

Evaluation of the Physico-chemical Quality of Drinking Water in the City of Daloa (Mid-West of Côte d'Ivoire) - Effects on Human Health

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Abstract: Water is the main water requirement of the human body. However, 80% of water-related diseases affect people in developing countries. Physicochemical analyzes (nutrient salts, mineral salts, physical parameters) were carried out on water points (springs, boreholes, wells and taps) in order to assess the level of contamination of drinking water in the city of Daloa. A total of 18 drinking water quality parameters were determined using standard water analysis techniques and the values obtained were compared to the drinking water standards recommended by the World Health Organization (WHO) and the Environmental Protection Agency (EPA). The descriptive analysis of the parameters showed that the waters have an acid pH with a more pronounced acidity in groundwater (pH 4.25 – 5.88). That made them non-compliant with the WHO standard (6.5 – 8.5). In addition, the temperature of the waters studied (25.2 – 28.4°C) is higher than the standard (25°C) for all the water points except tap R1 (24.3°C). Furthermore, these waters are weakly mineralized with conductivities (0.73 – 4.28 mg/L) and levels of total dissolved solids (0.32 – 2.41 mg/L) which meet WHO standards. Also, 4 water points (44.44%) are contaminated by nitrites; 8 (88.88%) are contaminated with ammonium and all the water points (100%) have chemical oxygen demand values above the WHO standard (10 mg/L). However, calcium (0.276 – 0.601 mg/L), magnesium (0.205 – 0.256 mg/L), sodium (20.37 – 37.13 mg/L), potassium (0.198 – 0.433 mg/L), sulfates (0.69 – 15.98 mg/L), chlorides (8.88 – 26.63 mg/L), orthophosphates (0.01 to 0.26 mg/L), nitrates (0.93 – 28.13 mg/L) and turbidity (0.16 – 4.16) comply with WHO standards for drinking water which are respectively 100 mg/L, 50 mg/L, 200 mg/L, 12 mg/L, 250 mg/L, 250 mg/L, 0.5 mg/L, 50 mg/L and 5 NTU. Moreover, all the waters sampled have a total nitrogen level (0.22 to 0.56 mg/L) that comply with the EPA standard (10 mg/L) for human consumption. In general, the physico-chemical quality of the waters sampled is acceptable but in some cases, it requires a specific treatment (filtration, adsorption, etc) before consumption.

Keywords: Physico-chemical Parameters, Wells, Springs, Boreholes, Drinking Water, Daloa

1. Introduction

Water is an essential element for humanity and it is

necessary for the well-being, security, social development, economic growth and food production [1, 2]. It is part of the nutritional needs of the body. Thus, it ensures the need for water, which represents the main constituent of living matter.

It constitutes about 70% of the mass of the human body [3].

The quality of drinking water is just as important as its quantity [4]. Indeed, water with an adequate chemical characteristic is essential for health and the flourishing of human life [5, 6]. Therefore, nutritional status is at risk when the population is exposed to high levels of infections due to unsafe water supply and inadequate sanitation [7]. This justifies the high rate (80%) of diseases directly linked to water that affect the population in developing countries [8]. The World Health Organization (WHO) estimates that 1.5 billion people in the world do not have access to drinking water and about 30 thousand people die every day from drinking dangerous water or from dehydration [9]. According to the United Nation (UN), more than 6000 children die every day in the world for having consumed undrinkable water [10].

In Côte d'Ivoire, drinking water supply is provided by the "Société de Distribution d'Eau en Côte d'Ivoire (SODECI)" since 1959 and by Village Hydraulics (VH) and Improved Village Hydraulics (IVH). This heavy task is often poorly assured because the organoleptic parameters such as taste, color are often objects of speculation on the potability of water. Further, the number of waterborne diseases is growing in our cities [11].

The city of Daloa located in the Mid-West of Côte d'Ivoire suffers greatly from the quality of its drinking water, mainly that distributed by SODECI. Thus, the drinking water distributed by SODECI-Daloa has a poor color followed by the formation of deposits at rest and an aftertaste. This reality leads almost all connected households to doubt its potability [12]. Such a characteristic of the water distributed by SODECI encourages most of the population to use other sources of water supply such as springs, wells and boreholes.

In addition, the rapid increase in population is giving rise to new neighborhoods which unfortunately only have well water as their only drinking water.

The purpose of this study is to determine the physico-chemical parameters of water samples taken from wells, springs, boreholes and taps used as sources of drinking water in Daloa. The determined parameters were selected taking into account their effect on the health of consumers.

2. Materials and Methods

2.1. Study Framework

The city of Daloa is located in the Mid-West of Côte d'Ivoire, capital of the "Hautassandra region". It is located 141 km from Yamoussoukro, the political capital and 383 km from Abidjan, the economic capital. This city is located between 6°30' and 8° North latitude and between 5° and 8° West longitude [13]. The population of the city of Daloa is estimated at 421,879 inhabitants in 2021 [14], with an area of 530.5 ha. It is the third most populated city in Côte d'Ivoire after Abidjan and Bouaké.

2.2. Presentation of Water Points

The study was carried out on nine (09) drinking water points (Figure 1) including two (02) sources in the Gbokora (S1) and Soleil 1 (S2) districts, two (02) boreholes in Tazibouo-University (F1) and Marais (F2), two (02) wells in Lobia (P1) and South C College (P2) and three (03) taps including one (01) in the Tazibouo-University district (R1) and two (02) in the village of the SODECI production site in Daloa (R2 and R3).

