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Assessment of Surface Water Quality Using the Water Quality Index (WQI) and Multivariate Statistical Analysis (MSA) in Nyanga River, Republic of the Congo

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Abstract

The aim of this study was to assess the physico-chemical and mineralogical quality of surface waters used by populations for their domestic and agro-pastoral activities in the Nyanga district in the south-west of the Republic of the Congo. Descriptive statistics, hydrochemistry (Piper diagram), Principal Component Analysis (PCA) and hierarchical ascending classification (HAC) were used to determine the quality, chemical facies and mineralization phenomena of surface waters. Physico-chemical analyses were carried out on 6 samples taken in May 2023. The results showed that the waters studied are acidic, with a pH between 4.99 and 5.76. They are poorly mineralized, with an average electrical conductivity of 12.37 µS/cm. In the study area, the water is chloride-calcium-magnesium and bicarbonate-calcium-magnesium. Analysis of heavy metals shows that all values, with the exception of iron and nitrate, comply with WHO guidelines on water potability, with the exception of the point sampled at the confluence of the Nyanga, where values were slightly higher than normal, *i.e.* 0.06 µg/L for manganese and 0.03 µg/L for nitrate. Other heavy metals such as Lead (Pb) and Copper (Cu) were analyzed and confirmed that their concentration was within the authorized detection limits. Water mineralization is controlled by phenomena such as soil rainwashing, acid hydrolysis of rocks and input from high rainfall. This study shows that water resources in the Nyanga watershed are not subject to anthropogenic pressure, but to a totally natural phenomenon. Given its acidity, untreated consumption of this water could present health risks for the population.

Keywords

Physico-Chemical Parameters, Mineralization, Water Index, Nyanga Watershed, Republic of the Congo

1. Introduction

Water is a natural resource that is essential for life in any ecosystem. Maintaining its quality is a major concern for a society that must meet increasingly important water needs. It plays a very important role in socio-economic development at the local, regional and national levels [1]. However, population growth, agricultural and industrial development are increasing the demand for water at the individual level, while the availability of water is decreasing significantly due to climate change and other factors [2]. This situation leads to a growing difficulty in access to drinking water in most African countries. Despite the agreement on the 17 Global Goals (SDGs) signed in 2015, 2.2 billion people worldwide do not have access to safe drinking water at home [3]. The Nyanga district in the Republic of the Congo, like all other Congolese localities, is also confronted with these water problems, which are recurrent in the basement zone, under forest cover, as is the case in Ivory Coast in the Abidjan-Agboville zone [4]. This region of about 18,910 inhabitants [5], is facing enormous population growth.

The Nyanga watershed, located in southwestern Congo, is an area with high natural resource potential. Several human activities are already present or are developing there, and some may constitute sources of future pressure on surface water quality. Among these, logging occupies a significant place, with associated risks such as soil erosion, sediment leaching, and the input of suspended matter into watercourses. There are also shifting cultivation practices and expanding subsistence crops on the banks, likely to lead to increased use of fertilizers or pesticides. Finally, the prospects of artisanal mining activities and growing small urban centers generate untreated domestic wastewater. These dynamics underscore the practical importance of conducting a thorough study to obtain reliable data on water quality and prevent any future degradation of water resources in the basin.

This will inevitably lead to the growth of human activities (agriculture) and consequently to the risk of degradation of the river's surface waters in quantity and quality. These risks reduce the availability of water. Thus, to ensure its sustainability and good management, in the context of sustainable development, it is wise to constantly monitor the physico-chemical and bacteriological quality of the water.

Prospecting and fieldwork carried out by the General Inspectorate for Cooperation Outside the Metropolis "Electricité de France" between 1961 and 1964 had made an approximate identification of the characteristics of a certain number of sites whose development was envisaged for the production of hydroelectric energy in this basin. Most recently, the Congolese government signed an agreement on May 22, 2022 in Brazzaville with a consortium of two Sino-Congolese private companies Energaz-CGGC (China Gezhouba Group Coorporation) for the construction of the Morala and Nyanga hydroelectric dams with a capacity of 331 megawatts, thus strengthening energy production in the Republic of the Congo. However, to date, no study has been carried out to assess the physico-chemical quality of the surface and/or groundwater of the Nyanga River. The present study therefore proposes to study the origin of the different processes that govern the mineralization of these surface waters in forest areas using water quality indices.

2. Presentation of the Study Area

The Nyanga watershed is located in Central Africa. It spans two countries in this region: Republic of the Congo and Republic of Gabon (**Figure 1**). The watershed is located between the parallels 1˚50 and 2˚50 South and meridians 11˚50 and 12˚40 East. It covers an area of about 5835 km², largely of a rain forest. The main river, the Nyanga river, originates in Gabon in the heart of the Birougou Mountains in the Chaillu massif at 975 m, it branches off to southwest to the Matingou rapid (the lower Nyanga) where it changes its south-south-east direction to south-west to flow into the Atlantic Ocean.

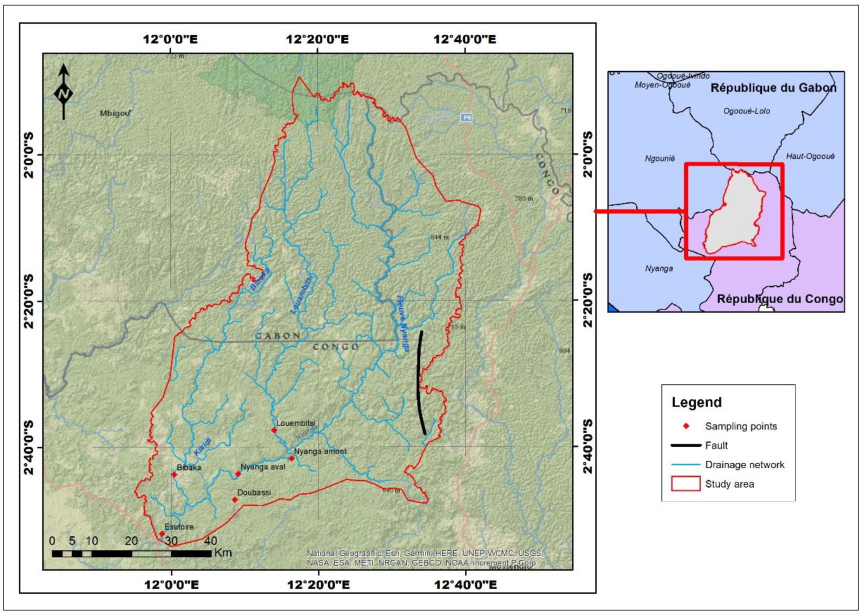


Figure 1. Location of Nyanga watershed with the sampling points.

