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Study of Groundwater-river Interactions Using Hydrochemical Tracers in Fissured Rock: Case of the Lobo Watershed at Nibéhibé (Central-West, Côte d'Ivoire)

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Authors' contributions

This work was carried out in collaboration among all authors. Author GSO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors BD and ABKW managed the analyses of the study. Authors JMOM and BK managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Water is a vital resource for all populations. However, there are warning signs that the water from the Lobo River used by SODECI to supply drinking water to the population is declining in quantity during the dry season and its quality is becoming poor due to climate variability and anthropogenic activities. However, the river is able to maintain a certain flow, probably with the contribution of groundwater. It is therefore a question of whether there is really a connection between surface water and groundwater. The aim of this study is to characterize the groundwater-river interactions based on the physico-chemical parameters of the Lobo watershed in Nibéhibé. The approach adopted is a coupled statistical-geochemical approach applied on data from two sampling

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campaigns (dry and rainy season). This coupled approach consisted, on the one hand, in understanding the chemical specificities within the water classes using the piper diagram and, on the other hand, in classifying the waters according to their physico-chemical similarity and highlighting the phenomena at the origin of the water mineralization using the Kohonen self-organized map (SOM). The results obtained from the piper diagram show that in both the wet and dry seasons, the chemical signature of the waters remains controlled by two main hydrochemical facies: the chlorinated calcium-magnesium nitrate hydrofacies and the bicarbonate calcium-magnesium hydrofacies. Kohonen's self-organized map has established that the mineralization of groundwater, under natural conditions, comes from the nature of the rocks crossed during infiltration and from the contact time between water and minerals. This work provides managers with decision-support tools for planning and searching for groundwater in support of surface water to reinforce the drinking water supply of the populations in this watershed.

Keywords: Groundwater; river; interactions; physico-chemical parameters; fissured rock; lobo watershed.

1. INTRODUCTION

In recent decades, countries around the world have faced several challenges in relation to the availability and use of water resources. This is due to climatic variations, anthropogenic pressures, poorly controlled urbanization and high population growth. The town of Daloa located in the catchment area of the Lobo river (Central-Western Ivory Coast) like some towns in the Ivory Coast is not on the fringe of the above-mentioned problems. Currently, the Lobo River is exclusively exploited by SODECI (Water Distribution Company in Côte d'Ivoire) to supply the population of Daloa with drinking water. However, in recent years, there have been warning signs that this resource is decreasing in volume, especially during the dry season, and its quality is becoming increasingly poor due to climate variability and anthropogenic activities pushing populations to seek water from wells and boreholes. In spite of all these hazards, this river and its main tributary the Dé can maintain a certain flow with probably the contribution of groundwater. Conversely, the recharge of groundwater by these rivers could encourage decision-makers to move towards groundwater use. Indeed, some authors have shown that groundwater and surface water are two interconnected components of the same resource [1-2] and that impacts on one of these two components affectent inevitably affect the other, whether qualitatively or quantitatively [3]. It is therefore important to study the relationships between these two hydrosystems (Lobo River and its underlying aquifers) in a context of climate change. In the area, no studies have been conducted on the Lobo River watershed to characterize and better understand the hydrodynamic functioning of the aquifer system and its interaction with the watershed. Studies conducted on the Lobo River basin by [4] and [5] have focused on the assessment and availability of groundwater resources. It is within this framework that this study, which aims at studying the groundwater-river interactions at the scale of the Lobo River watershed in Nibéhibé, is part of. The study consists in a characterization of water exchanges between the rivers and the underlying basement aquifers based on physico-chemical parameters.

2. MATERIALS AND METHODS

2.1 Study Area

The watershed of the Lobo River at Nibéhibé (Fig. 1) is located in the central-western part of Côte d'Ivoire between 6°15' and 6°55' West longitude and between 6°45' and 7°55' North latitude with an area of about 7000 square kilometers. It takes its source at an altitude of 400 meters south of Séguéla [5]. The basin belongs to the sub-equatorial climate characterized by four seasons: two dry seasons (December-March and July-September) and two rainy seasons (April-July more important and September-November very irregular). The average annual rainfall recorded over the period 1990-2015 is 1,238.2 mm. The trend in average monthly temperatures varies globally between 24°C and 28°C, i.e. a thermal amplitude of 4°C.

The geological formations of the basin are dominated by three geological entities, namely granite which occupies almost the entire basin, shale and flysch which are found in some places [6]. These geological formations make it possible to distinguish between two types of aquifers: alteration and fissure aquifers.

