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Assessment of the Physico-Chemical and bacteriological quality of water in the golo-djigbe industrial zone

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Abstract

The water resources within the Zone Economique Spéciale (ZES), facing significant anthropogenic and industrial pressures, could experience water quality deterioration. This concerning situation necessitates a diagnostic study to establish an integrated and sustainable water resource management plan for the zone. The objective of this work is to evaluate the physico-chemical and bacteriological qualities of the zone's water. Water samples were collected and analyzed in triplicate, following standard analytical techniques outlined by Rodier. Static water levels in wells or boreholes were measured using a piezometric probe. Finally, the overall water quality was determined using the SEQ-Eau system (2003). The piezometric study indicated a deep water table, located at a minimum depth of 48 meters. Physically, the groundwater exhibits a relatively acidic pH range (5.4–7.4). Recorded temperatures ranged from 27.2°C to 35.6°C. Turbidity values for groundwater were below 5 NTU, while surface water turbidity ranged from 36 to 75 NTU. Electrical conductivity was low, with values ranging from 58 to 342 µS/cm. Chemically, the concentrations of ions and compounds such as nitrate, nitrite, total nitrogen, chloride, calcium, magnesium, COD, DBO5, and trace metals (As, Cd, Cu, Zn, Hg, Ni, Pb) in the water samples were generally low and below current regulations. Based on the SEQ-Eau (2003) surface water assessment framework, the ZES's surface waters generally exhibit excellent quality for most parameters, with the exception of dissolved oxygen and fecal coliforms, which showed poor to very poor classifications. Ongoing monitoring of these parameters is recommended during the operational phase of the ZES.

Keywords: Physico-chemical, bacteriological parameters, special economic zone, anthropic pressures.

Introduction

For several years, the Republic of Benin has been actively working to elevate the nation's socio-economic standing and enhance the living standards and quality of life for its population. To achieve this objective, the establishment of an industrial zone at GoloDjigbé was incorporated into the Government Action Program (PAG) with the aim of fostering the growth of new industries, particularly in the agribusiness sector. To materialize this vision, the Beninese government enacted Decree n°2020-062 on February 5, 2020, which created the “Zone Industrielle de Glo-Djigbe”, abbreviated as “GDIZ”. The GDIZ is designed as an ecosystem to support industrial activities through the provision of high-quality infrastructure and facilities, which, in turn, will enable Benin to realize its goals of significant job creation and a robust, sustainable economy.

Industrial activities involve multiple stakeholders and utilize various inputs. They generate diverse products and waste, inevitably impacting the environment (soil, water, and air) and affecting people[1]. All necessary measures must be implemented to guarantee the required safety and health protection for workers and neighboring populations. This protection must extend to water resources and the environment in general, as well as to the preservation of the environment in case of pollution. Relevant international guidelines can also be referenced to minimize the risk of exposure for populations and ecosystems. The perimeter of the Golo-Djigbé economic zone requires significant attention, as does the Environmental and Social Impact Assessment (ESIA). To address this critical requirement, an assessment of the physico-chemical and bacteriological quality of the zone's water is an essential aspect.

This document focuses on the study of surface and groundwater parameters within the ZES. To determine the water quality classification of the zone's water resources, an evaluation of water quality is conducted using 'conventional' measurement methods for a series of physico-chemical parameters such as the 5-day Biochemical Oxygen Demand (DBO5), Chemical Oxygen Demand (COD), cyanide ions, nitrates, nitrites, pH, conductivity, dissolved oxygen, Trace Metal Elements (TMEs), etc., which are subsequently compared to approved standards or quality criteria. Indeed, to preserve water resources and prevent their degradation, a precise understanding of the water quality within the ZES is mandatory before the industrial zone becomes operational.

Methodology

Selection and identification of sampling sites: The selection of sampling sites was based on the significance of activities occurring at or in the vicinity of these locations. Some sites serve as drinking water supply sources, while others are situated near residential areas, and still others are located in areas with agricultural activities. A total of nine (09) accessible sites were identified for this study. Figure-1 illustrates the geographical distribution of these sampling sites.

Water sampling on site: For the purpose of this study, a sampling campaign was conducted during the major dry season to avoid the introduction of external pollution into the zone during rainfall events. Water samples from boreholes and surface water bodies were collected on Monday, January 3, 2022, between 8:30 AM and 7:30 PM in the vicinity of the ZES. Plastic bottles were used for sample collection as they are well-suited for most field applications and offer the advantage of being more robust[2]. Prior to water collection, the 1.5 L plastic bottles were thoroughly rinsed with the water to be sampled.

Each sample was identified using a sampling sheet containing reference information (site characterization, date, location, number, time of collection). Subsequently, following sampling and in-situ measurements, the samples were stored in a cooler and kept at a low temperature (2 to 4°C) using ice for transportation to the laboratory.

Drilling: Samples were collected from the taps of the boreholes. Sampling at this point allows for the assessment of the microbiological quality of the borehole water. The method used to collect the water in the container was designed to ensure sample integrity. To achieve this, the sampling was carried out as follows: i. wash hands with soap and water; ii. remove the faucet aerator; iii. first, disinfect the end of the tap and the closest parts using an alcohol swab and cotton; iv. flame the tap, paying particular attention to the plastic part; v. open the tap and let the water run for approximately 60 seconds, then fill the sterilized bottle or bag to three-quarters full; vi. keep the gas pistol on and near the water during filling; vii. identify the collected sample using adhesive tape and a pen; viii. Store the samples at ambient temperature in a cooler containing ice packs to prevent any external contamination.