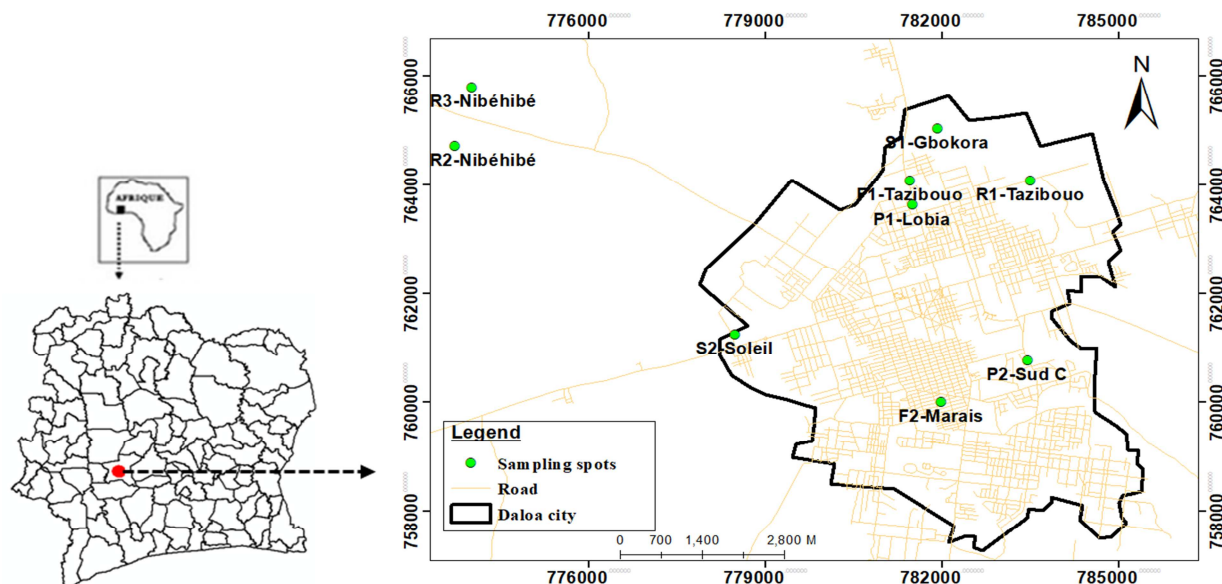


Figure 1. Location map of abstraction water points.

2.3. Sampling

The water samples were taken using 1.5 L and 0.5 L

polyethylene jars filled to the brim and previously rinsed with the water to be sampled. They are then kept in a cooler containing ice maintained at 4°C for the analysis of the

parameters in the laboratory according to the standard. However, a drop of concentrated hydrochloric acid was added to the 0.5 L samples intended for the analysis of major cations.

2.4. Methodology

A total of eighteen (18) physico-chemical parameters were determined during our study according to standard analysis techniques. Temperature (T) and hydrogen potential (pH) were measured using the HANNA HI 8424 portable multiparameter. Electrical conductivity (EC) and total dissolved solids (TDS) were measured using the HANNA HI 9835 conductivity meter. The turbidity of the water, for its part, was determined using a portable turbidimeter of the HANNA HI 93413 type. All these measurements were carried out *in situ*. Ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}) and sulphate (SO_4^{2-}) ions were measured by Molecular Absorption spectrophotometry according to standard NF T 90-012 and NF T 90-009 at respective wavelengths of 885 nm for PO_4^{3-} ; 415 nm for NO_3^- ; 543 nm for NO_2^- ; 630 nm for NH_4^+ and 650 nm for SO_4^{2-} . The Cl^- ions were determined by titrimetry according to standard NF T90-014. The Na^+ , Mg^{2+} , Ca^{2+} and K^+ cations were measured by atomic absorption in an air-acetylene flame with the atomic absorption spectrophotometer (AAS 20 type VARIAN) according to standard NF T 90-112. The total nitrogen was determined by the Kjeldahl method according to standard AFNOR T 90-110. The total phosphorus was evaluated according to the AFNOR T900-23 standard after filtration of the samples on Whatman filter paper with a 0.45 μm porosity. The spectrophotometer (Thermo-Scientific UV/visible – Orion aquamate 8000) was used for these analyses. The chemical oxygen demand (COD) was determined by the potassium dichromate method as defined by the French Association for Standardization (AFNOR NF T90 – 101) [15].

2.5. Data Processing

Statistical data processing was performed with STATISTICA 7.1 software. It allowed us to perform Principal Component Analysis (PCA). This descriptive multidimensional statistical method is used as a tool to help interpret a data matrix. The PCA will allow us to bring out the correlation circle on the F1 – F2 axes and the Bravais Person correlation matrix of the different water parameters.

3. Results and Discussion

3.1. Physical Parameters

The physical parameters analyzed are reported in Table 1. The drinking water sampled have temperatures between 24.3°C (R1) and 28.4°C (S1). All waters have a temperature above the limit of 25°C recommended by the WHO [7] except R1. The high values recorded during this study would be due to the influence of ambient temperature [16]. However, water temperatures above 25°C do not constitute a

danger [17] but could affect the organoleptic properties of the waters [18]. Indeed, high temperature values are not harmful to human health, but pose a problem of acceptability because cool water is generally more palatable than lukewarm water [19]. Consequently, drinking water from the sites studied in the city of Daloa does not constitute a danger for the consumer. According to the WHO [20], the temperature of 25°C is difficult to observe in West Africa for drinking water. Because the average water temperature in West Africa and in the humid tropical zone tends towards 30°C due to climatic conditions [21]. The values recorded during our study are lower than those obtained by [22] in the department of Soubre whose values oscillated between 25.3 and 30.6°C and by Bakouan et al. [23] in borehole waters in Tanlili and Lilgomdè in Burkina Faso which had values between 28 and 33°C.

