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Contribution of Major Ions in Identifying of Groundwater Flow in Dense Vegetation Cover Area: Case of Sassandra Watershed (South-Western Côte d'Ivoire)

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Authors' contributions

All authors participated in their different ways to work, the writing and reading of the manuscript. Therefore they agree the content.

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ABSTRACT

In West Africa, particularly in Côte d'Ivoire, the groundwater is contained in hard-rock aquifers and serves as main source of drinking water supplies to the population. To improve access, several studies were conducted in various parts of the country. Most of them use mapping of lineaments related to tectonic fractures to represent corridors of groundwater.
In this article, chemistry of major ions was used to highlight quantitatively the axes of groundwater movement, and mixing between different aquifers in Sassandra watershed which is located in the Southwest of the Ivory Coast.
The sampling campaigns were accomplished respectively during the dry and wet seasons in the department of Soubré (8 590 km^2), located in Sassandra watershed, area where the effects of climate change are observed. The processing of satellite images

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(optical and active) has produced a map of major lineaments. Geographic positions and technical data of boreholes were integrated into a geographic information system (GIS) to identify point near major lineaments for groundwater sampling and chemical analysis. The waters were collected, and then analyzed by using atomic absorption spectrometer (AAS) and a Varian Vista ICP.
The results indicate that groundwater samplings are primarily Ca-HCO_3 type or NaK-HCO_3 and NaK-SO_4 types. Calcium and low pH were encountered in the highlands where infiltration of meteoric water occurs relatively quickly through preferential pathways. Chadha diagram has highlighted differences in the chemistry of groundwater between aquifers on one hand, and between systems of surface runoff and deep runoff on the other hand. Most groundwater seems to move relatively quickly. In addition, some groundwaters show a denitrification coupled with pyrite oxidation. These groundwaters have been longer circulating along opened fractures with gentle slopes. The observations and hydrochemical characterization, especially SO_4^{2-}/Cl^- ratio, permitted to identify axes of groundwater movements in the study area. However, the major lineaments which are similar to major fractures are not primarily responsible for the groundwater motions. Rather, there are small fractures and topography which control the flow of groundwater in the crystalline hard-rock. Also, the groundwater levels are not always guided by the major lineaments observed. Some small lineaments and topography control fairly the groundwater flow.

Keywords: Fractured-rock;lineament; groundwater flow; major ions.

1. INTRODUCTION

In the in Côte d'Ivoire (West Africa country), groundwater is the major source of drinking water. This water can be found in the hard-rock zones where matrix permeability results from the formation of fissures or channels network. Geologically, 97% of the Ivorian territory is composed of metamorphic and crystalline rocks outcrop. Many studies showed that the largest and most potential groundwater resources of the country are enclosed in hard-rock aquifers, which were intensively fractured owing to various tectonic events. According [1], most of the groundwater resources are contained in the reservoirs of weathering and fissures that function as a composite aquifer, below which is often a fractures reservoir. This structuring of the hard-rock aquifers is the realistic assumption of groundwater reservoirs in the Southwest of the Ivory Coast, particularly in the department of Soubré.

Yet, the massive influx of population associated with the expansion of cultivated areas has extremely increased the demand for water both in terms of quantity and quality across the region. Moreover, it has been found that the boreholes drilled do not always meet the population's expectations. In fact, the low flows, early drying up, and non-drinking water constitute the major causes of this non-fulfillment. In response to these issues encountered in the hard-rock regions of the country, the study of lineaments has been widely used since the 1930s, especially with the advent of photogeologic. [2,3], defined lineaments as significant lines of landscape caused by joints and faults, revealing the architecture of the rock basement. Lineaments which may act as conduits for fluid flow are particularly important in hydrogeology.[4,5] reported that drilling with high flow rates is often located near major lineaments. In reality, the most important aquifers in the matter of quantity are located either around fractures or fracture nodes.

[6,7,8] mentioned that the knowledge of the chemical composition of groundwater can provide useful information about the environments in which it flows, the flow conditions, and the chemical evolution of groundwater table. In this study, chemical parameters will be used to not only characterize groundwater, but also to highlight the main roads in this part of Sassandra watershed where coffee and cocoa productions are preponderant. Also, this study will be the basis of future research works with regard to climate change and vegetation cover degradation. Further, such researches can help ascertain the impact of climate change and vegetation cover degradation on the behavior of the major ions in the groundwaters.

2. MATERIAL AND METHODS

2.1 Study Framework

The department of Soubré is located in the Southwest of the Côte d'Ivoire between latitudes 5°19 - 6°34 and longitudes 6°12 - 7°08, and has a surface area of 8 590 km^2 (Fig. 1).