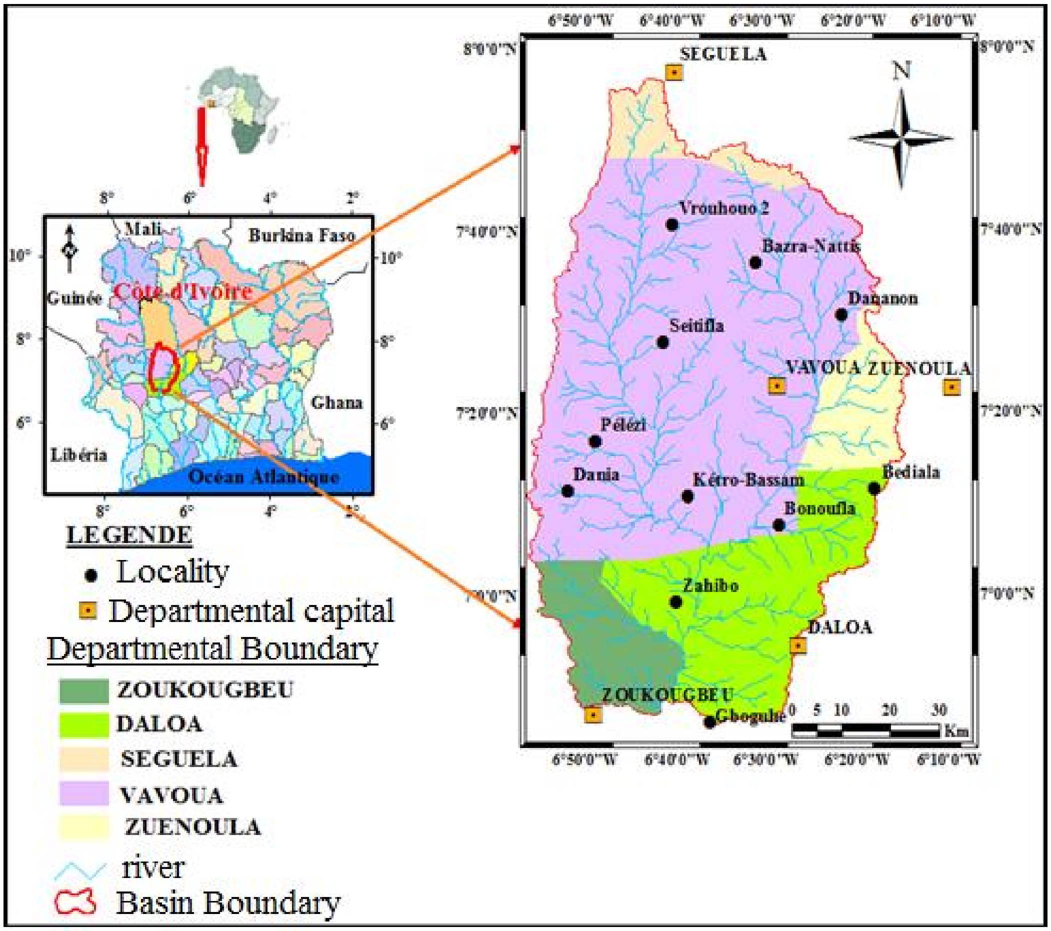

Fig. 1. Geographical location of the Lobo watershed at Nibéhibé

2.2 Data

To carry out this study, two sampling missions were carried out respectively during the rainy season (September 2018) and the dry season (February 2019). During each season, the water samples were collected in one (1) liter polyethylene bottles, stored in coolers containing carboglaces and analyzed less than 24 hours after the sampling campaign, at 44 stations well distributed in space so as to cover the entire watershed from Lobo to Nibéhibé (Fig. 2). In sum, the database obtained consists of 88 samples. These samples were subjected to physico-chemical measurements in situ (T, pH, EC, DO, TS) using a portable multiparameter HACH LANGE HQ40D and in the laboratory (Mg^{2+}, Ca^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-} NO_3^{-} et SO_4^{2-}, NO_2^{-}, PO_43^{-}, NH_4^{+}, Mn^{2+}, Zn^{2+} et Fe^{2+}) by spectrometry using a HACH DR 6000 spectrophotometer.

2.3 Determination of the Hydrochemical Facies of Basin Waters

The ternary diagram of water geochemical evaluation introduced by [7] was used for the identification and representation of the major hydrogeochemical facies that determine the predominance of primary ions. The realization of the diagram was made possible by version 3.6.1 of the R Studio software developed by [8]. It makes it possible to represent several water samples simultaneously and to characterize the geochemical facies of the waters. The Piper diagram is particularly adapted to the study of the evolution of water facies as mineralization increases. It is also used to compare groups of samples and indicate the dominant cation and anion types in order to find the geological origin of the reservoir.