From a pedological point of view, the soils of the watershed are classified in the category of poorly evolved, hydromorphic and ferralitic soils represented by the subgroup of erosion soils which are found on the steep limestone or calcareous-dolomitic slopes at the limit of the schisto-limestone series and sandstones of the

M'pioka series as well as in the Moussouva series [6]. The geological formation of this basin is entirely made up of superficial formations mainly of Precambrian age (**Figure 2**), limestones and schisto-limestones. The vegetation is largely dominated by a forest formation known as equatorial ombrophile and the hyparrhenia savannah without hymenocardia [7].

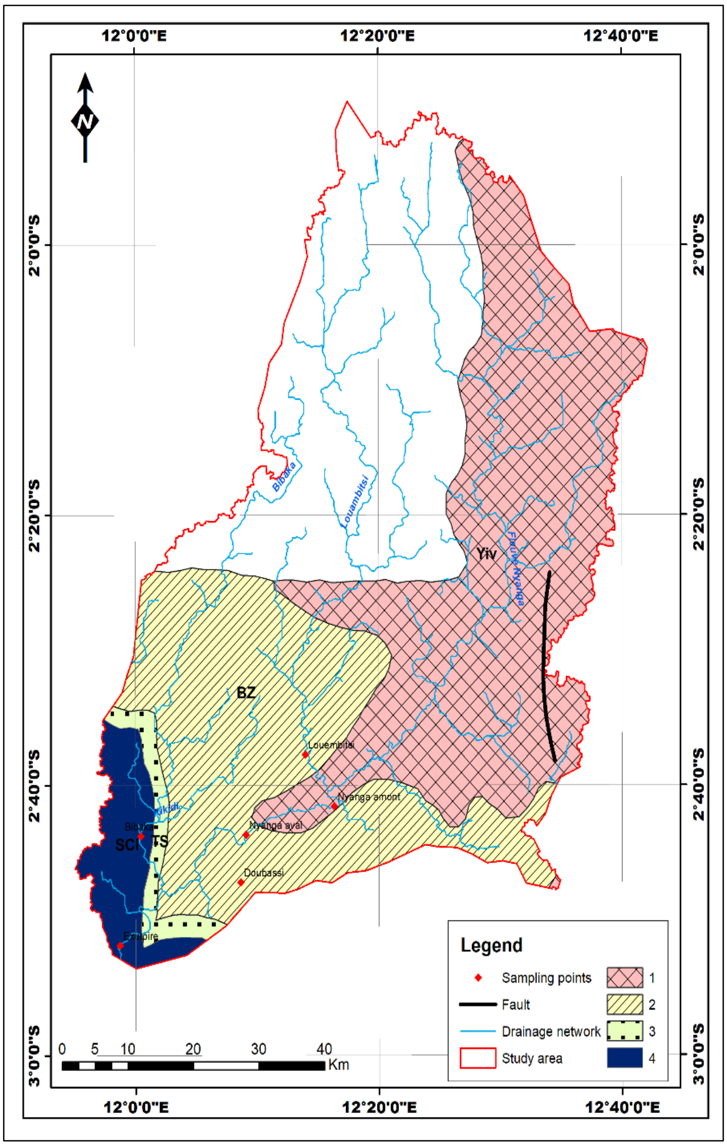


Figure 2. Summarized petrographic map of Nyanga River catchment area (after Geology map of Republic of the Congo, 1995) 1, Yiv: Lower Precambrian: Calc-alkaline granite; 2, Upper Precambrian: Louila and Bouenzien series: marly limestone, argilites and sandstone.

3. Materials and Methods

3.1. Sampling Materials

The study of the physico-chemical characteristics of the water was carried out mainly on the basis of samples taken at 6 points which constitute either the outlet of the sub-basins or the confluence of rivers (**Figure 1**). Field measurements, carried out in the May 2023 rainy season, accompanied the laboratory measurements. The sampling protocol was that recommended by [8]. It consisted first of all of rinsing the sampling and measuring equipment (electrodes of the multi-parameter) with distilled water and then three times in a row with the water to be sampled. Water samples are collected in clean one-liter (1 L) polyethylene vials filled to the brim. They are placed in a cooler for transport to the laboratory for analysis. Physical parameters such as temperature, electrical conductivity (EC) and pH, were measured in situ using a portable JQ006 multi-parameter. Ions were analyzed in the laboratory using the following techniques: spectrophotometry (nitrates, sulphates), titrimetry (chlorides, calcium, magnesium and carbonates) and flame spectrophotometer (potassium and sodium) [9].

The physical parameters measured in the field using the JQ006 multi-parameter allowed us to have a first idea of the water quality. Thus the temperature tells us about the way heavy metals behave in water, Color reflects the concentration of vegetation and inorganic matter in water. Although it has no direct influence on the safety of water, it makes water aesthetically unappealing. pH measures how acidic or basic water is. The electrical conductivity indirectly measures the ionic concentration of water by measuring its ability to carry or conduct an electrical current.

The study is based on a single sample taken during the rainy season (**Figure 1**). These results therefore provide an initial overview of the water quality in the basin studied. However, the physicochemical and microbiological quality of watercourses is likely to vary depending on hydrological and climatic conditions (**Figure 2**). It is therefore recommended to conduct additional monitoring at different times of the year, particularly during the dry and rainy seasons, in order to better understand the temporal dynamics of water quality and obtain a more representative and robust assessment.

3.2. Sampling Methods

The data processing was carried out using R studio software for the statistical processing of the variables and also for the Main Component Analysis, Diagram 6.1, for the determination of hydro-facies from the Piper diagram and Microsoft Excel for the calculation of the different water quality indices and Rstudio for hierarchical ascending diagram.

