International Journal of Innovation Engineering and Science Research
(ISSN: 2581-4591)
www.ijiesr.com

Evaluation of the Physico-Chemical Quality and Study of the Aggressivity of the Groundwater and Surface Water Exploited in Yaya District (NIARI Department, CONGO)

Essouli O. F.[1,*], Malanda Nimy E. N.[1], Miyouna T.[1], Moudzika Loubaki H. B., Matini L.[2], Boudzoumou F.[1, 3], Faye S.[4]

[1]*Université Marien NGOUABI, Faculté des Sciences et Techniques, Laboratoire de Géosciences, B.P. 69 Brazzaville, Congo*
[2]*Université Marien NGOUABI, Ecole Nationale Supérieure, Laboratoire de Chimie, B.P. 69 Brazzaville, Congo*
[3]*Institut National de Recherches en Sciences Naturelles et Exactes, B.P. 2400 Brazzaville, Congo*
[4]*Université Cheikh Anta Diop, Faculté des Sciences et Techniques, Département de Géologie, B.P. 743 Dakar-Fan, Senegal*

ABSTRACT

The physico-chemical study of the groundwater and surface water of Yaya district revealed that these waters are fresh, weakly mineralized, under-saturated with respect to anhydrite, aragonite, calcite, dolomite and gypsum and the alkalinity of these waters is dominated by bicarbonate ions (HCO_3^-). These waters are also characterized by two (2) chemical families (calcium and magnesian chlorinated and sulphated waters and calcium and magnesian bicarbonate waters). From the chemical facies point of view, surface and ground waters are mainly characterised by chemical facies of the magnesian sulphate and chlorinated and calcium and magnesian sulphate type. In terms of quality, the good potability of water is called into question by the presence of certain elements such as total iron (Fe_{tot}), hexavalent chromium (Cr^{6+}), lead (Pb^{2+}) and aluminium (Al^{3+}) at levels that sometimes exceed the maximum permissible concentrations for drinking water defined by the WHO. Finally, the determination of the aggressive character of groundwater and surface water revealed that these waters are aggressive and very highly corrosive.

Keywords: Hydrochemistry, physico-chemistry, chemical facies, water quality, aggressiveness

I. INTRODUCTION

In Congo, the drinking water supply of several localities depends on groundwater. To improve the quality of life and hygiene of the population of the Yaya district in Niari department, several hydraulic boreholes have been drilled, some equipped with human-powered pumps (PMH) and others with photovoltaic pumps. The lack of information on the physico-chemical characteristics of the ground and surface waters of Yaya district constitutes a health hazard for the populations who get their water from boreholes and surface waters because these physico-chemical characteristics provide necessary information on water quality. However, the equipment of the various boreholes in this district is not always adapted to the physico-chemical characteristics of the groundwater and rocks crossed. Although the groundwater is still of acceptable chemical and bacteriological quality, it very often poses problems of aggressiveness. These problems and the solutions applicable to them are closely related to the chemical composition of the water and the nature of the geological formations crossed.

This study focuses on the evolution of the physico-chemical characteristics of the ground and surface waters of the Yaya district as well as on the determination of the aggressive character of these waters in relation to the different geological facies. The specific objectives are to determine the chemical quality and the Langelier and Ryznar indices of the ground and surface waters of the Yaya district for a better understanding of the phenomenon of aggressiveness and a precision in the choice of dewatering columns (steel casings and pumps) for the equipment of new future boreholes in this part of Congo.

II. MATERIAL AND METHODS OF THE STUDY

2.1. General Presentation of the Study Area

The district of Yaya is located in the south-west of Congo, more precisely in the department of Niari. It is bordered to the east and south-east by the Mpoukou River and to the south-west and west by the Louessé River. Specifically, the Yaya district lies between parallels 12°7' and 13°03' east longitudes and 3°00' and 3°03' south latitudes (**Figure 1**).

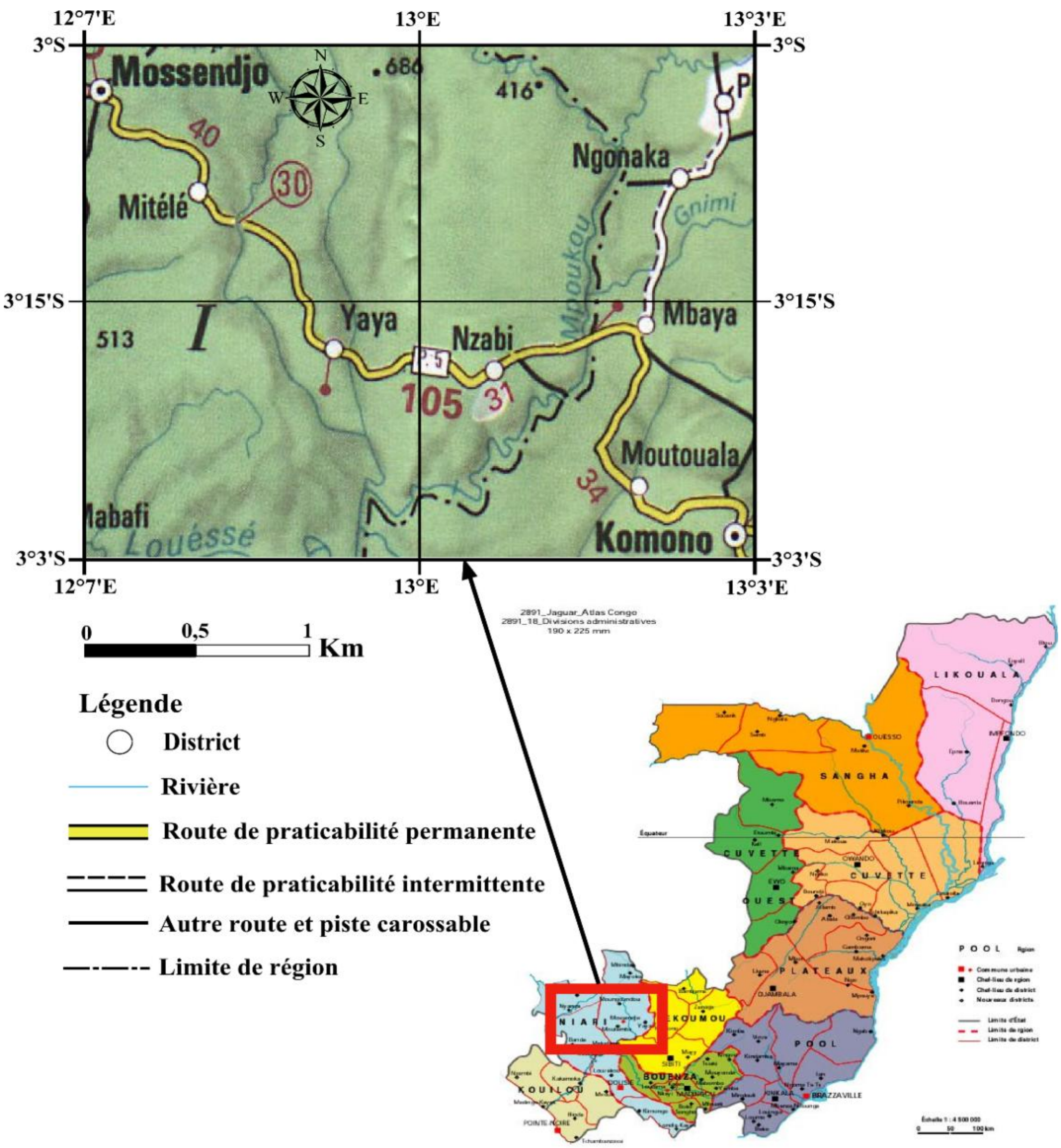

Figure 1. Location map of the study zone **[1]**

The Yaya district is characterized by a humid tropical climate due to its geographical position and relief. Annual rainfall varies between 1200 mm and 1800 mm and the interannual average from 2001 to 2013 is 1600 mm/year. These important precipitations can be explained by the fact that the atmospheric conditions are favourable (preponderance of low intertropical pressures, non-subsidized maritime trade winds and the intensity of thermal convection) and the relatively high relief **[2]**.

The district of Yaya is located in the Chaillu Massif, which is characterized by a plateau relief with a low relief and an average altitude of 500 m, reaching an altitude of 850 m in places. It is also marked by stepped levels of erosion under an almost continuous forest mantle, short hills and ranges framed by a very tight hydrographic network and narrow valleys with waterfalls and rapids indicating one or more rejuvenations. Collectors often have a rectilinear course over part of their course, following tectonic directions, mainly north-south, interrupted by bends **[3]**.

2.1.2. Geological Setting of Yaya District

Situated on the south-eastern edge of the Chaillu massif and close to the Bouenzien outcrop area, the Yaya district is essentially made up of the formations of the latter according to the geological map drawn up by **[4]** and **[3]**.

It is therefore important to carry out a litho-stratigraphic reconnaissance of the geological formations of the Chaillu massif and those of the Bouenzien as well as their tectonic structures in order to interpret the hydrogeological data in a way that is closer to the characteristics of our aquifer.

2.1.2.1. The Formations of the Chaillu Massif

The Chaillu Massif is located in the south-west of Congo, and covers an area of about 25,000 km2. It is defined as a granitoid complex of Meso to Neo-Archean age in which volcano-sedimentary rocks are individualized to form greenstone belts associated with gneisses and intrusive rocks.

The Chaillu Massif appears to be in a cartographic discordance with the Phanerozoic formations of the Batéké Plateaux to the east. On Gabonese territory, the Francevillian series are added to this boundary, which also constitute the northern limit of the basement **[6]**. To the west, it follows the cover formations of western Congo via the Bouenzian underlying this cover. It is a cartographic contact or discordance with these formations, of which the Niari basin of upper Proterozoic age is represented in Gabon by the Nyanga basin. This cover, together with the Bouenzien, also marks the southern limit of this massif **[6]**.

The granitisation of the Chaillu massif has spared some metamorphic sectors, appearing in kilometric massifs and hectometric to metric enclaves **[7]**. They are visible as an elongated structure, oriented northeast southwest in the west of the Chaillu (with a geometric appearance) and north-south in the east of the Chaillu, over a distance of about 30 km. The magmatic formations are represented by granitoid and peridotitic facies. Gneiss and migmatite accompany the magmatic rocks. It is associated with the previous group by amphibolites, pyroxenites, a schistose facies and ferruginous, banded and metamorphosed quartzites or BIF.

From a tectonic and structural point of view, the examination of aerial photographs revealed three (3) fracture directions **[8]**; **[3]**, namely:

- a frequent north-south meridian direction to the north and north-east of the massif. This fracture direction mainly concerns the small arteries, and is thought to be related to the effects of diaclases;
- a frequent NE-SW direction in the centre and west. This is the direction followed by most of the rivers such as the Nianga, the Louessé and the Mpoukou;
- a north-western direction which is mainly represented in the south of the Chaillu Massif.