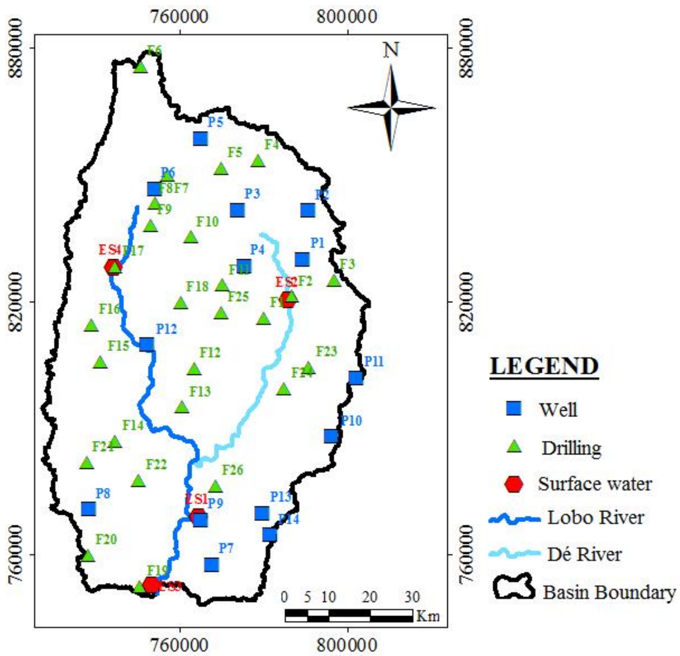

Fig. 2. Sampling network of water points on the Lobo watershed at Nibéhibé

2.4 Approach to Statistical Data Analysis

The physico-chemical data for groundwater (wells and boreholes) and surface water (Lobo River and Dé River) were subjected to a multivariate analysis method. The method adopted is that of physico-chemical differentiation between the different types of water by the application of SOM (Self-Organising Maps). It allows to determine the origins and the main mechanisms of water mineralization through the correlations between the variables. It also allows to characterize each type of water and to compare the composition of these different types of water between them in order to highlight similarities and dissimilarities.

The aim of the artificial neural networks (ANN) used in this work is to highlight the phenomena at the origin of water mineralization. For this purpose, 19 physico-chemical parameters (T, pH, CE, OD, TS, Mg^{2+}, Ca^{2+}, Na^+, K^+, HCO_3^-, Cl^-, NO_3^- et SO_4^{2-}, NO_2^-, PO_4^{3-}, NH_4^+ Zn^{2+}, Fe^{2+} et Mn^{2+}) were measured in well water (alteration layers), the borehole waters (basement aquifers) and surface waters (rivers) constitute the input parameters of the model whose "weights" in the different samples were estimated at the output on the Kohonen map.

Defining the architecture of an A.N.N. means making a judicious choice of the input vector, the size of the network (or total number of layers and neurons), the structure of the network, i.e. the type of interconnection between the neuron layers and the transfer functions, without having a standard procedure. Learning is done with different map sizes and the optimal size is chosen by minimizing the so-called quantization (QE) and topography (TE) errors [9-10].

The training matches the input space to the map and aims to adapt the W-weights in such a way that close examples in the input space are associated with the same neuron or with close neurons in the map. The different steps of the algorithm are: the virtual objects are initialized by randomly chosen objects from the data set; a real object is randomly chosen and present at the input layer; the distance between this object and each virtual object is calculated; the closest virtual object is called "Best Matching Unit (BMU)"; and all neurons in the vicinity of the BMU are modified (ordering and fitting). The neurons obtained from the map are grouped using an ascending hierarchical classification procedure whose principle of grouping is based on Ward's criterion. It consists in grouping together samples with similar behaviour on a set of variables in order to give a more global view of the map.

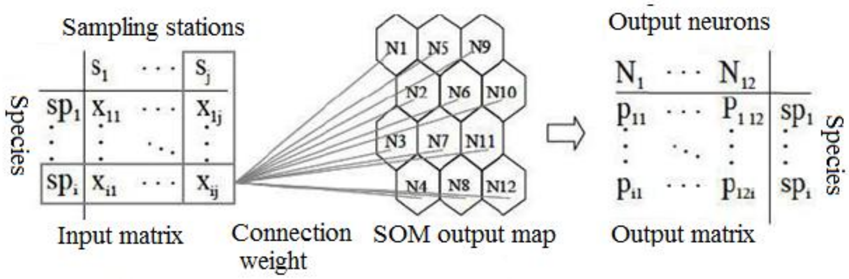

Fig. 3. Simplified representation of the self-organizing map [11]

3. RESULTS

3.1 Hydrofacies of Groundwater and Surface Water Studied

In the wet season, the chemical signature of the waters remains controlled by two main hydrochemical facies: the chlorinated nitrated calco-magnesian hydro-facies and the bicarbonate-calco-magnesian hydro-facies. A few samples, however, are characterized by hydrochloride sodium-potassium hydroxide facies (Fig. 4a). In the dry season, the two main hydro-facies of the high-water period are maintained (calco-magnesian bicarbonate and calco-magnesian chloride nitrate) but the third (the sodi-potassium chloride hydro-facies) hydro-facies does not appear more (Fig. 4b).