3.3. Analysis of the Physicochemical Characteristics of Surface Water

The hydrochemical characterization of the water was carried out using the Diagramme software developed by the Avignon Hydrogeology Laboratory. This software allowed us to develop the commonly used Piper triangle diagram with good results [10]-[13] made it possible to account for the distribution of water points in hydrochemical facies and to understand the correlation between the different chemical parameters.

3.4. Statistical Analysis of the Physical-Chemical Parameters of Surface Water

Principal Component Analysis (PCA) aims to highlight the similarities or oppositions that exist between the variables and to identify the variables that are most correlated with each other [14]. It made it possible to construct from a correlation matrix, allowing a graphical representation of the links between variable n (n > 2) and the positions of individuals in relation to the vectors of these variables. The statistics expressed were extreme values (minimum and maximum), mean (center), and standard deviation (dispersion parameter).

3.5. Evaluation of Water Quality Index

The Water Quality Index (WQI) is a water classification technique that is based on the comparison of water quality parameters (**Table 1**) with respective international standards [15]. The parameters used to calculate Water Quality Index (WQI) are: temperature, pH, electrical conductivity, turbidity, nitrates, phosphates (PO_4^{3-}), Chlorides (Cl^-), heavy metals. There parameters cover basic physicochemical conditions (temperature, pH, EC), organic and nutrient pollution (PO_4^{3-} , turbidity), and specific chemical contaminants (chlorides, heavy metals). This multidimensional selection ensures a reliable, reproducible, and comparable assessment of water quality, both from an ecological and heath perspective. This index is calculated using the weighted arithmetic index method [16]. In this approach, a numerical value called relative weight (Wi), specific to each physical-chemical parameter, is calculated according to the following formula:

$$Wi = k/Si \tag{1}$$

where Wi is the relative weight, k is the proportionality constant and can also be calculated using the equation:

$$k = \frac{1}{\sum_{i=1(\frac{1}{si})}^{n}} \tag{2}$$

where n is the number of parameters and Si the maximum value of the WHO standard on water potability.

The quality scale (qi) is computed by dividing its concentration in each water sample by its respective standard [17]

$$Qi = \left(Ci/Si\right) * 100 \tag{3}$$

where Qi is the scale for evaluating the quality of each parameter and Ci is the concentration of each parameter in mg/l.

Finally, the overall water quality index is calculated by the following equation:

$$WQI = \frac{\sum_{i}^{n} Qi * Wi}{\sum_{i=1}^{n} Wi} \tag{4}$$

Five quality classes can be identified according to the values of the IQE water quality index (**Table 1**).

Table 1. Classification and potential water use by QEI.

WQI value	Type of water
0 - 25	Excellent quality
25 - 50	Good quality
51 - 75	Poor quality
76 - 100	Very poor quality
>100	Non-potable water

3.6. Irrigation Water Quality Index

The quality of surface and/or groundwater for irrigation depends on the effects of mineral concentrations in the water, on the soil and plant [18]. The effect of salts on soils leads to changes in soil structure, permeability, and consequently affects plant growth [19]. In this study, we evaluated the suitability of the water for irrigation use through four indices: the Sodium Absorption Ratio (SAR), the Permeability Index (PI).

3.7. Sodium Absorption Ratio (SAR)

The sodium absorption ratio is an important parameter in determining the suitability of surface water for irrigation purposes because it measures the hazard of alkali-sodium to crops. Due to its effects on soils, it is considered one of the main factors governing irrigation water. This ratio is determined using the equation:

$$SAR = \frac{Na + K}{\sqrt{\frac{Ca_2 + Mg^{2+}}{2}}} \quad (5)$$

3.8. Permeability Index (PI)

The adequacy of irrigation water is also evaluated using the permeability index, or PI. According to, excess Ca^{2+}, Mg^{2+}, and bicarbonate create soil permeability problems. The index is computed as follows [20].

$$IP = \frac{Na + \sqrt{HCO_3^-}}{CA + Mg + Na} \quad (6)$$

3.9. Kelly Report (*KR*)

The Kelly Report (KR) is used to determine irrigation water quality. Sodium is compared to calcim and magnesium. A $KR > 1$ indicates an excess of salt, whereas a KR < 2 indicates a shortfall in water and is computed using the following formula 7 [21].

$$KR = Na/(Mg + Ca) \quad (7)$$

4. Result and Discussion

a. Results

Physicochemical quality of surface water

- **Physical parameters**

The results of the physical-chemical parameters of the sampled water are reported in **Table 2**. The temperature of the surface water is almost homogeneous throughout the catchment area, varying between 25.4 and 28.6˚C with an average of 27.13˚C. These values reflect the ambient air temperature, which averages 28˚C and is in line with the WHO guide, which states that good water should have a temperature between 25 and 30˚C. The pH varies between 4.99 and 5.76 with an average of 5.42, which allowed us to classify this acidic water. According to the WHO 2011, fresh drinking water has a pH between 6.5 and 8.5. With a conductivity of 9.5 and 20 µS/cm and an average of 12.37 µS/cm, these values are below the WHO guide value, thus testifying to a low mineralization of the surface waters of the Nyanga River. The complex bordering the Upper Nyanga watershed consists almost entirely of Precambrian formations, overlain by Quaternary alluvium and Plio-Pleistocene formations. Three types of soil predominate in the region: yellow ferrallitic soils, derived from metamorphic rocks; red ferrallitic soils, shallow and relatively undeveloped; and undifferentiated hydromorphic soils. These soils are mainly characterized by the individualization of iron and aluminum hydroxides, the latter being toxic to roots. This phenomenon, more generally known as ferrallitization, is typical of acid soils under rainforests [22], and is unfortunately confronted by massive deforestation by logging companies in the study area. Deforestation contributes to increased CO_2 emissions.

Table 2. Basic statistics of the physico-chemical parameters of the Nyanga Watershed.