Well: For wells, sampling was conducted not only using the pump but also with the small buckets typically used by the local population.

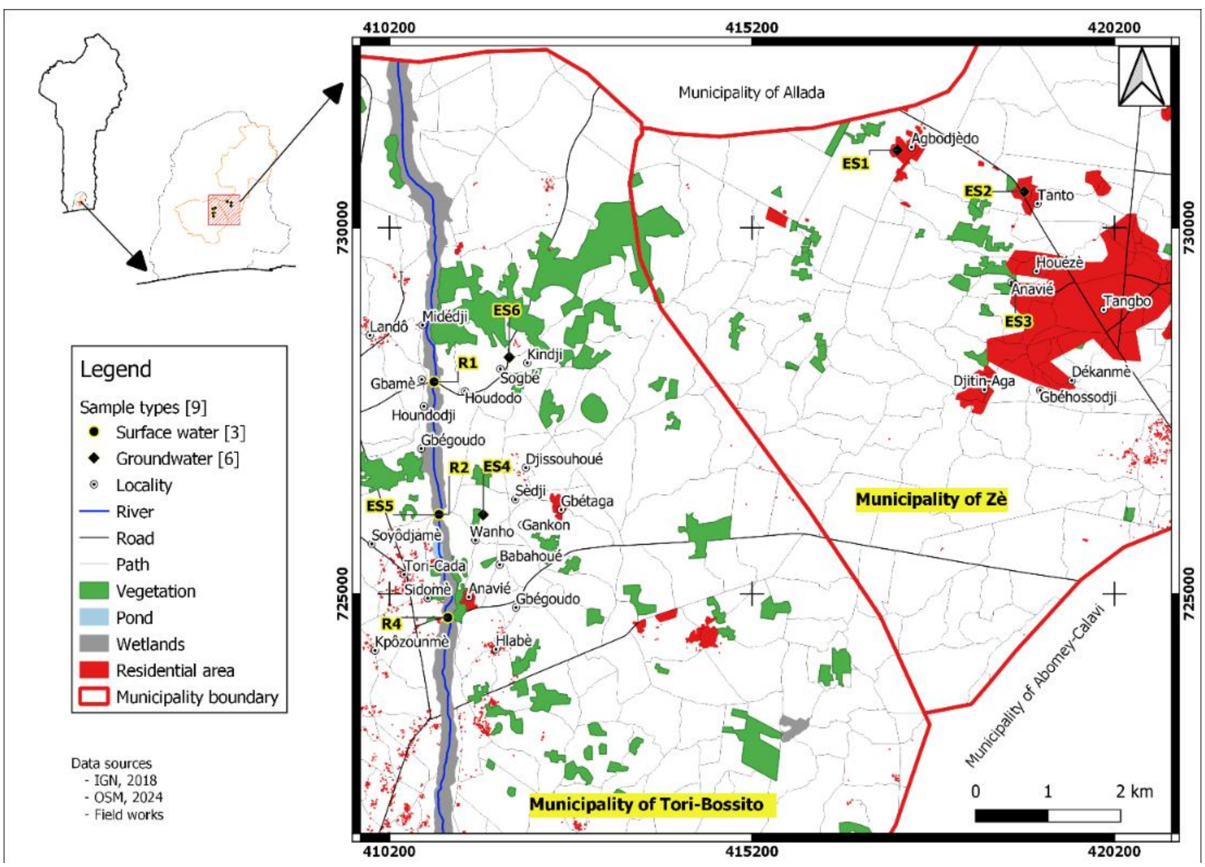

Figure-1: Geographical location of water sampling sites, Yessoufou and al 2024.

Surface water: The bottles used for sampling were submerged vertically at a specific distance from the bottom (15 cm) and the surface, and then filled. The plastic caps, also pre-rinsed with water from the site, were placed to ensure no air bubbles were trapped and that they would not be ejected during transport, according to Rodier[3].

In total, nine (9) samples were collected as follows: i. Six (6) groundwater samples, including one well and five boreholes, labeled ES1, ES2, ES3, ES4, ES5, and ES6. ii. Three (3) surface water samples, labeled R1, R2, and R3.

The samples were then stored in a cooler containing ice and transported to the Applied Hydrology Laboratory (LHA) of the National Water Institute (INE), where further analyses were conducted. These samples were subsequently stored cool in a refrigerator at 4°C before their analysis began the following day.

Choice of physico-chemical parameters: The study of physico-chemical parameters is crucial for assessing water quality. The report by Damania[4] on the invisible water quality crisis recommends key parameters monitored under the Sustainable Development Goal (SDG). Therefore, the focus will be on the physical balance, oxygen balance, nutrient loads, physicochemical balance, microbiological balance, and overall environmental health of water bodies. This aligns with the three main water quality indicators of SDG 6.3.2.

Piezometric study of the water table: The equipment used for the groundwater piezometric study includes: i. A piezometric probe for measuring static water levels. ii. An automatic data logger (thalweg meter type). iii. Field sheets for recording field data.

This phase involves measurement using the piezometric probe (Figure-11). The probe is used to measure the static level (free water surface) in wells or boreholes. For our study, we used a light probe. The measurement is taken by vertically positioning the device on the well, then unwinding the measuring tape while lowering the probe into the well. Once the probe contacts the water, a red light turns on. The static level is read from the graduated tape, which is the static level relative to the well casing. The above-ground part level (casing height) is also measured to subtract it from the previously read value. This corrected value gives the static level relative to the ground surface.