3.2 Results of Multivariate Statistical Analysis of Physicochemical Parameters of the Groundwater Studied

3.2.1 Choice of output matrices: Dimension of Kohonen's map

The first result obtained is the graphic representation of the learning phase. This graph shows the evolution of the average distance to the nearest node in the map. In our case, after several iterations of the RLEN values, we observe a strong decrease in the curve leading to a plateau in the final part with values of RLEN = 400 for the high-water period and RLEN = 200 for the high-water period. low water. At the end of the learning phase, the dimensions of the

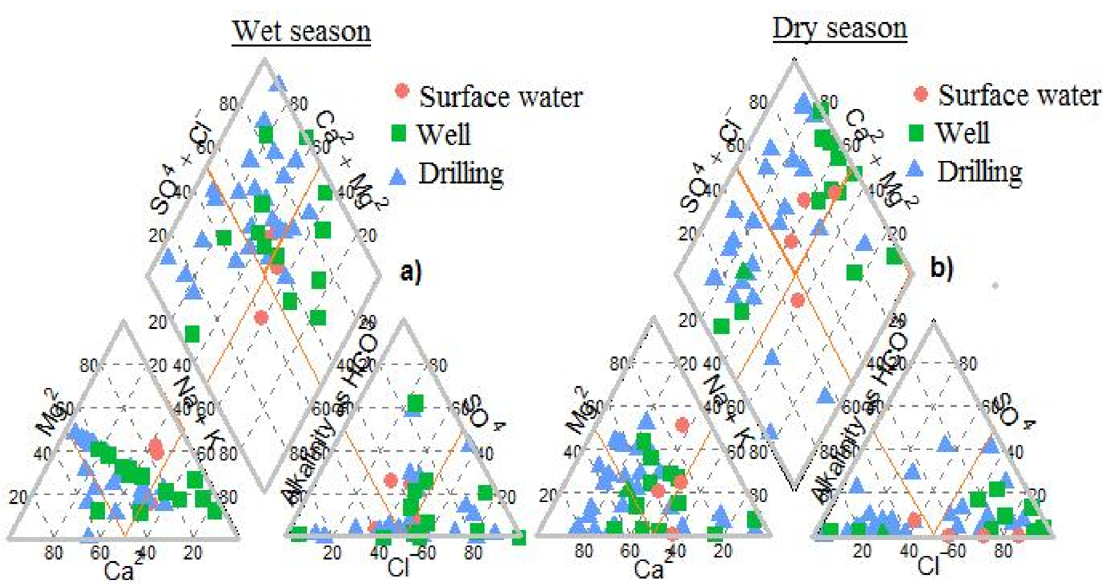

Fig. 4. Piper ternary diagram of the different types of water in the wet season (a) and in the dry season (b)