The pH values of drinking water recorded during the present study oscillate between 4.25 (P1) and 6.67 (R1). The waters studied are therefore acidic with pH values that do not comply with WHO standards, between 6.5 and 8.5 [7] except for R1. This acidity is consistent with that of the waters encountered in several regions of Côte d'Ivoire as indicated by Adjiri et al. [24], Orou et al. [25], Ahoussi et al. [26] and Ahoussi et al. [27] respectively in Daloa and Zoukougbeu (pH = 4.81), Agboville (pH = 6.20), Bondoukou (pH = 6.23) and Man (pH = 5.17). The acid character of the waters studied could be explained by the fact that they come from alterite layers. In fact, according to Adjiri et al. [24], the acidity of these waters results from the disappearance of easily alterable primary minerals. In addition, in the humid tropics, the acidity of the water comes mainly from the decomposition of plant organic matter, with the production of CO_2 in the first layers of the soil [25, 28]. Other authors such as Adjiri et al. [29] and Ahoussi et al. [30] justify the acidity of water from wells and springs by the fact that they come from shallow sources. Moussima et al. [31] states that slightly acidic water is not harmful to the health of consumers. However, a low pH as indicated by well P1 (4.25) may indicate the presence of a pollutant in the water [32].

However, the acid tendency of the waters of the study area is one of the essential characteristics of groundwater in Côte d'Ivoire, as observed by Ohou-Yao et al. [16] on traditional well water in the Soubre region in the south-west of Côte d'Ivoire.

Electrical conductivity is an indicator of the taste or salinity of water because high values of electrical conductivity are linked to bad taste and a high percentage of total dissolved solids [4]. The electrical conductivity values fluctuate between 0.73 (S1) and 4.28 $\mu\text{S}/\text{cm}$ (P1). These values are well below the maximum value recommended by the WHO, which is 1200 $\mu\text{S}/\text{cm}$ [7]. The waters sampled belong to the class of weakly mineralized waters ($0 < \text{EC} < 80 \mu\text{S}/\text{cm}$) [24]. According to some authors, water from boreholes has a more pronounced mineralization than that from wells and springs [33]. Poulichet et al. [34] explain this differentiation by the longer residence time for deeper borehole waters. Furthermore, Gnamba et al. [35] explain the

low mineralization of well and spring waters by the fact that they come from the hydrolysis of silicate complexes and the various chemical reactions of ion production which necessarily need a relatively long time to settle. According to Elmarkhi *et al.* [36] and Ohou-Yao *et al.* [16], several polluting factors can influence water conductivity such as the quantity of mineral or organic matter in suspension, the physico-chemical quality of urban, agricultural or industrial discharges and evaporation phenomena. According to the classification made by the United States Department of Agriculture (USDA), the waters sampled would be of low salinity. Indeed, according to the USDA, waters whose conductivity is less than 250 $\mu\text{S}/\text{cm}$ have a low salinity while those whose conductivity is between 250 and 750 $\mu\text{S}/\text{cm}$ are of moderate salinity and those whose conductivity oscillate between 750 and 2250 $\mu\text{S}/\text{cm}$ are of high salinity while waters with a conductivity greater than 2250 $\mu\text{S}/\text{cm}$ are of very high salinity [37, 38]. The conductivities found during our study are much lower than those obtained by Ohou-Yao *et al.* [16] in Soubré Region (Côte d'Ivoire), Mangoua-Allali *et al.* [38] in the town of Bocanda (Côte d'Ivoire) and Okoundé *et al.* [39] in the hills department in Benin which oscillate respectively between 200.3 $\mu\text{S}/\text{cm}$ 1801 $\mu\text{S}/\text{cm}$, between 62.1 $\mu\text{S}/\text{cm}$ and 2660 $\mu\text{S}/\text{cm}$ and from 56 to 1735 $\mu\text{S}/\text{cm}$. However, it should be noted that conductivity is a parameter that has no direct impact on human health [4, 38].

Regarding the turbidity values, they oscillate between 0.16 (F1) and 4.16 NTU (P1). The drinking waters studied have a turbidity content consistent with that (< 5 NTU) prescribed by the WHO and could indicate clear water [7]. These waters should be free from materials such as clay, silt, fine organic and inorganic matter, plankton and other microscopic organisms suspended in the water [40]. However, the values recorded are higher than those obtained in groundwater in Port Harcourt (Nigeria) oscillating between 0.01 and 0.97 NTU [41].

However, our values are lower than those obtained in well water in Bocanda (Côte d'Ivoire) between 0.76 NTU and 66.10 NTU [38], in spring water and wells in the departments

of Daloa and Zoukougbeu (Côte d'Ivoire) varying between 1.24 NTU and 146 NTU [24] and in water from wells and boreholes in the Baya watershed in the East of Côte d'Ivoire oscillating between 1.61 NTU and 130 NTU [42]. In general, waters with high turbidity have an unpleasant appearance, color, taste and odor caused by the presence of suspended and colloidal matter [4]. In addition, waters with high turbidity could lead to gastrointestinal diseases by the attachment of microorganisms to the particles suspended in these waters [38].

Total dissolved solids (TDS) generally reflect the amount of dissolved mineral in the water [4]. High TDS values have adverse public health effects like the central nervous system, causing paralysis of the tongue, lips and face, irritability, dizziness [43]. The total dissolved solids have values between 0.32 (S1) and 2.41 mg/L (P1). These values are much lower than the limit value recommended by the WHO (< 600 mg/L) and would be good quality water [7]. According to Mouncherou *et al.* [44], waters with TDS values below 600 mg/L would be sufficiently diluted to be drinkable. The low TDS levels of the waters studied justify their low mineralization (0.73 – 4.28 $\mu\text{S}/\text{cm}$). The values obtained in this study are much lower than those obtained by Ojukwu & Nwankwoala [41] in Nigeria and Mehounou *et al.* [45] in the Commune of Aplahoué in the department of Couffo (South-West of Benin) varying respectively between 200 – 684 mg/L and 78 to 660 mg/L. Mehounou *et al.* [45] stipulate that the high TDS values obtained are probably due to the fertilizers used in the production area and which run off into the waterways. Indeed, agricultural and urban runoff can cause a surplus of minerals in waterways [45].