Physico-chemical variables	Unit	WHO Standards 2011	Min.	Max.	Average	Standard deviation	CV (%)
pH	-	6.5 - 8.5	4.99	5.76	5.42	0.28	0.052
T	˚C	25 - 30	25.4	28.6	27.13	1.11	0.041
CE	µS/cm	≤500	9.5	20	12.37	3.84	0.31
HCO_3^-	mg/L	-	6.37	24.78	13.26	7.13	0.54
NO_3^-	mg/L	≤50	0.25	8.2	2.37	2.95	1.24
SO_4^{2-}	mg/L	≤250	0.1	7	3.29	2.41	0.73
PO_4^{3-}	mg/L	≤5	0.03	0.08	0.05	0.02	0.4
Cl^-	mg/L	<250	2.25	14.5	7.85	4.52	0.57
Ca^{2+}	mg/L	≤100	2.3	8.12	4.66	2.36	0.507
Mg^{2+}	mg/L	≤50	0.58	2.44	1.24	0.69	0.556
K^+	mg/L	≤12	0.29	0.9	0.59	0.27	0.452
Mn^{2+}	mg/L		0.01	0.06	0.03	0.023	0.77
Al^{3+}	mg/L	≤0.2	0.03	0.07	0.04	0.02	0.440
Fe^{2+}	mg/L	≤0.2	0.01	0.06	0.03	0.02	0.798
Ni^{2+}	mg/L	≤0.07	0.01	0.03	0.02	0.01	0.490
Cu^{2+}	mg/L	≤1	0.01	0.06	0.04	0.02	0.506
Na^+	mg/L	-	0.42	4.37	2.09	1.65	0.79

- **Chemical parameters**

The chemical elements of the water make it possible to know, first of all, the nature of the composition, the quantitative predominance of certain elements; secondly, to assess the physico-chemical aggressiveness of the waters and, consequently, the rate of soluble elements transported [23]. The main elements are:

- Calcareous (Ca^{2+}): calcium levels are relatively low with an average of 4.66 mg/L. All sampled points have values below the WHO guideline value (≤100). The low levels can be explained by the fact that rainwater, which had become runoff, did not have time to saturate.
- Magnesium (Mg^{2+}): the values are much lower than those of calcium. They vary between 0.58 and 2.44 mg/L. The average magnesium content is 1.24 mg/L. All sampled points have values below the WHO guideline value (≤50).
- The sodium-chloride group (Na^+-Cl^-): the sodium and chloride ions are brought by rain. Their concentration in the rainfall testifies to their prior accumulation by vegetation, then to their mobility during leaching [24], in the canopy. Sodium values are low with an average of 2.09 mg/L. As for chlorides, their concentrations correlated with sodium are low. These low concentrations are related to the weathering of rocks poor in sodium elements.
- Bicarbonate and carbon dioxide (HCO_3^- -CO_2): the level of bicarbonates in the waters of the Nyanga reaches a maximum of 24.78 mg/L and a minimum of 6.37 mg/L with an average value of 13.26 mg/L. As for the values of carbon dioxide (CO_2), they show fluctuations similar to those of bicarbonates. The maximum CO_2 levels are 11 mg/L, while the minimum is 2.58 mg/L. The evolution of these two elements attests to a common origin, probably due to the dissolution of the limestone of the schisto-limestone series of the Upper Precambrian. The existence of carbonate rocks in the northern part of the catchment area explains the high concentrations upstream and their gradual decrease downstream. Carbon dioxide (CO_2) and bicarbonate play a crucial role in regulating water acidity. CO_2, when dissolved in water, forms carbonic acid (H_2CO_3), which then dissociates into hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). Bicarbonate, in turn, can buffer H^+ ions and keep the water's pH within a relatively stable range.
- Potassium (K^+): its values are relatively low. The average value is 0.58. The maximum and minimum are 0.9 and 0.29 mg/L respectively and do not exceed the WHO guide value (≤12).

Metal trace element

Copper concentrations varied from 0.01 to 0.06 mg/L with an average of 0.04 mg/L not exceeding the WHO standard which states that the presence of copper in a sweet water must be less than 1, ferrous Iron (Fe^{2+}) varies from 0.01 mg/L for the minimum values and 0.06 mg/L for the maximum values for an average of 0.03 mg/L. The presence of iron in the water indicates leaching of ferralitic soils, but these values remain below the standard set by the WHO, which is 0.2 mg/L. Aluminium (Al^{3+}) levels ranged from 0.03 to 0.07 mg/L with an average of 0.04

mg/L but did not reach the WHO threshold of 0.2 mg/L. In general, all trace metal elements sampled in the surface waters of the Nyanga River are well below the WHO guideline values. The degree of variability (or coefficient of variation) of trace elements is almost homogeneous all along the river.

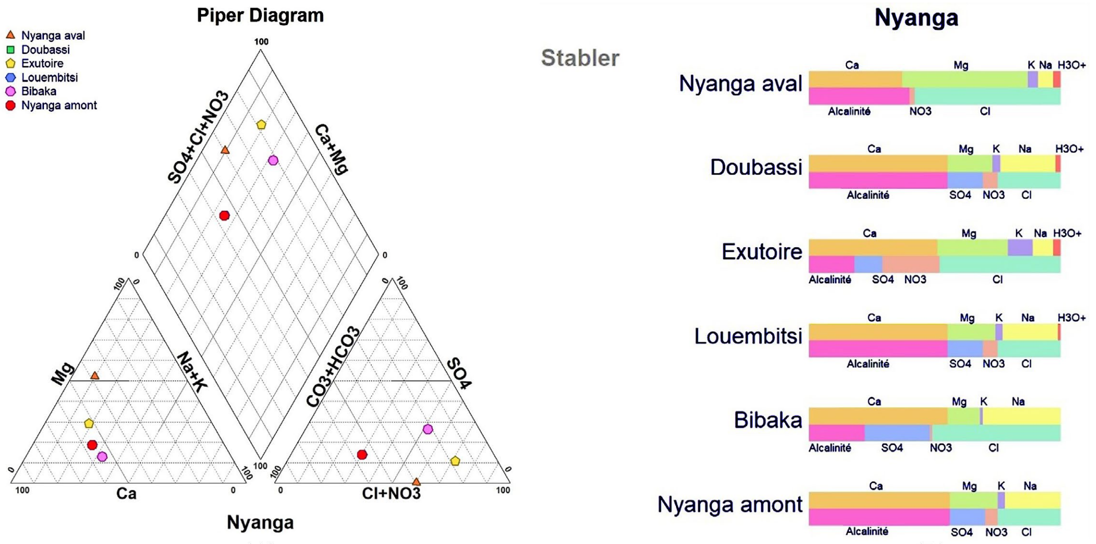
Hydrochemical classification of water

The analysis of the Piper and Stabler diagrams (Figure 3(A)) allowed us to determine the type of hydrochemical facies of the samples. It appears from this analysis that the waters of the Nyanga are divided into two groups according to their facies:

- The calcium and magnesium bicarbonate facies (33.33% of the water analysed): it corresponds to the waters coming from the calcareous, calcareous-sandstone massifs of the schisto-limestone series of the Upper Precambrian schisto-limestone. The ratio of Mg^{2+} to Ca^{2+} varies between 0.14 and 0.83. The magnesium waters come from the limestone and dolomitic outcrops of this series. Crushing promotes the dissolution of the dolomite by a longer water-rock contact.
- The calcium and magnesium chloride and sulphate facies (66.67% of the water analysed): this facies is the most dominant and corresponds to the point sampled between the upstream and downstream of the basin. It is characterized by a predominance of chlorides over bicarbonates for anions and alkaline earths over alkalines for cations.

The order of importance of the main ions (Figure 3(B)) in the surface waters of the Nyanga River watershed is summarized as follows: $Ca^{2+} > Mg^{2+} > K^+ > Na^+$ for cations and $HCO_3^- > NO_3^- > SO_4^{2-} > Cl^-$ for anions.

To better visualize the mineralization of the sampled points, we have chosen to use the Schoeller-Berkaloff graph which has the advantage of presenting both the mineralization and the responsible ionic elements.



(A) (B)

Figure 3. (A) Piper diagram and (B) Stabler diagram for Nyanga river.

The analysis of the Berkaloff graph (**Figure 4**) shows the existence of a single group: the weakly mineralized group formed by the points of the Nyanga confluence, the Boulou, Nyanga bridge, Doubassi and the Louambitsi bridge, the conductivity of this group varies between 10.3 and 20 µS/cm. It is essential to remember that water will only become loaded with soluble products if they exist and if they are in contact with them in order to be able to dissolve them. The low conductivity values explain the low mineralization of the surface waters of the Nyanga River and are therefore little influenced by anthropogenic activity, and therefore their conductivity is placed in the class of good water quality.

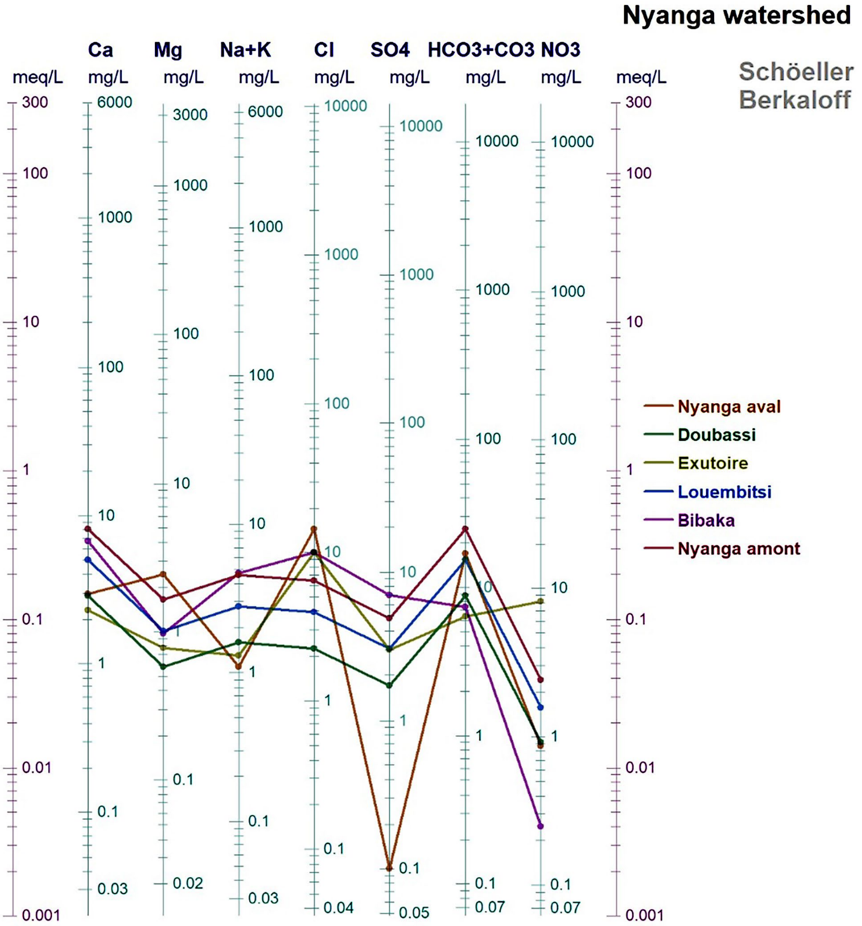


Figure 4. Schôeller Berkalof diagral for Nyanga river.

Principal Component Analysis

Variable correlation matrix

The relationships between all the variables taken in pairs, as well as the correlation coefficients between these different variables, are given by the correlation matrix (**Table 4**). There is a strong correlation between two variables when the correlation coefficient exists and is greater than 0.50. Analysis of this table showed that some parameters were strongly correlated. This is the case, for example, of the alkaline earths Ca^{2+} and Na^+ (r = 0.93), Mg^{2+} and Cl^- (r = 0.67) or O_2 and

SO_4^{2-} (r = 0.89). Similarly, these results showed that electrical conductivity was well correlated with all major cations (0.81) with K^+; (r = 0.72) with Na^+; with SO_4^{2-} (r = 0.90) thus confirming that all these elements participate in the mineralization. These correlations show that the parameters mentioned above had a common origin or they had a common natural phenomenon.

Eigenvalues and variance expressed by factors

Using the R software, a factor analysis of the different chemical constituents of the surface water of the Nyanga watershed was carried out, taking into account electrical conductivity, pH, all cations and anions. The eigenvalues, the percentage variance and the cumulative percentage variance of the factors are given in Table 3. The first eigenvalue is 8.22, which represents 37.38% of the total variance and this is the first and main factor. The second and third eigenvalues are 5.77 and 3.74 and represent 26.27% and 17.02% of the total variance, respectively. The three factors (F1, F2, F3) in Table 3 reflect most of the information sought and allow the scatter plot to be represented in a meaningful way because the sum of the variance expressed by these factors is 80.67%.