In situ physico-chemical analysis: Hydrogen potential (pH), temperature, electrical conductivity, and dissolved oxygen were measured in the field using an AQUAREAD AP-700 multi-parameter meter (Figure-2). Color was measured using a DR 890 colorimeter. For each measurement, the probe was first rinsed with distilled water and then with the sample water. The probe was then immersed in the water, and the different parameters were read after stabilization.

Figure-2: Groundwater extraction by pump (left) and tap (right).

Figure-3: Various views of a piezometer probe for static measurement of the water table.

Figure-4: AQUAREAD AP-700 multi-parameter and in-situ parameter measurements.

Laboratory analysis: Analysis of chemical parameters: Water samples were analyzed three times using the standard analytical techniques summarized in Table-1.

Table-1: References of analytical methods used[3].

Parameters	References
Hydrogen Potential	5
Temperature	6
Electrical Conductivity	7
Dissolved Oxygen	8
Turbidity	9
Color	10
Taste	-
Alkalimetric Titre (AT)	3
Complete Alkalimetric Title (CAT)	3
Hardness	3
Calcium	3
Magnesium	3
Chlorides	3
Fluorides	11
Nitrates	3
Nitrites	3
Sulfates	3
Phosphorus Total	3
Boron	12
Iron	3
Arsenic	13
Hexavalent Chromium	14
Cadmium	15
Nickel	15
Cobalt	15
Copper	15
Zinc	15
Chromium	15
Lead	15
Mercury	16
Cyanide	17
Manganese	15
TPH	18

Bacteriological analysis of water samples: Water samples were analyzed the day after sampling using the pour plate method for well water and the cellulose membrane filtration technique for borehole water.

Our bacteriological analysis aimed to detect common bacteria indicating poor hygiene, thermotolerant coliforms and Escherichia coli (indicators of human fecal pollution), and fecal streptococci (indicators of animal fecal pollution). To perform the laboratory analyses, the following steps were necessary:

Preparation of culture media for thermotolerant coliforms and Escherichia coli: For detecting these two types of bacteria, a single culture medium was used: Rapid E. coli 2 Agar (REC 2). The preparation steps for this medium were as described on the packaging by the manufacturer, specifying the weight of powder to be dissolved in a given volume of distilled water. For a 400mL volume of REC medium, 9.4g of powder were dissolved in 400mL of distilled water. The medium was then brought to a boil for 1-2 minutes on a hot plate, allowed to cool to 50-60°C, and then autoclaved (15 min at 121°C). After autoclaving, the medium was placed in a water bath at 45-50°C to maintain it in a molten state before use.

Preparation of culture media for common germs: For detecting total aerobic bacteria, Plate Count Agar (PCA) was used. The preparation steps are also provided by the manufacturer on the packaging, indicating the weight of powder per volume of distilled water. For a 400mL volume of PCA medium, 9.4g of powder were dissolved in 400mL of distilled water. The medium was then brought to a boil for 1-2 minutes on a hot plate, allowed to cool to 50-60°C, and then autoclaved (15 min at 121°C). After autoclaving, the medium was placed in a water bath at 45-50°C to maintain it in a molten state before use.

Preparation of culture media for faecal streptococci: For detecting fecal streptococci, Slanetz and Bartley medium was used. The preparation steps are also provided by the manufacturer on the packaging, specifying the weight of powder per volume of distilled water. For a 400mL volume of Slanetz and Bartley medium, 9.4g of powder were dissolved in 400mL of distilled water. The medium was then heated in a water bath until completely dissolved, avoiding excessive heating. After complete dissolution, the water bath was adjusted to 45-50°C to maintain the medium in a molten state before use.

Inoculation of samples by immersion in culture media: After preparing the culture media, they were placed in a water bath to prevent solidification before inoculation (super cooling). The samples were placed on a workbench that had been cleaned and disinfected with bleach and alcohol. Before starting the inoculation, the Petri dishes were labeled with: i. Sample order number. ii. Culture medium code (e.g., REC). iii. Incubation temperature (37°C or 44°C). iv. Sample volume (1mL). v. Date of manipulation.

Each sample had four distinct Petri dishes. For the pour plate method, a sterile 5 mL syringe was used to transfer 1 mL of the sample into each Petri dish. Then, the molten culture medium was poured over the sample and mixed thoroughly. The agar was allowed to solidify before being incubated at the appropriate temperature and for the recommended duration based on the target bacteria: 37°C for 24-48 hours (common bacteria), 44°C for 24 hours (thermotolerant coliforms and E. coli), and 37°C for 24 hours (fecal streptococci).

Inoculation by cellulose membrane filtration technique: A six-station filtration ramp was used. This technique began with sterilizing each funnel of the ramp using a gas burner. While the funnels cooled, the remaining steps were performed.

After preparing the culture media, they were placed in a water bath to prevent solidification before inoculation (super cooling). The samples were placed on a workbench that had been cleaned and disinfected with bleach and alcohol. The Petri dishes were labeled with: i. Sample order number (laboratory code). ii. Culture medium code (e.g., REC). iii. Incubation temperature (37°C). iv. Date of manipulation.