The values of the TDS/EC ratio are close to 0.5. This suggests a strong mineralization of the sampled waters [24]. However, these ratios do not agree with the conductivity values obtained, which indicate weakly mineralized waters. This discrepancy between the TDS/EC ratios and the conductivity classes would be due to the existence of unmeasured minor ions [24].

Table 1. Physical parameters of sampled water.

| | Unit | S1 | S2 | F1 | F2 | P1 | P2 | R1 | R2 | R3 | WHO [7] |
|--------|-------------------------|------|------|------|------|------|------|------|------|------|-----------|
| pH | | 5.19 | 5.06 | 5.12 | 5.88 | 4.25 | 5.40 | 6.67 | 6.40 | 6.39 | 6.5 – 8.5 |
| T° | °C | 28.4 | 27.1 | 25.2 | 27.0 | 27.3 | 26.3 | 24.3 | 27.9 | 27.9 | 25 |
| EC | $\mu\text{S}/\text{cm}$ | 0.73 | 0.89 | 1.2 | 2.26 | 4.28 | 1.38 | 2.41 | 2.38 | 2.54 | 120 |
| Tub | NTU | 3.61 | 0.89 | 0.16 | 0.15 | 4.16 | 0.97 | 3.25 | 2.16 | 2.01 | < 5 |
| TDS | mg/L | 0.32 | 0.48 | 0.66 | 1.28 | 2.41 | 0.75 | 1.4 | 1.3 | 1.38 | < 600 |
| TDS/CE | | 0.44 | 0.54 | 0.55 | 0.57 | 0.56 | 0.54 | 0.58 | 0.55 | 0.54 | – |

3.2. Chemical Parameters

3.2.1. Mineral Salts and Chlorides

Table 2 shows the mineral salt and chloride ion contents of the water samples. The calcium content of drinking water samples varies between 0.276 and 0.601 mg/L. These values are all below the maximum authorized concentration for human consumption, which is 100 mg/L [7]. These waters are therefore safe for consumers. High levels of calcium, in

fact, can cause intestinal diseases and concretions in the body such as kidney or bladder stones and urinary irritation [46]. Our results are lower than those of Bakouan *et al.* [23] who had calcium contents between 4.8 and 25.2 mg/L. Moreover, these results remain on the whole lower than those of Ohou-Yao *et al.* [47] who recorded values ranging from 0.08 to 15.2 mg/L during their study on the contamination of traditional well water by nitrates in the Lobo watershed in Buyo (south-west of the Côte d'Ivoire).

Magnesium is an essential element for growth, which acts as a plastic element in bone and also as a dynamic element in enzymatic and hormonal systems [48]. However, high magnesium concentrations can cause cardiovascular diseases [49]. The magnesium contents are between 0.205 and 0.256 mg/L. These values are very much lower than the WHO standard (50 mg/L) for water intended for human consumption and are therefore harmless. Our results are lower than those of Ohou-Yao et al. [47] (0.024 - 5.66 mg/L and Bakouan et al. [23] (0.7 - 11.5 mg/L).

The Mg^{2+}/Ca^{2+} ratio of drinking water varies from 0.34 to 0.84. A value that remains for all drinking water, less than 1. This indicates that the Mg^{2+} ions come from the decomposition of ferromagnesian minerals such as biotite present in the rocks of the region [26]. Therefore, the low concentrations of calcium and magnesium are explained by the fact that they come from the hydrolysis of silicate minerals present in the soil [32].

In fact, Ligban et al. [33] in their study on the hydrogeochemical process and origin of natural springs in the square degree of Daloa, obtained 5.00% CaO and 20.71% MgO. This could justify the low levels of calcium and magnesium in the waters studied.

Potassium comes from the alteration of silicate formations (gneiss, shale), potassic clays and the dissolution of chemical fertilizers. In addition, rainwater has a considerable influence in the production of K^+ ions [50]. Potassium levels in the samples in this study are low and range from 0.198 to 0.433 mg/L. These values are below the potability limit (12 mg/L) defined for human consumption water [7], which is without danger to health. The values recorded are lower than those of Mahamane & Guel [51] who found concentrations ranging from 2.93 to 22.32 mg/L in groundwater in the locality of Yamtenga (Burkina Faso).

The sodium content of all samples was between 20.37 and 37.13 mg/L. These values are lower than those of Ohou-Yao et al. [47] who recorded concentrations ranging between 1.68 and 166.5 mg/L. Excessive consumption of sodium in

drinking water leads to greater availability of sodium ions in the blood, leading to higher than normal heart activity, enlarged heart, increased risk of hypertension and stroke [4]. However, the values obtained in our study complied with the limit prescribed by the WHO (200 mg/L) for human consumption water [7]. The main sources of sodium and potassium are probably rock weathering as well as wastewater [4, 52].

Sulphate ion levels in drinking water samples range from 0.69 to 15.98 mg/L. Our values are superior to those of Bakouan et al. [23] who recorded concentrations ranging from 0.99 ± 0.01 to 4.59 ± 0.01 mg/L. However, these values are close to those obtained by Adjiri et al. [24]; values between 1 and 14 mg/L. High levels of sulphates can give an unpleasant taste and cause gastrointestinal disorders [46]. On the other hand, dehydration due to diarrhea is a common problem due to the intake of large amounts of magnesium or sodium sulfate in drinking water [4]. However, the values in this study are consistent with the standard of 250 mg/L recommended for drinking water [7].