Table 3. Correlation between variables and factors.

Parameter	F1	F2	F3
pH	0.40	**−0.80**	−0.18
T˚C	0.08	0.38	**0.77**
CE	**0.96**	−0.03	0.13
CT	0.47	**0.53**	−0.33
TDS	**0.83**	−0.33	−0.26
TAC	**0.79**	0.40	0.08
Ca^{2+}	**0.84**	−0.49	−0.10
Mg^{2+}	0.25	0.47	−0.04
K^+	0.41	0.33	**0.81**
Na^+	**0.63**	**−0.72**	−0.27
Mn^{2+}	0.49	**0.69**	−0.40
Fe^{2+}	**0.96**	−0.10	0.18
Cu^{2+}	**0.57**	**0.60**	−0.41
Al^{3+}	−0.34	**0.66**	**−0.66**
Ni^{2+}	**0.74**	0.06	**0.64**
SiO_2	**0.86**	0.27	0.16
O_2	0.39	**−0.78**	−0.25
NO_3^-	−0.16	0.09	**0.82**
PO_4^{3-}	**0.60**	**0.65**	−0.43
SO_4^{2-}	0.44	**−0.88**	0.00
Cl^-	−0.22	0.05	0.13
HCO_3^-	**0.79**	0.40	0.08

This percentage was sufficient to provide the information needed to identify the natural phenomena responsible for surface water mineralization. **Figure 5** illustrates the plane defined by the factors F1 and F2. In this factorial space, CE, Ca^{2+}, TDS, TAC, Na^{+}, Fe^{2+}, Cu^{2+}, Ni, SiO_2, PO_4^{3-} and HCO_3^{-} cluster at the positive end of axis 1.

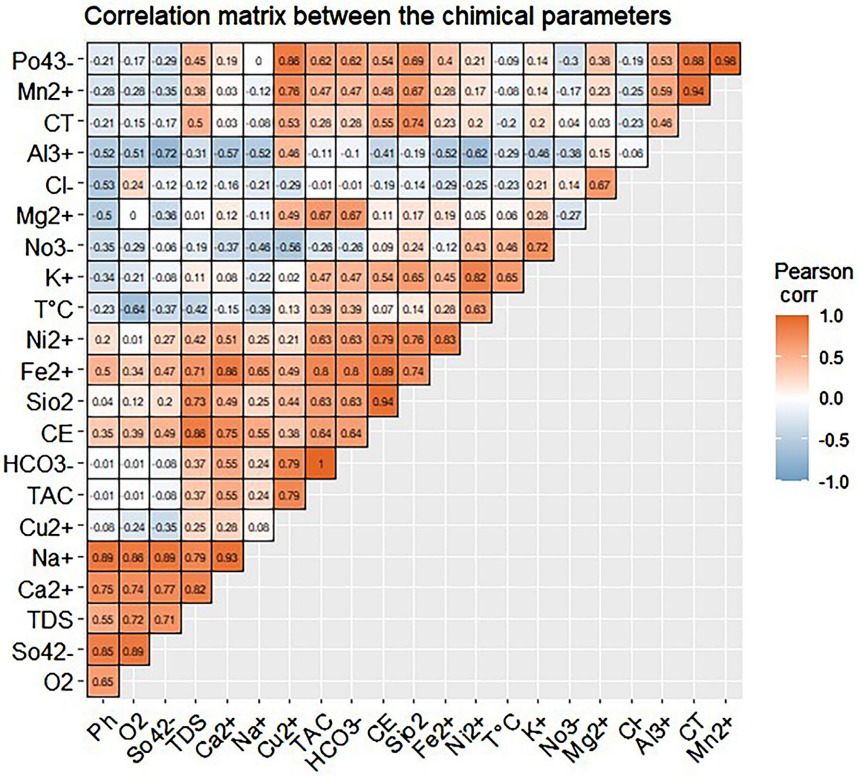


Figure 5. Correlation matrix between the chemical parameters studied.

This grouping indicates that the variables concerned evolved in the same way and were dependent on the same or similar phenomena (**Figure 6**). The Ca^{2+}, Na^{+}, HCO_3^{-} ions have the particularity of appearing in the water after prolonged contact of the water with the surrounding rocks. As for the factor 2, it was determined by pH, Na^{+}, O_2, SO_4^{2-} grouped at the negative end while CT, Mn^{2+}, Cu^{2+}, Al^{3+}, PO_4^{3-} is positioned at the positive end of this factorial axis. The presence of pH (acidic) in this axis increases the risk of the presence of metals in a more toxic ionic form.

Data analysis using the hierarchical ascending classification method (**Figure 7**), using the average distance between classes, made it possible to group together all the physicochemical parameters studied on the one hand, and, on the other hand, between the sampling points based on their similarity in the variation of these parameters. The dendrogram resulting from the hierarchical ascending classification highlights four main groupings of variables: TC; followed by the grouping consisting of pH, Ca^{2+}, SO_4^{3-}, NO_3^{-}, K^{+}, Fe^{2+}, Ni^{2+}, Al^{3+}, PO_4^{3-}, Cu^{2+}, CT, Mn^{2+}, Mg^{2+}, SiO_2, Na^{+}, O_2; the third grouping is composed of TAC, HCO_3^{-} and the fourth grouping is composed of Cl^{-}, CE, TDS. The first grouping highlights the temperature which affects the amount of salts, gases, and other substances that can dissolve in water. The second grouping highlights most of the major and trace elements, the presence of iron and manganese in this grouping highlights a strong contribution of leaching from the soil and the surrounding rock crossed by the watercourse, the presence of certain metals marks organic pollution; the third grouping on the other hand accounts for mineralization-residence time or the phenomenon of hydrolysis of minerals. The formation of bicarbonates in mineral water is linked to the interaction of water with rocks and minerals, often in the presence of carbon dioxide. Finally, the fourth group reveals low pollution linked to anthropogenic activities.