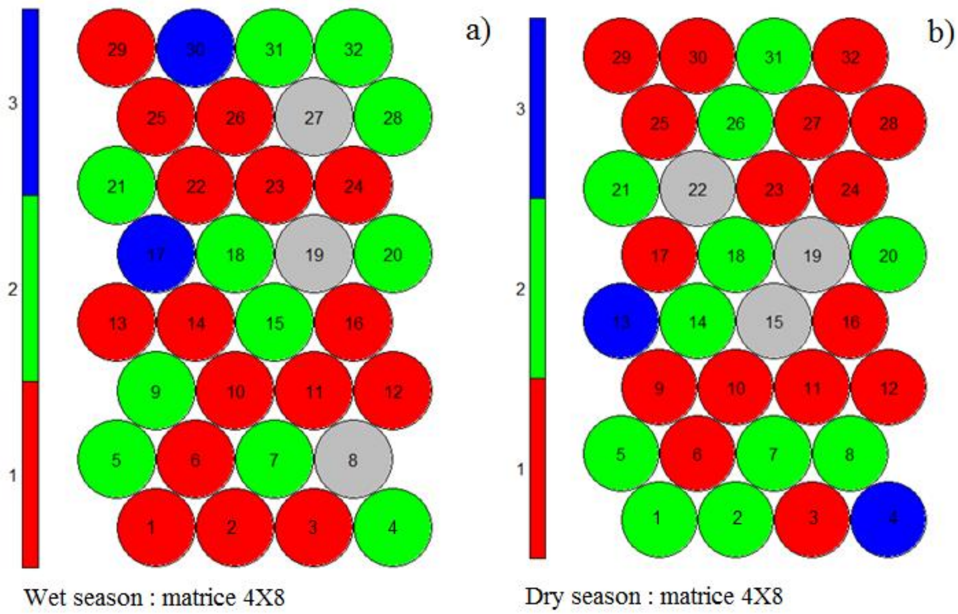

Fig. 5. Kohonen self-organizing maps generated from the chosen matrices

matrices retained on the basis of the RLEN values are 4x8 hexagonal grids or 32 knots for the two seasons (Fig. 5). The numbers in the nodes indicate a good distribution of the samples at the level of the different maps. On each of the maps, we observe 3 three empty nodes out of 32 nodes. So we have 29 nodes that contain at least one sample hence an ideal distribution of samples.

3.2.2 Hierarchical classification dendrograms

The ascending hierarchical classification (CAH) made it possible to group all the groundwater and surface water of the wet season into 4 chemically distinct classes (CI; C.II; C.III and C.IV) with a cut-off level of the shaft at 12 (Fig. 6a). Beyond a Euclidean distance of 12 or 15, the samples of classes C.I and C.II come together to form a single class. Also, the samples of classes C.III and C.IV also come together to form a single class.

As for the dry season, a more distinctive classification appears when the Euclidean distance is 12 (Fig. 6b). For this distance, the samples are grouped into 3 classes (C'.I; C'.II and C'.III). On the other hand, with a tree cut-off level of 15, we obtain 2 groups just like the classification obtained in the wet season. Thus, the samples of classes C'.II and C'.III would form the same class and would be different from class C'.I and C'I.

3.2.3 Distribution of samples on the Kohonen map

During the wet season, the samples constituting the different classes generated from the dendrogram at a Euclidean distance of 12 are distributed on the Kohonen map (Fig. 7a). All classes appear heterogeneous to varying degrees: Class C.I (F5, P3, F6, F2, F17), except for the presence of a well sample (P3), remains mainly composed of water from the basement water table with nearly 80% representativity. Class C.II (P5, P12, P15, F13, P9, P4, P10, F14), except for the presence of two drilling samples (F13, F14), remains mainly composed of alteration water. Class C.III (F1, F19, P2, P8, F20, F22, P13, P7, P11, F23, F24, F25, ES3, F26, F10), except for the presence of one surface water sample (ES3), is distinguished by the grouping of groundwater (alteration and basement water table) with a slight predominance of basement water. Class C.IV (F21, F11, ES2, ES1, F3, ES4, P1, F12, F15, F9, F18, F16, P6, F7, F4, F8) appears particularly heterogeneous because it is characterized by the grouping of surface water (rivers), alteration layers and basement layers (wells and boreholes) in almost identical proportions.

During the dry season, the classes remain more or less heterogeneous (Fig. 7b). Class C'I, which was characteristic of basement aquifers in the wet season, becomes characteristic of alteration aquifers, basement aquifers and surface waters, the proportions of which vary from one group to another. Class C'II is mixed and is the smallest like class C.I in the wet season with two well samples and one surface water sample. Class C'III contains more than half of the basement groundwater with almost 45% of the samples.

