American Journal of Water Science and Engineering
2021; 7(4): 150-164
http://www.sciencepublishinggroup.com/j/ajwse
doi: 10.11648/j.ajwse.20210704.13
ISSN: 2575-1867 (Print); ISSN: 2575-1875 (Online)

Geophysical and Hydrochemical Study for the Implantation of Ten Boreholes in the Schisto-Limestone Group: Nkayi-Loudima Zone (Bouenza Department)

Essouli Olivier Florent[1, 2, *], Malanda Nimy Edmond Nicaise[1], Miyouna Timothée[1], Samba Prefina Risiany Rachelle[1], Matini Laurent[3], Boudzoumou Florent[1, 2], Faye Serigne[4]

[1]Laboratory of Geosciences, Faculty of Sciences and Techniques, Marien Ngouabi University, Brazzaville, Congo
[2]National Institute for Research in Exact and Natural Sciences, Brazzaville, Congo
[3]Laboratory of Chemistry, Higher Normal School, Marien Ngouabi University, Brazzaville, Congo
[4]Département of Geology, Faculty of Sciences and Techniques, Cheikh Anta Diop University, Dakar, Senegal

Email address:
oflorentessouli@gmail.com (E. O. Florent)
[*]Corresponding author

To cite this article:
Essouli Olivier Florent, Malanda Nimy Edmond Nicaise, Miyouna Timothée, Samba Prefina Risiany Rachelle, Matini Laurent, Boudzoumou Florent, Faye Serigne. Geophysical and Hydrochemical Study for the Implantation of Ten Boreholes in the Schisto-Limestone Group: Nkayi-Loudima Zone (Bouenza Department). *American Journal of Water Science and Engineering*. Vol. 7, No. 4, 2021, pp. 150-164.
doi: 10.11648/j.ajwse.20210704.13

Received: November 9, 2021; **Accepted**: December 7, 2021; **Published**: December 24, 2021

Abstract: In the aim of supporting the implementation of basic community infrastructure (drinking water, schools, hospitals), ten hydraulic boreholes with human-powered pumps (HPP) were built in the districts of Kayes and Loudima in the Bouenza department in the southwest of the Republic of Congo. However, there is no study that has assessed the quality of groundwater in this area. The electrical train profiles carried out in the study area revealed several anomalies which are mainly of type (V). The interpretation of the anomalies along the electrical drilling profiles yield to characterize the variation of the thicknesses of the potential aquiferous horizons in units of the Schisto-calcaire Group. Therefore, eight positive drillings having been implemented in the carbonates layers of the Schisto Calcaire Group. The physico-chemical analyses of the groundwater showed that the waters are weakly to moderately mineralize with electrical conductivity values lower than 1000 µS/cm. These waters are divided into two chemical families of waters: chloride sulfate calcic and magnesian and bicarbonate calcic and magnesian. Also, pH and saturation values obtained indicate that the groundwater of the area is aggressive. The major elements of the groundwater in the Madingou-Nkayi-Loudima area have levels below the maximum allowable concentrations defined for drinking water by the WHO. Furthermore, all the sampled water hadvery high levels of heavy metals such as cadmium, and their levels of minor elements (iron, fluorine, copper, aluminum and manganese) at some water points exceed the maximum allowable concentrations defined for drinking water by the World Health Organization. In addition, the study of water suitability for irrigation using the USSL Richards diagram, showed that the groundwater has good quality (class C1-S1) and can be used for irrigation for all types of plants and soils.

Keywords: Hydrogeology, Geophysics, Hydrochemistry, Groundwater, Potability, Irrigation

1. Introduction

Water is the main constituent of all living beings (bacteria, fungi, plants, trees, animals, humans). Its volume on Earth is estimated at about 1.4 billion km^3. When it is healthy, it is the most beautiful gift that human beings can offer to their fellow human beings. In many developing countries in general and in Congo in particular, access to drinking water is not always assured for a large number of rural and urban populations. Nearly 60% of the Congolese population uses more or less protected and uncontrolled water catchment facilities. Only the large urban agglomerations have access to drinking water supplied by the Société Nationale de Distribution d'Eau

(SNDE). It is therefore important to mobilize resources to develop water infrastructure in rural and urban areas.

In the Republic of Congo, within the framework of its support program for the implementation of basic collective infrastructures (drinking water, schools, etc.) in the department of Bouenza, the European Union wanted to carry out a preliminary hydrogeological and geophysical survey for the implementation of new boreholes in order to meet the ever-increasing water needs of the populations. This program has known a failure during the realization of the first drillings by the FORECO Company because of the catchment in the altrites and especially of a very low flow rate at dewatering: less than 500 L/h for a minimum requested of 700 L/h.

It is within this framework that SOPEX CONGO was commissioned to drill ten (10) boreholes equipped with human-powered pumps (PMH) in order to improve the availability and quality of drinking water for the populations of this region. Hence the need to deepen the geological, geophysical and hydrogeological research of the rocks in the study area and to know if they are favourable to the infiltration and storage of rainwater.

The objectives of this study are:

1. the improvement of the living conditions of the populations of the Bouenza department by the realization of basic collective social infrastructures (Drinking water, School, Hospitals...) and the present study aims at contributing to the knowledge of the geological, hydrogeological and hydrochemical characteristics of the exploited aquifers by using the data of the hydraulic works (village wells and boreholes) realized in the sectors of Madingou - Nkayi - Loudima.
2. the realization of a detailed hydrogeological study for the drilling works (of drinking water) with small diameters for village hydraulic works (pumps with human drive) with more precision and the evaluation of the physico-chemical quality of the ground water because nowadays the impact of the water quality on the health of the populations is not any more to demonstrate.

2. Materials and Methods

2.1. Presentation of the Study Area

The Republic of Congo covers an area of 342,000 km^2. Located in Central Africa astride of the equator, it has several departments including the department of Bouenza (Districts of Kayes and Loudima) located in the southwest of the country (Figure 1).

With an annual average rainfall of 870 mm, the Loudima station is the pole of drought in Congo [2]. This makes it possible to distinguish two (2) seasons:

1. a wet season (from October to May) with a maximum in April (207.4 mm) at the Nkayi station and 194.2 mm at the Loudima station in November;
2. a dry season (from June to September).

The study area is part of the Niari Basin and the outcropping formations are classically attributed to the West Congolian supergroup. This one contains from bottom to top: the Diamictite and Sandstone Group, the Schisto-limestone and Schisto-grit Group [3].

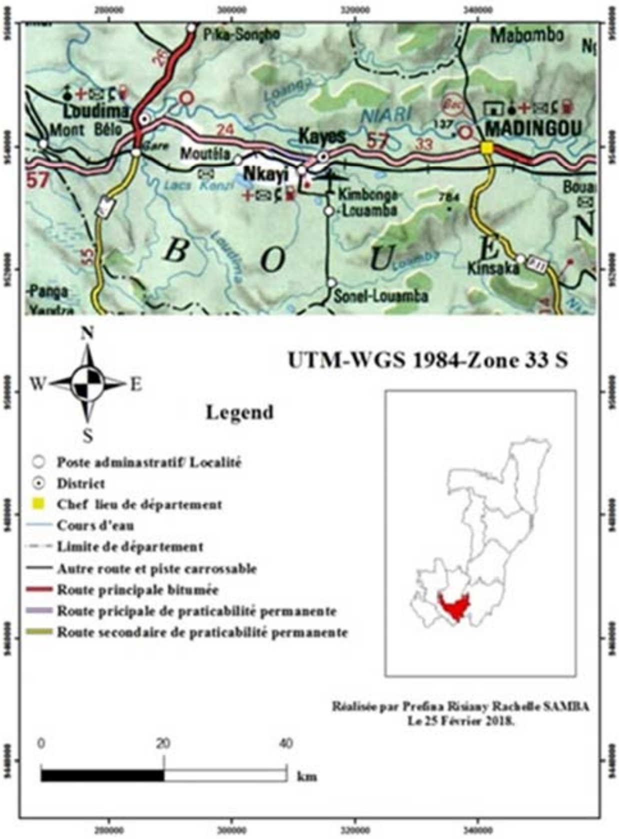

Figure 1. *Map of the geographical location of the Study Area [1].*

The analysis of geological data allows the identification of four aquifer groups in the Congolese territory [3]:

1. the aquifers of the coastal sedimentary basin (Secondary, Tertiary and Quaternary);
2. the aquifers of the river sedimentary basin (Secondary, Tertiary and Quaternary);
3. aquifers of the hold sedimentary series (Upper Precambrian);
4. crystalline and crystallophyllian rock aquifers (Middle and Lower Precambrian).

Only the last two are concerned by this study. These are discontinuous aquifers characterized by compact and indurated sedimentary rocks, granitic rocks. In these sets the porosity of fissures dominates and their depth ranges from 1 to 70 m.

