2018) 1–14.

[18] G.E. Takem, D. Chandrasekharam, S.N. Ayonghe, P. Thambidurai, Pollution characteristics of alluvial groundwater from springs and bore wells in semi-urban informal settlements of Douala, Cameroon, Western Africa, Environ. Earth Sci. 61 (2010) 287–298.

[19] J.F. Lindgren, K. Salo, S. Brynolf, K. Andersson, E. Svensson, M. Zetterdahl, L. Granhag, M. Magnusson, The natural environment and human impacts, in: K. Anderson, S. Brynolf, J.F. Lindgren, M. Wilewska-Bien (Eds.), Shipping and the Environment, Springer, Berlin, 2016, pp. 29–74.

[20] D.G. Ahoulé, Hydrochemical characterization of the aquifer of the city of Abidjan: case of the communes of Abobo, Attécoubé, Koumassi and Yopougon, J. Soc. Ouest-Afr. Chim. 44 (2017) 51–57.

[21] K.E. Ahoussi, Spatial-temporal evolution of nitrate content of groundwater in the city of Abidjan (Côte d'Ivoire), Int. J. Pure App. Biosci. 1 (3) (2013) 45–60.

[22] N. Aghui, J. Biemi, Geology and Hydrogeology of Groundwater the Region of Abidjan and Risks of Contamination, 20, Annal National University of Côte d'Ivoire Series C (Sciences), 1984, pp. 314–347.

[23] General Census of Population and Housing (RGPH), Report of the Permanent Technical Secretariat Overall Results by Sub-prefecture (Côte d'Ivoire), 2014, p. 22p.

[24] K.I. Kouamé, Physico-chemical Pollution of the Waters in the Akouédo Landfill Area and Analysis of the Risk of Contamination of the Abidjan Aquifer by a Simulation Model of the Flows and Transport of Pollutants, PhD Thesis, University of Abobo-Adjamé, 2007, p. 206.

[25] B.F.E. Loroux, Contribution to the Hydrogeological Study of the Sedimentary basin of Côte d'Ivoire, Postgraduate Thesis, University of Bordeaux I, 1978, p. 93.

[26] G.A. Douagui, Risks of Pollution of the Quaternary Aquifer of the Southern Zone of the Abidjan District: Case of the Vridi- Grand-Bassam Canal Sector (Côte d'Ivoire), Postgraduate Thesis, Nangui Abobo University, 2013, p. 150p.

[27] N. Kherici, D. Messadi, H. Kherici, Evolution of nitrates in a system of superimposed aquifers (Annaba-Algeria), in: Géologie Méditerranéenne, 18, 1991, pp. 199–206.

[28] M.S. Oga, C. Marlin, L. Dever, Refill of the continental terminal and quaternary aquifers in the greater Abidjan region (Côte d'Ivoire), in: International Conference Abidjan 98 on the Variability of Water Resources in Africa in the 20th Century, Collection of Posters, 1998, pp. 127–130.

[29] T. Lasm, O.D. Lasm, M.S.Y. Oga, M. Youanta, D. Baka, F. Kouame, T.K. Yao, Hydrochemical characterization of cracked aquifers of the San Pedro region (South-West of Côte d'Ivoire), Int. J. Biol. Chem. Sci. 5 (2) (2011) 642–662.

[30] I. Sandao, Doctoral Thesis, in: Hydrodynamic, Hydrochemical and Isotopic Studies of Groundwater in the Korama/South Zinder Watershed, Niger: Impacts of Climate Variability and Anthropogenic Activities, Abdou Moumouni University of Niamey, Niger, 2011, p. 211p.

[31] M. Bakary, A. Christian, C. Raoul, P. Jean, Hydrochemical facies and mineralization of coastal groundwater from the TRARZA aquifer (Mauritania), Soc. Ouest-Afr. Chim (1998) 105–130, 005 et 006.