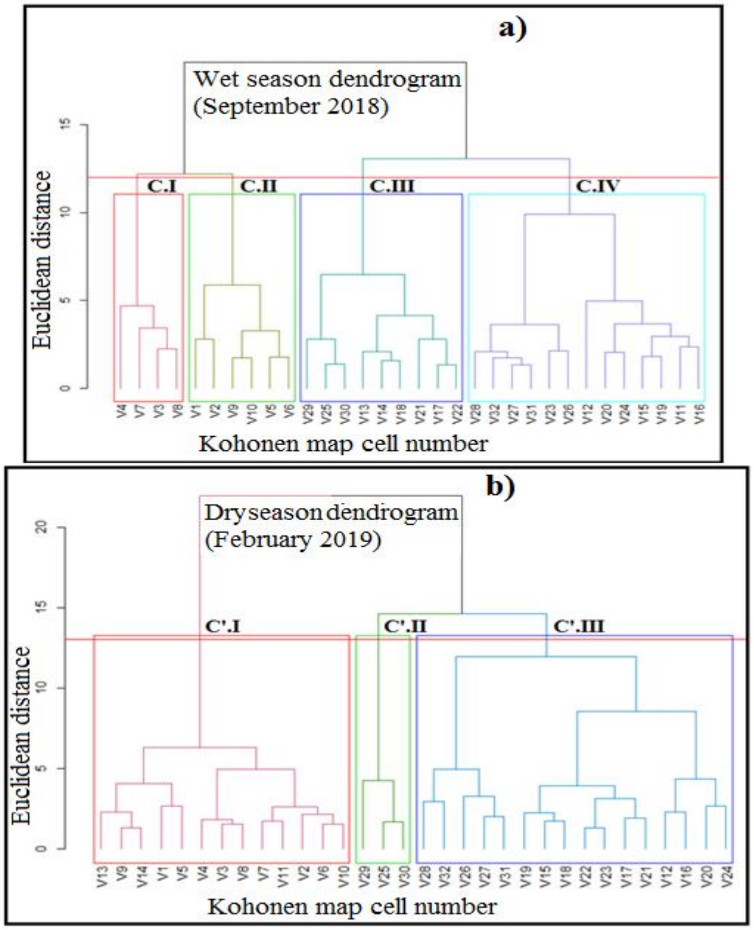

Fig. 6. Kohonen map cell classification dendrogram as a function of physicochemical parameters

Table 1. Number of samples and representativeness of surface, well and borehole water in each Kohonen class

Class	Total samples	% Surface water	% Well	% Boreholes
Wet season				
C.I	5	0	7,14	15,38
C.II	8	0	42,85	7,69
C.III	15	25	35,71	30,77
C.IV	16	75	14,29	42,31
Dry season				
C'.I	23	50	69,23	40,74
C'.II	3	50	0	3,70
C'.III	18	0	30,77	51,85

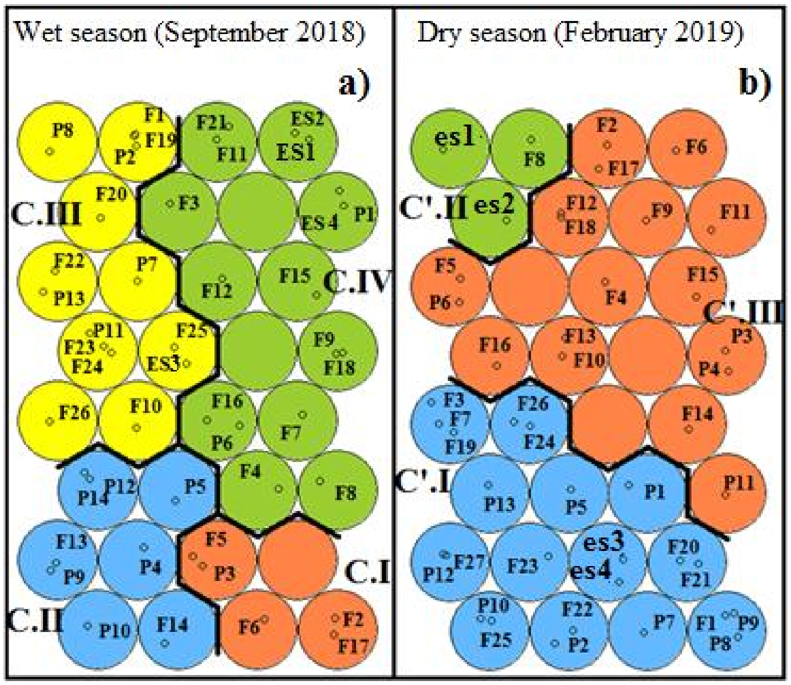

Fig. 7. Distribution of water classes resulting from the dendrogram on the Kohonen map: (a) wet season, (b) dry season

3.2.4 Physico-chemical differentiation of water classes

The importance of physicochemical parameters in the classification of sampling points is shown in Fig. 8.

During wet periods (Fig. 8a):

Class C.I, which is mainly made up of basement groundwater, has a high conductivity characteristic of high concentrations of dissolved elements (Ca^{2+} Mg^{2+}); this class also has high concentrations of Na^+, K^+, Cl^- and Fe^{2+}. The other chemical elements are moderately or weakly represented. The temperature remains very high with a basic pH.

Class C.II, which is mainly made up of alteration ground water, has a slightly lower electrical conductivity than class C.I with slightly lower concentrations of dissolved elements. Here, only Na^+ and Mn^{2+} have a particularly high average concentration, the others being weakly or very weakly represented. The temperature remains very high with a slightly basic pH.