Since the volume was always 100mL for the filtration technique, it was not necessary to write it on the dish. A sterile 0.45 µm cellulose membrane was aseptically opened and placed on the filter support using forceps that had been previously dipped in alcohol and flamed. The funnel was then placed on the membrane and locked onto the support. The sample corresponding to the Petri dish in front of the funnel was homogenized, and 100mL of this sample was poured into the funnel. The vacuum pump was then turned on until all the water in the funnels had been filtered. Finally, the membranes were carefully removed using forceps that had been previously dipped in alcohol and flamed and placed on the prepared agar in the Petri dishes. Incubation was carried out at the appropriate temperature and for the recommended duration based on the Petri dish and the target bacteria: 37°C for 24 hours for fecal coliforms and 37°C for 24-48 hours for common bacteria.

Reading: At this stage, the number of bacterial colonies that grew after incubation at a specific temperature and for a specific duration was counted. On the chromogenic medium after incubation at 37°C for 24 hours, fecal coliforms (blue colonies) and E. coli (purple colonies) were enumerated. On the PCA medium after incubation at 37°C for 24-48 hours, common bacteria, identified by colorless dots, were counted. Counting was done using a marker to identify each countable colony for the specific type of bacteria being sought.

Data and information processing: To create maps showing the location of sampling sites and the geographical location of the municipalities and districts in the study area, QGIS 3.10 software was used. Excel spreadsheet software (version 2016) was used to determine descriptive statistics and construct graphs.

Results and Discussion

Characteristic borehole results: Pumping rates were not evaluated because the source water was already clear. However, it should be noted that we allowed the population to pump the water for approximately 30 to 40 minutes to obtain stable physico-chemical parameters (temperature, pH, and electrical conductivity) before taking samples. The measurement results are recorded in Table-2.

From a hydrogeological perspective, there is a deep aquifer. The water table is at a relatively average depth (48 m or more in some places). Consequently, the ground water table is less influenced by rainwater, and the risk of groundwater contamination from various types of waste is therefore low.

Results for physico-chemical and bacteriological parameters: According to the guidelines and water quality indicators of SDG 6.3.2 and considering the numerous parameters measured, the results will be grouped into physical, oxygen, and nutrient balances. The analysis and interpretation of these results are based on Decree N°2001-094 of February 20, 2001, setting the standards for drinking water quality in the Republic of Benin for groundwater, and literature values for surface water[19-21].

Oxygen balance: Three parameters were considered: dissolved oxygen (DO), Chemical Oxygen Demand (COD), and Biochemical Oxygen Demand over 5 days (DBO5). Figure-3 shows the variations of these parameters.

Table-2: Borehole characteristics.

Sampling location		ES1	ES2	ES3	ES4	ES5	ES6
Groundwater depth from top of borehole/pipe (m)	Before sampling	52	59	56	53	48	43
	After sampling	57	64	60	57	58	46
Sampling method (pump/bailer)		pump	pump	pump	pump	pump	bailer
Time for water to clear (min)		0	0	0	0	0	0
Total pumping time (min)		0	0	0	0	0	60
Water temperature (ºC)		31,10	29,60	29,60	32,83	30,25	31,3
Sample colour		Incolore	Incolore	Incolore	Incolore	Incolore	Incolore
Sample odour		Inodore	Inodore	Inodore	Inodore	Inodore	Inodore

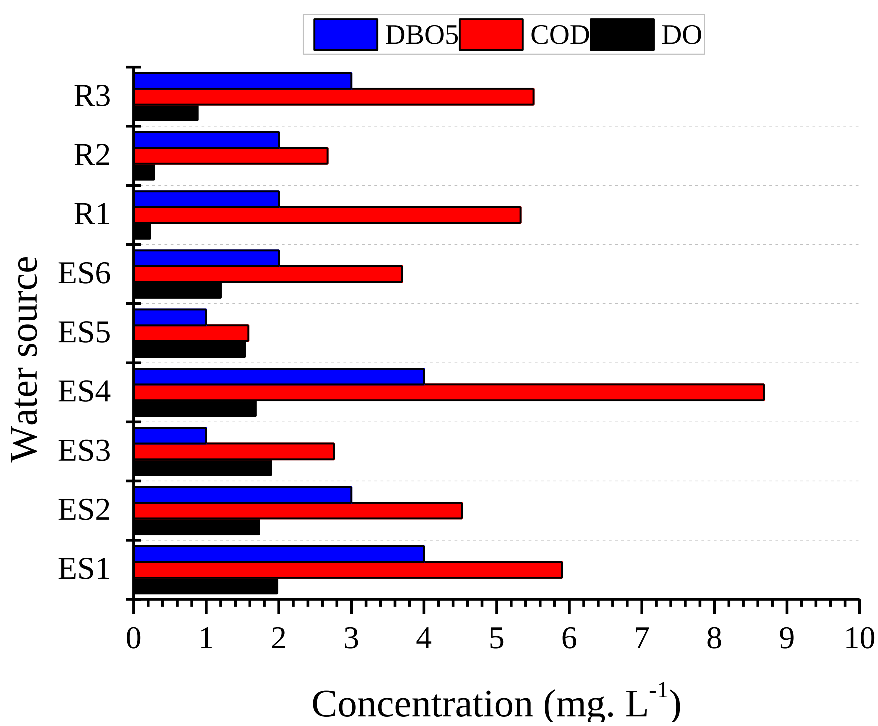

Figure-3: Variation in dissolved oxygen, COD and DBO5.

Dissolved oxygen is an important element for aquatic life. Dissolved oxygen in surface water primarily comes from the atmosphere and the photosynthetic activity of algae and aquatic plants. The measured values are all below 3 mg/L, which is the threshold for good development of aquatic life in rivers.