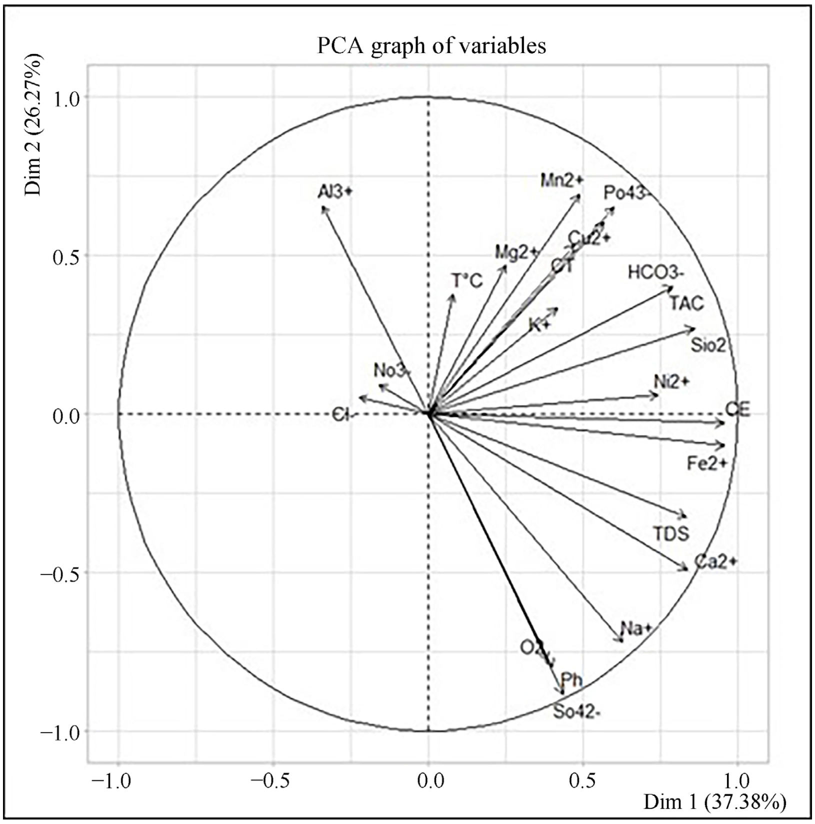


Figure 6. Space of F1 and F2 factorial plane variables.

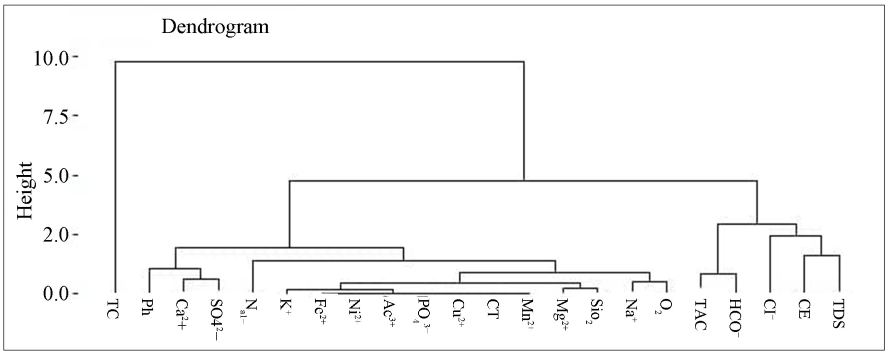


Figure 7. Hierarchical ascending classification (HAC) of water brands based on physicochemical on Nyanga water.

Water Quality Index Calculation Results and Water Quality Assessment

The relative weight (Wi) of each physicochemical parameter and the proportionality constant k are calculated first using the maximum values of WHO standard [15], the physicochemical parameters studied (**Table 4**).

Table 4. Weights of physicochemical parameters and the WHO standard 2011.

Parameters	Standard OMS	1/If	*Wi*	*Vi*	Intelligence quotient	WQI
PH	6.5	0.154	0.0062	4.99	76.769	0.4725
Neither	0.07	14.286	0.5715	0.01	14.286	8.1648
Cu	2	0.5	0.0200	0.05	2.5	0.0500
Ly	0.2	5	0.2000	0.06	30	6.0011
Ly	0.2	5	0.2000	0.06	30	6.0011
SO4	200	0.005	0.0002	0.1	0.05	0.0000
CL	250	0.004	0.0002	14.5	5.8	0.0009
MG	30	0.033	0.0013	2.44	8.133	0.0108
CA	75	0.013	0.0005	2.95	3.933	0.0021
Sum		24.995	1			20.704
	$K = 1/\sum(1/Si)$	0.040				

After the calculation of the water quality index (WQI) using the results of physico-chemical analyses and the standard values of the 2011 WHO guide standard on the drinking water quality directive, the water quality class of the Nyanga River is determined for the 6 points sampled. Thus, two water quality classes are identified: excellent water and good water (**Table 5**).

Table 5. EQI Index values and surface water quality class of the Nyanga River during the May 2023 campaign.

Sampled Points	**EQI Water Quality Index Values**	**Quality class**	**Possible use**
Boulou	15.14	Excellent	Drinking Water, Irrigation and Industry
Doubassi	22.72	Excellent	Drinking Water, Irrigation and Industry
Nyanga bridge	22.59	Excellent	Drinking Water, Irrigation and Industry
Louambitsi Bridge	23.13	Excellent	Drinking Water, Irrigation and Industry
Nyanga	20.704	Excellent	Drinking Water, Irrigation and Industry
Nyanga confluence	31.26	Good	Drinking Water, Irrigation and Industry

Irrigation Water Quality Index

The SAR values of waters studied are all less than 10 (**Table 6**). These results show that the waters present a low risk of alkalinity for the soil.

The permeability index calculated fer the 6 water samples in this study is between 58.77 and 89.94% with an average of 74.93%. Compared to PI values, the waters of Nyanga River define an excellent quality for crop irrigation (**Table 6**).

KR values fluctuate between 0.09 and 0.57 with an average of 0.32. All calculated values are less than 1. Therefore, the surface waters of the Nyanga are suitable for irrigation.

Table 6. Value of water quality indices for irrigation.