Fissured carbonate and karst aquifers of the schistoclimestone series are widely represented in the Niari Valley (southwestern Congo) where schistoclimestone outcrops occupy about 22900 km^2 and allow to distinguish the SCI, SCII and SCIII aquifer system and associated formations [3].

The Niari synclinorium is subdivided into two branches: a NW-SE branch called Middle-Niari and a NE-SW branch also called Upper-Niari [4]:

1. the NW-SE branch presents a monoclinal NE flank slightly inclined resting in fundamental discordance on

the base of the Chaillu and a folded SW flank at the edge of the Mayombe chain. The axes of the folds of the SW flank are oriented globally NW-SE (Mayombian direction parallel to the Mayombe relief);

2. the NE-SW branch is characterized by anticlinal and synclinal folds of roughly NE-SW axis (this direction is that of the Combian faille.

2.2. Methodology Used

In hydrogeology, several methods are used to locate reservoir layers and to collect information on physical and chemical parameters.

In the field we have used electrical prospecting methods applied to hydrogeology for vertical exploration of the subsoil. Its application on several points makes it possible to appreciate the lateral variations along an electric curve. We can distinguish two investigation methods which are the electric trains (TE) and vertical electric soundings (SEV). In the case of this study, the electric trains made it possible to detect anomalies in the subsurface while measuring the apparent resistivity (ρa), and to study the lateral variations of this apparent resistivity according to the Wenner configuration (aligned and equidistant electrodes) with an inter-electrode spacing of (a), thus a total length of the device (L) of 3a (Figure 2) [5].

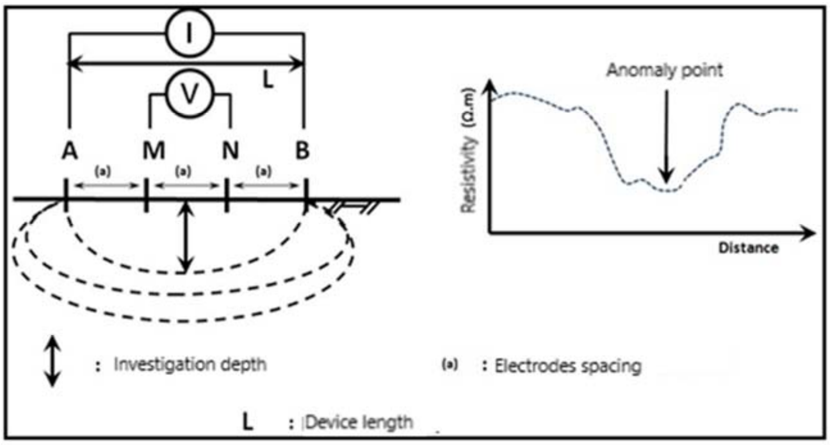

Figure 2. *Wenner's configuration and associated Electric Drag profile (Barker, 1989).*

On the other hand, the vertical electric prospecting allowed the direct current to be injected into the soil via two electrodes A and B, called intensity electrodes, and to measure the potential difference at the terminals of two internal electrodes M and N, called potential electrodes (Figure 3). From this method, we determined the apparent resistivity (ρa) of the underlying geological formations through which the current flows.

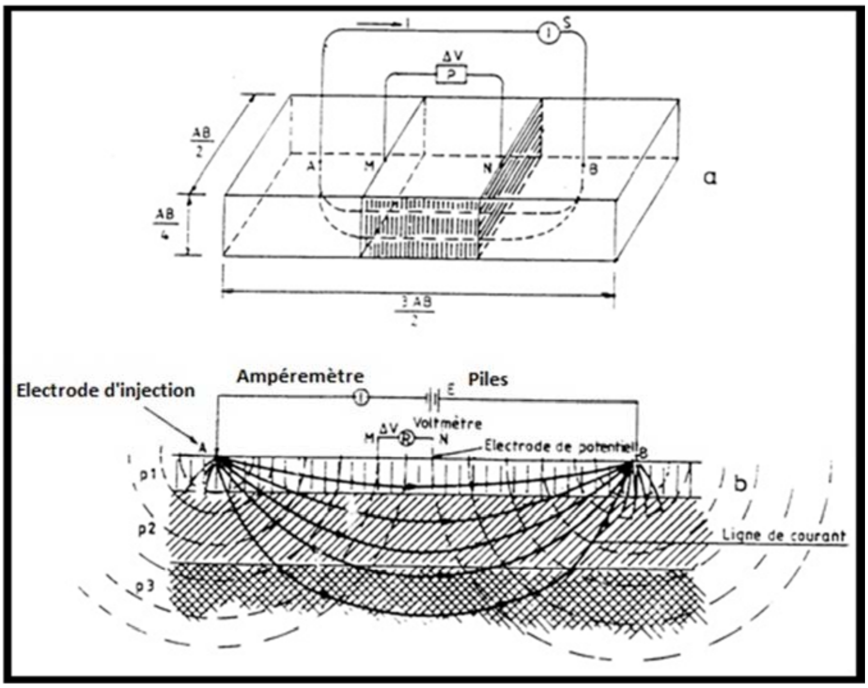

Figure 3. *Schematic diagram of the Schlumberger device and volume of investigation [6].*

The methods used for drilling in this area are mud rotary and down the hole hammer (DTH). This is a mixed technique qualified as destructive drilling [7]. Indeed, this technique is based on the crushing and abrasion of rocks by the tool.

However, the mud rotary method is applied to soft and moderately consolidated soils, whereas the MFT method is applied to consolidated soils (basement, compact limestone).

Collection of hydrochemical data

The study sites are located in the Bouenza region, more precisely in the districts of Kayes and Loudima (Figure 4).

Figure 4. *Location of water points sampled in the Study Area [1].*

Figure 5. *Different types of water points sampled in the Study Area [1].*

A few watercourses from these different sites were studied: this is the case of the Niari River, the Loudima River, the Louadi River, the Loamba River, the Mouindi River, the Fila River, the Divouba River, the Silla River, the Nsassa River, the Louvila River, the Soulou River and the Pikasongho River. Fourteen (14) water samples were taken for physico-chemical analyses for the February 2014 campaign. They were distributed as follows: eight (8) samples taken from the drill holes, one (1) spring sample and five (5) samples taken from the rivers.

For the December 2017 campaign, a total of twenty-one (21) samples were taken, including twelve (12) drilling samples and nine (9) river samples (Figure 5). The water samples were taken using 1.5 L plastic bottles, filled with a neck to prevent oxidation of organic matter. A total of twenty-one (21) physico-chemical parameters were analyzed for the waters of the February 2014 campaign and eighteen (18) for those of December 2017. Thus, to carry out this work, several methods of chemical analysis have been applied in the laboratory.

3. Results and Discussion

3.1. The Results Obtained

3.1.1. Electric Trains

The electric trains have made it possible to detect several anomalies such as fractures and altered zones which are zones conducive to the circulation of groundwater. These zones correspond to low resistivity values read on the device and make it possible to subsequently locate sites favourable for electric prospecting. Electrical resistivities range from 20.51 to 901 Ωm (Figure 6).