Chloride ions are contained in varying concentrations in natural waters, generally in the form of potassium (KCl) and sodium (NaCl) salts [46, 53]. Chlorides are inorganic anions often used as a pollution index [46]. Chloride in natural water comes from agricultural activities, industries and chloride-rich rocks [4]. The values obtained for this parameter vary between 8.88 and 26.63 mg/L. These values are lower than those recorded by Mwanza et al. [54] in well water in the spontaneous district of Luwuwoshi (DR Congo); values between 11.54 and 49.7. Moreover, our results are much lower than those of Rabilou et al. [55] who had results ranging from 5.680 to 124.86 mg/L in bedrock groundwater in the Zinder region of Niger. A high concentration of chloride gives a salty taste to water [4] and high doses of sodium chloride in drinking water give an unpleasant taste to water [54] and cause hypertension [46, 56]. The maximum permitted limit for chloride in drinking water is 250 mg/L [7]. The sampled waters are therefore safe for health.

Table 2. Mineral salts and chloride ions in the water sampled.

| | Unit | S1 | S2 | F1 | F2 | P1 | P2 | R1 | R2 | R3 | WHO [7] |
|-------------------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------|
| Ca^{2+} | mg/L | 0.338 | 0.304 | 0.276 | 0.363 | 0.337 | 0.298 | 0.601 | 0.572 | 0.564 | 100 |
| Mg^{2+} | mg/L | 0.256 | 0.255 | 0.206 | 0.250 | 0.205 | 0.206 | 0.207 | 0.256 | 0.255 | 50 |
| Na^+ | mg/L | 37.13 | 26.75 | 23.09 | 25.47 | 29.89 | 20.37 | 26.97 | 26.97 | 27.65 | 200 |
| K^+ | mg/L | 0.291 | 0.198 | 0.205 | 0.281 | 0.433 | 0.198 | 0.262 | 0.298 | 0.262 | 12 |
| Mg^{2+}/Ca^{2+} | - | 0.76 | 0.84 | 0.75 | 0.69 | 0.61 | 0.69 | 0.34 | 0.45 | 0.45 | - |
| SO_4^{2-} | mg/L | 15.98 | 11.39 | 0.84 | 62 | 56.52 | 3.9 | 12.16 | 0.69 | 10.79 | 250 |
| Cl^- | mg/L | 10.65 | 8.88 | 12.43 | 14.20 | 26.63 | 9.76 | 16.86 | 15.08 | 15.08 | 250 |

3.2.2. Nutrients and Chemical Oxygen Demand (COD)

The concentrations of nutrients, total phosphorus, total nitrogen and chemical oxygen demand are given in Table 3. The concentrations of orthophosphate (PO_4^{3-}) in our drinking water vary from 0.01 to 0.26 mg/L. These concentrations meet the potability standards prescribed by the WHO for drinking water, which is 0.5 mg/L [7]. Higher concentrations were obtained by N'Guettia et al. [42] in groundwater from

the Baya watershed in Côte d'Ivoire (0.37 to 5.23 mg/L) and by Dippong et al. [6] in well waters at Remeti in Romania (0.06 - 0.78 mg/L). Sources of phosphate are the interactions of water with rocks and soil, the use of phosphorus fertilizers and detergents that use phosphates as softeners [6]. It should be noted that phosphate-rich water influences the development of algae, leading to a change and alteration in the taste and color of the water [57]. In addition, a high level of phosphate causes muscle damage, respiratory problems

and kidney failure [43, 58] in consumers.

The ammonium (NH_4^+) levels in the drinking water sampled vary from 0.16 (F1) to 2.6 mg/L (R1). Apart from borehole F1, the drinking water studied is contaminated by NH_4^+ with values above the limit value (0.5 mg/L) recommended for human consumption [7]. Ahoussi *et al.* [59] explain the NH_4^+ contamination of groundwater by the fact that it would have a superficial origin and would come from several polluting sources such as discharges of domestic effluents, the natural reduction of nitrates and the incomplete degradation of organic matter. Depending on the dose ingested and the duration of exposure, ammonium salt can cause human health problems such as pulmonary edema, dysfunction of the nervous and renal systems and increased blood pressure [46, 60]. The levels in this study could therefore have effects on the health of the population. Lower values have been recorded in other studies. Indeed, Yapou *et al.* [61] recorded values ranging from 0.02 to 0.4 mg/L in well water for market gardening and domestic use in Korhogo (Côte d'Ivoire) while Adjiri *et al.* [24] had levels ranging from 0.12 to 1.12 mg/L. However, higher concentrations than those in the present study were obtained by Ohou-Yao *et al.* [16] oscillating between 0.00 and 14.19 mg/L.

Nitrates are the end product of the biochemical oxidation of ammonia [4]. Its high levels in drinking water can cause infantile methemoglobinemia (Blue Baby Syndrome) and may be associated with unintended abortions and infertility problems [2]. Children under the age of one suffered the most from drinking nitrate-contaminated water [43]. Nitrate observed in drinking water samples has a minimum of 0.93 mg/L (R3) and a maximum of 28.13 mg/L (F2). These values are higher than those of Mohammadpour *et al.* [2] who recorded concentrations ranging between 0.3 and 18.3 mg/L in groundwater from counties of Hormozgan province in southern Iran. However, our values are within the desirable limit of 50 mg/L for human consumption [7]. According to Azizullah *et al.* [62], low concentrations of Nitrates in groundwater can reach high values due to runoff or leaching from agricultural land. Diffuse sources of nitrates are organic matter decomposition, chemical fertilizer leaching, animal leaching, and discharges from septic tanks and sewers [16]. With regard to the effects of nitrates on human health, monitoring nitrate levels in the drinking water supply is of paramount importance [4, 63].