Class C.III is heterogeneous (presence of both surface water, alteration and base) and has a very low electrical conductivity. This class has particularly average levels of PO_4^{3-} and Na^+. The others are weakly or very weakly represented. The temperature remains very high with a basic pH.

Class C.IV being the most heterogeneous class (presence of surface water, alteration and base) has an average electrical conductivity with average concentrations of dissolved elements as well. This class also has average concentrations of HCO_3^-, PO_4^{3-}. The others are weakly or very weakly represented. The temperature remains very high with a very basic pH.

In dry periods (Fig. 8b):

Class C'.I as well as class C.III in wet period is heterogeneous (presence of both surface water, alteration and basement) and presents a very low electrical conductivity, characteristic of very low concentrations of dissolved elements (Ca^{2+} Mg^{2+}). This class has particularly average levels of PO_4^{3-} Na^+ and Fe^{2+}. The others are weakly or very weakly represented. The temperature remains high with a slightly basic pH.

Class C'.II, consisting mainly of surface water, has average electrical conductivity with average concentrations of dissolved elements as well. This class has high concentrations of Zn^{2+} and average concentrations of PO_4^{3-}. The others are weakly or very weakly represented. The temperature remains very low with a very basic pH.

Class C'.III being heterogeneous (presence of both alteration and base waters) has a slightly higher electrical conductivity than class C'.II with slightly higher concentrations of dissolved elements as well. Here only NO_3^- has a high concentration. This class also has average concentrations of HCO_3^-, Cl^-, SO_4^{2-}, PO_4^{3-} with the others being weakly or very weakly represented. The temperature remains high with a basic pH.