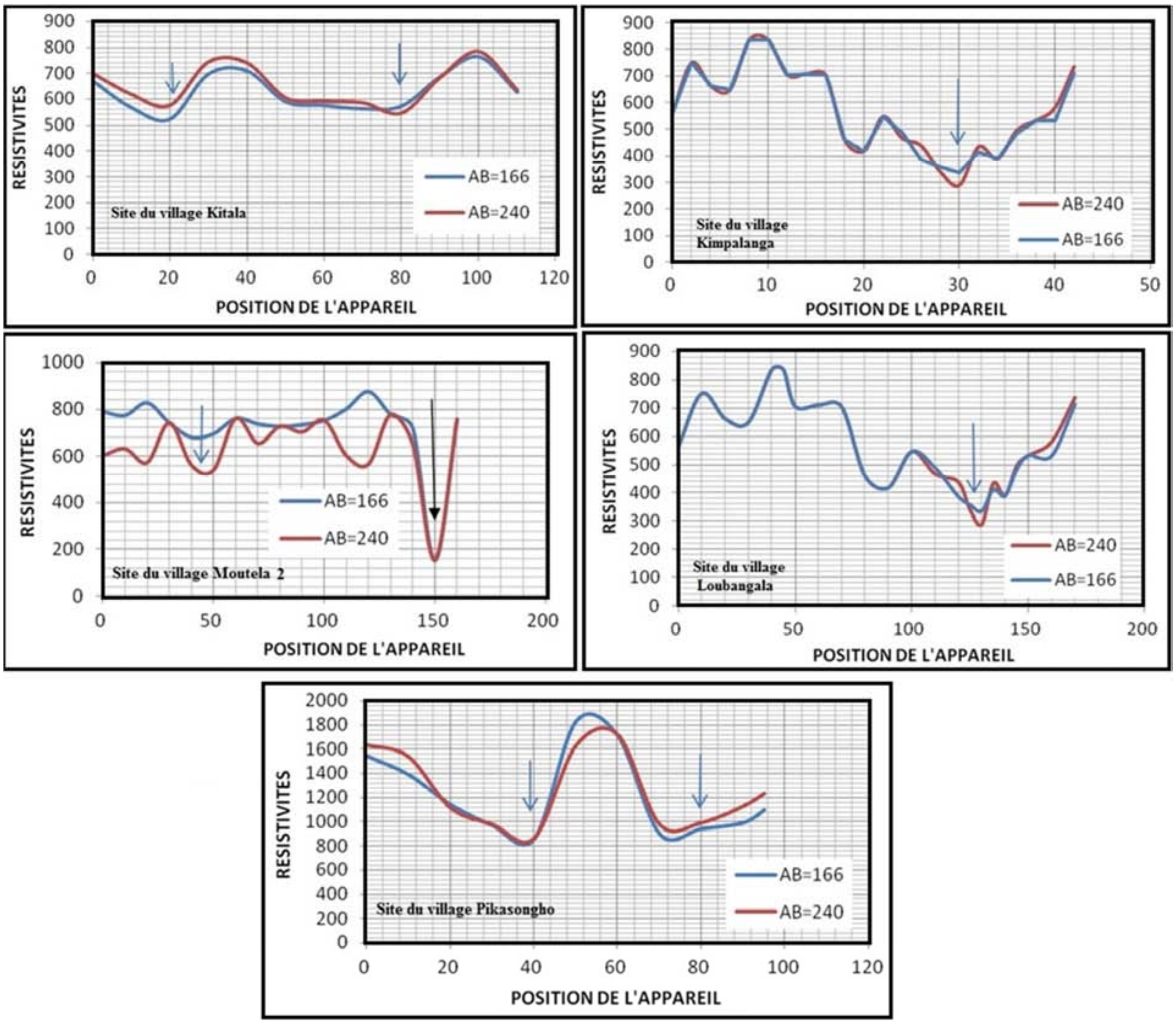

Figure 6. *Profiles of electric trains [8].*

Thus, for the Moutela 2 site, point 10 (P10: position of the device) corresponds to a resistivity of 464 Ωm. The results obtained from the other sites are reported in the table below (Table 1).

Table 1. *Electrical resistivities values of studies sites*

Sites	Respective pointes	Resistivities in Ωm
KITAKA	20 and 80	523 and 537
KIMPALANGA	30	336.37
LOUBANGALA	130	336.87
KINDOUNGA	10and 80	20.51 and 108
LOUADI	10	350.52
MOUTELA 2	40 – 50 and 150	678.55 and 7616
KIOSSI	150 and 220	524 and 482
MOUINDI	210	186
PIKASONGHO	40 and 80	859 and 901

3.1.2. Electric Prospecting

The electric prospecting determined the nature of the geological formations, the thickness of the aquifer formations and the approximate maximum drilling depth. The depth of current injection depends on the distance between the two injection electrodes (Figure 7).

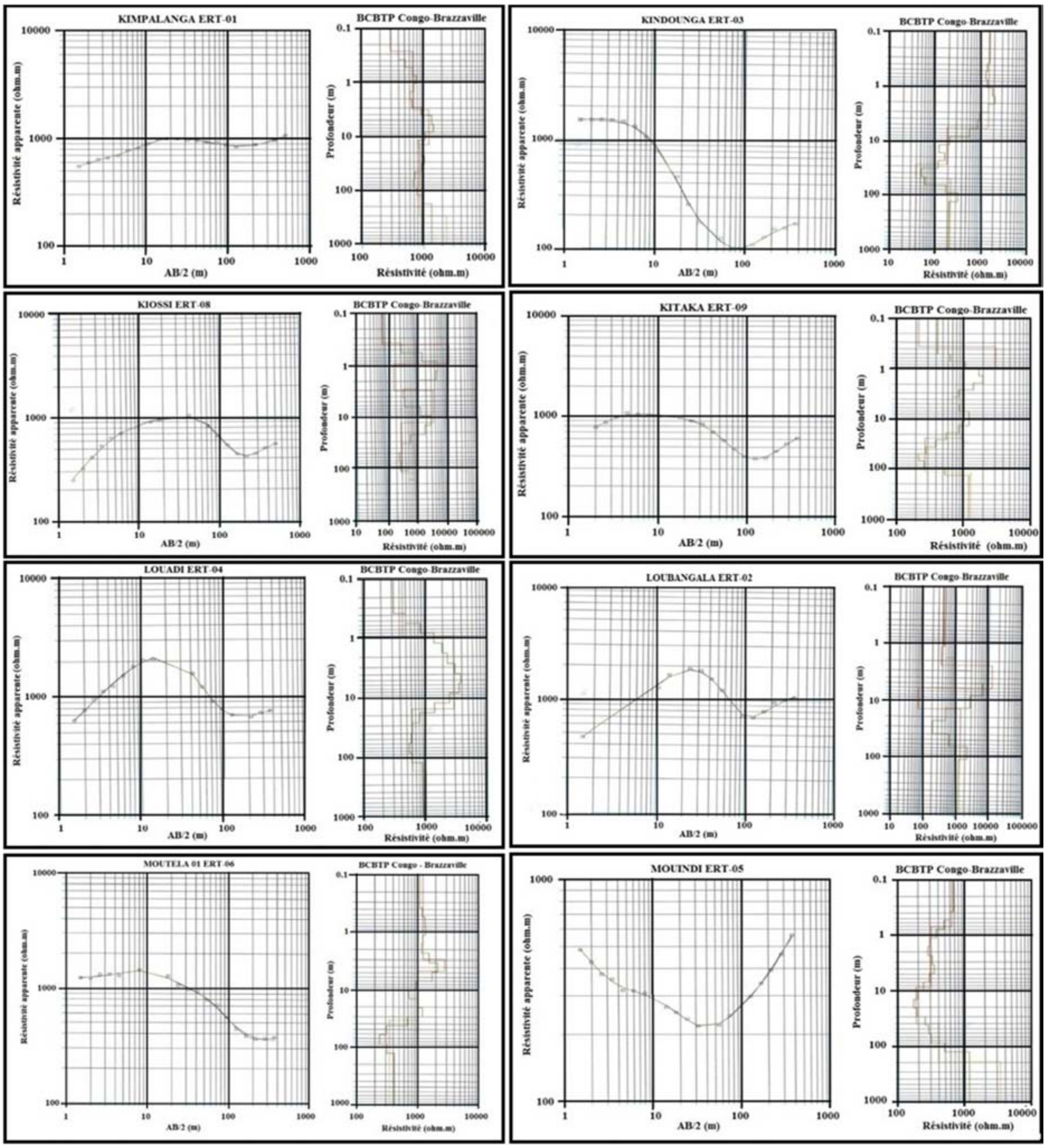

Figure 7. *Vertical electrical surveys and associated soil models [8].*

The results of the electric prospecting of Kimpalanga; Mouindi; Loubangala; Louadi; Moutela1, Kindounga and Moutela 2 give the value of 150 m depth of investigation and the presence of four (4) layers (yellow clay, laterite, alternating yellow clay and laterite, limestone). On the other hand, Kiossi and Pika-Songho have the same depths (150 m) but differ in the number of layers, namely: five (5) layers for Kiossi (clay; laterite; alternating clay-limestone-laterite and silexite; alternating marl-silexite and limestone; alternating marne-silexite and dolomite) and six (6) layers for Pika-Songho (yellow clay; laterite; alternating laterite-limestone and dolomite; alternating limestone-dolomite and clay; bedrock).

3.1.3. Borehole Execution

Eight boreholes were drilled in the Kayes and Loudima districts. Drilling began with the completion of eight-inch (8") diameter pilot holes. After the installation of a guide tube in soft ground, the drilling was continued by reconnaissance with rotary- mud and then with a down-the-hole hammer in diameter of six one-half inches (6"1/2) and equipped with 113 mm diameter PVC tubes and strainers and a PVC decanter tube at the base (Figures 8 and 9).