The nitrite content in consumer samples ranges from 0.39 mg/L to 7.32 mg/L. Water from boreholes (F1 and F2) and

wells (P1 and P2) have levels above the standard recommended by the WHO (3 mg/L). Nitrites are very soluble and therefore very little present in groundwater, except in the event of pollution [21]. Consequently, the high levels of nitrites recorded in the waters of the boreholes and wells studied indicate that these waters are polluted. Higher nitrite contents (0 to 11 mg/L) have been reported by Ahoussi *et al.* [59] in their study on the spatio-temporal evolution of nitrate levels in groundwater in the city of Abidjan. For these authors, the presence of nitrites in the waters of the Quaternary period would reflect surface contamination from waste water of sewers, septic tanks and cesspools. Nitrites have known effects on human health. Indeed, an excess of nitrites in drinking water can cause methemoglobinemia that can go as far as asphyxiation in bottle-fed newborns [46]. Furthermore, there is a link between nitrite exposure and cancer in humans [4].

Phosphorus is a naturally not very mobile element whose transfer is discontinuous in time and space [64]. Total phosphorus (TP) in drinking water varies between 0.011 (P1) and 0.051 mg/L (R3). All groundwater has values within the range of natural concentrations (0.001 – 0.05 mg/L) accepted for groundwater [64]. These values would therefore be without danger for the population consuming these waters. According to Chery & Barbier [64], high phosphorus levels in groundwater are linked to anthropogenic pollution.

The total nitrogen content (TN) oscillates between 0.22 (F1) and 0.56 mg/L (P1). The presence of nitrogen in groundwater is greatly influenced by the amount of nitrogen applied to agricultural land; anything that in the long term leads to increased nitrate ions in these waters [65]. Groundwater and drinking water standards are set at a maximum of 10 mg/L by the US Environmental Protection Agency [66]. The values in this study are therefore in line with the standard and are safe for consumers.

The chemical oxygen demand (COD) is used to assess the total amount of organic pollution [67]. It corresponds to the quantity of oxygen necessary during the decomposition of organic matter and the oxidation of inorganic chemicals present in the water [68]. COD concentrations in mg of oxygen range between 16.70 and 659.48 mg/L. These results are all above the standard recommended by the WHO [20] of 10 mg/L [68]. According to Amneera *et al.* [69], if the COD concentration is higher, then the water is considered polluted. This state of affairs could have adverse effects on human health.

Table 3. Nutrients and chemical oxygen demand (COD).

| | Unit | S1 | S2 | F1 | F2 | P1 | P2 | R1 | R2 | R3 | WHO [7] |
|--------------------|------|-------|-------|-------|-------|-------|--------|-------|--------|-------|---------------|
| PO_4^{3-} | mg/L | 0.026 | 0.01 | 0.02 | 0.26 | 0.01 | 0.01 | 0.05 | 0.03 | 0.052 | 0.5 |
| NO_2^- | mg/L | 0.97 | 2.49 | 4.33 | 6.35 | 7.32 | 6.01 | 0.39 | 0.96 | 0.21 | 3 |
| NO_3^- | mg/L | 4.3 | 11.03 | 19.18 | 28.13 | 32.43 | 26.62 | 1.73 | 4.25 | 0.93 | 50 |
| NH_4^+ | mg/L | 0.9 | 0.81 | 0.16 | 0.64 | 1.96 | 0.83 | 2.6 | 2.58 | 2.24 | 0.5 |
| TP | mg/L | 0.021 | 0.023 | 0.019 | 0.029 | 0.011 | 0.018 | 0.036 | 0.035 | 0.051 | 0.001 – 0.05* |
| TN | mg/L | 0.34 | 0.34 | 0.22 | 0.34 | 0.56 | 0.28 | 0.28 | 0.34 | 0.28 | 10 ** |
| DCO | mg/L | 50.09 | 50.09 | 16.70 | 91.83 | 25.04 | 659.48 | 58.43 | 317.22 | 83.48 | < 10 *** |

*Chery & Barbier [64]; **EPA [66]; ***WHO [20].

3.3. Relations Between the Physico-chemical Parameters of Water

Correlations between the variables measured in the water samples are established using principal component analysis (PCA) and a correlation matrix. These methods are widely used to characterize and assess the existing relationships between variables [23, 46, 53, 70-72].

The analysis was performed on a data matrix consisting of 18 variables and 9 water sources, i.e. 18 variables and 9 individuals. In the factorial plane $F1 \times F2$, the eigenvalues of the two components $F1$ and $F2$ and their contribution to the total inertia are given in table 4. The two axes taken into consideration to describe the correlations between the physico-chemical parameters of the water alone hold 62.59% of the total information with 34.41% for axis 1 and 28.18% for axis 2. These factorial axes are therefore representative of the variance of all the data and turn out to be sufficient to convey most of this inertia.

Table 4. Eigenvalue, inertia and cumulative inertia between axis $F1$ and axis $F2$.

| | F1 | F2 |
|------------------------|-------|-------|
| Own value | 6.19 | 5.07 |
| Inertia (%) | 34.41 | 28.18 |
| Cumulative inertia (%) | 34.41 | 62.59 |

The correlation circle presents the projection of the different variables on the $F1$ and $F2$ axes. Axis 1 is defined

only on the negative side by NT , K^+ , Cl^- , EC , TDS , SO_4^{2-} and Turb . The second axis is defined by NO_3^- and NO_2^- on the positive side. On the negative side, it is defined by NH_4^+ , Ca^{2+} , TP , pH , Mg^{2+} and Na^+ . The physico-chemical parameters defined on the same side of an axis are positively correlated with each other, while those defined on different sides of the same axis are negatively correlated with each other [23].