2.1.2.2. The Geological Formations of the Bouenzien

The Bouenzien outcrops on the southeastern edge of the Chaillu Massif is part of the super group of western Congo where its lateral equivalent is the Louila formation **[9]**.

However, from a genetic point of view **[10]** attributes this geological formation to a detrital series containing subcontinental and sometimes coastal facies indicating sedimentation at the edge of a desert continent.

From a lithological point of view, the most complete succession of the Bouenzien has been described in the locality of Sibiti by **[11]** where it is constituted from bottom to top by: a schistose argillite (BZ1), a feldspathic sandstone (BZ2), a marly limestone (BZ3) and a calcareous sandstone (BZ4).

According to **[3]**, "the Bouenzien series lies in major discordance on the Chaillu granite complex". In the large morphological depressions in the valleys, a small metric level of fine arkosic sandstone, locally coarse, with conglomeratic lenses, is locally observed in contact with the granite, where the clays of the upper level lie directly on the substratum. Furthermore, on the southwestern flank of Chaillu the series is subhorizontal while on the southeastern flank it is folded. In addition to this, lateral variations in facies and truncations mean that the lithology of the Bouenzien varies according to the locality chosen. For our locality, we will refer to the lithology described by **[10]**. The latter noted the presence of only two (2) lower levels of the series, namely: the BZ1 which consists of reddish argillite with sandstone lenses and locally a thin sandstone bank (arkose) in contact with the granite and finally an upper level BZ2. It evokes the difficulty of tracing the contours of the Bouenzien in general and those of its four (4) levels in particular due to the aspects mentioned above, added to these the rarity of intact outcrops and the similarities of the facies of levels BZ1 and BZ3 on the one hand and BZ2 and BZ4 on the other.

From a regional geological standpoint, the upper tillite lies in continuity to the west and in gullying discontinuity to the east over the Bouenzien series, and this tillite supports the schistose limestone and Mpioka group **[3]**; **[12]**.

From a tectonic point of view, the Bouenzian, which belongs to the extreme foreland, shows almost no metamorphism except for a few fold schistosites.

2.1.3. Hydrogeological Context

In Congo, one distinguishes two (2) hydrogeological contexts: sedimentary regions with generalized aquifers formed essentially by loose sedimentary rocks, very little or not consolidated having a porosity of interstice i.e. with very appreciable hydrogeological potentialities and covering the 70 % of the territory and crystalline regions having a porosity of fissures, with random resources, whose aquifers are discontinuous and formed of compact and indurated sedimentary rocks, magmatic and metamorphic rocks and covering the 30 % of the territory.

The permanence of these aquifers depends on climatic regimes, modes of feeding, and the intrinsic hydrogeological and geological contexts of the environment. The Yaya district belongs to the latter context, i.e. crystalline regions, and the crystalline rocks that act as aquifers there are very diverse from the petrographic point of view. In spite of this great diversity, these rocks show a comparable hydrogeological behaviour because in a healthy state they have a great compactness which confers them a porosity and a permeability quasi zero. We see here, the primordial role of the network of local and regional fractures on the one hand, and on the other hand, that of the porosity and permeability of the altered fringe in the system of collection and accumulation of groundwater.

Thus, the work carried out by **[13]** on the "Hydrogeological characterization of exploited aquifers in Yaya district", revealed that it was a discontinuous aquifer. This result is also consistent with previous studies by **[14]** on the hydrogeological map of Africa and **[2]** on the hydrogeology of Congo.

The judicious analysis of the synthetic lithological sections of the various drill holes (**Figure 2**) shows the presence of a thick argilo-silt and lateritic cover that lies on a clay-lateritic to sandy level and the latter, lies on a medium to coarse sandy level. The whole is supported by a substratum made up of blackish arkosic sandstone.

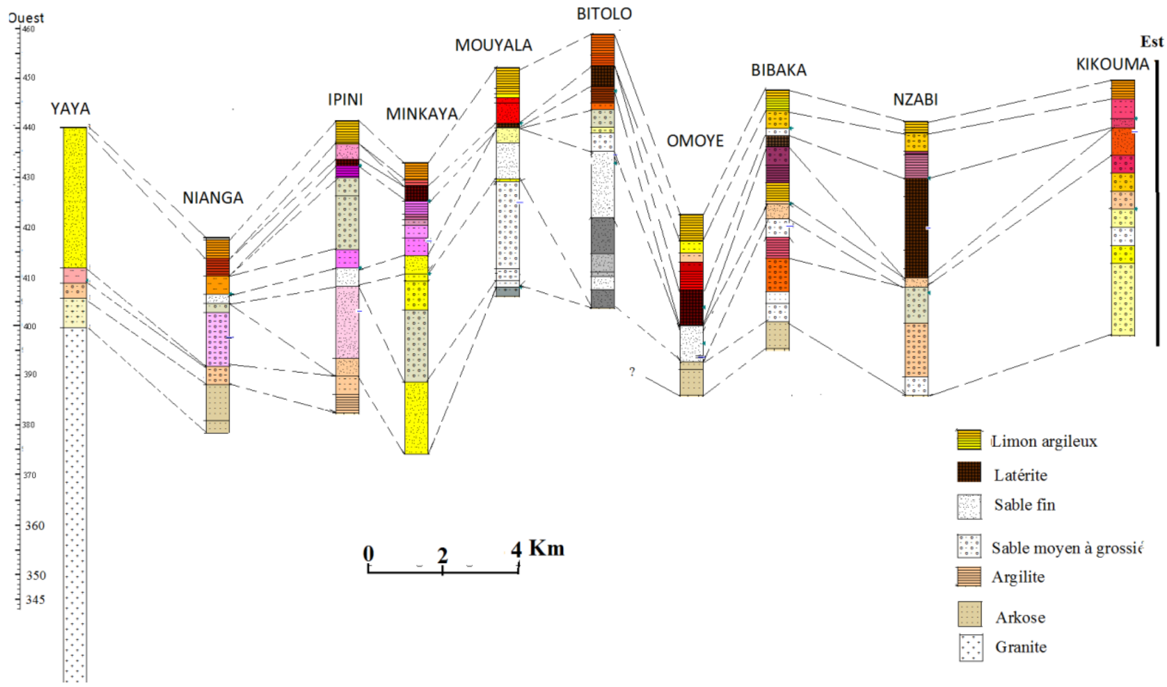

Figure 2. Lithological correlation of the different boreholes drilled in the Yaya district **[12]**

2.2. Methodology used

2.2.1. Acquisition of study data

For this study, samples were taken from more than thirty water points (boreholes, springs and rivers) in Yaya district in August 2015 (dry season) for the first season and in January 2017 (rainy season) for the second season (**Figures 3 and 4)**.

However, it is important to note that, depending on the different types of water, one sample was taken from each borehole and/or spring and two samples were taken from the watercourses (upstream or downstream) depending on whether the sampling was done at the level of the structures on the watercourses (bridges or dallos) or on the right and left banks when there were no geotechnical structures on the watercourses.

2.2.2. Laboratory phase

Samples taken in the field were then sent to the IRSEN laboratory for analysis. At the laboratory, pH and electrical conductivity were determined and the following elements were chemically analysed: Cl^-, SO_4^{2-}, NO_3^-, HCO_3^-, PO_4^{3-}, F^-, Na^+, K^+, Mg^{2+}, Ca^{2+}, Al^{3+}, Pb^{2+}, total iron (Fe_{tot}) and Cr^{6+}.

The pH and electrical conductivity were determined using a pH meter and a conductivity meter, respectively. The chemical analyses of Cl^-, SO_4^{2-}, NO_3^-, Na^+, K^+, Mg^{2+} and Ca^{2+} ions were carried out using a PC7000 type photometer; those of Al^{3+}, Pb^{2+}, F^-, PO_4^{3-}, total iron (Fe_{tot}) and Cr^{6+} ions were carried out using a Lovibond type spectrodirect and those of bicarbonate ions (HCO3-) by titrimetry.

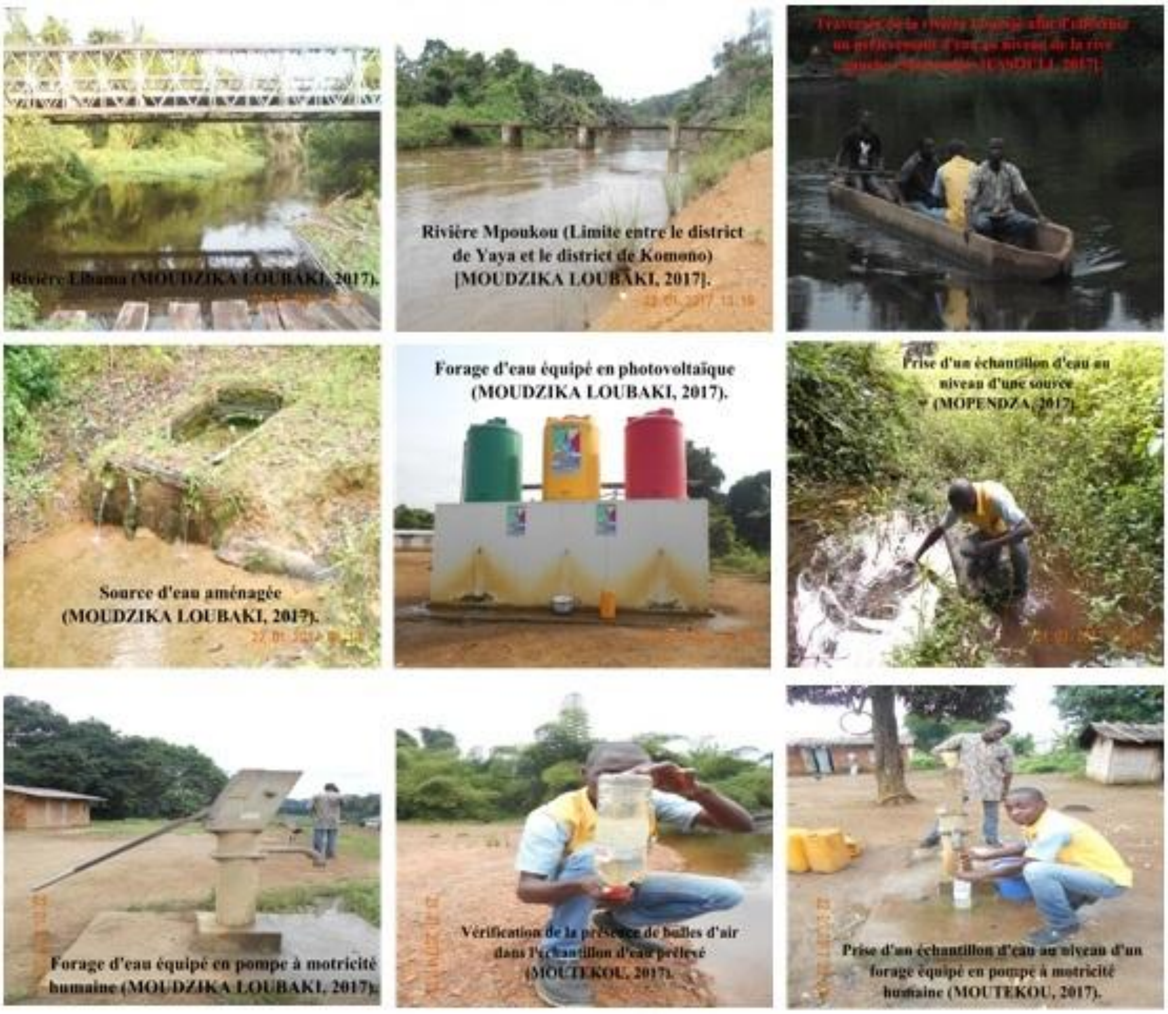

Figure 3. Different groundwater and surface water abstraction points in Yaya District [1]