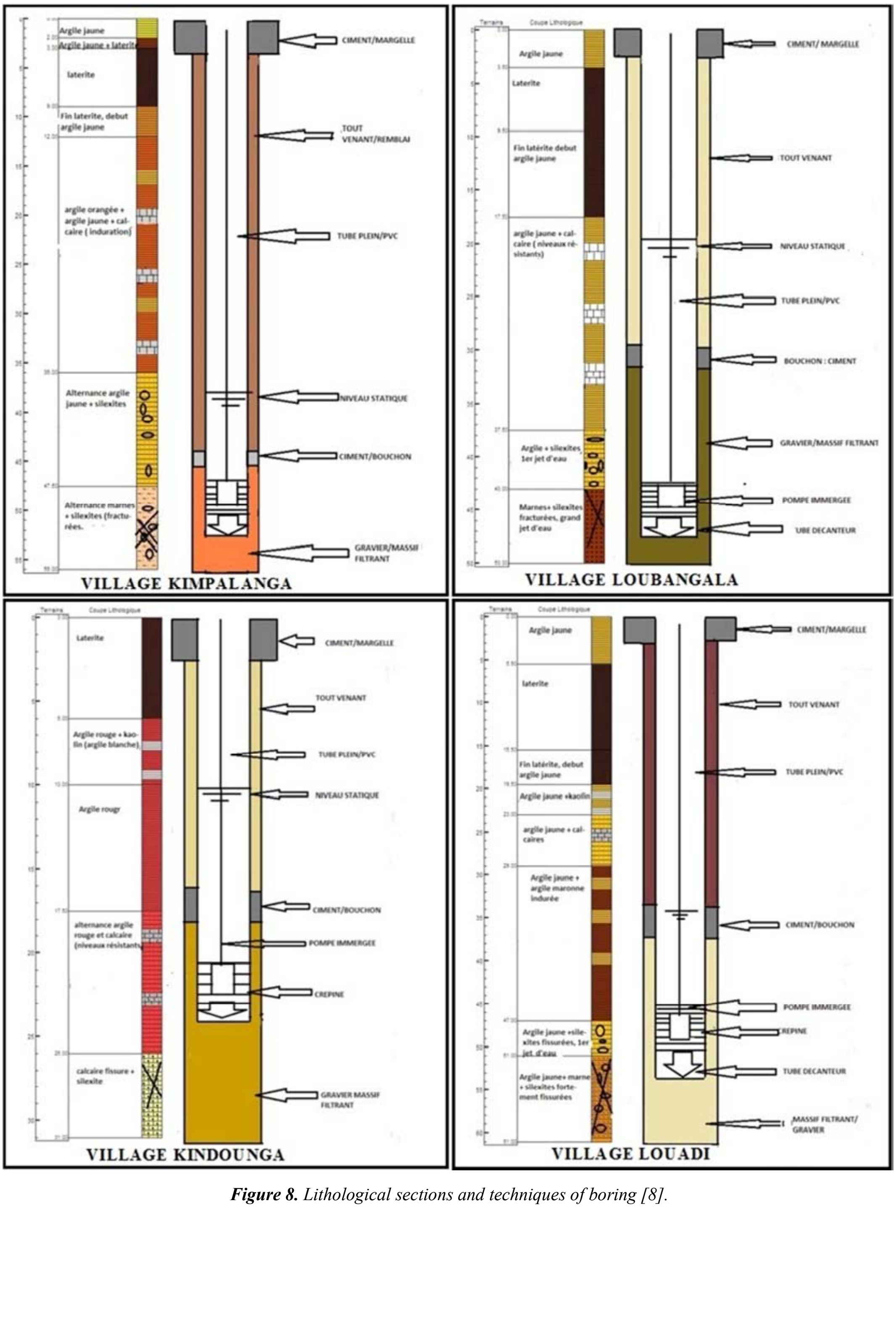

Figure 8. Lithological sections and techniques of boring [8].

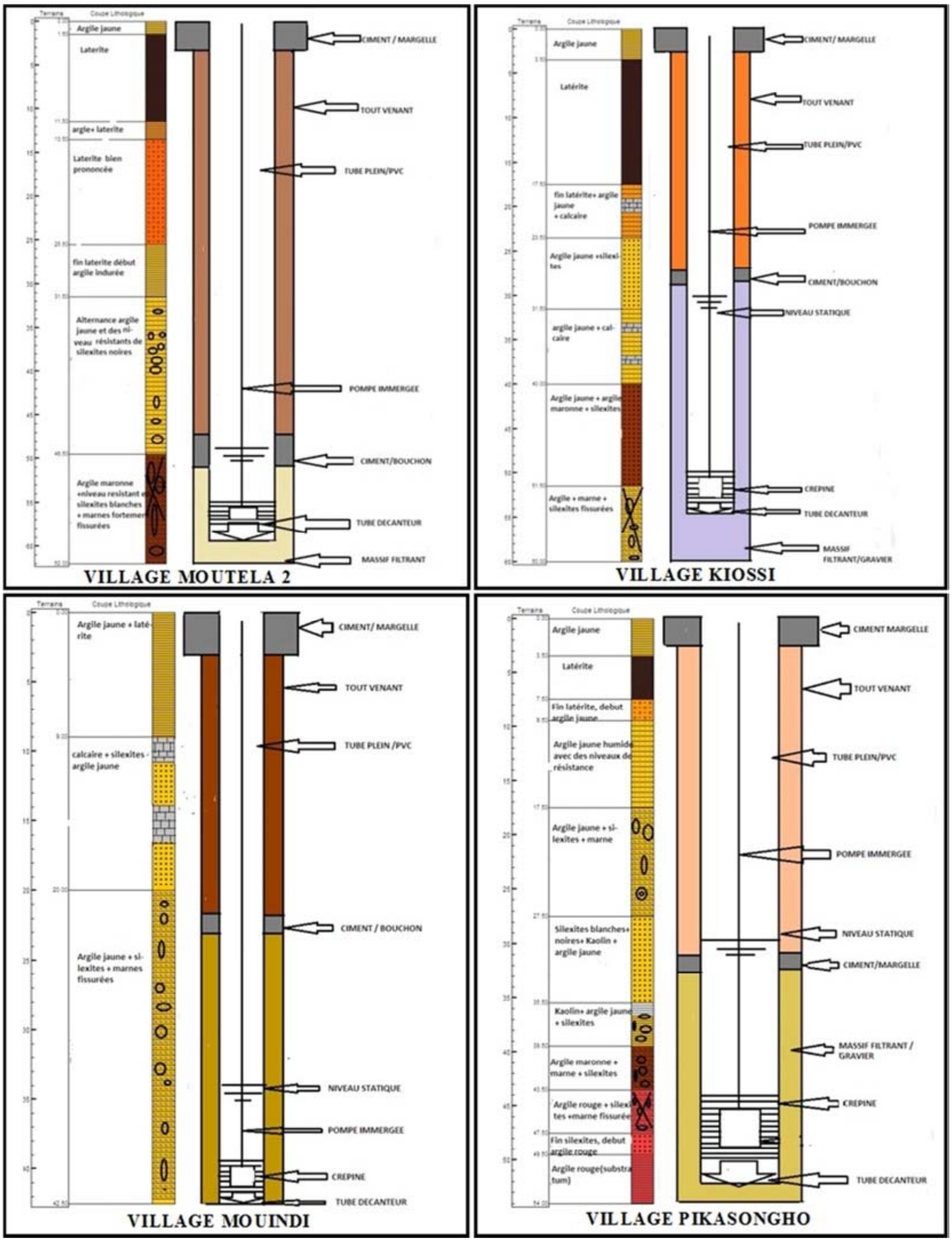

Figure 9. *Lithological sections and techniques of boring [8].*

The kimpalanga and Loubangala boreholes reached depths of about 56 and 50 m respectively. The static levels reached are respectively of the order of 37 and 20.16 m deep and have for respective exploitation flows of 3.6 m^3/h or 3600 L/h and 4 m^3/h or 4000 L/h. The first borehole was equipped from 52 m and the second at 49 m depth. The flow rates are practically good.

On the other hand, the Kindounga and Louadi boreholes reached depths of 31 m for the first one and 61 m for the second and were equipped from 24.2 m and 53.2 m depth respectively. The collected flows are good of the order of 4.5 m^3/h or 4500 L/h for the first and 3.6 m^3/h or 3600 L/h for the second, having respectively for static level 10.70 m and 35.80 m of depth.

The drillings of Moutela 2 and Kiossi, have final depths reached respectively of 62 m (equipped from 60 m) and 60 m (equipped from 54 m). The flow rates are practically good at about 3 m^3/h or 3000 L/h and 0.86 m^3/h or 860 L/h. The static levels are respectively 50 m and 30.6 m deep.

Finally, the Mouindi and Pikasongho boreholes located in the Loudima district reached final depths of 42.5 m and 54 m respectively. The various exploitation flows are of the order of 2.67 m^3/h or 2670 L/h and 0.72 m^3/h or 720 L/h, with static levels of the order of 33.90 m and 29 m.

3.1.4. Hydrochemistry of Groundwater

(i). General Characteristics of Groundwater

Ground and surface waters for the February 2014 campaign are acidic to neutral with pH values ranging from 4.32 (F-08) to 7.10 (F-05) for groundwater and from 5.91 (RIV-06) to 7.55 (RIV-02) for surface water. However, the waters of the December 2017 campaign are acidic to slightly neutral, with pH values ranging from 5.38 (F-05) to 6.91 (F-08) for groundwater and from 5.63 (R-02) to 6.95 (R-04) for surface water.