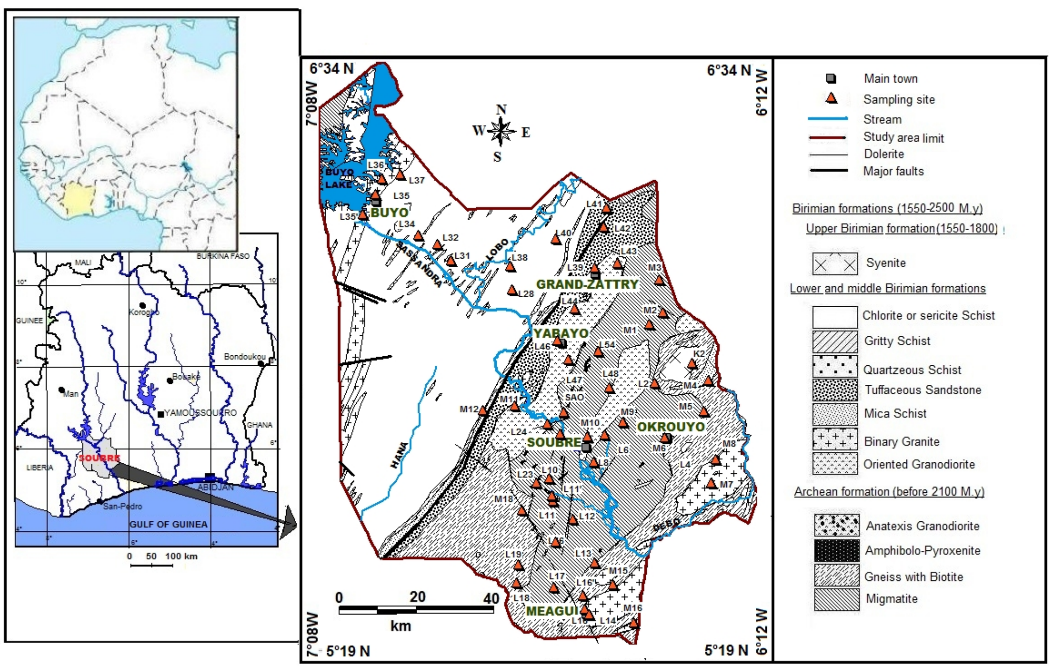

Fig. 1. Study area with main geological units

The area is part of a vast slightly undulating peneplain, with 200 m mean altitude and inclined towards the sea (in south) with a mean gradient of 1‰. It is drained by Sassandra River which offers a variety of configurations along its course and benefits from a sub-equatorial climate (hot and humid). Rains are abundant (between 1600 mm and 1800 mm) and reach a peak around June and July. During the year, temperatures vary between 26 °C and 32 °C [9]. In general, 10 m to 120 m deep boreholes equipped with electric or manuals pumps are used to provide water to the population [10].

These hydraulic structures are located in geologic formations that belong to Eburnean domain (2500-1550 My). The Eburnean formations are characterized by a variety of plutonic rocks. They are intrusive granitoids in metamorphic rocks (gneisses, migmatites) older. Explicitly, the geological formations can be described in different compartments. The Northwest compartment (Buyo area) consists of various schists and sandstones (flyschoid) which are the products of dismantling the chain of Liberia [11].

Two separate tectonic events are recognizable in the structuring of formations found in the watersheds of Hana River and Lobo River [12]. This phase of NW-SE compression (D1) with isoclinal folding early SW-NE axis, followed by the creation of schistosity is oriented SSW-NNE. The second phase of deformation (D2), with opening quartz vein direction W-E scattered in almost all rocks of the belt Birimian. This phase is accompanied by a dextral shear along the direction SSW-NNE.

Some fissures are observed in the meta-sedimentary formations and volcanic-sedimentary layers of management in organized regional NNE-SSW to N-S. There is also a series of NW-SE faults that cut up the binary granite intrusions, schist and meta-sedimentary formation [13].

In Okrouyo-Meagui which is an area of intrusive rocks, several secondary faults are observed with a maximum length of 15 km, mostly oriented NW-SE and marked by mylonite which are widespread in the granodiorite and migmatite. The presence of dolerite dykes NW-SE is also reported. However, in this unit, the fractures are oriented mainly along three main directions: SSW-NNE, SW-NE, and N-S.

2.2 Methodology

2.2.1 Mapping of lineaments

Satellite images (ETM + and Radarsat-1) and maps (topographic and geological) of the region were used to map lineaments. All treatment processes, extraction and validation of lineaments were extracted from previous studies performed by [14,15,16,17,4]. The application of appropriate methodology namely principal components analysis, speckle reduction, and spatial and directional filtering revealed a network of major lineaments that staked the study area. After validation, they were assimilated to fractures of tectonic origin, products of geological history in the Western region of Côte d'Ivoire.

2.2.2 Sampling and analytical procedures

Based upon the map of fractures obtained, the drilling was more close to the major fractures. The fieldwork was carried out in May 2007 (wet season) and March 2008 (dry season) following the protocol recommended by AFNOR [18,19].

The groundwater samples were collected from 57 boreholes for chemical analysis. The temperature, potential hydrogen (pH), Total Hardness (THt), Total Alkali (TA) and Electrical Conductivity (EC) were monitored during pumping. The EC, pH and temperature were measured using portable Ciba Corning pH meters. Alkalinity of water was determined using tabs of TA, and THt was measured in water with a hardness test kit Aquamerck® containing a total of titrant and a reagent color indicator. Indeed, the samples were collected from boreholes after 10 minutes of pumping and filtered in-situ using 0.45 mm membrane filters. The Filtrate was acidified with nitric acid immediately following filtration to $pH < 2$, except those used for the dosage of nitrate. Afterwards, the groundwater samples were poured into three new 100 ml and 50 ml polyethylene bottles respectively. All sampling bottles were first rinsed with de-ionized water and then with filtered sample water. Thus, a total of 57 samples of groundwater and surface water were collected to determinate the chemical parameters.