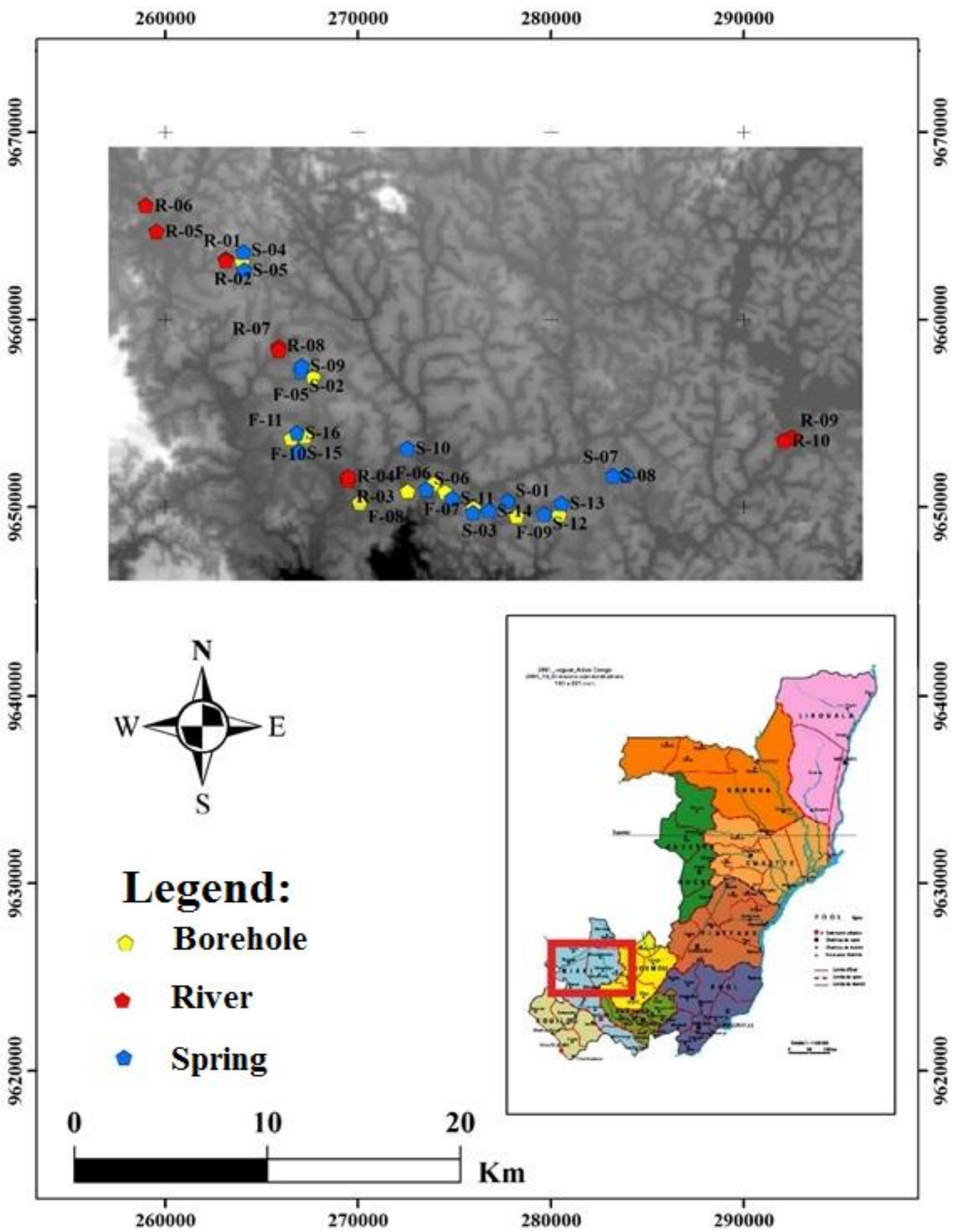

Figure 4. Location of groundwater and surface water sampling points in Yaya District [1]

2.2.3. Data processing

2.2.3.1. Verification of the ionic balance

The solutions are electrically balanced and therefore the sum of the positive charges is equal to the sum of the negative charges. The ionic balance must be correct, i.e. the sum of the cationic charges must be equal to the sum of the anionic charges.

Before any data processing, the calculation of the ionic balance, which is the relative difference between the sum of the cations and the sum of the anions, is indispensable because it allows the accuracy of the analytical methods used and the validity of the chemical determinations to be verified **[15]**; **[16]**. If the relative deviation is less than 5%, the analyses can be considered good. When the value is between 5% and 10%, the analyses may be retained. Above 10 %, the analyses should be rejected because there were errors in sampling or the analytical methods are imprecise or one or more elements in solution have not been determined.

In our study, the ion balances were less than 5% over all the analyses performed, which is a testimony to the good quality of the analyses. The collected data were then processed by different methods of interpretation of the hydrochemical data.

2.2.3.2. Study of the aggressiveness of groundwater and surface water in the Yaya district

The phenomenon of water aggressiveness has been studied by several authors who have proposed methods for its qualitative and quantitative evaluation. These authors include Langelier, Ryznar, Larson, Stiff and Davis for qualitative methods; Hallopeau-Dubin, Girard, for quantitative methods. However, in the case of this study, we have chosen the stability indices of Langelier and Ryznar.

Langelier Stability Index (LSI)

The Langelier Index is a measure of the involvement of the chemical quality of the water in the premature destruction of strainers, pumps and water pipes.

Langelier assesses the aggressiveness of the water using as data the total salinity or dry residue at 110°C, temperature, calcium content and alkalinity. He thus calculates the pH that the solution should have to be in equilibrium with the calcium carbonate. By comparing the calculated value with the pH of the water, he determines whether the water is aggressive or encrusting, thus defining an aggressiveness index:

$$\mathbf{ISL=pHmes-pHsat}$$

With: pHmeas = pH measured in the field and pHsat = pH saturation (calculated) from the chart software.

Table 1 below shows the relationship between Langelier stability index values and the aggressive tendency of the water.

Langelier Stability Indexes	Aggressive Water Trend
$IS_L>0$	Scaling or encrusting waters. This phenomenon can lead to clogging of certain parts of the collecting system, which considerably reduces the pumping flow rate.
$IS_L=0$	Water in balance
$IS_L<0$	Aggressive waters and can attack metal equipment in water pipes.

Ryznar Stability Index

The Ryznar stability index is an empirical expression that determines the corrosive tendency of water and is calculated by the following formula:

$$\mathbf{SRI = S - C\text{-}pH = 2pHsat - pHmes}$$

With:

SRI: Ryznar stability index; pHsat = pH saturation (calculated); pHmes: measured pH; S: constant derived from dissolved solids;
C: constant derived from alkalinity and calcium.

Table 2 below shows the relationship between the Ryznar stability index and the corrosive tendency of the water:

IS_R	Trend
4 à 5	Heavy scaling
5 à 6	Low scaling
6 à 7	Equilibre
7 à 7,5	Slight corrosivity
7,5 à 8,5	High corrosivity
>8,5	Very high corrosivity

III. RESULTS AND DISCUSSION

3.1. Physico-chemical characteristics of groundwater and surface water

The present study, which deals with the data of the January 2017 campaign (**Table 3**) and the August 2015 campaign (**Table 4**), is taken up here with a view to estimating the spatial and temporal evolution of the mineralization of ground and surface water in the Yaya district.

Groundwater and surface water have pH values that range from 5 to 6.32 for groundwater and 6.07 to 7.08 for surface water. These recorded pH values indicate that groundwater and surface water are acidic to slightly neutral and that alkalinity is mainly controlled by bicarbonate ions (HCO_3^-).

Depending on the electrical conductivity, these waters have electrical conductivity values between 20 and 48 µS/cm for ground water and between 27 and 50 µS/cm for surface water. On the whole, they are weakly mineralized because the electrical conductivity values are lower than 250 µS/cm **[17]**.

Figure 5 shows the groundwater and surface water classification for the January 2017 and August 2015 campaigns based on Piper's triangular diagram.

The lozenge diagram of the January 2017 campaign shows that the surface and groundwater of Yaya District are characterized by two (2) chemical families, namely:

- the chemical family of calcium and magnesium chloride sulphates, which represents 95%;
- and the chemical family of calcium and magnesium bicarbonates which represents 5%.

However, the lozenge diagram of the August 2015 campaign shows that groundwater and surface water are characterized by four (4) chemical families, namely:

- the chemical family of calcium and magnesium chloride sulphates, which represents 47%;
- the chemical family of calcium and magnesium bicarbonates which represents 39%;
- the chemical family of sodium and potassium chlorides or sodium sulphate which represents 11%;
- the chemical family of sodium and potassium bicarbonates, which represents 3%.

The triangular diagram of the anions of the January 2017 campaign, shows a predominance of water points with evolution towards the sulphated pole which represent 52%; water points with evolution towards the pole with mixed facies i.e. where no anion dominates the other which represent 43% and two (2) water points with evolution towards the bicarbonate pole which represent 5%.