The electrical conductivity values of the groundwater and surface water for the February 2014 campaign show that: water points and rivers [F-01 (4.77 µS/cm), F-02 (6.54 µS/cm), F-03 (5.5 µS/cm), F-04 (4.96 µS/cm), F-05 (7.1 µS/cm), F-06 (6.48 µS/cm), F-07 (7 µS/cm), F-08 (4.32 µS/cm), S-01 (32 µS/cm), Fl-01 (78 µS/cm) and RIV-06 (19 µS/cm)] have electrical conductivity values *below* 100 µS/cm. These waters are said to have very *low* mineralization. Whereas most rivers [RIV-01 (296 µS/cm), RIV-02 (328 µS/cm), RIV-03 (327 µS/cm), RIV-04 (309 µS/cm) and RIV-05 (240 µS/cm)] have electrical conductivity values between 200 µS/cm and 400 µS/cm, thus with *average* mineralization. On the other hand, the waters of the December 2017 campaign are very weakly to strongly mineralized because the electrical conductivity values oscillate between 72.3 µS/cm (F-04) and 1818 µS/cm (R-05).

With respect to the TDS, the values of the mineralization of groundwater vary from 93 to 511 mg/L and those of surface water vary from 72 mg/L to 165 mg/L, these values are lower than 1000 mg/L; these waters are generally *fresh*, as well as those of the campaign of December 2017 for which, the values are between 23 mg/L (F-10) and 102 mg/L (F-05) for groundwater and between 32 mg/L (R-01) and 96 mg/L (Fl-01) for surface water.

The chemical analysis data acquired during the sampling campaign of February 2014 and December 2017 in the Kayes and Loudima districts were plotted on the Piper triangular diagram *(Figure 10).*

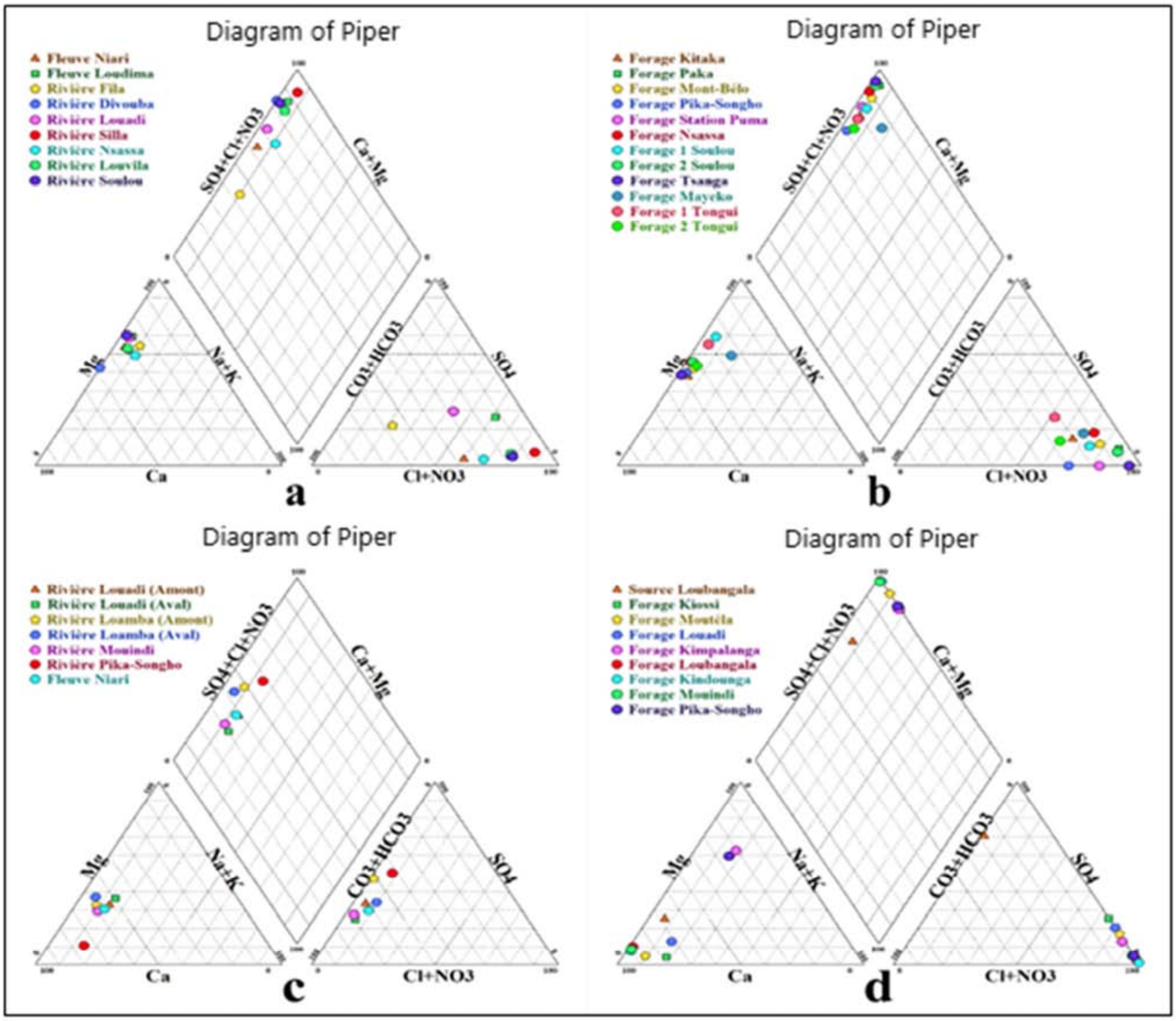

Figure 10. *Ground and surface water classification from Piper's diagram (February 2014 and December 2017 campaigns) [1].*

The interpretation of these diagrams shows that the groundwater and surface water of the two campaigns are generally characterized by two major chemical families which are the calcium and magnesian sulphate chlorides; and the calcium and magnesian bicarbonates.

In detail, the triangular diagram of the surface water anions of the February 2014 campaign (Figures 6a and 6b) shows a predominance of water points evolving towards the bicarbonate pole (RIV-01, RIV-02, RIV-04, RIV-05, RIV-06 and Fl-01, i.e. 85, 71%) and one water point evolving towards the sulphate pole (RIV-03, i.e. 14.29%) on the other hand, the groundwater point shows that all the water points are evolving towards the chloride pole (F-01, F-02, F-03, F-04, F-05, F-06, F-07, F-08 and S-01; i.e. 100%). However, the triangular diagram of surface water anions of the December 2017 campaign *(Figures 10c and 10d)* shows a predominance of water points with evolution towards the chloride pole (R-02, R-04, R-05, R-06, R-07, Fl-01 and Fl-02; i.e. 77.78%); one water point with evolution towards the bicarbonate pole (R-01, i.e. 11.11%) and another water point with evolution towards the zone where no anion dominates the other (R-03, or 11.11%).

Groundwater, for its part, shows that all the water points evolve towards the chloride pole (F-01, F-02, F-03, F-04, F-05, F-06, F-07, F-08, F-09, F-10, F-11 and F-12; i.e. 100%).

In addition, the triangular cation diagram of the surface water cations for the February 2014 campaign shows an evolution of all water points towards the calcium pole (RIV-01, RIV-03, RIV-04, RIV-05, RIV-06 and Fl-01; or 85.71%) except for RIV-02 (14.29%) which is in the zone where no cation dominates the other. The triangular diagram of groundwater cations shows, on the other hand, a predominance of water points evolving towards the calcium pole (F-01, F-02, F-03, F-05, F-06, F-07 and S-01; i.e. 77.78%) and two (02) water points evolving towards the magnesian pole (F-04 and F-08, i.e. 22.22%). The triangular diagram of surface water cations for the December 2017 campaign indicates that all the water points evolve towards the magnesian pole (R-01, R-02, R-03, R-04, R-05, R-06, R-07, Fl-01 and Fl-02; or 100%). However, the triangular diagram of groundwater cations shows a predominance of water points evolving towards the magnesian pole (F-02, F-03, F-05, F-06, F-07, F-08, F-10, F-11 and F-12; i.e. 75%) and three (03) water points evolving towards the zone where no cation dominates the other (F-01, F-04 and F-09; i.e. 25%).