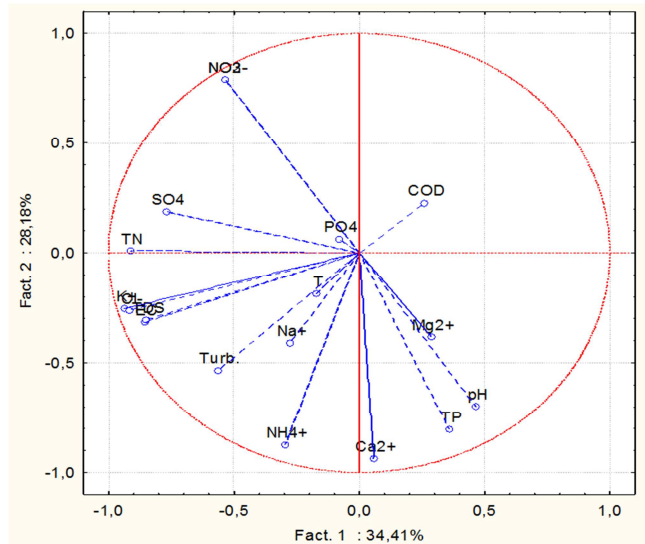


Figure 2. Projection of water variables on the factorial plane $F1$ and $F2$.

Table 5. Linear correlation coefficients Bravais – Pearson r between drinking water quality parameters.

| | pH | T | EC | Turb | TDS | Ca^{2+} | Mg^{2+} | Na^+ | K^+ | SO_4^{2-} | Cl^- | PO_4^{3-} | NO_3^- | NO_2^- | NH_4^+ | TP | TN | COD |
|--------------------|--------|-------|-------|-------|-------|------------------|------------------|---------------|--------------|--------------------|---------------|--------------------|-----------------|-----------------|-----------------|-------|-------|-----|
| pH | 1 | | | | | | | | | | | | | | | | | |
| T | -0.18 | 1 | | | | | | | | | | | | | | | | |
| EC | -0.03 | 0.03 | 1 | | | | | | | | | | | | | | | |
| Turb | -0.10 | 0.22 | 0.48 | 1 | | | | | | | | | | | | | | |
| TDS | -0.02 | -0.01 | 0.99* | 0.46 | 1 | | | | | | | | | | | | | |
| Ca^{2+} | 0.85* | -0.04 | 0.37 | 0.35 | 0.37 | 1 | | | | | | | | | | | | |
| Mg^{2+} | 0.29 | 0.75* | -0.28 | -0.09 | -0.30 | 0.22 | 1 | | | | | | | | | | | |
| Na^+ | -0.16 | 0.56* | 0.02 | 0.72* | -0.01 | 0.10 | 0.44 | 1 | | | | | | | | | | |
| K^+ | -0.31 | 0.34 | 0.82* | 0.73* | 0.80* | 0.14 | -0.08 | 0.52* | 1 | | | | | | | | | |
| SO_4^{2-} | -0.34 | 0.18 | 0.58* | 0.15 | 0.58* | -0.21 | -0.01 | 0.21 | 0.68* | 1 | | | | | | | | |
| Cl^- | -0.19 | -0.01 | 0.95* | 0.60* | 0.95* | 0.26 | -0.37 | 0.19 | 0.89* | 0.58* | 1 | | | | | | | |
| PO_4^{3-} | 0.30 | 0.02 | 0.11 | -0.39 | 0.13 | 0.06 | 0.29 | -0.10 | 0.06 | 0.63* | 0.00 | 1 | | | | | | |
| NO_3^- | -0.65* | -0.10 | 0.31 | -0.25 | 0.32 | -0.68* | -0.48 | -0.38 | 0.27 | 0.62* | 0.30 | 0.26 | 1 | | | | | |
| NO_2^- | -0.65* | -0.10 | 0.30 | -0.25 | 0.32 | -0.68* | -0.48 | -0.38 | 0.27 | 0.62* | 0.30 | 0.26 | 0.99* | 1 | | | | |
| NH_4^+ | 0.54* | 0.06 | 0.62* | 0.63* | 0.62* | 0.89* | 0.06 | 0.20 | 0.45 | -0.07 | 0.55* | -0.18 | -0.48 | -0.48 | 1 | | | |
| TP | 0.89* | 0.03 | 0.08 | -0.02 | 0.08* | 0.86* | 0.43 | -0.01 | -0.19 | -0.26 | -0.08 | 0.23 | -0.72* | 0.72* | 0.58* | 1 | | |
| TN | -0.56* | 0.41 | 0.69* | 0.59* | 0.67* | -0.14 | -0.04 | 0.42 | 0.88* | 0.69* | 0.74* | -0.05 | 0.44 | 0.44 | 0.26 | -0.44 | 1 | |
| COD | 0.14 | 0.02 | -0.15 | -0.23 | -0.15 | -0.05 | -0.17 | -0.52* | -0.32 | -0.34 | -0.32 | -0.15 | 0.20 | 0.20 | -0.01 | -0.09 | -0.20 | 1 |

Values with the symbol (*) are significant correlation coefficients at $p < 0.05$.