The water samples were analyzed at analytical laboratory Engineering of "Conservatoire National des Arts et Métiers de Paris" in Paris (France) using atomic absorption spectrometer (AAS) and a Varian Vista ICP-MS, except for nitrate which was analyzed using the cadmium reduction column method for nitrate. The verification of the validity of test results was done by calculating the ionic balance. In fact, the analysis is of good quality if the balance is less than or equal to 5%. However, for water in hard rock in West Africa, where mineralization of water is often low, a balance of 10% is acceptable [20].

The Statistca (Statsoft) and Diagramme 4.0 [21] computer program were used to perform all the statistical analysis. The physicochemical parameters of the groundwater data were statistically analyzed, and the results are presented in the form of minimum, maximum, mean and standard deviation in the Table 1).

All the results were compared with standards permissible limit as recommended by the World Health Organization [22].

2.2.3 Hydrochemical interpretations

Field data and chemical analysis results were treated statistically to understand the characteristics of water and emphasize the phenomena of mixing between aquifers and hydrochemical poles through Chadha diagram [23].

This diagram was constructed by plotting on one hand, the difference in milliequivalent percentage between alkaline earths and alkali metals expressed as percentage reacting values on the X axis; and on the other hand, the difference in milliequivalent per liter (me/L) percentage between weak acidic anions and strong acidic anions also expressed as percentage reacting values on the Y axis. The milliequivalent percentage differences from the X and Y coordinates are extended further into the main study sub-fields of the Chadha diagram, which defines the overall character of water. The Chadha diagram was also used to clarify the relationship between the poles, and to identify groups of intermediate water.

The use of major ions to determine groundwater paths flow in fractured aquifers has been successfully applied by [8] to 50 km^2 sub-catchment in Australia. In this case, to identify possible hydraulic continuity between groundwater tapped at different places along a lineament, similarity of water chemistry or the existence of some gradients that are known to be typical of groundwater flow in a tropical environment were tested [24]. According to [6], Na/K ratio remains low in drainage media from upstream to downstream along the flow direction while SO_4^{2-} content decreases. The ratio SO_4^{2-}/Cl^- follows this trend whereas the ratio Mg/Ca increases.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Major lineaments

The lineaments with a length greater than or equal to 9 km (300 pixels) were considered as major in the study. Thus, a total of 168 major lineaments were identified, and are illustrated in the Fig. 2. As depicted on the Fig. 2, these lineaments are related to the fractures of preferred orientations between N40-N70, N100, N120 and N150-160. The N80-N90 and N130-140 directions are less important. In overall, the major lineaments are very heterogeneous in their orientation with a preponderance of family N40-N70. However, by comparing the major lineaments directions pinpointed in Soubré to the rest of the country, most directions already known were identified in different proportions [25].

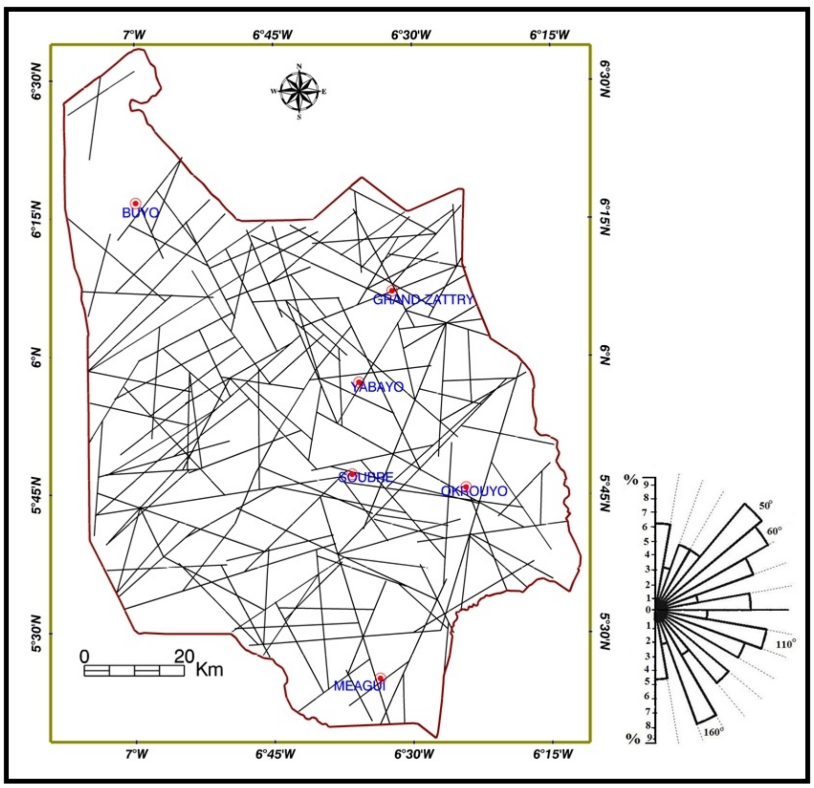

Fig. 2. Fracture network and directional rose diagram of the main fractures of Soubré

3.1.2 Physico-chemical

3.1.2.1 Hydrochemical characters

The results of the chemical analysis are summarized in the Tables 1 and 2. The analysis results are acceptable because more than 75% of the waters indicate an ionic balance less than or equal to 5%. The groundwater samples have a close temperature range and pH values quite consistent. Also, more than 57% of the water has electrical conductivity (EC) less than 300 µS.cm^{-1}; those with EC between 300 and 800 µS.cm^{-1} represent 39% of samples. Only 5% have EC above 800 µS.cm^{-1}. Among the anions, bicarbonate (HCO_3^-) is the most abundant followed by sulfate (SO_4^{2-}). The peak nitrate concentrations were met in some places. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) represent respectively 35% and 25% of cations.