(ii). Physico-chemical Quality of Groundwater and Surface Water

Ground and surface water potability

Physical parameters have no direct health effects. However, the physical characteristics of drinking water may indicate a higher risk of microbiological and chemical contamination, able to present a danger for the human health (*Table 2).*

Table 2. *Physicochemical water parameters (February 2014 and December 2017 campaigns) [1].*

Physico-chemical parameters	WHO (2017) maximum allowable values	Physico-chemical groundwater parameters			
		December 2017 campaign		February 2014 campaign	
		Minimum	Maximum	Minimum	Maximum
pH	8,5	5,38	6,91	4,32	7,10
CE (µS/cm)	2000	72,3	3.370	4,32	32
TDS (mg/L)	600	23	102	93	511
Ca^{2+} (mg/L)	100	2,78	42,7	11	386
Mg^{2+} (mg/L)	50	4,08	34,5	2	22
Na^{+} (mg/L)	100	0,4	3,1	0,17	7,20
K^{+} (mg/L)	12	0,41	4,1	1,20	36
Cl^{-} (mg/L)	200	12,92	147,67	0,55	120
HCO^{3-} (mg/L)	-	4,80	68,34	0,05	27,73
SO_4^{2-} (mg/L)	250	0	35,73	0,96	54,55
NO_3^{-} (mg/L)	50	0	0,74	0,73	41,33
Al^{3+} (mg/L)	0,2	0	1,23	0,01	0,20
F^{-} (mg/L)	1,5	0	2	0,46	2,22
NO_2^{-} (mg/L)	3	0	1,31	-	-
PO_4^{3-} (mg/L)	0,5	0,13	0,57	-	-
Fe total (mg/L)	0,3	0	3,03	0,01	6,33
Br^{-} (mg/L)	-	-	-	0,01	0,90
Cu^{2+} (mg/L)	2	-	-	0,12	3,50
Pb^{2+} (mg/L)	0,01	-	-	0,12	2,15
Zn^{2+} (mg/L)	3	-	-	0	0,11
Cd^{2+} (mg/L)	0,003	-	-	0	0,13

The WHO recommends pH values between 6.5 and 8.5 for drinking water. Groundwater for the December 2017 campaign has pH values ranging from 5.38 (F-05) to 6.91 (F-08). For a total of twelve (12) water samples analyzed, nine (09) water points (F-01, F-02, F-03, F-04, F-05, F-06, F-07, F-09 and F-12) do not comply with the WHO standard. For the February 2014 campaign, the groundwater has pH values ranging from 4.32 (F-08) to 7.10 (F-05). For a total of nine (09) water samples analyzed, five (05) water points (F-01, F-03, F-04, F-08 and S-01) are not within the norm defined by the [9].

The most common undesirable substances encountered in water pollution are: nitrates, phosphates, nitrites, fluorides, iron etc. The toxic compounds are either mineral or organic. Toxic mineral compounds are essentially: heavy metals (mercury, lead, cadmium etc.); minerals of agricultural origin; minerals of industrial origin; certain natural compounds. Toxic organic pollutants are mainly pesticides and detergents. These latter are not toxic but they promote the assimilation of toxic substances.

From a physico-chemical quality point of view, the good quality of groundwater is called into question by the presence of certain elements such as calcium, potassium, ferrous iron (Fe^{2+}), aluminium (Al^{3+}), manganese (Mn^{2+}), fluorine (F^-), copper (Cu^{2+}), lead (Pb^{2+}) and cadmium (Cd^{2+}) whose contents sometimes exceed the maximum admissible concentrations defined for drinking water by the WHO (2017). With the exception of bicarbonates and bromides, Mg^{2+}, Na^+, SO_4^{2-}, NO_3^-, Cl^- and Zn^{2+} are in conformity with the WHO drinking water potability standards (2017).

Suitability of ground and surface water for irrigation

The SAR (Sodium Absorption Ratio) or rate of sodium absorption makes it possible to apprehend the risks of salinization in NaCl salt induced by irrigation, it expresses the ratio between the concentration of sodium and that of alkaline earth (calcium and magnesium).

Six (6) groundwater points have conductivities lower than 250 µS/cm: F-01, F-02, F-03, F-04, F-05 and F-08 (class C1) and two (2) groundwater points have values between 250 and 750 µS/cm: F-06 and F-07 (class C2), four (4) rivers have values lower than 250 µS/cm (Riv-02, Riv-04, Riv-05 and Riv-06: class C1) and the other two have values between 250 and 750 µS/cm (Riv-01 and Riv-03: class C2). On the other hand, the SAR values for both groundwater and surface water are all less than 10 (class S1). The classification of groundwater according to electrical conductivity and SAR gave the following classes: class C1-S1 and class C2-S1. This method is called the River Side method.

Study of the aggressiveness of water

The water saturation indices for the mineral phases (aragonite, calcite, dolomite, gypsum and anhydrite) present in the matrices of the aquifers collected by drilling were calculated from the Wateq program *(Table 3) [10]*.

The results gave negative values with an overall minimum of -9.91 and a maximum of -1.55 for boreholes (groundwater), while rivers (surface water) had a minimum of -7.34 and a maximum of -1.05. This reflects an under-saturation of water concerning the mineral phases. The results on the calco-alkaline equilibrium and pH equilibrium show that all the water points sampled in Kayes and Loudima districts (Figure 11), whether underground or surface, have equilibrium pH higher than the measured pH (ΔpH<0) *(Table 3)*, therefore these waters are aggressive.

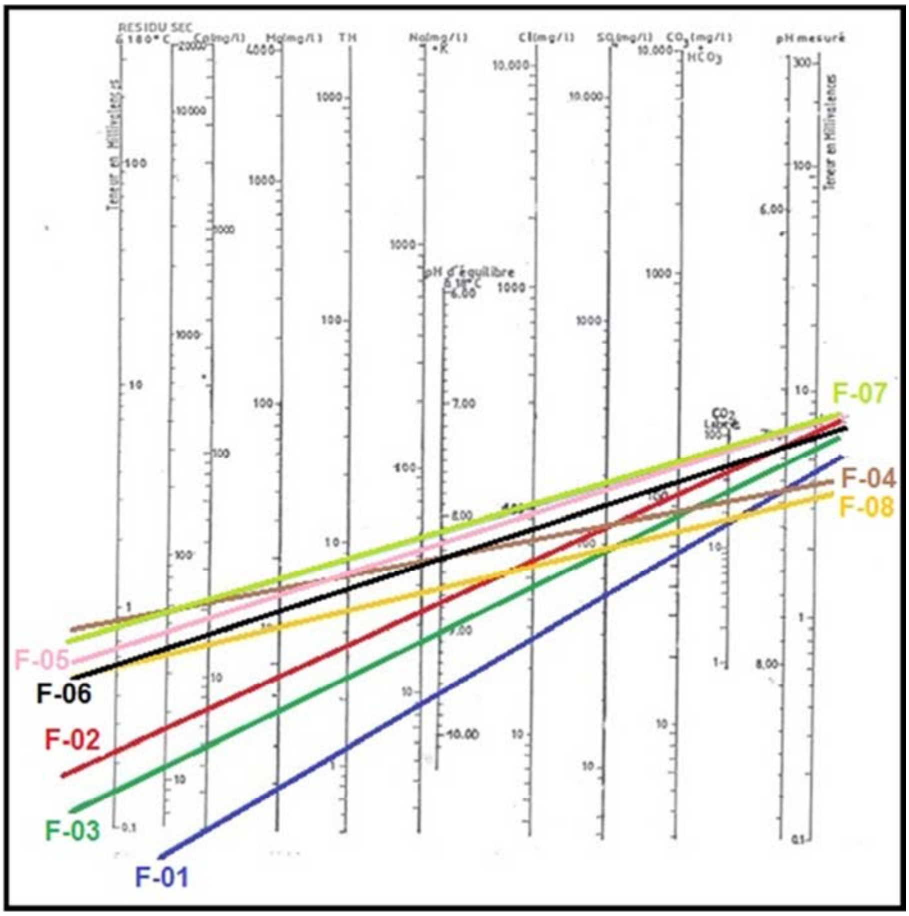

Figure 11. *Diagram of Schoeller and Berkaloff: determination of equilibrium pH or saturation pH values of groundwater.*

Table 3. *Saturation index and equilibrium pH values.*

Water point	Calcite	Aragonite	Dolomite	Gypsen	Anhydrite	Measured pH	Equilibrium pH	ΔpH
F-01	-5.09	-5.24	-8.91	-4.08	-4.30	4.77	9.59	-4.82
F-02	-1.93	-2.08	-2.80	-3.11	-3.33	6.54	8.75	-2.2
F-03	-3.89	-4.03	-6.98	-3.31	-3.53	5.50	9	-3.5
F-04	-3.93	-4.07	-7.88	-2.80	-3.02	4.96	8.37	-3.41
F-05	-2.05	-2.20	-4.47	-2.74	-2.97	7.1	8.21	-1.27
F-06	-2.47	-2.61	-4.97	-2.81	-3.03	6.48	8.37	-1.89
F-07	-1.55	-1.69	-3.45	-2.83	-3.05	7	8.11	-1.11
F-08	-4.52	-4.66	-9.91	-2.69	-2.91	4.32	8.64	-4.32
Riv01	-1.05	-1.19	-2.70	-2.82	-3.04			
Riv02	-3.19	-3.33	-7.23	-2.56	-2.78			
Riv03	-1.91	-2.06	-4.47	-2.74	-2.92			
Riv04	-1.28	-1.42	-3.29	-2.81	-3.03			
Riv05	-3.04	-3.18	-7.34	-2.79	-3.01			
Riv06	-1.71	-1.85	-4.10	-2.83	-3.05			

3.2. Discussion

3.2.1. Geophysical Prospecting: Geo-electric Methods

This method allowed to determine the electrical resistivity distribution of a site as a function of depth in order to establish the geo-electrical section of this point. Its application on several points makes it possible to appreciate the lateral variations along an electrical curve. Geological formations have undergone deformations over time as a result of various tectonic movements (fracturing). Also, they have undergone more or less significant alteration under the influence of external geodynamic agents such as water, wind, etc... These deformed geological formations represent zones of hydrogeological interest that correspond to fractured or strongly altered zones. These so-called anomaly zones are characterized by low electrical resistivity. The nature of the geological formations as well as the number of layers (4, 5 or even 6 layers) were determined by the electrical drillings.