Chemical Oxygen Demand (COD) corresponds to the amount of oxygen required for the chemical degradation of organic compounds present in water using a strong oxidant. It measures the total organic matter content (except for some non-degradable compounds), including those not biodegradable by bacteria. It is therefore an important parameter for characterizing the overall pollution of water by organic compounds. The measured COD (1.58 mg/L - 8.6 mg/L) and DBO5 (1 mg/L - 4 mg/L) values are low, indicating an absence of organic pollution.

Nutrient balance: For this balance, Nitrate (NO_3^-), Nitrite (NO_2^-), Total Phosphorus, and Sulfate (SO_4^{2-}) were considered, and their variations are presented in Figure-4.

The graphs in Figure-4 show the absence of sulfates in the ground water. They also indicate that only the water from site ES1 has a nitrate concentration above 45mg/L. The proximity of this borehole to a cemetery could explain this high nitrate concentration. High nitrate concentrations in drinking water can cause methemoglobinemia in infants. Furthermore, for the surface water samples, all nitrate concentrations are below 44 mg/L. Thus, according to Beaux[21], the surface waters do not exhibit nitrogen pollution.

Physical assessment: Electrical Conductivity (EC), temperature, turbidity, and pH are considered. The results for temperature and electrical conductivity are shown in Figure-5.

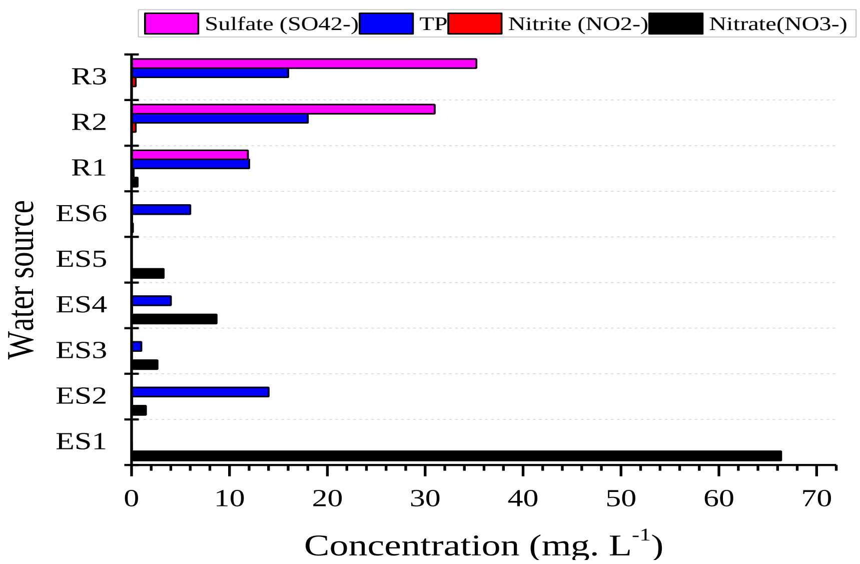

Figure-4: Variations in nitrate, nitrite, sulfate and total phosphorus concentrations in analyzed water samples.

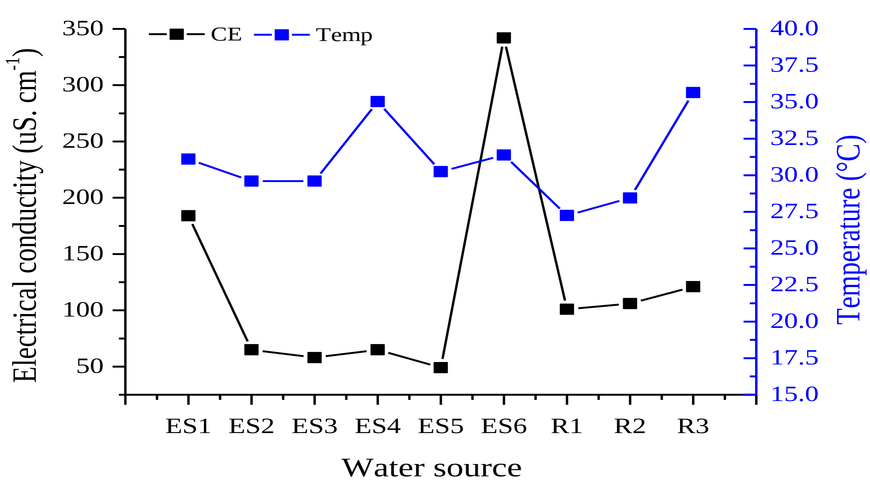

Figure-5: Variations in electrical conductivity and temperature of analyzed waters.

The electrical conductivity of water indicates its level of mineralization. For the different sampled sites, the electrical conductivity values are all below the Beninese standards for drinking water (2000µS/cm) and 400µS/cm for surface water according to AGRBC[20] and Beaux[21]. Therefore, the waters are weakly mineralized.

The temperature of surface waters ranges between 25°C and 35°C. According to Beaux[21], a temperature above 30°C for surface water indicates pollution. Site R3 is therefore subject to pollution because the water temperature at this site is above 30°C.

All sampled waters in the study area have a pH within the acceptable range for both groundwater and surface water, except for the waters from sites ES5 and ES6, which show an acidic pH.

Groundwater exhibited turbidity below 5 NTU, while surface water showed turbidity between 36 NTU and 75 NTU. The variations in turbidity and pH are presented in the graphs in Figure-6.