Table 1.Physico-chemical parameters of water sampled

	pH	T (°C)	E.C (µS.cm^{-1})	TDS (mg.L^{-1})	TA (°F)	THt (°F)
Minimum (m)	5.9±0.1	25±0.2	61.0±0.5	82.0±1	1.4±0.2	2.3±0.2
Mean (µ)	7.1±0.1	27.1±0.2	313.8±0.5	297.9±1	10.8±0.2	13.5±0.2
Maximum (M)	7.6±0.1	30.6±0.2	1128.0±0.5	1054±1	34.7±0.2	60.4±0.2
Standard Deviation (α)	0.4	1.0	212.6	172.8	7.3	11.4
Cv= (α/µ)	0.05	0.04	0.68	0.58	0.67	0.84

Table 2. Chemistry of sampled water of Soubré

	Chemical analysis in the laboratory										
	Anions (mg.L^{-1})				**Cations (mg.L^{-1})**				**Dissolvedmetals (µg.L^{-1})**		
Statisticalparameters	**HCO_3^-**	**Cl^-**	**SO_4^{2-}**	**NO_3^-**	**Ca^{2+}**	**Mg^{2+}**	**Na^+**	**K^+**	**Al^{3+}**	**Fe^{2+}**	**Mn^{2+}**
Minimum (m)	16.8	3.2	6.0	<1	5.7	2.0	3.6	3.8	<5	<5	<5
Moyenne (µ)	130.6	18.2	52.2	14.9	30.9	13.8	25.8	11.3	30.0	200	40.0
Maximum (M)	423.2	67.0	401.7	99.3	169.4	86.1	86.4	30.1	70.0	1400	300.0
Standard Deviation (α)	87.8	13.7	74.7	22.4	28.3	15.7	13.0	5.9	20.0	300	60.0
Cv = (µ/α)	0.67	0.75	1.43	1.50	0.91	1.14	0.50	0.52	1.54	1.48	0.67

3.1.2.2 Comparison of the physico-chemical parameters of Soubré groundwater to WHO standard

The comparison of the physico-chemical parameter concentrations with WHO standards was previously done by [26] regarding the potability of water in the same study area.

In fact, they concluded that except the nitrate, magnesium, and calcium sulfate; most of the waters were found to have relatively low chemical element concentrations. Indeed, some waters contain high levels of chemical parameters. This is the case in Négreadji (M15) where sulphate and calcium are present at elevated levels in the water. The L39 samples are rich in iron, manganese, magnesium, and potassium sulphate. In addition, it was found out that 18% of the waters have nitrate concentrations exceeding the WHO standard (50 mg.L^{-1}).

They concern in descending order L13, SAO, L14, L11, L28, L2, and L23. On the whole, more than 32% of the water presents in excess of 20 mg L^{-1} levels.

3.1.2.3 Hydrochemicalfacies

The groundwater samples of Soubré are 72% bicarbonate. Moreover, 50% of the samples are sodi-potassium and the other 50% are calcium/magnesium. Sulphated waters (18%) are predominantly sodi-potassium. Finally, we find chloride facies in 10% of sampled water.

The positioning of the contents of major ions in the Chadha diagram (Fig. 3) helped identify the hydrochemical facies and set the demonstration of hydrochemical poles. Group A represent the pole calcium bicarbonate water (group Pca). Group B contains the 7 alkaline bicarbonate water (Pole Pal). Within this group, we have low mineralization water (L6, L10, L44 and L46) or much nitrated water (SAO, L11 and L14). Group C brings together two sulfated alkaline water samples (L47 and M18) in the pole Psa. Group D consists of calco-magnesium sulfate samples (Psc pole). This pole contains water of L11', L39 and M15 which are rich in sulfate, which should now add water L16' rich in chloride. The L36 is at the limit of this group but remains in the mixing unit (intermediate phase). The mixing water in their chemical evolution is indicated by Mca-al, Mca-sc, Mca-sa (Fig. 3).

These water samples are very various in their chemical composition. There may be some mixing between the waters of Group A and Group B in varying proportions, and for groups A and D. In addition, this diagram shows another intermediate group between Pca (group A) and Psa (group C) that will be called Mca-sa containing samples L2, L16, M7 and M16. It's in fact intermediate points between the group Mca-al (mixing water) and the group C.