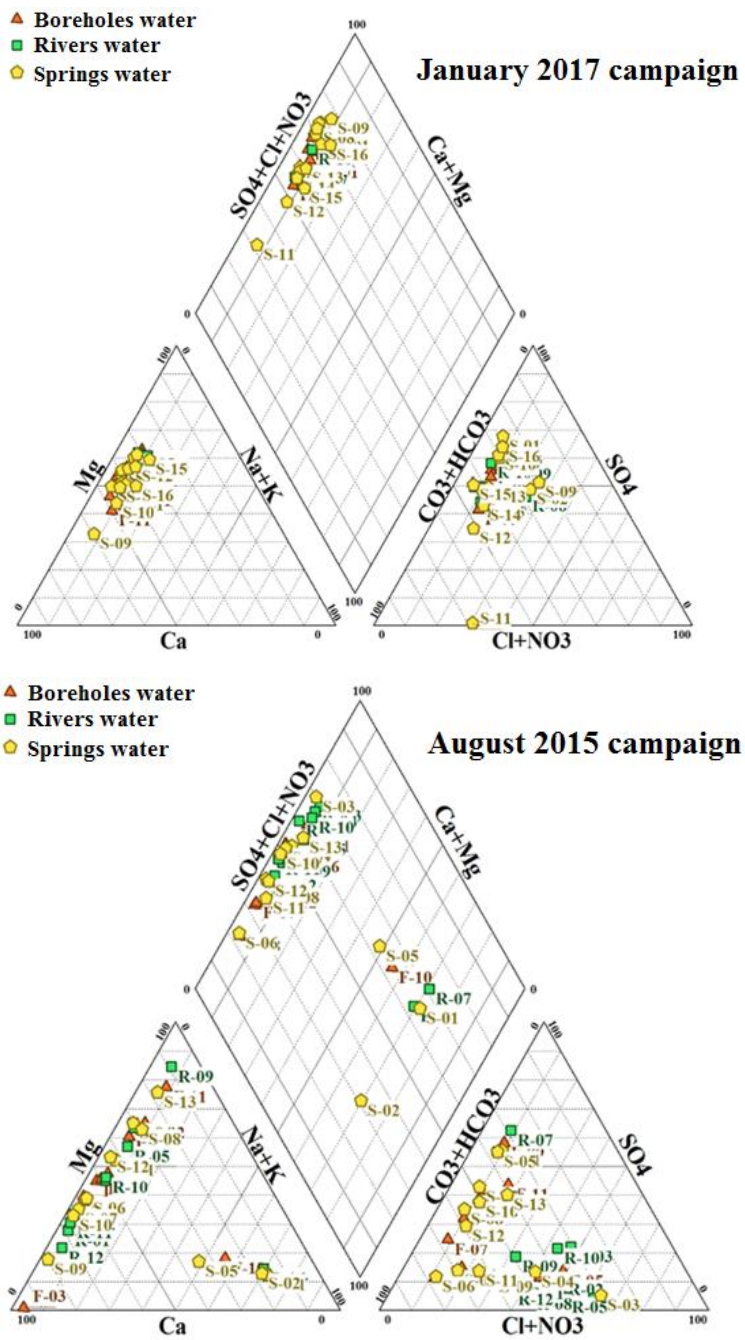

Figure 5. Classification of groundwater and surface water using Piper's triangular diagram **[1]**.

Contrary to the triangular diagram of the anions of the campaign of January 2017, that of August 2015, shows a predominance of the water points with evolution towards the bicarbonate pole which represent 42%; water points with evolution towards the pole with mixed facies i.e. where no anion dominates the other which represent 30%; water points with evolution towards the sulphated pole which represent 17% and four (4) water points with evolution towards the chlorinated pole which represent 11%.

Table 3. Results of physico-chemical analyses in mg/L of groundwater and surface water in Yaya district (January 2017)

Names of works	Labels	pH	EC (µS/cm)	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	SO_4^{2-}	NO_3^{-}	Al^{3+}	Pb^{2+}	Fe_{tot}	Cr^{6+}	F^{-}	PO_4^{3-}
Bibaka village borehole	**F-01**	5,74	25	130	15	11	0,3	8,5	5,76	38,55	50,37	0,67	0,1	0,1	0,09	0,08	0,12	0,17
Bitolo village borehole	**F-02**	5,06	30	134	17	13	0,17	3,3	6,92	36,83	56,31	0,60	0,9	0,7	0,1	0,08	0,19	0,11
Gonaka village borehole	**F-03**	6,17	40	118	13	12	0,18	4	7,92	42,83	37,96	0,01	0,9	0,29	0,11	0,08	0,16	0,12
Ipini village borehole	**F-04**	6	20	121	17	10	0,15	3,9	5,18	37,83	46,51	0,73	0,1	0,8	0,7	0,07	0,18	0,13
Mikoubou village borehole	**F-05**	6,03	20	154	17	14	0,22	7	9,28	56,92	44,98	1,83	0,7	0,7	0,9	0,07	0,11	0,11
Mingaya village borehole	**F-06**	6,17	25	142	17	14	0,18	4	6,32	40,90	58,81	0,61	0,1	0,12	0,6	0,06	0,13	0,13
Mouyala village borehole	**F-07**	5,22	30	100	11	10	0,15	3,7	4,71	24,41	43,77	0,18	0,1	0,18	0,1	0,07	0,9	0,1
Nianga village borehole	**F-08**	5,6	30	116	10	13	0,14	5	7,10	47,37	33,28	0,24	0,7	0,3	0,09	0,06	0,16	0,15
Nzabi village borehole	**F-09**	6,02	24	109	13	10	0,18	5	5,62	35,20	40,28	0,10	0,13	0,11	0,1	0,08	0,12	0,17
Central Yaya borehole 1	**F-10**	6,07	30	115	10	12	0,13	6,5	3,29	42,98	39,88	0,12	0,9	0,2	0,8	0,08	0,16	0,22
Central Yaya borehole 2	**F-11**	5,82	25	138	20	10	0,18	6,9	6,76	39,79	53,95	0,48	0,1	0,1	0,08	0,09	0,9	0,15
Gonaka river (Upstream)	**R-01**	6,17	50	118	11	13	0,18	4,7	7,32	42,98	38,60	0,16	0,9	0,21	0,08	0,06	0,17	0,15
Gonaka river (Downstream)	**R-02**	6,25	45	108	10	12	0,17	4	6,33	42,36	33,25	0,05	0,6	0,19	0,06	0,07	0,15	0,11
Libama river (Upstream)	**R-03**	6,20	40	102	9	11	0,12	5,2	3,84	38,18	35,02	0,07	0,13	0,4	0,9	0,06	0,16	0,13
Libama river (Downstream)	**R-04**	6,22	30	110	10	12	0,1	4,9	6,95	42,06	33,54	0,14	0,1	0,32	0,8	0,07	0,17	0,18
Louesse river (left strand)	**R-05**	6,07	50	134	18	11	0,19	8	17,18	35,38	43,69	0,49	0,15	0,35	0,13	0,11	0,18	0,2
Louesse river (right strand)	**R-06**	7,02	50	154	19	11,8	0,19	8,4	18,17	37,47	46,74	0,54	0,16	0,35	0,13	0,11	0,18	0,22
Moutamba river (Upstream)	**R-07**	7,05	40	95	9	10	0,11	5	5,06	33,22	32,79	0,19	0,12	0,18	0,09	0,07	0,17	0,2
Moutamba river (Downstream)	**R-08**	6,42	50	86	7	9	0,13	4,8	2,77	31,71	28,20	0,07	0,1	0,25	0,08	0,06	0,13	0,14
Mpoukou river (left strand)	**R-09**	7,08	28	108	12	11	0,17	4,7	7,76	27,64	44,20	0,50	0,12	0,28	0,9	0,12	0,15	0,2
Mpoukou river (right strand)	**R-10**	7,06	27	123	15	11	0,1	5	3,00	36,63	49,00	3,18	0,9	0,17	0,7	0,06	0,13	0,26
Bibaka village spring	**S-01**	6,00	20	145	18	12	0,33	8,7	4,54	32,63	68,02	0,91	0,11	0,13	0,09	0,05	0,13	0,13
Bibayi village spring	**S-02**	5,32	25	136	17	14	0,18	4,1	18,08	33,58	48,76	0,35	0,1	0,12	0,8	0,09	0,19	0,18
Bitolo village spring	**S-03**	5,00	20	132	18	12	0,16	3,4	6,47	32,72	58,64	0,65	0,8	0,8	0,11	0,09	0,2	0,15
Gonaka village spring 1	**S-04**	6,00	30	111	11	12	0,18	3,9	6,85	40,74	36,26	0,13	0,1	0,3	0,1	0,09	0,14	0,13
Gonaka village spring 2	**S-05**	6,02	48	127	12	14	0,2	4,9	8,93	47,91	39,22	0,15	0,1	0,28	0,09	0,08	0,14	0,1
Ipini village spring	**S-06**	5,17	25	123	15	11	0,17	4,8	5,70	44,56	40,84	0,74	0,7	0,1	0,8	0,05	0,16	0,12

Kikouma village spring 1	**S-07**	6,13	39	138	16	14	0,2	4,2	6,68	37,73	58,79	0,50	0,12	0,1	0,12	0,07	0,2	0,42
Kikouma village spring 2	**S-08**	6,32	40	118	14	12	0,19	3,2	5,76	30,66	51,68	0,34	0,11	0,9	0,9	0,06	0,2	0,11
Mikoubou village spring	**S-09**	6,00	20	85	15	5	0,2	3,5	11,15	16,82	29,98	0,32	0,12	0,17	0,9	0,07	0,15	0,18
Mingaya village spring	**S-10**	6,13	30	116	16	9	0,2	5,8	4,92	30,70	48,78	0,39	0,9	0,12	0,7	0,05	0,14	0,14
Mouyala village spring	**S-11**	5,30	33	111	12	11	0,18	4	16,77	66,08	0,69	0,57	0,12	0,25	0,12	0,08	0,12	0,16
Nzabi village spring	**S-12**	5,77	35	110	11	11	0,15	5,2	7,71	48,90	26,10	0,01	0,1	0,27	0,06	0,07	0,1	0,1
Nzabi village spring	**S-13**	5,90	22	100	12	9	0,16	4,8	5,73	34,46	34,09	0,02	0,11	0,9	0,9	0,07	0,11	0,15
Omoye village spring	**S-14**	6,05	40	103	13	9	0,13	4,2	6,71	39,66	30,39	0,16	0,9	0,13	0,7	0,06	0,14	0,13
Central Yaya spring 1	**S-15**	6,01	28	96	8	10	0,11	6,2	3,03	35,87	32,72	0,02	0,7	0,17	0,7	0,09	0,14	0,18
Central Yaya spring	**S-16**	5,70	25	89	10	8	0,16	6	3,79	21,76	39,56	0,16	0,8	0,15	0,08	0,07	0,13	0,15

Table 4. Results of physico-chemical analyses in mg/L of ground and surface water in Yaya district (August 2015 campaign)