3.2.2. Drilling Work

Within the framework of this study, eight (8) holes were drilled by *Sopex Congo*. Overall, these holes reached depths of at least thirty meters (30 m). The greatest depth reached is 62 m (Moutela 2). The analysis of the cuttings shows that all the geological formations crossed by drilling are constituted by the presence of clay to great depths, silexites and marls. All the drillings show good exploitation rates, compared to the minimum flow rate required (700 L/h). Only the drilling of Pika-Songho presents a flow rate close to the order of (720 L/h) compared to the minimum flow rate. Among all the drillings, Kindounga with 4500 L/h has the best flow rate and is located in the SCI formations. However, [3] qualifies the SCI aquifer system and the surface water table as being of lesser importance and that for him the SCI would be of interest only if the networks of caverns and cavities observed along the Niari extended south of it and would be located at a coast lower than that of the Niari and would subsequently be constantly drowned. This system could provide significant flows, but there is nothing to explain these appreciable flows. It is likely that the water level of the Niari may have drowned the cave system episodically. Therefore, we suppose that the drilling of the Kindounga village could be an example. Moreover, the waters of the boreholes are on the whole quite clear. However, the Loubangala, Kiossi, MTL2 and Mouindi boreholes show turbid waters. This turbidity would be due to the fact that the strainers are placed in the clay layers. These results are comparable to those of [11] who, in his book entitled "Connaissances des méthodes de captage des eaux souterraines" (Knowledge of Groundwater Catchment Methods), mentions that clay and silt particles in the water make the water turbid or cloudy because of their size.

3.2.3. About the Aggressiveness of the Waters

The role of physico-chemical characteristics of groundwater is important to determine the choice of drilling equipment. Thus, the measurement of some parameters such as equilibrium pH, free CO_2, can help in the choice of the adequate equipment for the equipment of the catchment works. Thus, the majority of water points sampled in the study area have pH equilibrium pH higher than the measured pH (ΔpH<0). These waters are therefore aggressive and can attack metallic drilling equipment. Hence the choice of stainless steel equipment for the drilling equipment of this project. Indeed, drinking water should not be aggressive or corrosive [12].

According to *Beauchamp* [12], in calcareous soils, the water is hard, moderately to highly mineralized in calcium and magnesium salts; at the origin of the plugging of the pipes. Whereas in crystalline (granitic), sandy and sandstone soils, i.e. rich in siliceous and silicate minerals, the waters are soft; they are little mineralized but acidic and aggressive. However, it was demonstrated during the February 2014 campaign that the results found, go against those found by [12] in that the ground and surface waters have an equilibrium pH higher than the measured pH (ΔpH<0: the water is acidic) and negative saturation indices. These waters are therefore aggressive and cause the problem of corrosion for metallic drilling equipment because the boreholes used here are at PHM. During the campaign of December 2017, it was thus demonstrated by the values of the indices of stability of Ryznar that the waters are on the whole very strongly corrosive, consequently are aggressive; result in correlation with that of February 2014. Due to the PVC pipes and strainers used for ASPERBRAS works, it will not cause any corrosion problems.

3.2.4. The Physico-chemical Quality of Water

(i). The Major Elements

The study of the concentrations of the main major elements (Cl^-, SO_4^{2-}, NO_3^-, HCO_3^-, Ca^{2+}, Mg^{2+}; Na^+ and K^+) and of the conductivity of the water allowed to trace the origin of the mineralization of the water.

Alkalis (Na^+ and K^+). All the waters analyzed give K^+ ion concentrations higher than those of Na+. This could be explained on the one hand by the great stability of the sodium feldspars and on the other hand by the absorption and mobilisation of Na^+ in the neoformed minerals during alteration [13]. The dominance of K^+ over Na^+ is also due to the selective absorption of clays, so it follows that the waters contain more potassium than sodium. The alkaline contents of the waters are lower than those of the alkaline earths. The potassium and sodium ions could come from the decomposition of minerals (feldspars, pyroxenes, micas and amphiboles), ion exchanges with clay minerals and pollution from human activity [13].

Alkaline earths (Ca^{2+} and Mg^{2+}). Calcium and magnesium ions result from the weathering of rocks following a long time of water-rock contact and the acid hydrolysis of silicate minerals [14]. Calcium is generally the dominant element in groundwater and its proportion varies essentially according to the nature of the land crossed (limestone or gypsum). Some water points have shown levels higher than 20 mg/L this would be explained by the leaching of the calcium mineral-rich soil profile [10]. All of the water points have levels below the WHO maximum allowable concentration value for drinking water (40 - 160 mg/L).

The majority of natural waters generally contain a small quantity of magnesium, its content depending on the composition of the rocks encountered. It comes from the carbonic acid attack of magnesian rocks and the setting in solution of magnesium as carbonates and bicarbonates [15]. The source of the magnesium seems to be related to the contact of water with the calcareous, dolomitic rocks of the study area (schistose limestone). Ground and surface water showed acceptable levels of this element and its presence in the water would indicate a natural origin given by the nature of the geological formations met in the study area.

Nitrates (NO_3^-) come from the application of fertilizers and animal manure to crops, carried by rainfall, and are then found in rivers or groundwater. According to the WHO [16] nitrates can result from over-application of fertilizers or leaching of wastewater or other organic wastes to surface and ground waters. The presence of nitrates and nitrites in water is associated with methemoglobinemia, particularly in bottle-fed children. The quality limit for nitrates is 50 mg/L and in the case of this study the nitrate levels in all water points (surface and depth) are below the acceptable value for drinking water.

Chlorides (Cl^-). They are generally subject to special monitoring. A high chloride content may indicate pollution by domestic wastewater (regenerating salts used in dishwashers) or by some industrial wastewater.

Sulphates (SO_4^{2-}). Under natural conditions sulphates, the most common form of dissolved sulphur in natural waters, have essentially two origins: geochemical and atmospheric [15].

Sulphates generally come from several sources; sulphide minerals, organic sulphur products and sulphate minerals. According to *Truesdel and Jones* [10], sulphates in groundwater come from the dissolution of gypsum. All water points in the study area had sulphate levels below the WHO maximum allowable concentration for drinking water (250 mg/L).

(ii). About Undesirable Substances

The physico-chemical parameters are linked to the natural course of water and the elements that determine them are sometimes beneficial to health.

For the February 2014 campaign, total iron levels in ground and surface water are generally below the maximum allowable concentration defined for drinking water by the WHO (0.3 mg/L). On the other hand, the water from boreholes F-04 and F-08, show high levels of iron exceeding the maximum allowable concentration defined for drinking water by the WHO (0.3 mg/L).

Total iron (Fe_{Tot}) levels in groundwater for the December 2017 campaign vary from 0 (F-09 and F-12) to 3.03 mg/L (F-04). Eight (08) water points (F-01, F-02, F-04, F-05, F-06, F-08, F-10 and F-11) of 12 analyzed, have total iron levels equal to or exceeding the maximum allowable concentration defined for drinking water by the WHO (0.3 mg/L).

The abnormal iron levels may be explained by the concentrations of metal ions in the sludge lining the river bed according to *Eblin and al* [14]. They can probably drain ferruginous soils.

Fluorine (F^-). The fluorine concentrations in groundwater in the December 2017 campaign are on the whole below the WHO standard (1.5 mg/L) with the exception of F-12, which has a value of 2 mg/L. On the other hand, the fluorine levels in the groundwater of the February 2014 campaign indicate that it meets the maximum concentration value defined for drinking water by the WHO, with the exception of F-08, which has a value of 2.22 mg/L. The fluoride ion according to *Djellouli and Taleb* [17] is a trace element that has a strong tropism for teeth and bones. This element is sometimes beneficial to health in that it prevents tooth decay for a minimum of 0.5 mg/L and also prevents the risk of kidney stones formation. On the other hand, a high fluoride content leads to dental fluorosis (white stain on the enamel) and bone fluorosis [17]. Fluorides would come from phosphate rocks rich in apatites.