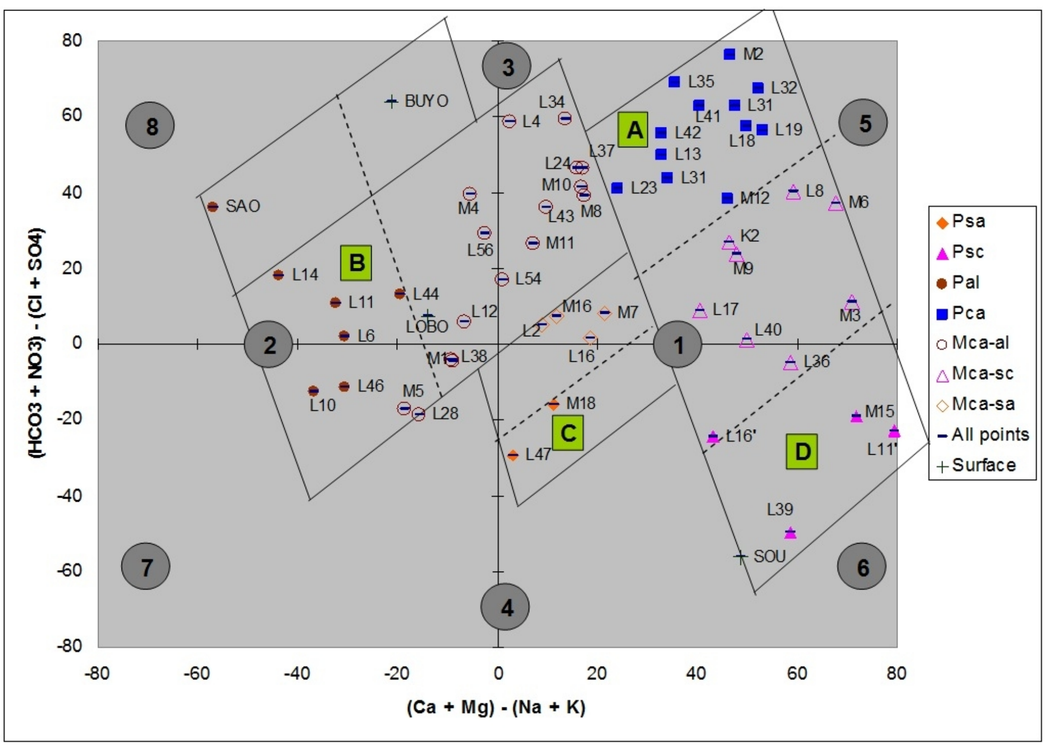

Fig. 3. Chadha plot of hydrochemical samples

3.1.2.4 Saturation index

The Fig. 4 shows the diagram Calcite Saturation Index (CSI) versus Dolomite Saturation Index (DSI). Based on the disposition of the points in Fig. 2, two main were singled out. The set 1 is defined as “moderately aggressive water” and “frankly aggressive water” represents the set 2. In addition, two distinct groups were distinguished respectively at the end of each set. The group 1 is tagged as low aggressive water. It is quite close to the origin which is low or no aggressive, and includes seven points namely M2 and L31 of the PCA, L39 and M15 PSC, M8 Group MCA-AL, M12 and M3 MCA-SC. The group 2 or very aggressive water is found at the end of the set 2, which contains 28 samples belong. The CSI values of the set 2 range from -0.62 to -1.56. Clearly, L35 and L32 are in the PCA group shale, L17 and L23 MCA-SC in the migmatite, L56 and L16 in MCA-AL group which is composed of 6 samples after less unsaturated group 1. Eighteen samples were frankly aggressive water. There concern L13 (nitrated) of the PCA, L6 and L11 (nitrated) PAL, L12, L34, L37 and L38 of MCA-AL and L36 from MCA-CS, which are the 8 most unsaturated after group 2. The CSI values of this set vary between -1.51 and -2.22. Five samples (L28 of MCA-AL, L44, L10 and L14 of the PAL and finally L47, only representative of PSC) were selected from water samples with high aggression (group 2). PSC are the lowest values of CSI and IDS of -2.30 and -2.51, and -4.64 and -5.63 respectively.