Names of works	Labels	pH	EC (µS/cm)	TDS	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Fe_{tot}	Al^{3+}	PO_4^{3-}	Mn^{2+}	NH_4^+	Cu^{2+}
Bibaka village borehole	**F-01**	5	13	182	30	12,4	1,2	0,72	74,04	6,27	51,01	6,12	0,01	0,02	0,06	0,16	0,04	0,9
Bibayi village borehole	**F-02**	4,38	14	112	8,5	12,5	2,7	1,4	55,45	3,83	23,76	2,62	0,031	0,018	0,07	0,36	0,012	0,48
Bitolo village borehole	**F-03**	5	10	276	70	0,44	3	1,16	149,07	18,44	25,77	7,18	0,09	0,012	0,07	0,3	<0,02	1,25
Mouyala village borehole	**F-04**	5,6	15	197	35	11	3	0,15	83,20	5,63	50,21	8,58	0,012	0,021	0,08	0,17	<0,02	0,015
Ipini village borehole	**F-05**	4,51	13	132	12,4	13,3	2,2	1,1	40,89	7,15	11,74	41,68	0,017	0,014	0,08	0,6	0,014	0,57
Gonaka village borehole	**F-06**	4,45	22	158	12,3	15,9	3,6	2,1	57,72	2,95	11,39	50,51	0,035	0,03	0,08	0,5	0,014	0,6
Kikouma village borehole	**F-07**	5,07	15	127	18	9,5	2,12	0,18	69,62	3,47	20,27	3,10	0,014	0,017	0,08	0,14	0,017	0,014
Nzabi village borehole	**F-08**	6,1	17	133	18	10	2,1	0,65	83,51	4,71	9,73	4,22	0,029	0,015	0,05	0,14	0,03	0,12
Boudzouka village borehole	**F-09**	4,43	13	132	18	11	2,2	1,25	38,04	3,45	52,68	4,13	0,012	0,019	0,07	0,17	<0,02	0,12
Mingaya village borehole	**F-10**	5	10	14	0,8	0,34	3	0,22	3,95	0,19	4,67	0,58	0,02	0,037	0,05	0,12	0,06	0,8
Central Yaya borehole	**F-11**	4,7	12	79	3,22	10,7	1,1	1,55	26,44	0,10	23,31	11,85	0,03	0,018	0,06	0,37	0,015	0,58
Libama river (right strand)	**R-02**	6,70	17	268	48,8	15,3	0,8	1,67	89,94	33,35	19,30	58,13	0,012	0,017	0,05	0,48	0,04	0,53
Libama river (left strand)	**R-09**	6,40	19	104	2,7	15	1,6	1,2	43,39	2,47	12,81	24,08	0,019	0,015	0,06	0,38	0,011	0,53
Louesse river (right strand)	**R-03**	6	20	214	30,3	17	2,1	3,14	57,50	24,90	32,64	46,33	0,02	0,01	0,08	0,28	0,07	0,55
Gonaka river (right strand)	**R-04**	5,7	19	125	10,7	13,3	1,65	1,3	34,10	8,22	3,46	51,79	0,026	0,027	0,06	0,39	0,012	0,52
Gonaka river (left strand)	**R-05**	4,65	10	123	12,2	11,6	1,87	1,6	41,51	7,26	3,66	42,73	0,026	0,028	0,05	0,41	0,013	0,55
Mpoukou river (right strand)	**R-06**	6,27	23	15	0,67	0,36	2,12	2,05	3,95	0,19	4,67	0,58	0,017	0,018	0,06	0,09	0,07	0,16
Mpoukou river (left strand)	**R-07**	6,1	24	16	0,7	0,33	3	1,75	3,25	0,17	5,51	0,70	0,018	0,017	0,07	0,2	0,07	0,14

Libama river (Ipini) (right strand)	**R-08**	6,94	13	130	10,8	14	1,8	0,85	54,92	5,71	4,68	36,44	0,009	0,016	0,06	0,45	0,012	0,55
Libama river (Ipini) (left strand)	**R-01**	6,14	17	332	60,2	14,8	1,6	2,7	124,07	15,37	13,10	100,13	0,012	0,018	0,09	0,34	0,05	0,48
Louesse river (left strand)	**R-10**	6,14	20	208	28,9	16,8	2,07	2,8	63,45	22,91	30,71	39,94	0,024	0,01	0,07	0,3	0,07	0,5
Moutamba river (right strand)	**R-11**	4,35	12	263	47	13	2,2	0,95	110,91	14,10	15,60	58,53	0,027	0,028	0,07	0,16	0,05	0,36
Moutamba river (left strand)	**R-12**	5,6	10	202	39	7	2,9	1,08	89,49	8,42	9,12	44,40	0,027	0,03	0,06	0,18	0,04	0,37
Mingaya village spring 2	**S-01**	4,9	13	16	0,72	0,33	1,8	2,6	4,12	0,23	5,11	0,75	0,018	0,013	0,08	0,1	0,06	0,1
Yaya central spring 2	**S-02**	4,74	15	21	0,98	0,44	2,25	3,18	10,14	0,80	1,61	1,12	0,013	0,015	0,08	0,11	0,04	0,13
Gonaka village spring	**S-03**	4,38	21	198	30	12	1,7	1	46,70	4,66	6,53	93,71	0,03	0,045	0,08	0,58	0,03	0,62
Ipini village spring	**S-04**	4,75	14	158	13,4	17,4	2	1,16	60,99	8,72	14,15	39,49	0,018	0,013	0,09	0,67	0,01	0,62
Kikouma village spring	**S-05**	5,7	12	14	1	0,3	2,25	0,3	3,95	0,19	4,67	0,58	0,027	0,048	0,08	0,18	0,05	0,11
Nzabi village spring	**S-06**	5,14	16	141	22	9	1,5	0,7	88,19	5,16	10,55	4,02	0,015	0,02	0,07	0,12	0,03	0,13
Bibaka village spring	**S-07**	4,75	15	167	29	10	1,14	0,96	68,02	4,23	47,62	5,29	0,013	0,026	0,05	0,14	0,03	0,1
Bibayi village spring	**S-08**	4,35	12	124	10	13,3	3	1,6	59,07	3,18	28,92	3,25	0,04	0,02	0,08	0,33	0,013	0,55
Bitolo village spring	**S-09**	4,4	12	370	82	11	2,7	1,45	184,43	44,06	28,46	14,43	0,01	0,019	0,06	0,14	<0,02	0,75
Mingaya village spring 1	**S-10**	4,25	10	236	42	13	2,9	0,18	99,74	6,20	58,15	12,45	0,08	0,04	0,05	0,13	0,03	0,6
Mouyala village spring	**S-11**	4,51	11	169	20	15	4	0,82	89,70	14,98	15,53	7,76	0,014	0,017	0,08	0,28	<0,02	0,28
Omoye village spring	**S-12**	6,12	13	123	15	11,2	2,17	0,16	61,34	4,40	24,00	4,57	0,01	0,03	0,07	0,2	0,03	0,017
Central Yaya spring 1	**S-13**	5,4	10	94	4,75	12,4	1,85	0,97	33,09	0,02	25,41	15,32	0,028	0,02	0,05	0,4	0,017	0,6

The triangular diagram of cations for the January 2017 campaign shows a predominance of water points with evolution towards the magnetic pole, which represent 70%; water points with evolution towards the pole with mixed facies, i.e., where no cation dominates the other, which represent 27%, and one water point with evolution towards the calcium pole (S-09, which represents 3%). In contrast to the triangular cation diagram of the January 2017 campaign, the August 2015 campaign shows a predominance of water points with evolution towards the calcium pole, which represent 36%; water points with evolution towards the magnetic pole, which also represent 36%; water points with evolution towards the pole with mixed facies, i.e. where no cation dominates the other, which represent 14% and water points with evolution towards the sodium and potassium pole, which also represent 14%.

The diagram (**Figure 6**) below shows the classification of ground and surface water in Yaya District for the campaigns of August 2015 and January 2017:

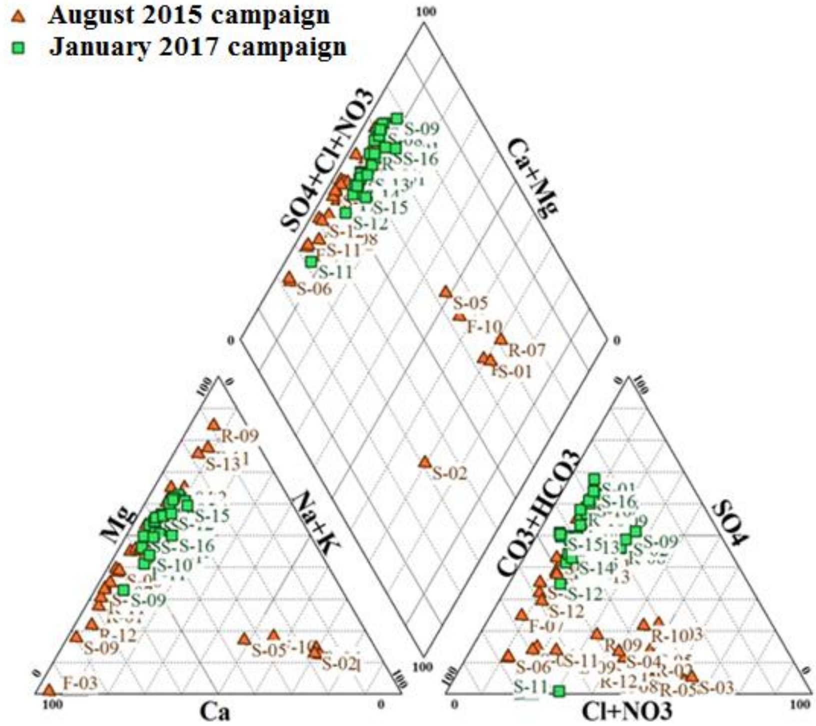

Figure 7. Evolution of water chemistry between August 2015 and January 2017 **[1]**

3.2. Ground and Surface Water Quality in Yaya District

Tables 5and 6 present the drinking water standards for some physico-chemical water parameters established by the World Health Organization **[18]** and the physico-chemical contents (minimum and maximum) of ground and surface water in Yaya District.

Figures 8 to **10** below show the variations in nitrate, magnesium, aluminium, lead, total iron and hexavalent chromium levels in the ground and surface waters of Yaya District.

Fluorine concentrations range from 0.1 to 0.9 mg/L for the January 2017 campaign and from 0.13 to 0.18 mg/L for the January 2017 campaign. As the WHO maximum allowable concentration value for fluoride in drinking water is 1.5 mg/L, all water points tested during both campaigns have fluoride levels that are below the WHO maximum allowable concentration for drinking water. However, fluoride concentrations below 0.5 mg/L in drinking water can promote dental caries **[19]**. However, at very high concentrations (above 1.5-2 mg/L), fluoride in drinking water can cause dental and/or bone fluorosis (**[20]**; **[21]**).

Total iron (FeTot) concentrations range from 0.06 to 0.9 mg/L for the January 2017 campaign and 0.06 to 0.12 mg/L for the August 2015 campaign. Since the WHO maximum allowable concentration value for total iron in drinking water is 0.3 mg/L, only 16 of the 37 water points tested in the January

2017 campaign have FeTot concentrations that exceed the WHO guideline value (**Figures 8c** and **9c**). Although iron is essential for the human body, very high iron concentrations affect the organoleptic properties of water and also stain laundry. In groundwater, iron can exist as soluble ferrous iron (Fe2+) or as insoluble ferric iron (Fe3+) which can be complexed, colloidal or precipitated. The presence of iron in water can promote the growth of certain strains of bacteria that precipitate iron or corrode pipes **[22]**.