Copper (Cu^{2+}). The absence of intense industrial (paint and ceramic) and metallurgical activity in the study area proves that these high copper level could be naturally related to minute accumulations of copper in the rocks. The Niari Basin is marked by metalliferous mineralization represented by the oxidized minerals of lead, zinc, copper (malachite, azurite, cerusite and calamine) which is trapped through dislocations in the distension zones favorable to karstification, this mineralization would explain the natural origin of copper. According to *Desborde (2000)*, these copper level could be explained by the pipes, drains and various installation structures (iron alloy used) that are part of the development of some water points mentioned by *Desborde* [18].

Manganese (Mn^{2+}). Only borehole F-02 (0.21 mg/L) had a high manganese ion content exceeding the drinking water potability standard (0.005 mg/L). All others water points had levels below the standard. High iron and lower manganese levels have disadvantages on the appearance or taste of the water according to *Eblin and al.* [14].

Aluminium (Al^{3+}). Drill holes (F-01, F-02 and F-08) had high aluminum level. This element is believed to come from the geological strata crossed. In water, aluminium is present either associated with suspended particles or under particular pH conditions (either acidic or basic).

Zinc (Zn^{2+}). Abundant in rocks in general, it is quite soluble and migrates easily into the water table. Zinc has, a priori, no negative action on human health, apart from an unpleasant taste and appearance of water above 5 mg/L. Zinc, like other metalloids, is often present in groundwater as a result of pollution, especially industrial pollution. The different water points analyzed in the study area showed zinc levels below the WHO maximum allowable concentration for drinking water of 5 mg/L.

(iii). About Toxic Substances

Cadmium (Cd^{2+}). All samples showed high concentrations of this element compared to the WHO standard. These toxic elements originate in most cases in some domestic waste or in the drainage of wastewater discharged by industrial companies. Cadmium is found in phosphate fertilizers, in the form of dust, or it is naturally found in forest fires and cigarette smoke. In the case of the present study, intense industrial activities are absent in the area; cadmium is thought to come from the agricultural activities of the SARIS CONGO company (forest fires, incineration of sugar cane leaves,...).

Lead (Pb^{2+}). The presence of this element in groundwater originates from contact with lead pipes in distribution networks. This is all the more so as the time of water stagnation in the pipes is long; the length of lead pipes is important and the water is acidic and weakly mineralized (Marisol, 2013). Lead is present in several sources such as: pesticides, old pipes, fertilizers, plastic PVC [19]. The boreholes in the study area were equipped with plastic PVCs, the water is acidic and weakly mineralized, these results are compliant with those of Marisol [20] and Abdoulaye and al. [19].

3.2.5. Irrigation Water Suitability

Two classes of suitability for irrigation are distinguished according to the results obtained: class C_1S_1 and class C_2S_1. The waters in the study area have excellent irrigation quality. This is because these waters reflect more a risk of salinity than alkalization because the classes of electrical conductivity measured are higher than the different classes of SAR (SAR<10: water at low risk of soil alkalization). On the other hand, for heavy and poorly drained soils and for sensitive plants (fruit trees) water of class C_2S_1 must be used with care.

4. Conclusion

The study carried out in the project area allowed not only to determine the sites suitable for the implementation of hydraulic works by geophysical prospecting (profiles of electric trains and vertical electric prospecting, but also to follow the mineralogical evolution of the studied waters according to the chemical parameters analyzed to assess the potability of the groundwater. On the other hand, the surface waters allowed to follow the mineralogical evolution of the waters over time. The results obtained throughout this work are arranged as follows:

1. The geophysics carried out in the study area showed that the water table is located in the Schisto-limestone aquifer. Drilling confirmed the geophysical results based on the lithological interpretation of the sections over the entire study area. It is a semi-captive aquifer due to the shallow depths captured and the nature of the land.
2. The hydrogeology of the region shows that our study area is characterized by fissured and karstic carbonate aquifers of the Schisto-limestone series (the SCI, SCII and SCIII aquifers).
3. Drilling of Kindounga and Pikasongho were drilled in the SCI aquifer (respectively SCIa-b and SCIc); and those of Loubangala, Kimpalanga, Kiossi, Moutela 2, and Mouindi were drilled in the SCII aquifer and Louari in SCIII,
4. The processing of hydrochemical data using the Piper diagram reveals two major chemical families of waters: calcium and magnesium chlorinated sulphate waters and calcium and magnesium bicarbonate waters.
5. The ground and surface waters studied have levels of major elements below the maximum allowable concentrations defined for drinking water by the WHO. However, very high levels of cadmium and lead were observed in all water points in the study area. For total iron, fluoride, copper, aluminium and manganese, some water points had levels that exceeded the WHO maximum acceptable concentrations for drinking water.
6. The surface and ground water in the study area are of excellent quality for irrigation.

References

[1] Samba P. R. (2018). Application des méthodes statistiques multivariées à la caractérisation hydrochimique et qualite des eaux souterraines exploitées dans les districts de Kayes et Loudima (Département de la Bouenza). Master's Geosciences, Faculty of Science and Technology, Marien NGOUABI University of Brazzaville (Congo), 66 p.

[2] Viland M. (2011). Water and health practical guide for rural stakeholders, Cameroon, 109 p.

[3] Moukolo N. (1992). Hydrogéologie du Congo. Edition du BRGM n°210, Orléans (France), 142 p.

[4] Boudzoumou F., Malounguila N. D., Diakubuka E., Mouanda, Moumpossa R. S., Ondongo C., Ongouya Akiaoue E., Missamdu A., Malera M. and Kiba V. (1993). Notice explicative de la carte géologique de la République du Congo au 1/1.000.000, 27p.

[5] Barker R. D. (1989). Depth of investigation of collinear symmetrical four-electrode arrays. Geophysics, 129 p.

[6] Van Nostrand R. G. & Cook K. L. (1966). Interpretation of resistivity data, USGS, Paper 499.

[7] Chapelier D. (1987). Diagrams applied to hydrogeology. Lavoisier Tec et Doc, Paris, 165 p.

[8] Sitou-Goma C. D. B. (2015). Hydrogeology and hydrochemistry of surface and ground waters of Kayes, Loudima and Madingou. Master's Geosciences, Faculty of Science and Technology, Université Marien NGOUABI of Brazzaville (Congo), 47 p.

[9] OMS/WHO (2017). Guidelines for Drinking-water Quality, 4th ed. 564 p, retrieved from https://creativecommons.org/licenses/by-nc-sa/3.0/igo.

[10] Truesdel A. and Jones B. (1976). Wateq a Fortran IV version of wateq, a computer program for calculating chemical aquarium of natural waters. US geological survey water resources investigations 76 (13), 49 p.

[11] Van der Wal A. (2010). Knowledge of groundwater abstraction methods. Fondation Practica, 41 p.

[12] Beauchamp J. (2006). Groundwater quality and pollution: online course DESS environnement. Université Jules Verne de Picardie, 17 p.

[13] Kuitcha D., Fouépé A. L., Takounjou & Ndjama J. (2013). Contribution de l'hydrochimie et de l'isotope de l'environnement à la connaissance des ressources en eaux souterraines de Yaoundé, Cameroun. Journal of Applied Biosciences 67: 5194-5208, ISSN 1997-5902, 15 p.

[14] Eblin S. G., Soro G. M., Sombo A. P., Akan N. & Kambireo Soro N. (2014). Hydrochemistry of groundwater in the Adiaké region (South-East Côte d'Ivoire). Larhyss journal, n°17, pp. 193-214.

[15] Nouayti N., Khattach D. & Hilali M. (2015). Evaluation de la qualité physico-chimique des eaux souterraines des nappes du Jurassique du haut bassin de zizi (haut d'Atlas Central, Morocco), Assessment of ground waterof the jurassic aquifers inhigh bassin of zizi (Central High Atlas, Marocco). ISSN: 2028-2508, 14 p.

[16] OMS/WHO (2004). Drinking Water Quality Guidelines, Third Edition, Volume 1, 110 p.

[17] Djellouli H. M. & Taleb S. (2005). Qualité chimique et bactériologique des eaux de consommation du sud Algérien, Laboratoire de chimie analytique appliquée, Faculté des Sciences, Université D. Liabes de Sidi Bel-Abbès (Algeria). International Colloquium on Groundwater Resources in the Sahara (CIRESS), 26 p.

[18] Desborde A. (2000). Groundwater pollution in Picardy. Mémoire Maîtrise BG, Faculté des Sciences, Amiens, 50 p.

[19] Abdoulaye D. N., Mohamed O. & Khalid I. (2013). Contribution to the study of the origin of lead contained in steppe effluents used in agriculture in the Sebkha marshland perimeter (Mauritania). Larhyss journal n°12, 8 p.

[20] Marisol T. (2013). Origin of lead in tap water. Ministry of Social Affairs and Health, 75350 Paris, 5 p.