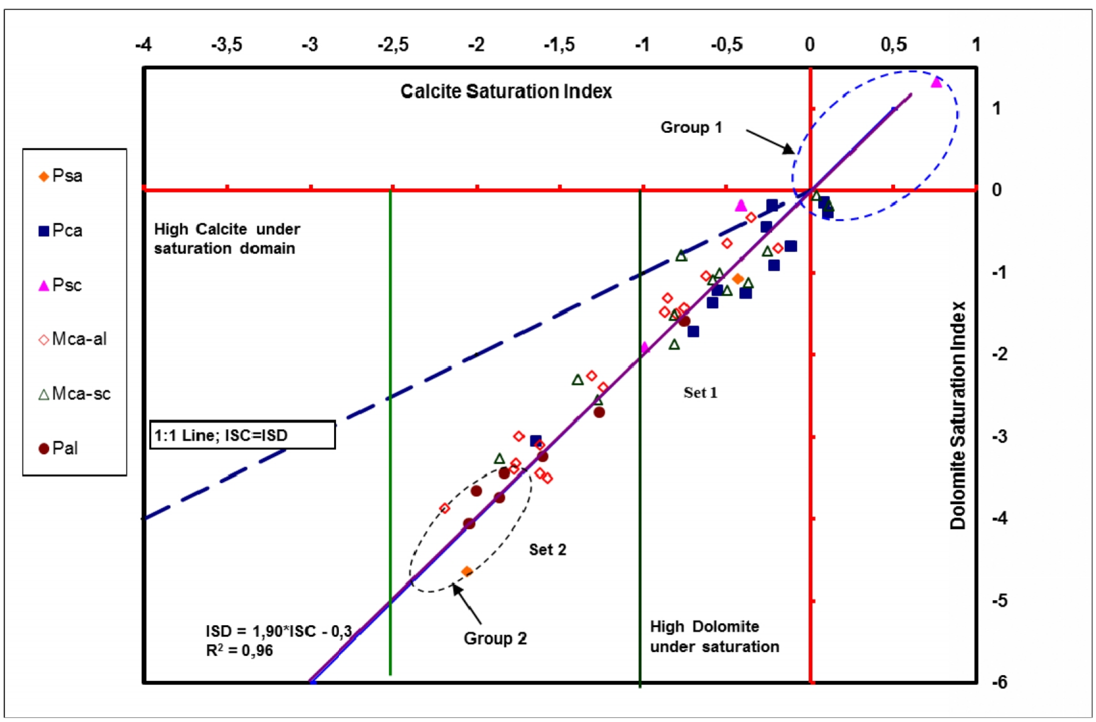

Fig. 4. CSI *vs.* DSI diagram of ground water from calculated using the DIAGRAMME program

3.1.3 Report SO_4^{2-}/Cl^- and flow direction of groundwater

Fig. 5 shows different variations of chemical ratio SO_4^{2-}/Cl^- of the boreholes. It is pointed out the directions in which this report decreases and consequently the direction of groundwater flow in the region. In considering variations in ratio SO_4^{2-}/Cl^- and similarity between the major ions, flow axes have been identified (Fig. 6). These are: L18-L19, L11-L10, L2-M9, M10, L48, L37, L35 and L34-L31. These axes follow flow direction in the majority of surface water drainage. By extending this theory to water surrounding the map, we identify other opportunities for hydraulic continuity between other ground waters. Thus, it could have connectivity between the water tables of locality: M4 and M5, L39 and L38, M11 and M12, L42 and L41, M1 and M2, M15 and M16, etc. Against, we see that fractures which are located near locality L19 and L18, L10 and L11, L40 and L39, K2 and L2, M6 and M9, L24 and SAO are paths of movement of groundwater.