Table 5 presents the correlation matrix between the physico-chemical parameters of water. Examination of the correlation matrix between the variables reveals positive and significant correlations between the different physico-chemical parameters such as: $\text{pH} - \text{Ca}^{2+}$ ($r = 0.85$), $\text{pH} - \text{NH}_4^+$ ($r = 0.54$), $\text{pH} - \text{TN}$ ($r = 0.89$), $\text{T} - \text{Mg}^{2+}$ ($r = 0.75$), $\text{T} - \text{Na}^+$ ($r = 0.56$), $\text{EC} - \text{TDS}$ ($r = 0.99$), $\text{EC} - \text{K}^+$ ($r = 0.82$), $\text{EC} - \text{SO}_4^{2-}$ ($r = 0.58$), $\text{EC} - \text{Cl}^-$ ($r = 0.95$), $\text{EC} - \text{NH}_4^+$ ($r = 0.62$),

$\text{EC} - \text{TN}$ ($r = 0.69$), $\text{Turb} - \text{Na}^+$ ($r = 0.72$), $\text{Turb} - \text{K}^+$ ($r = 0.73$), $\text{Turb} - \text{Cl}^-$ ($r = 0.60$), $\text{Turb} - \text{NH}_4^+$ ($r = 0.63$), $\text{Turb} - \text{TN}$ ($r = 0.59$), $\text{TDS} - \text{K}^+$ ($r = 0.80$), $\text{TDS} - \text{SO}_4^{2-}$ ($r = 0.58$), $\text{TDS} - \text{Cl}^-$ ($r = 0.95$), $\text{TDS} - \text{NH}_4^+$ ($r = 0.62$), $\text{TDS} - \text{TN}$ ($r = 0.67$), $\text{Ca}^{2+} - \text{NH}_4^+$ ($r = 0.89$), $\text{Ca}^{2+} - \text{TP}$ ($r = 0.86$), $\text{Na}^+ - \text{K}^+$ ($r = 0.52$), $\text{K}^+ - \text{SO}_4^{2-}$ ($r = 0.68$), $\text{K}^+ - \text{Cl}^-$ ($r = 0.89$), $\text{K}^+ - \text{TN}$ ($r = 0.88$), $\text{SO}_4^{2-} - \text{Cl}^-$ ($r = 0.58$), $\text{SO}_4^{2-} - \text{PO}_4^{3-}$ ($r = 0.63$), $\text{SO}_4^{2-} - \text{NO}_3^-$ ($r = 0.62$), $\text{SO}_4^{2-} - \text{NO}_2^-$ ($r = 0.62$), $\text{SO}_4^{2-} - \text{TN}$ ($r = 0.62$), $\text{NO}_3^- - \text{NO}_2^-$ ($r = 0.99$), $\text{NO}_3^- - \text{NH}_4^+$ ($r = -0.48$), $\text{NO}_3^- - \text{TP}$ ($r = -0.72$), $\text{NO}_3^- - \text{TN}$ ($r = 0.44$), $\text{NO}_2^- - \text{NH}_4^+$ ($r = -0.48$), $\text{NO}_2^- - \text{TP}$ ($r = 0.72$), $\text{NO}_2^- - \text{TN}$ ($r = 0.44$), $\text{NH}_4^+ - \text{TP}$ ($r = 0.58$), $\text{NH}_4^+ - \text{TN}$ ($r = 0.26$), $\text{TP} - \text{TN}$ ($r = -0.44$), $\text{TP} - \text{COD}$ ($r = -0.09$), $\text{TN} - \text{COD}$ ($r = -0.20$).

= 0.69), $\text{Cl}^- - \text{NH}_4^+$ ($r = 0.56$), $\text{Cl}^- - \text{TN}$ ($r = 0.74$), $\text{NO}_3^- - \text{NO}_2^-$ ($r = 0.99$), $\text{NH}_4^+ - \text{TP}$ ($r = 0.58$). The significantly positive correlations observed between the variables could reflect the mutual dependence of the parameters on each other or a similar behavior.

Indeed, a high correlation coefficient between two variables shows that they have a common source, mutual dependence and similar behavior during transport [71, 73]. The strong positive correlation observed between $\text{NO}_3^- - \text{NO}_2^-$ ($r = 0.99$) would therefore be due to the fact that these nutrients come from the same polluting sources such as wastewater; and the use of fertilizers and pesticides in agricultural activities [68].

Furthermore, significant negative correlations are observed between $\text{pH} - \text{NO}_3^-$ ($r = -0.65$), $\text{pH} - \text{NO}_2^-$ ($r = -0.65$), $\text{pH} - \text{TN}$ ($r = -0.56$), $\text{Ca}^{2+} - \text{NO}_3^-$ ($r = -0.68$), $\text{Ca}^{2+} - \text{NO}_2^-$ ($r = -0.68$), $\text{Na}^+ - \text{COD}$ ($r = -0.52$), $\text{NO}_3^- - \text{TP}$ ($r = -0.72$), $\text{NO}_2^- - \text{TP}$ ($r = -0.72$). These coefficients show inverse relationships between the variables taken in pairs. These results suggest that the decrease or low values of one of the parameters leads to an increase in the other [46, 72].

4. Conclusion

In this study, we analyzed the physico-chemical parameters of the drinking water of the city of Daloa in order to assess the quality of this water and to understand the health risks. A total of eighteen (18) physico-chemical parameters were determined and compared to the standards recommended for water intended for human consumption. The results obtained indicate that 86.67% of the parameters meet the recommended standards. However, the temperature, pH, chemical oxygen demand, ammonium and nitrites are above WHO standards in all the waters sampled except in borehole F1 for ammonium and in spring and tap waters for nitrites. This contamination in nitrogen compounds results from anthropogenic activities that manifest themselves through the infiltration of domestic wastewater, the unhealthy environment and the use of fertilizers. The principal component analysis revealed significant correlations between certain parameters, thus reflecting the interdependence of these studied parameters. The pollution of sampled drinking water is a real health risk. Overall, the physico-chemical quality of the water sampled is acceptable but in some cases it requires specific treatment (filtration, adsorption, etc.) before consumption. In addition, regular monitoring should be carried out in order to avoid the consumption of contaminated water and its harmful effects on the health of the population.

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