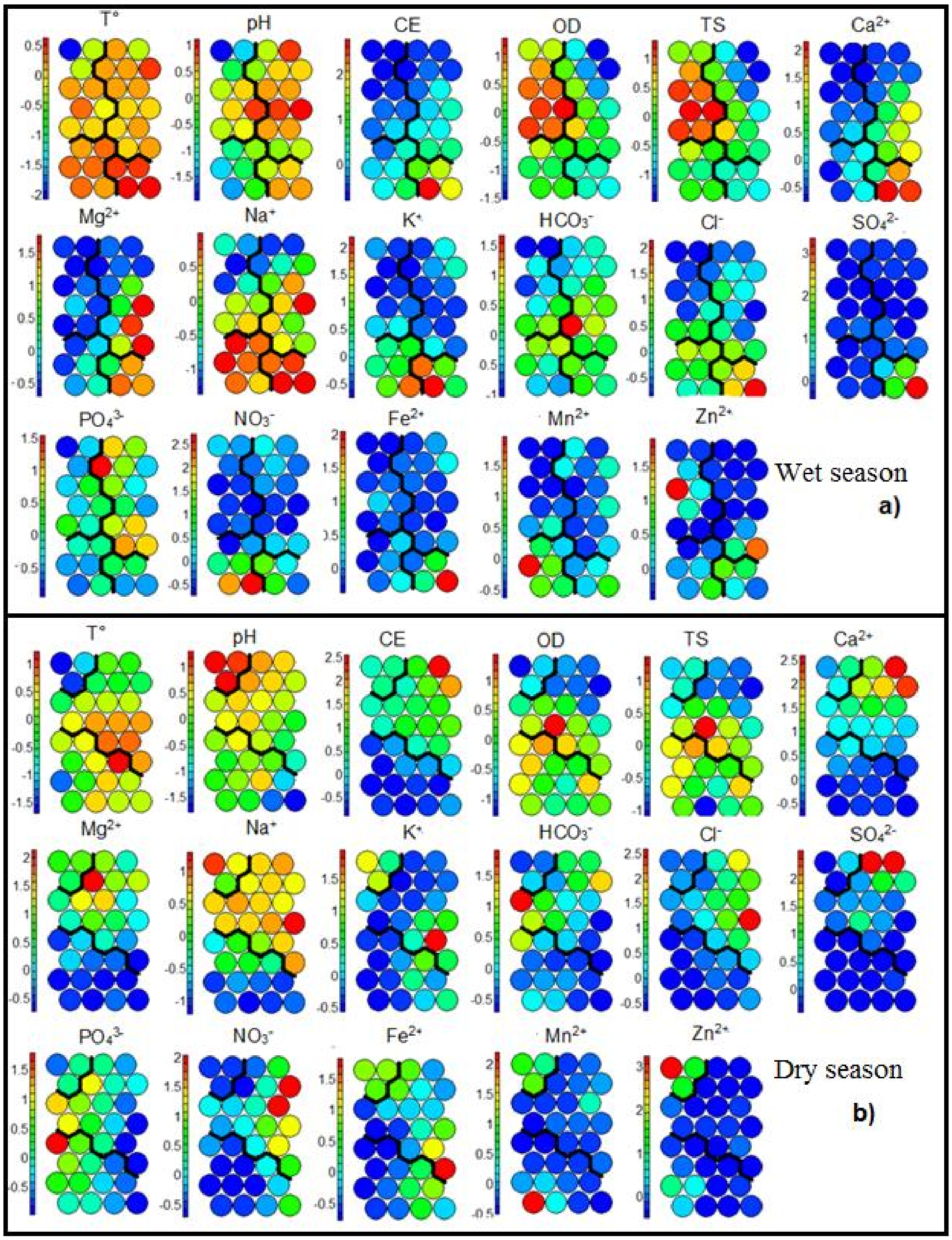

Fig. 8. Weight of physico-chemical parameters in the definition of classes: (a) wet season and (b) dry season

4. DISCUSSION

The study of the relations between the water table and the river, based on physico-chemical parameters, was carried out using the Pipper diagram and biostatistical tests. The use of the piper diagram brought out two hydrofacies in the dry season and three in the wet season, which highlighted at a certain level the interactions between river water tables. Indeed, of the three hydrofacies determined, the chlorinated hydrofacies calcium-magnesium nitrate nitrate remains characterised by a high prevalence of nitrate and chloride. This presence could be explained by a pluvio-leaching of pollutants resulting from anthropogenic activities towards the water tables [12-14]. The connection between groundwater and rivers could also be explained by the high levels of certain parameters such as phosphate, iron and manganese. In fact, the high levels of these parameters observed in water types (surface, alteration and base) testify to this connection. Among these parameters, while phosphate could come from the surface, this is not the case for iron and manganese, which would be due to the dissolution of crystalline and crystallophyllized rocks present in the study area [15]. The same results were obtained by [16] in the east and [17] in the mountainous west of Côte d'Ivoire. These authors showed that iron and Manganese would come from the dissolution of biotite-rich crystalline formations (biotite granite).

Biostatistical and geochemical tests were used to classify surface water, alteration sheets and fissured basement sheets according to similarities. Analysis of the results obtained shows that the different classes identified, independently of the season, are heterogeneous. The strong heterogeneity observed at the level of classes C'.I, C'.II, C'.III and C'.IV, which indicates the presence in the same class of surface water, alteration layers and basement layers, reflects a connection between these different types of water.

It has been established that the mineralisation of groundwater, under natural conditions, comes on the one hand from the nature of the rocks crossed during infiltration and on the other hand from the contact time between water and minerals [18-19]. If this were the case here, surface water, due to its openness to rainfall, would be less mineralised than well water [20]. Secondly, the fissured crystalline basement aquifers receiving water from the more superficial layers of overlying alteration should be more mineralised. According to this rule of increasing mineralisation evolution with depth, a clear discrimination based on the mineralisation differential between surface water, alteration layers and fissured basement layers should prevail. This lack of clear discrimination between waters could then translate, on the one hand, a hydraulic connection with the possibility of mixing of waters between the different layers housed in the alteration zones [21-23] and, on the other hand, between the cracks in the crystalline basement [24]. In addition to this first hydraulic connection, hydraulic continuity could be added between alteration aquifers and fissured basement aquifers, a continuity that will tend to bring the physico-chemical characteristics of the waters of these two aquifers closer together. Moreover, the rapprochement of the physico-chemical characteristics of surface water and groundwater (heterogeneous classes) could also reflect a strong interaction between the water table and the river. In this case, rivers could constitute drains for the aquifers of the fissured basement, but also for the fractures which would be corridors allowing the evacuation of these surface waters [25]. This idea is supported by the assertion that the major Ivorian rivers are generally located in the fractures of the crystalline and crystallophyllized basement [26].

5. CONCLUSION

The study of groundwater-river relations based on the analysis of physico-chemical parameters using the piper diagram and biostatistical tests has yielded several results. Firstly, the analysis of the piper diagram allowed the determination of two main hydrochemical facies, namely the chlorinated magnesium-calcium nitrate hydrofacies and the magnesium-calcium bicarbonate hydrofacies. These hydrofacies are characteristic of three types of water reflecting a mixture between these waters and consequently an interaction between these surface waters, alterations and basement. The biostatistical and geochemical discrimination of the samples made it possible to classify the points of surface water, alteration sheets and fissured basement sheets according to similarities related to chemical compositions and their seasonal variations. The analysis of the different classes presents a heterogeneity which shows an important exchange between surface water and groundwater which results in high contents of parameters such as iron, manganese and phosphate in both surface water, alteration aquifers and basement aquifers.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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