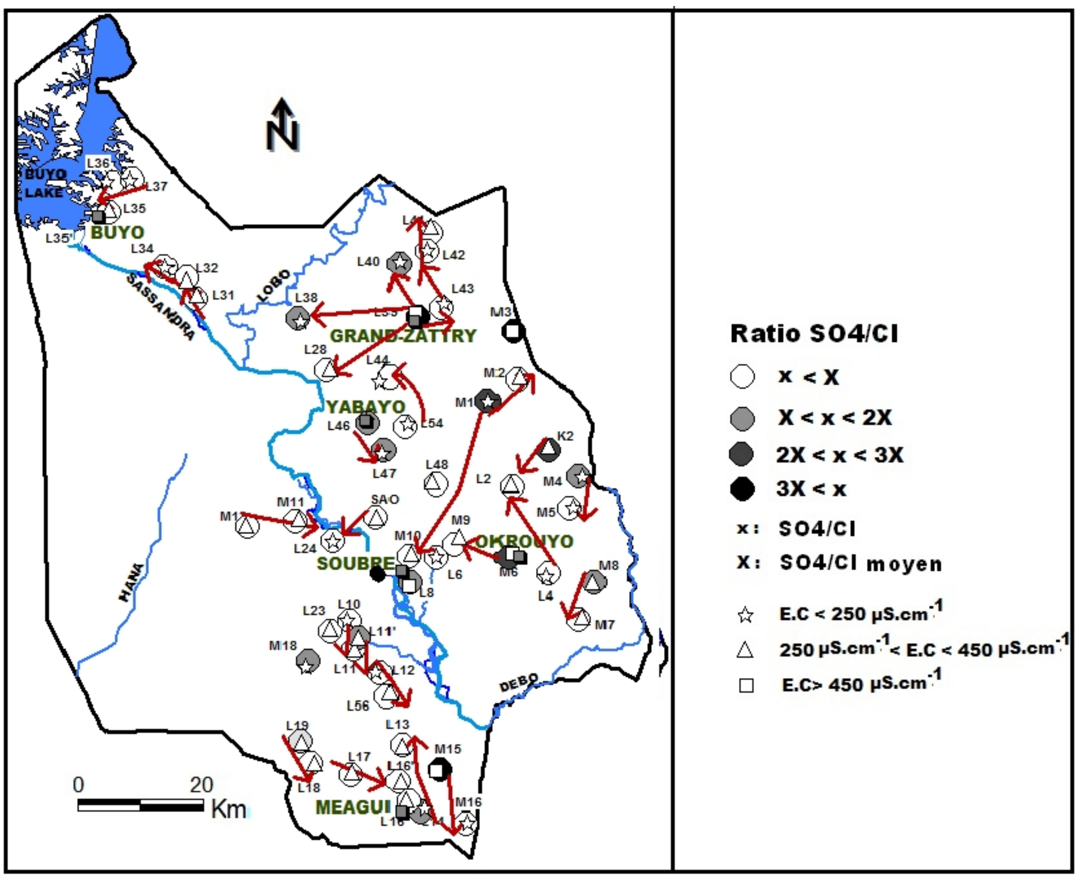

Fig. 5. Spatial distribution of the SO_4/Cl ratio and resulting flow axis

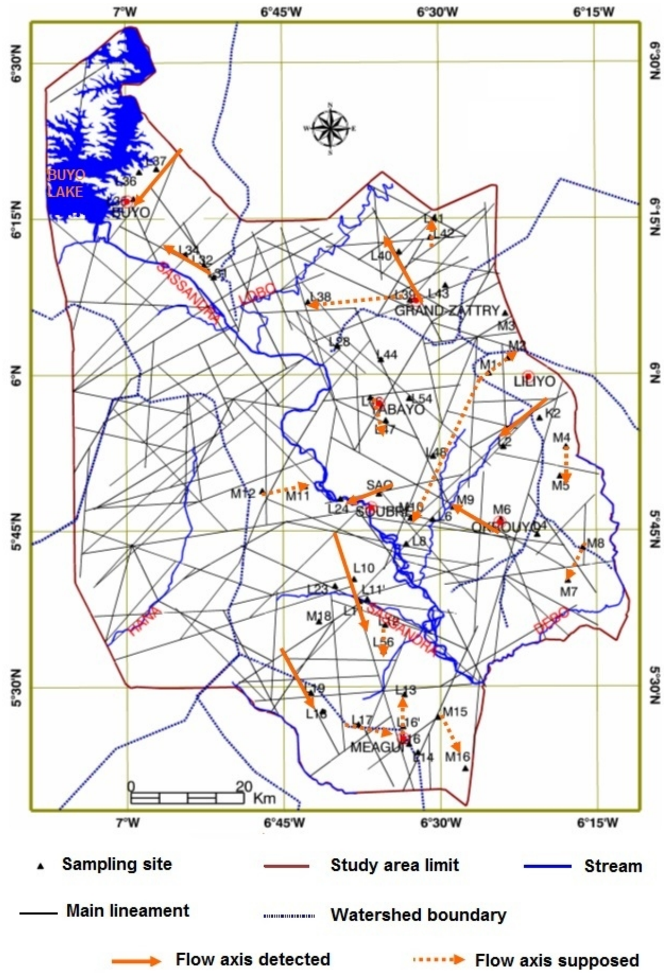

Fig. 6. Relationships between main lineaments, watersheds, sampling borehole sites, and flow axis

3.2 DISCUSSION

The groundwaters of the department of Soubré are intermediate mineralized (conductivity is less than 750 µS.cm^{-1}) regardless of the geological formation. Nevertheless, they are relatively more mineralized granitoids, particularly NaK-HCO_3 or Ca-HCO_3.

The SO_4^{2-} concentrations are sometimes higher than the maximum (2.39 me.L^{-1}) that was noticed by [27] in various crystalline formations. In some places, the water has elevated nitrate concentrations, reaching sometimes 1.65 me.L^{-1}. However, the nitrate levels remain below 3.55 me.L^{-1}, value observed by [28] in Birimian formations of the Côte d'Ivoire. In fact, the presence of nitrate in the different waters indicates a right infiltration of rainwater in the region.

The high sulfate level in places where nitrate is insignificant seems to be a direct consequence of denitrification [10], which occurs in several boreholes. Indeed, the denitrification results from the activity of Thiobacillusdenitrificans, and coupled with the oxidation of pyrite. According to Mariotti [29], the thiobacillusdenitrificans is a bacterium that can oxidize various connections involving reduced sulfur (thiosulfate, polythionates, and sulfides), by "breathing" the nitrate and using CO_2. This denitrification contributes to the reduction of nitrate levels in many boreholes, thereby reducing the impact of the nitrate stemming from the high infiltration of rainwater in the area.

The analysis of different facies also reveals the transition between the calcium Pole and the alkali Pole with sulfate enrichment involving the notion of time [10]. As result, alkaline water has a longer residence time in the aquifer. They move slowly in areas more or less confined (regolith). Subsequently, they infiltrate under the altered sound interface and begin at that time to get rich in Calcium. Generally, alkaline waters have a longer residence time while calcium-magnesian waters moving quickly into the fractures are younger (short residence time). Both types can mix with the infiltrated water or with the water flowing in the areas of weakness (fractures, veins and altered shear corridors).

These observations are justified by the saturation indexes that show the dynamic nature of the groundwaters of Soubré. Group 1 waters show a significant contribution of bicarbonate, therefore, a more complete renewal. These waters flow and seem to have a short residence time in the aquifer. Moderately aggressive waters are slightly less young renewed water capable of providing bicarbonate. Therein, the water flows slow and distance identical to that of group 1 (or more) time stay is necessarily longer. These waters are generally older than those of the group 1.

Group 2 waters seem to have a long residence time of the aquifer. As noticed in L47 (low ratio of Mg / Ca) and M18, group 2 waters circulate in fresh basement slightly fractured.