Physico-chemical balance: The quality parameters used are calcium ion Ca^{2+} color, hardness, Total Alkalinity (TAC), iron ion Fe^{2+}, magnesium ion Mg^{2+}, manganese ion Mn^{2+}, zinc ion Zn^{2+}, chloride ion Cl^{-}, and fluoride ion F^{-}. Figure-7, 8, and 9 show the variations of these parameters.

The color of water from sites ES2 and ES4 is above the threshold value (15 Pt-Co). All surface water samples collected in the area show color values exceeding this threshold.

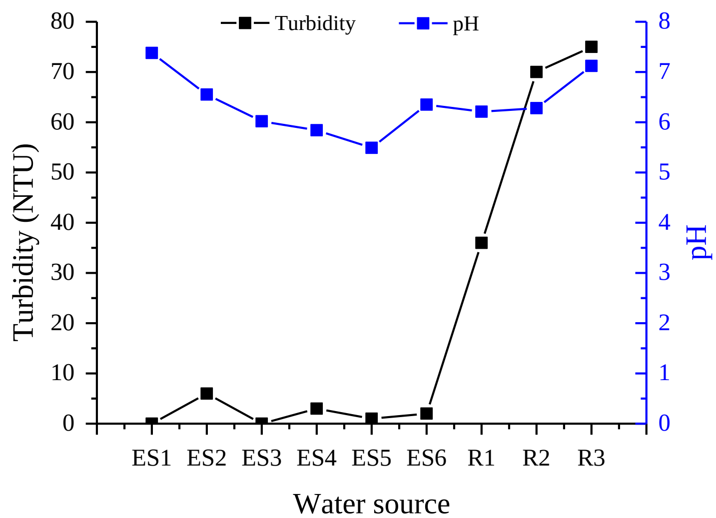

Figure-6: Turbidity and pH variations.

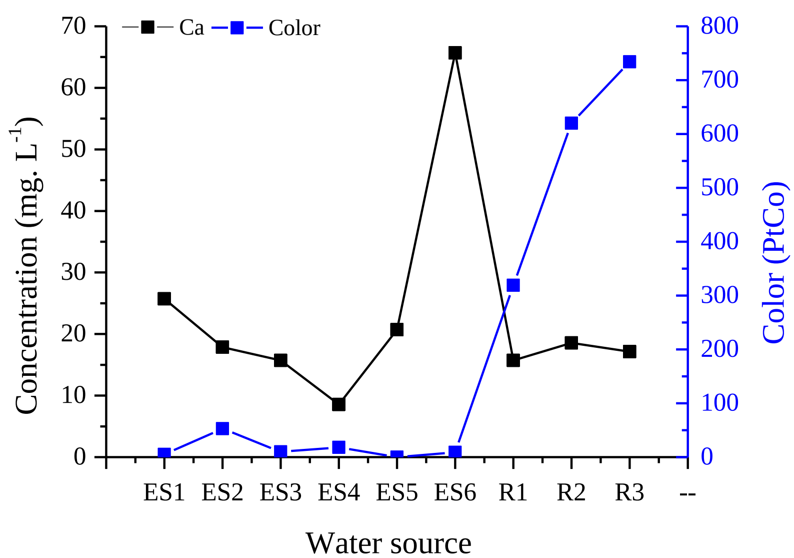

Figure-7: Variations in Ca concentration and color of sampled waters.

Analysis of Figure-8 shows that hardness and TAC (Total Alkalinity) concentrations vary in the same direction, with a high level at ES6. According to Figure-7, ES6 showed a very high concentration of calcium ions. Indeed, the Total Alkalinity corresponds to the content of alkalis, carbonates, and bicarbonates of alkaline and alkaline-earth metals in water. The Total Hardness, or water hardness, is an indicator of the mineralization of water by divalent alkaline-earth cations that can precipitate as limescale. It is solely due to calcium and magnesium ions.

Water with high hardness can cause corrosion or scaling. All collected waters have a hardness below 20°f, indicating they are soft waters. This is supported by the calcium and magnesium ion concentrations being below the Beninese standard for drinking water. Alkalinity, an index of the water's buffering capacity, is closely related to hardness. The sampled waters show low alkalinity values. However, the hardness of groundwater at ES6 is 9.75°f. For this site, a high concentration of calcium ions, iron, and TAC observed could explain this hardness value at ES6.

Balance of trace metal and cyanide ion: Mercury (Hg), lead (Pb), Arsenic (As), cadmium (Cd), nickel (Ni), chromium (Cr), and copper (Cu) are the metals identified in the sampled waters. Figure-10 presents their concentrations.

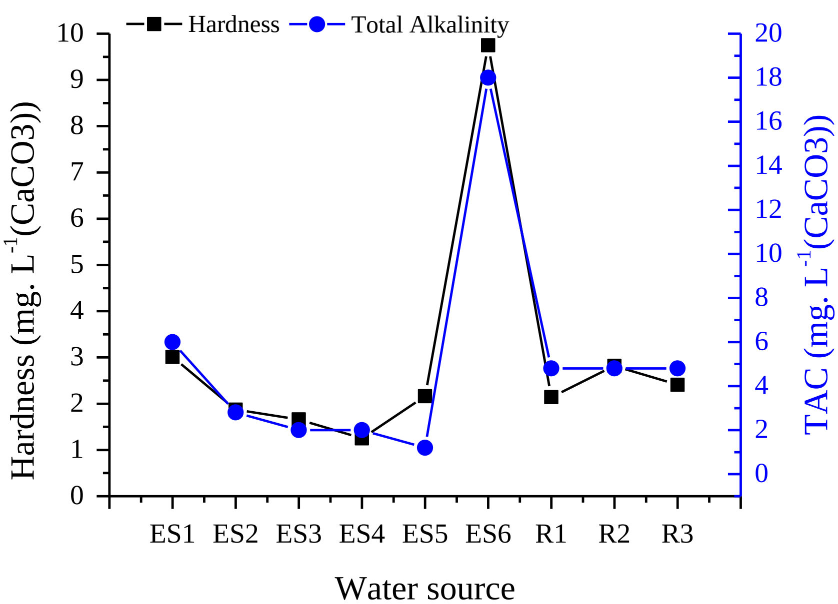

Figure-8: Variations in hardness and TAC.