Hexavalent chromium (Cr6+) concentrations range from 0.05 to 0.12 mg/L for the January 2017 campaign and from 0.06 to 0.12 mg/L for the August 2015 campaign. For both sampling campaigns, the chromium levels in the various water points analysed are greater than or equal to the maximum allowable concentration of 0.05 mg/L defined for drinking water by the WHO (**Figures 8** and **9**). Concentrations above this guideline value in drinking water can lead to skin rashes, gastric ulcers, a weakened immune system, and even lung cancer as a cumulative effect.

Lead (Pb^{2+}) levels range from 0.1 to 0.9 mg/L for the January 2017 campaign and 0.17 to 0.40 mg/L for the August 2015 campaign. Lead concentrations above the WHO drinking water potability guideline value can lead to brain and reproductive disorders, and the most severe type of lead poisoning leads to encephalopathy **[23]**.

Aluminum (Al^{3+}) concentrations range from 0.1 to 0.9 mg/L for the January 2017 campaign and 0.1 to 0.9 mg/L for the August 2015 campaign. Since the WHO drinking water guideline value for aluminum in drinking water is 0.1 mg/L, all water points tested have aluminum levels greater than or equal to the WHO drinking water guideline value (**Figures 9** and **10**).

Table 5.WHO (2004) potability standards and levels of physico-chemical groundwater parameters (January 2017 campaign)

Physico-chemical parameters	WHO (2004) maximum allowable values	Content of physico-chemical groundwater parameters	
		Minimum	Maximum
EC (µS/cm)	2000	20	48
pH	9,60	5	6,32
TDS (mg/L)	500	86	155
Ca^{2+} (mg/L)	100	8	20
Mg^{2+} (mg/L)	50	5	14
Na^{+} (mg/L)	100	0,11	0,33
K^{+} (mg/L)	12	3,20	8,70
Cl^{-} (mg/L)	200	3,03	18,08
HCO_3^{-} (mg/L)	-	16,82	66,08
NO_3^{-} (mg/L)	50	0,01	1,83
SO_4^{2-} (mg/L)	250	0,69	68,02
F^{-} (mg/L)	1,5	0,10	0,90
Fe_{tot} (mg/L)	0,3	0,06	0,9
Cr^{6+} (mg/L)	0,05	0,05	0,09
Pb^{2+} (mg/L)	0,01	0,10	0,9
Al^{3+} (mg/L)	0,1	0,10	0,9
PO_4^{3-} (mg/L)	0,5	0,10	0,42

Table 6. WHO (2004) potability standards and levels of physico-chemical parameters in surface waters (January 2017 campaign)

Physico-chemical parameters	WHO (2004) maximum allowable values	Contents of the physico-chemical parameters of surface waters	
		Minimum	Maximum
EC (µS/cm)	2000	27	50
pH	9,60	6,07	7,08
TDS (mg/L)	500	87	157
Ca^{2+} (mg/L)	100	7	19
Mg^{2+} (mg/L)	50	9	13
Na^{+} (mg/L)	100	0,10	0,19
K^{+} (mg/L)	12	4	8,40
Cl^{-} (mg/L)	200	2,77	18,17
HCO_3^{-} (mg/L)	-	27,64	42,98
NO_3^{-} (mg/L)	50	0,05	3,18
SO_4^{2-} (mg/L)	250	28,20	49
F^{-} (mg/L)	1,50	0,13	0,18
Fe_{tot} (mg/L)	0,30	0,06	0,90
Cr^{6+} (mg/L)	0,05	0,06	0,12
Pb^{2+} (mg/L)	0,01	0,17	0,40
Al^{3+} (mg/L)	0,10	0,10	0,90
PO_4^{3-} (mg/L)	0,50	0,11	0,26

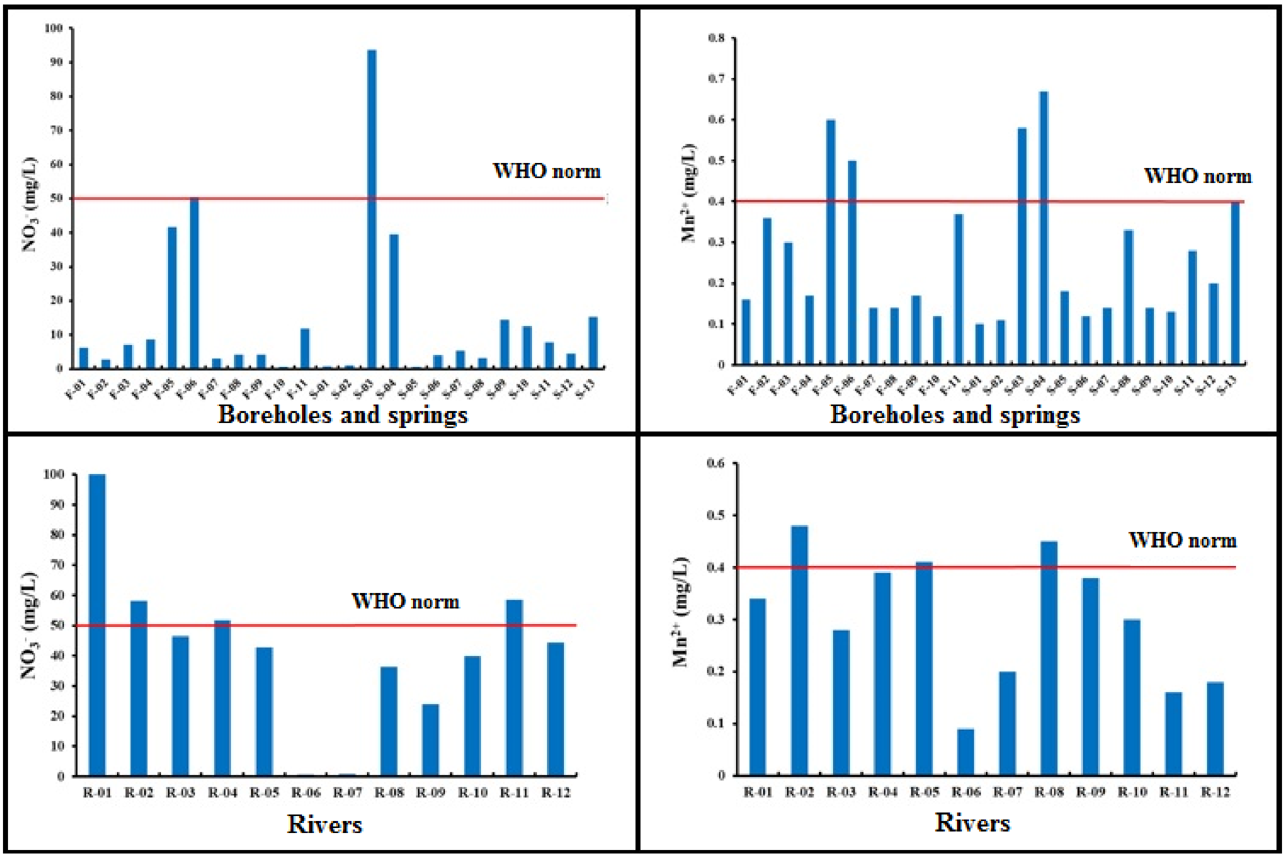

Figure 8. Variation of nitrate and manganese contents in groundwater and surface water for the August 2015 campaign **[1]**

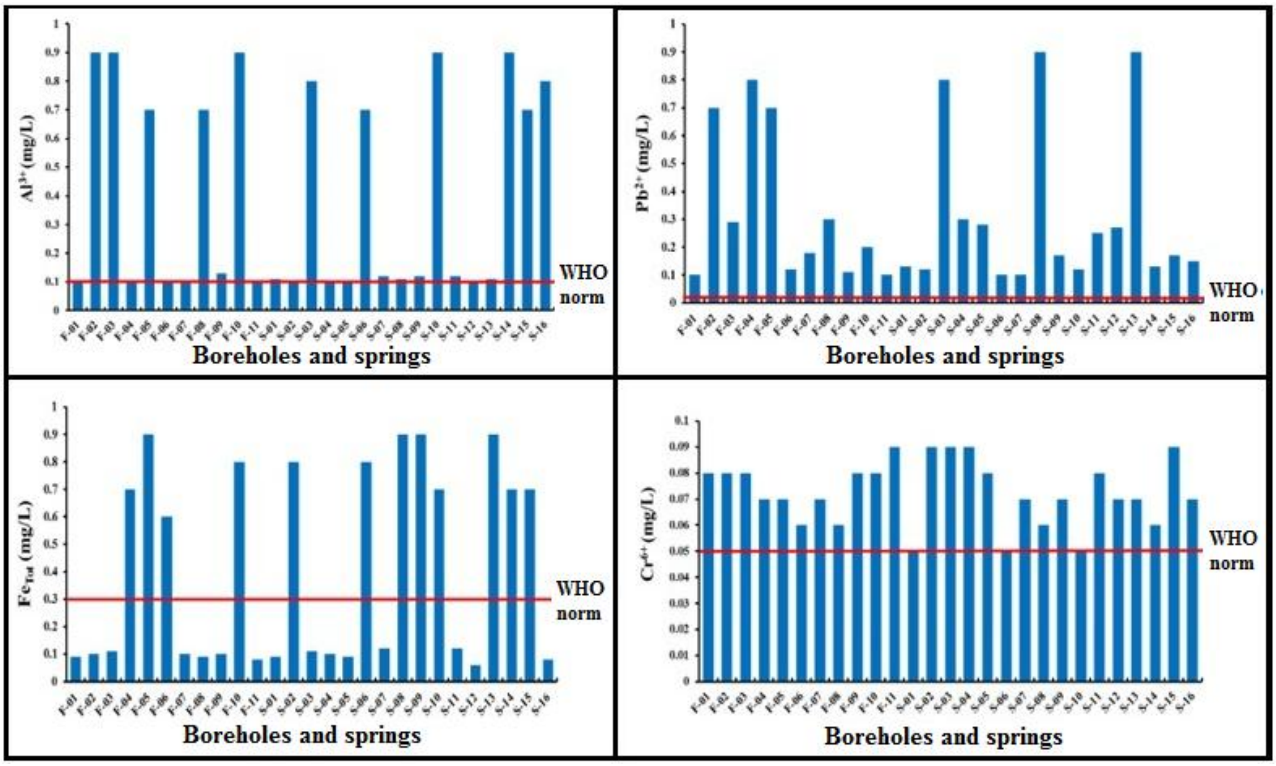

Figure 9. Diagrams of changes in the levels of aluminium, lead, total iron and chromium in groundwater [1]