Groundwater flowing in aquifers or compartmentalized individual but can communicate through fractures [30,31,32,33]. Chadha diagram (Fig. 3) shows the mixing water of different facies. This reflects the contribution of groundwater axes knowledge in the hard-rock area. Based on this fact and on the work of Dramendrail [6], the continuity between groundwater along a same major fracture was studied.

In addition, the use of major ions to trace groundwater flow in fractured aquifers has been successfully applied by [8,34]. Before choosing the SO_4^{2-}/Cl^-, several ratios such as Mg/Ca, Na/K and Na/Cl and SO_4^{2-}/Cl^- were tested as tracers at a regional watershed scale. However, the high infiltration of rainwater observed in some places with its corollary of nitrate pollution and multi-parametric nature of geochemistry of groundwater make the use of these ratios difficult. Nevertheless, SO_4^{2-}/Cl^- ratio seems to be a reliable tracer of the flow through aquifers gneiss-granite.

In sum any flow axis is most often an expression of the topographic slope but does not necessary coincide with a major lineament. It's the case of boreholes M4, M5 and M8, M7 in the South-eastward. In some cases, the flow follows a lineament, but not the regional slope of Sassandra River (L31-L32-L34 northward from Lobo River is an example). In addition, some major lineaments that are not underlined by flow axes are unlikely to be fracture zones opened to water: SSW-NNE lineament marked out by wells L2-L6-L8 along the Bo River.

However, a structural control is suspected at the regional scale (a few km to a hundred of km), via a relationship of lineament to maximum expected yield from the same wells that were sampled for water chemistry analysis. Based upon the knowledge of fracture length/width relationship at different scales in granitoids [35], boreholes are actually close enough to the lineaments (distance ranging from 100 m to 2 km) for a hydraulic influence on yields to be realistic. According to the global map of the stress regime by Zoback [36], the prevailing compressive stress system is W-E in West-Africa, but many variations may exist from a region to another. For instance, the study of Bertone and Le Guellec [37]which took place at few hundred km east from the current study area, suggests that an optimized compressive direction N105 would better explain the fracture sets (N140 in Togo, N70 in Ghana) which statistically exhibit the most productive wells.

The map of the major lineaments (Fig. 6) also displays the watershed and sub-catchments limits, water sample points, and flow directions interpreted from the hydro-chemical ratio [10].

Five of the seven major flow axes highlighted are compatible with a N105 mean compression strike in the N70 to N140 sector, and the Grand-Zattry flow axis is N150. A special case is the Liliyo flow axis related to the Bo River striking orthogonally to the main compression. It is consistent that it does not allow the groundwater to flow since the presence of a permanent stream suggests a very low permeability of the lineament-based fracture zone [38,39]. The location of surface channels is likely controlled by fracture zones without openness or filled with fault gouge.

It not statistically proved that fractures are opened under the current regional stress system since in large range no preferential strike appears in those lineaments is revealed as flow paths for groundwater. In other words, regional topography of the watershed and in field topography-controlled loads may have the leading role. Actually, both factors are convergent. For instance, in Lobo watershed, the main surface drainage axis is south-westward: the hillsides slopes and lineaments strike NW-SE, compatible with opening under the regional stress system, and NW-SE is also the trend of groundwater flow discharging to the Lobo.

Finally, opened or not, either barrier to groundwater flow (higher water table) or water conduits (lower water table), fracture zones or lithological boundaries, including most of major lineaments are all hydraulically active axes which are combined with the regional aquifer slope to drain the watershed. But, the classical concept of isolated aquifers linked to a connected network of fault corridors does not prove a sufficient model for hard-rock aquifers any longer, and the need is proved for the new concept developed during the last decade of a continuous stratiform aquifer related to fissure layer of weathering profile. Indeed, the wide range of lineament strikes related to successful boreholes observed in Sassandra watershed as well as in other regions of Africa [40] is suggestive of a pervasive influence such as discharge from the weathered fissured saprock aquifer through some local fracture systems or slope scarps.

4. CONCLUSION

The study showed the application of major ions in groundwater flow determination in a forest area. The use of major ions in groundwater has highlighted the heterogeneity of the hard-rock aquifers, to not only determine the direction of flow in the aquifer, but also study the connectivity of aquifers along major lineaments in Soubré area (south-western of the Côte d'Ivoire).

Groundwater of this zone is intermediate mineralized with peaks of nitrate and sulfate in some locations. The high concentrations of these elements indicate an increase of nitrate pollution followed by denitrification in some boreholes. Chadha diagram used to characterize groundwater hydrochemicalfacies, demonstrated the mixing water between different aquifers by rainwater infiltration through lineaments. The analysis and interpretation of the SO_4^{2-}/Cl^- ratio revealed that most of the flow axis goes to the Sassandra River in a NW-SE direction. However, the groundwater levels are not always guided by the major lineaments observed, rather, small lineaments and topography control the groundwater flow. Thus, a local study of underground hydrodynamic could lead to a better comprehension.

As the major ions are responsive to the environment of the aquifer, such study can be carried in a few years to evaluate the impact of deforestation, and therefore, climate change on groundwater resources in Southwest of the Côte d'Ivoire.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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