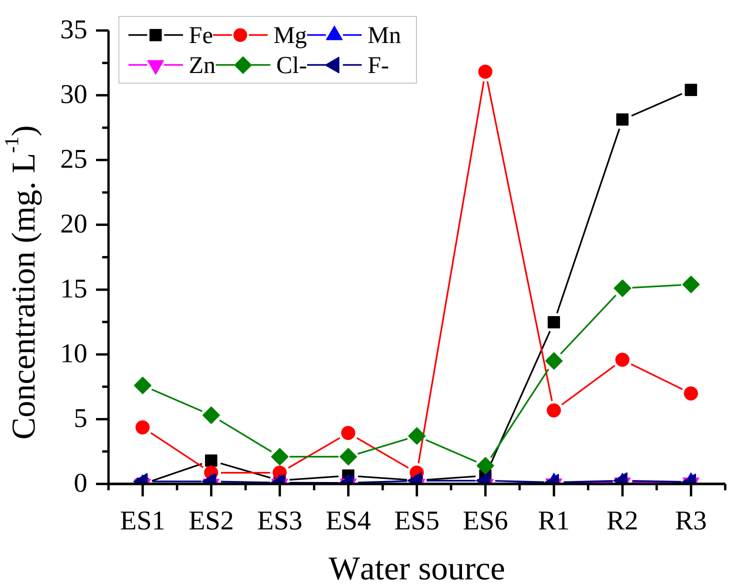

Figure-9: Variations in major ion concentrations.

Trace Metal Elements (TMEs) (Copper, Zinc, cadmium, mercury, etc.) are dangerous for human health and aquatic life. Above the threshold, they are responsible for numerous diseases. For the groundwater and surface water sampled in this study, all measured values are below the limit that can cause harm to human and aquatic life.

Regarding hydrocarbons dissolved in water, oils and greases can be toxic to aquatic organisms even at very low concentrations. The analyses carried out revealed that total petroleum hydrocarbons are all below the recommended threshold in groundwater and surface water. Similarly, oils and greases are absent in the samples.

Microbiological analysis: Thermotolerant coliforms and E. coli were detected. Figure-11 shows their variations. The search for pathogenic bacteria in the waters indicated that the waters from sites ES3 and ES6 are contaminated by thermotolerant coliforms and E. coli. All sampled surface waters (R1, R2, and R3) are contaminated by the same bacteria. The presence of E. coli in water is a sign of fecal contamination.

Assessment of surface water quality in the ZES: Based on the SEQ-Eau[8] surface water assessment grid, the average values of the recorded physico-chemical parameters are distributed into five classes ranging from Class I to Class V according to Table-3. The analysis of this table shows that the surface water in the study area is of excellent quality for the parameters in Table-3, with the exception of dissolved oxygen and fecal coliforms, which showed poor or very poor quality.

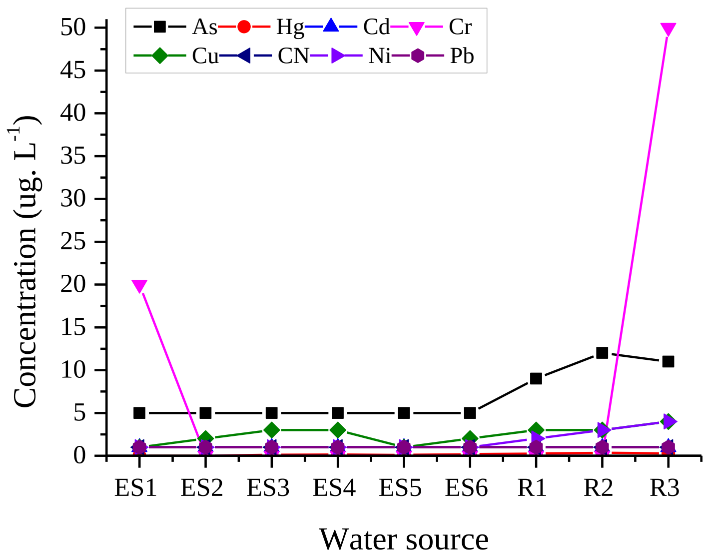

Figure-10: Variations in concentrations of trace metals ETM and cyanide.