Picking point	SAR	IP	KR
Nyanga	0.67	78.53	0.09
Doubassi	1.23	89.48	0.38
Nyanga bridge	1.06	84.11	0.14
Luambitsi	1.62	74.33	0.37
Boulou	2.38	58.77	0.57

5. Discussion

The surface waters of the study area are generally low in minerals. Mineralization was less than 500 mg/L. This mineralization is almost comparable to the results obtained by [25] and [10]. Apart from the northern plateau of the Congo Basin where mineralization values are high, the entire southern part of the country if not almost all of it would be very weakly mineralized as mentioned in the research work of [26]-[28]. Analyses of surface water in the Nyanga watershed during the rainy season have shown that the waters are acidic. Indeed, the acidity of surface water has been observed in several rivers in the country. These include the Loua river south of Brazzaville [10], groundwater in the Nganga-lingolo area, and the Paris-sangha spring in Dimonika [25]. According to Matini *et al.* (2009), this acidity of water in humid tropics is mainly linked to the decomposition of plant organic matter, with the production of CO_2 in the first layers of the soil. This acidity reflects the corrosive nature of the water. Coupled with low mineralization, it could pose a health problem, as a mild one could be associated with cardiovascular disease [29].

Dissolved oxygen concentrations are one of the most important parameters of water quality as they are essential for aquatic life and for the degradation of biodegradable pollutants for self-purification [30]. Overall, the closer the dissolved oxygen concentration is to saturation, the greater the river's ability to absorb pollution. Its average content in unpolluted surface water is 8 mg/L.

The results of our study showed almost homogeneous values between 2.23 and 2.58 mg/L. Depending on the temperature, the solubility of oxygen in water is significantly lower than normal. The presence of organic matter reduces the dissolved oxygen content in the water by oxidation through a microbiological process. The content decreases when the temperature increases or the atmospheric pressure decreases with altitude.

Nitrates generally come from the decomposition of organic matter by bacterial oxidation of nitrites and are thus the ultimate product of nitrification [31]. Nitrate levels are between 0.01 and 0.03 mg/L. This low mineralization is explained by the very pronounced leaching of the soils, characteristic of the rainfall regime of the humid equatorial zone.

The analysis of heavy metals in surface water shows the absence of cadmium, chromium and zinc, but metals such as iron, aluminium and lead have been detected in varying concentrations, always remaining far from the WHO standards for these metals. The recorded metal traces show that their origin could only be geological and natural insofar as the watercourses are in a rural area and there is no intense industrial agricultural activity.

The Principal Component Analysis and the Hirearchical Ascending Classification give similar results on the origin of the mineralization of surface waters in the Nyanga watershed. These show that the mineralization is controlled by the nature of the geological formations present in the region. Indeed, the origin of ions in surface water is controlled by water-rock contact, as indicated by the results of the various statistical studies. The geology of the region is dominated by the Precambrian formations consisting mainly of biotite granodiorite, argillites, sandstone, marly limestone, limestone dolomites and conglomerates. The hydrolysis of such rocks, rich in alkaline feldspars and acid plagioclases, explains why the Ca^{2+} and Na^{+} contents are dominant for cations in surface water. These ions are the result of the weathering of rocks and the hydrolysis of silicate minerals. According to [32], the calcium released during the acid hydrolysis of plagioclases evolves in conjunction with bicarbonates in the waters according to the reaction: 5 (Na 0.8, Ca 0.2) (Al 1.2, Si 2.8, O 8) + 6 H + 19 H_2O 3 Al_2O_5 (OH) 4 + 4 Na^+ + Ca^{2+} + 8 H_4SiO_4.

Although the watershed is locally underlain by limestone and dolomite formations, their buffering effect on water acidity remains limited. Indeed, these carbonate rocks are either weakly outcropping or covered by a thick cover of highly weathered ferrallitic soils. In this context, the intense chemical weathering typical of tropical environments gradually leaches carbonates and reduces their availability. In addition, carbonate dissolution is relatively slow compared to the high acid load generated by organic matter and pedogenic processes. Therefore, the potential neutralizing capacity of limestone and dolomite rocks is not significantly reflected in the observed surface water chemistry.

This reaction is more marked in surface waters, so that the correlation between Ca^{2+} and HCO_3^- is strong (r = 0.55). As the study area is a dense forest area, it is during the infiltration of rainwater in depth into these soils that the water laden with CO_2 will dissolve the formations and be enriched in bicarbonates. It is this acid hydrolysis of the surrounding rocks that controls the diversity of bicarbonate facies in the surface waters of the Nyanga. The Cl^- ions; SO_4^{2-} and part of the cations, come from rain and soil leaching by it, as indicated by the results of the multivariate analysis. The natural origin of lead may be related to the fact that this metal is mainly a substitute for potassium, strontium and barium. Thus, trace amounts can be found in potassium minerals such as feldspars or micas [33]. However, for these authors, high concentrations of lead of natural origin are very rare even in favorable geological contexts because it is a poorly soluble element, easily absorbed on clays, hydro (oxides) and organic matter and which can precipitate easily in the form of carbonates or phosphates [11].

The analysis of the various parameters for irrigation showed that the waters of the Nyanga would not pose any risk to the crops.

6. Conclusion

The objective of the study was to understand the hydrochemical functioning of surface waters in the Nyanga River watershed in the southwest of the Republic of the Congo. The study was carried out using a combination of graphical hydrochemical methods and multivariate statistical analysis. This study showed that the waters of the Nyanga are acidic with a pH below 6.5 and very low mineralization (EC varied between 9.5 and 20 µS/cm). Mean surface water ion levels remained generally within the WHO recommended drinking water standards for human consumption. The hydrochemical facies obtained by Piper's diagram presents two classes: the calcium and magnesium bicarbonate facies and the calcium and magnesium chloride and sulphate facies. Multivariate analysis methods have shown that mineralization is governed by three phenomena including soil rainfall, then rainfall inputs and especially acid hydrolysis of the minerals of the host rocks. The results of this study are certainly interesting and deserve special attention in order to guarantee the good health of populations and especially the good growth of aquatic plants which play a major role in maintaining the temperature following climate change.

Authors' Contributions

Conceptualization, Writing Original Draft: H.S.D.K. and A.E.; Data acquisition and quality check, Data processing, Data Curation, Validation: H.S.D.K. and M.N.M; Formal analysis, Investigation, Visualization: H.S.D.K.; Review & Editing: H.S.D.K., A.E, M.N.M and VREB; All authors reviewed the manuscript.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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