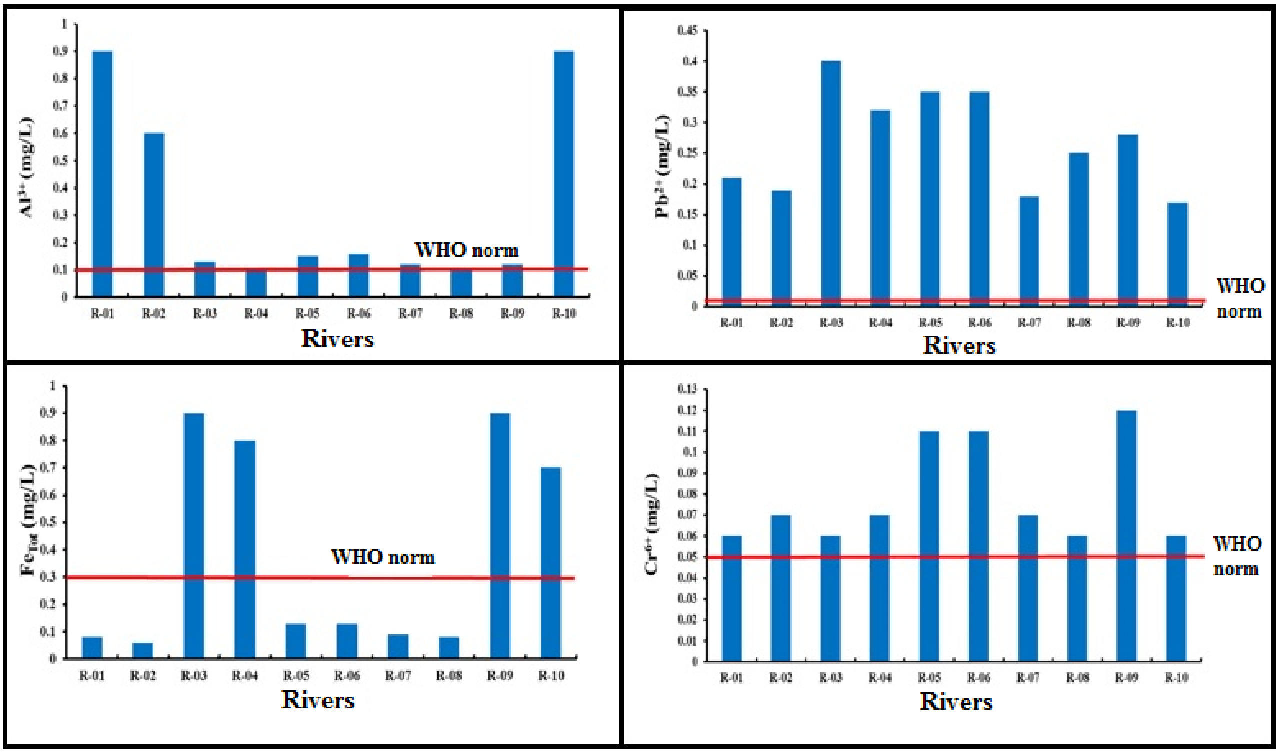

Figure 10. Diagrams of variation in the contents of aluminium, lead, total iron and chromium in surface waters [1]

3.3. Groundwater and surface water stress in Yaya District

Within the framework of this study, the Ryznar and Langelier indices for determining the aggressive character of the ground and surface waters of the Yaya district were determined using the hydrogeochemical diagram software of Roland Simler from the University of Avignon. **Tables 7 and 8** below show the different values of the Ryznar and Langelier stability indices.

Table 7. Ryznar and Langelier stability index of groundwater and surface water (January 2017)

Names of works	Labels	IS_R (Ryznar)	IS_L (Langelier)
Bibaka village borehole	**F-01**	11,46	-2,86
Bitolo village borehole	**F-02**	12,09	-3,51
Gonaka village borehole	**F-03**	11,06	2,44
Ipini village borehole	**F-04**	11,11	-2,55
Kikouma village borehole	**F-05**	10,74	-2,36
Mingaya village borehole	**F-06**	10,89	-2,36
Mouyala village borehole	**F-07**	12,63	-3,70
Nianga village borehole	**F-08**	11,76	-3,08
Nzabi village borehole	**F-09**	11,37	-2,67
Yaya centre borehole 1	**F-10**	11,38	-2,65
Yaya centre borehole 2	**F-11**	11,12	-2,65
Gonaka river (Upstream)	**R-01**	11,20	-2,51
Gonaka river (Downstream)	**R-02**	11,20	-2,48
Libama river (Upstream)	**R-03**	11,43	-2,62
Libama river (Downstream)	**R-04**	11,24	-2,51
La Louessé river (left strand)	**R-05**	11,06	-2,49
La Louessé river (right strand)	**R-06**	10,03	-1,50
Moutamba river (Upstream)	**R-07**	10,69	-1,82
Moutamba river (Downstream)	**R-08**	11,57	-2,57
Mpoukou river (left strand)	**R-09**	10,59	-1,76
Mpoukou river (right strand)	**R-10**	10,18	-1,56
Bibaka village spring	**S-01**	11,21	-2,60
Bibayi village spring	**S-02**	11,91	-3,29
Bitolo village spring	**S-03**	12,20	-3,60
Gonaka village spring 1	**S-04**	11,41	-2,70
Gonaka village spring 2	**S-05**	11,19	-2,58
Ipini village spring	**S-06**	11,90	-3,37
Kikouma village spring 1	**S-07**	11,05	-2,46
Kikouma village spring 2	**S-08**	11,14	-2,41
Mikoubou village spring	**S-09**	11,88	-2,94
Mingaya village spring	**S-10**	11,21	-2,54
Mouyala village spring	**S-11**	11,60	-3,15
Nzabi village spring 1	**S-12**	11,47	-2,85
Nzabi village spring 2	**S-13**	11,57	-2,83
Omoye village spring	**S-14**	11,23	-2,59
Yaya centre spring 1	**S-15**	11,77	-2,88
Yaya centre spring 2	**S-16**	12,32	-3,31

Table 8. Ryznar and Langelier stability index of groundwater and surface water (August 2015).

Names of works	Labels	SRI (Ryznar)	SLI (Langelier)
Bibaka village borehole	**F-01**	12,69	-3,85
Bibayi village borehole	**F-02**	13,93	-4,74
Bitolo village borehole	**F-03**	11,51	-3,26
Mouyala village borehole	**F-04**	11,59	-2,66
Ipini village borehole	**F-05**	13,77	-4,66
Gonaka villageborehole	**F-06**	13,65	-4,60
Kikouma villageborehole	**F-07**	12,55	-3,74
Nzabi village borehole	**F-08**	11,52	-2,71
Boudzouka villageborehole	**F-09**	13,96	-4,77
Mingaya village borehole	**F-10**	15,90	-5,45
Central Yaya borehole	**F-11**	14,72	--5,01
Libama river (Ipini) (Upstream)	**R-01**	11,16	-2,11
Libama river (Ipini) (Downstream)	**R-02**	10,75	-2,31
Louesse river (left strand)	**R-03**	11,29	-2,65
Louesse river (right strand)	**R-04**	11,10	-2,48
Gonaka river (Upstream)	**R-05**	12,63	-3,47
Gonaka river (Downstream)	**R-06**	13,46	-4,41
Mpoukou river (right strand)	**R-07**	14,34	-4,04
Mpoukou river (left strand)	**R-08**	14,66	-4,28
Libama river bridge (Upstream)	**R-09**	10,33	-1,82
Libama river bridge (Downstream)	**R-10**	12,87	-2,94
Moutamba river (Upstream)	**R-11**	12,89	-4,27
Moutamba river (Downstream)	**R-12**	11,53	-2,97
Bibaka village spring	**S-01**	12,85	-4,05
Bibayi village spring	**S-02**	13,79	-4,72
Bitolo village spring	**S-03**	12,04	-3,82
Gonaka village spring	**S-04**	13,27	-4,45
Ipini village spring	**S-05**	13,04	-4,15
Kikouma village spring 1	**S-06**	14,85	-4,58
Mingaya village spring 1	**S-07**	12,94	-4,35
Mingaya village spring 2	**S-08**	15,53	-5,32
Mouyala village spring	**S-09**	13,27	-4,38
Nzabi village spring 1	**S-10**	12,33	-3,60
Omoye village spring	**S-11**	11,83	-2,86
Yaya central spring 1	**S-12**	13,44	-4,02
Yaya central spring 2	**S-13**	15,56	-5,41

3.3.1 Ryznar stability index (RSI)

The values of the Ryznar stability index of groundwater and surface waters of Yaya District for the January 2017 and August 2015 campaigns are on the whole higher than 8.5 (Tables 7 and 8). This means that the groundwater and surface water of Yaya District are very highly corrosive.

3.3.2 Langelier Stability Index

The values of Langelier stability index of groundwater and surface water in Yaya District for the January 2017 and August 2015 campaigns are on the whole below 0, which means that groundwater and surface water are aggressive, i.e. they dissolve calcium carbonate and can attack metal equipment in boreholes and water pipes.

3.4. Discussion

3.4.1. From the Physico-chemical Point of View

The study of physico-chemical parameters from the January 2017 sampling campaign of ground and surface waters of Yaya district located in Niari department, showed that these waters have pH values ranging between 5 (Bitolo village Spring) and 6.32 (Kikouma village Spring 2) for ground waters and between 6.07 (Louesse river) and 7.08 (Mpoukou river) for surface water. These recorded pH values indicate that the groundwater and surface waters of Yaya district are acidic to slightly neutral and that the alkalinity of these waters would be essentially controlled by bicarbonate ions (HCO_3^-). This result is in agreement with that of the August 2015 campaign, since their pH values ranged between 4.25 and 6.12 for groundwater and between 4.35 and 6.94 for surface waters **[24]**.

The total mineralization of groundwater and surface water as assessed by dissolved solids content (DST) measurements has shown that these waters are generally fresh, with DSTs ranging from 85 to 154 mg/L for groundwater and 86 to 154 mg/L for surface water. While based on electrical conductivity measurements, these waters are weakly mineralized as their electrical conductivities range from 20 to 48 50µS/cm for groundwater and 27 to 50 µS/cm for surface water. These results agree with those of the campaign of August 2015 where the groundwater and surface waters had TDS values between 14 and 370 mg/L for groundwater and between 15 and 332 mg/L for surface waters and electrical conductivity values between 10 and 22 µS/cm (Gonaka village borehole) for groundwater and from 10 µS/cm (Gonaka and Moutamba rivers) to 24 µS/cm (Mpoukou river) for surface water **[25]**.

From the point of view of chemical families and facies, the groundwater and surface water of the January 2017 campaign are characterized by two (2) chemical families (chlorinated and sulphated calcium and magnesian waters and bicarbonate calcium and magnesian waters) and are mainly represented by chemical facies of the sulphated magnesian and chlorinated and sulphated calcium and magnesian type. These results differ from those obtained by Poho Ngala during the August 2015 campaign where the ground and surface waters were characterized by four (4) chemical families (calcium and magnesian chlorinated-sulphated waters, calcium and magnesian bicarbonate waters, sodium and potassium chlorinated-sulphated waters and sodium and potassium bicarbonate waters) and were mainly represented by calcium and magnesian bicarbonate chemical facies.

Piper's triangular diagram of the evolution of water chemistry between the two sampling campaigns of August 2015 and January 2017 shows that there has been a change in the classification of water chemistry facies (**Figure 7**). The water points that were divided into four (4) chemical families (chlorinated-sulphate calcium and magnesian waters; bicarbonate calcium and magnesian waters; sodium and potassium chlorinated-sulphate waters and sodium and potassium bicarbonate waters) during the August 2015 campaign, and they are divided into two (2) chemical families (calcium and magnesium chlorinated-sulphate waters and calcium and magnesium bicarbonate waters) during the January 2017 campaign. This change in facies observed during the January 2017 campaign may be the result of an enrichment in chlorides, sulphates, calcium and magnesium (Mingaya borehole, Mpoukou river, Mingaya spring and spring 2 central Yaya) and a depletion in bicarbonates (boreholes in the villages of Bibayi, Bitolo, Kikouma, Mouyala and Nzabi ; Libama and Moutamba rivers; springs in the villages of Bibayi, Bitolo, Mouyala, Omoye, spring 1 in the village of Mingaya and spring 2 in the central Yaya), sodium and potassium (boreholes in the village of Mingaya, Mpoukou river and spring in the village of Mingaya).

The evolution of the sodium and potassium bicarbonate and sodium and potassium chloride sulphate chemical families towards the calcium and magnesium chloride and sulphate chemical family would probably be due to an enrichment in chlorides, sulphates, calcium and magnesium and a depletion in bicarbonates, sodium and potassium of the ground and surface waters between the two (2) campaigns. Chloride and sulphate enrichment would likely be the result of rock weathering or dissolution during the rainy season (high-water period) of the rock minerals in the area or through soil leaching.

3.4.2. From the Point of View of Chemical Quality

The comparative analysis of the physico-chemical parameters of the ground and surface waters of Yaya District with the values of maximum acceptable concentrations defined for drinking water by the WHO (**Tables 2** and **3)**, makes it possible to say that the good potability of these waters, is called into question by the presence of certain elements such as total iron (Fe_{tot}), hexavalent chromium (Cr^{6+}), aluminium (Al^{3+}) and lead (Pb^{2+}), the levels of which sometimes exceed the maximum admissible concentrations defined for drinking water by the WHO.

In addition, one of the most important health-related elements in drinking water is fluoride. Fluoride is present in water in the form of fluoride ions (F^-). Fluoride in water comes mainly from the dissolution of natural minerals present in rocks and soils with which water reacts **[26]**. Fluorite (CaF_2), cryolite (Na_3AlF_6), fluo apatite [$Ca_5F(PO_4)$] and micas are the main minerals that contain fluorine.

3.4.3. From the Point of View of Water Aggressiveness

Aggression is a complex phenomenon involving several factors of a chemical, electrochemical and even microbiological nature. The multiplicity of these factors makes the study of these problems extremely complex.

Indeed, the determination of the aggressive character of the ground and surface waters of Yaya district from the Langelier and Ryznar indices, allowed us to know that the ground and surface waters of Yaya district are aggressive and very strongly corrosive, i.e. they dissolve calcium carbonate and can attack the metallic equipment of the boreholes. On this basis, we recommend to the drilling companies the use of PVC pipes for the piping of the water distribution network for the entire service system.

IV. CONCLUSION

The study of the physico-chemical parameters of ground and surface water in Yaya district located in Niari Department revealed the following information:

- Ground and surface waters of the Yaya district are mild, weakly mineralized with acidic to slightly neutral pH values and the alkalinity of these waters is dominated by bicarbonate ions (HCO3-). Ground and surface waters of Yaya District are undersaturated with respect to anhydrite, aragonite, calcite, dolomite and gypsum;

- The ground and surface waters of Yaya district are characterized by two (2) chemical families (family of calcium and magnesian chloride sulphates which represents 95% and family of calcium and magnesian bicarbonates which represents 5%). From the chemical facies point of view, the ground and surface waters of the Yaya district are mainly characterized by chemical facies of the magnetic sulfate and chlorinated-sulfated calcium and magnesian type;

- From a quality point of view, the comparative analysis of the physico-chemical parameters admissible by the WHO and of ground and surface water has shown that the good potability of these waters is called into question by the presence of certain elements such as total iron (Fe_{tot}), hexavalent chromium (Cr^{6+}), lead (Pb^{2+}) and aluminium (Al^{3+}), the levels of which sometimes exceed the values of maximum admissible concentrations for drinking water defined by the WHO. In addition to these elements, there are also fluorine and nitrates, which, although they are present at levels acceptable to WHO standards, can cause adverse health effects in the long term for the population of Yaya District.

Finally, the determination of the aggressive character of the ground and surface waters of Yaya district from the Langelier and Ryznar stability index, allowed us to know that the ground and surface waters of Yaya district are aggressive and very strongly corrosive, i.e. they dissolve calcium carbonate and can attack the metallic equipment of the boreholes.

REFERENCES

[1] **Moudzika Loubaki, H. B. (2017).** Evolution des caractéristiques physico-chimiques et étude de l'agressivité des eaux souterraines et de surface du district de Yaya (Département du Niari). Mémoire de Master de Géosciences, Faculté des Sciences et Techniques, Univ. Marien NGOUABI (Brazzaville), 73 p.

[2] **Moukolo, N., Samba-Kimbata, M. J., Mpounza, M., Nzalabaka, J., Maziezoula, B. & Ossete, J. M. (1992).** Hydrogéologie du Congo. Bulletin du BRGM n°210, 125 p.

[3] **Dadet, P. (1969).** Notice explicative de la carte géologique de la République du Congo au 1/500.000, zone comprise entre les parallèles 2° et 5° sud. Brazzaville : BRGM rapport, 103p.

[4] **Gerard, G. (1958).** Carte géologique de l'Afrique équatoriale française au 1/2000000. Notice explicative. Publ. Dir. Mine et Géo. A.E.F., Brazzaville, 198 p.

[5] **Chevallier, L., Makanga, J.F. & Thomas, R.J. (2002).** Notice explicative de la Carte géologique de la République Gabonaise à 1/1000000. Editions DGMG Gabon, 195 p.

[6] **Boudzoumou, F. (1986).** La chaine ouest-congolienne et son avant-pays au Congo : Relations avec le Mayombien ; Sédimentologie des séquences d'âge protérozoïque supérieur. Thèse de Doctorat de 3ème cycle, Univ. D'Aix Marseille III. pp. 21-42.

[7] **Thieblemont, D., Castaingt, C., Billa, M., Bouton, P. & Preant, A. (2009).** Notice explicative de la carte géologique et ressource minérales de la République Gabonaise (Libreville), (384), pp. 18-84.

[8] **Vennetier, P. (1966).** Géographie du Congo-Brazzaville. Centre d'Enseignement Supérieur de Brazzaville, GAUTHIER-VILLARD-Paris. 174 p.

[9] **Boudzoumou, F., Sounga, J.D. & Moussiessie, J. (2005).** Lithostratigraphie : Le groupe des diamictites et grés inferieurs ; bases du Super-Groupe de l'Ouest-Congo. Ann. Univ. M. NGOUABI, Vol. (6, 1), pp. 85-90.

[10] **Van Daalhoff, H. (1966).** Mission paléogéographique du Bouenzien. Recherche des gisements stratiformes. Rapp. BRGM. Inédit, BRA-65-A-8.

[11] **Boineau, R. (1957).** La série du Bouenzien dans la coupure Sibiti-Ouest. Publ. Dir. Mine et Géol. A.E.F., n° 8, 1957, pp. 17-20.

[12] **Boudzoumou, F. & Trompette, R. (1988).** La chaine panafricaine Ouest-Congolienne au Congo (Afrique Equatoriale) : Un socle polycyclique charrié sur un domaine subautochtone formé par l'aulacogène du Mayombe et le bassin de l'Ouest-Congo. Bulletin de la Société Géologique de France, Vol. 6, pp. 889-896.

[13] **Ahmat Mahamat, H. (2014).** Caractérisation hydrogéologique de la nappe exploitée dans le district de Yaya : Géométrie de l'aquifère. Mémoire de Master de Géosciences, Faculté des Sciences et Techniques, Univ. Marien NGOUABI (Brazzaville), 47p.

[14] **Seguin, J.J. (2005).** Projet Réseau SIG-Afrique Carte hydrogéologique de l'Afrique à l'échelle du 1/10000000, BRGM/RP-54404-FR. 66 p.

[15] **Kirchmer, J.C. (1983).** Quality control in water analyses. Environmental Science and Technology, 17 (4), pp. 178-181.

[16] **Fetter, C.W. (1994).** Applied hydrogeology. Prentice Hall Inc., New Jersey (USA), 691 p.

[17] **Rodier, J. 1996 (p12)**. L'analyse de l'eau, eaux naturelles, eaux résiduaires, eaux de mer. Edition Dunod, 1434 p.

[18] **OMS/WHO (2004).** Guidelines for drinking-water quality third edition, 504 p.

[19] **Jordana, S. & Batista, E. (2004).** Natural groundwater quality and health. Geologica Acta, Vol. 2, n°2, pp. 175-188.

[20] **OMS/WHO (2000).** Directives de qualité pour l'eau de boisson. 2nd Ed., Vol. 2, Critères d'hygiène et documentation à l'appui, 1050 p.

[21] **Brouwer, I.D., De Bruin, A., Dirks, O.A. & Hautvast, J. (1988).** Unsuitability of WHO guidelines for fluoride concentration in drinking water in Senegal. Lancet, 1, pp. 223-225.

[22] **Kothari, N. (1988).** Groundwater, iron and manganese: an unwelcome trio. Water/Engineering & Management, Vol.135, n°2, pp. 25-26.

[23] **Abdoulaye Demba, N., Mohamed, O. & Khalid, I. (2013).** Contribution à l'étude de l'origine du plomb contenu dans les effluents de la Step utilisés en agriculture dans le périmètre maraicher du SEBKHA (Mauritanie). Larhyss n°12, 8 p.

[24] **Bakalowicz, M. (1979).** Contribution de la géochimie des eaux à la connaissance de l'aquifère karstique et de la karstification. Doctorat d'Etat, Univ. Pierre et Marie Curie, Paris VI. 343 p.

[25] **Banton, O., Bangoy, L.M., Chevalier, S., Houenou, P., Lafrance, P. & Rivard, C. (1997).** Hydrogéologie : Multiscience environnementale des eaux souterraines. Presses de l'Université du Québec/AUPELF, 460 p.

[26] **Ravindra, K. & Garg, V.K. (2007).** Hydrochemical survey of groundwater of Hisar City and assessment of defluoridation methods used in India. Environ Monit Assess, n°132, pp. 33-43.