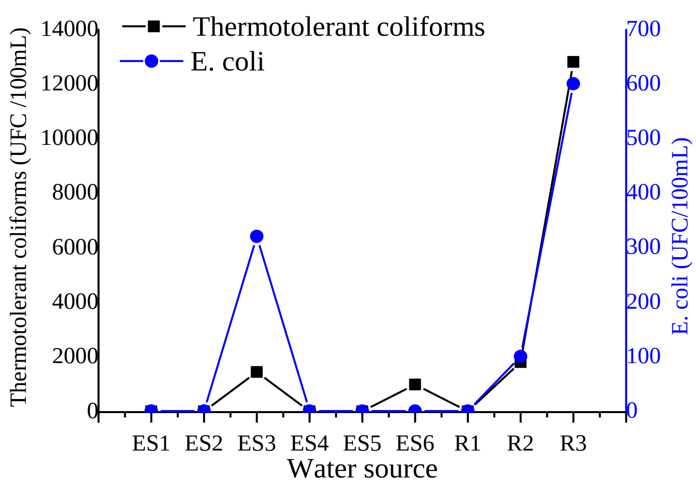

Figure-11: Variations in pathogen concentrations in water.

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Table-3: Extract from the general physico-chemical quality grid used to classify surface waters in the ZES.

Quality classes		Class 1: Excellent	Class 2: Good	Class 3: Medium	Class 4: Bad	Class 5: Very Bad
Parameters	Units	Alteration				
I- Organic and oxidizable matter MOOX						
O_2dissolved	mg/L	>7	7-5	5-3	3-1	<1 (0,23-0,8)
DBO 5	mg/L	<3(2-3)	03-06	06-10	10-25	>25
DCO	mg/L	<30 (2.67 – 5.51)	30-35	35-40	40-80	>80
II- Mineralization						
Conductivity at 20°C	µS/cm	100–750 (101-121)	750-1300	1300-2700	2700-3000	3000 -7000
III- Suspended solids MES						
Turbidity	NTU	<15(36–75)	15-35	35-70	70-100	>100
IV- Nitrates						
Nitrates (NO_3^-)	mg/L	≤10 (0.1–0.06)	10-25	25-50	>50	
V- Nitrogenous elements excluding nitrates						
Ammonium	mg/L	≤0.1	0.1-0.5	0.5-2	2-8	8 – 50
Nitrite (NO_2^-)	mg/L	≤0.03 (0.21–0.42)	0.03-0.3	0.3-0.5	0.5-1	>1
VI– Phosphorus matter						
Ortho-phosphate (PO_4^{3-})	mg/L	≤0.2 (0.012–0.018)	0.2-0.5	0.5-1	1-5	>5
VII – Microorganisms						
Faecal coliforms	(UFC/100ml)	≤20	20-2000	2000-20000 (1800 -	20000-50000 12.800)	>50 000

Discussion: The average pH values indicate that the waters of the study area's river are slightly acidic, ranging between 5.5 and 7.4. According to Decree N°2001-94 of February 20, 2001, for drinking water, these values do not meet the potability standard. However, these values are favorable for aquatic life in surface waters according to Rodier[3], AGRBC[20], and Beaux. The recorded pH values are consistent with the results obtained by Adido[22] and Eninhou[23] in the Agbado station dam and those obtained by Barkat[24] in the Beni Haroun dam. Beninese standards for drinking water quality recommend 6.5 < pH < 8.5. The recorded values fall within this pH range. Therefore, these values do not indicate pollution in the studied environment.

The pH values of the surface waters in the study area are within the drinking water standards in the Republic of Benin. SEQ-Eau[25] reveals that the waters of the study area are of excellent quality with respect to pH for drinking water use. However, these waters require disinfection treatment because these surface waters are of poor quality due to the presence of bacteria such as Thermotolerant Coliforms and E. coli.

The temperature results for the waters of the study area are consistent with the work of Koné[26] in Lake Kossou, Ivory Coast, with an average temperature of 28.85 ± 1.08°C during the dry season. These temperature values are close to the value found by Adido[22] (29.2°C) in May 2020. Similarly, the average temperature values are very close to those obtained by Akognongbe[27] in the Ouémé basin, who found an average value of 27.0°C during the dry period. Furthermore, all the average values obtained are higher than the WHO[28] standard (25°C) and fall into Class IV (25°C-28°C) of the surface water assessment grid[25], indicating poor water quality. Indeed, a high water temperature stimulates the growth of microorganisms and can increase problems related to taste, odor, color, and corrosion[29].

The low dissolved oxygen levels obtained in the surface waters of the study area differ from the values obtained by Koné N. et al.[26] in Lake Kossou. These authors obtained average oxygen levels of 6.74 ± 1.03 mg/L during the rainy season and 5.50 ± 0.88 mg/L during the dry season.

The average values (0.23–0.88 ± 0.01mg/L) obtained show that the waters of the study area's river are less oxygenated during the rainy season than the dry season. According to WHO[30], good quality water should have an oxygen concentration above 7mg/L. However, the average dissolved oxygen levels obtained during this study are below 7 mg/L. Consequently, the surface waters of the study area are not of good quality and require complex treatment during the dry season for this reason[25]. This depletion of dissolved oxygen in water supplies can stimulate the microbial reduction of nitrates to nitrites and sulfates to sulfides[29]. The average dissolved oxygen levels are much lower than those obtained by Odjohou L. E.[31] on Lake Labion.

The highest measured conductivity value is obtained at ES1 (184 µS/cm) for groundwater and 121 µS/cm at R3 for rivers. This indicates that these waters have low mineralization. However, these average conductivity values are below the Beninese standard, which recommends 2000 µS/cm for the Maximum Admissible Concentration (MAC) for drinking water and 1500 µS/cm for surface water. According Damania R. et al.[4], a conductivity between 100 < EC < 200 µS/cm for a watercourse also signifies low mineralization of salts present in the environment and, by extension, between 60 and 3500 µS/cm indicates water of passable or average quality requiring conventional treatment for drinking water supply[25]. These average conductivity values are higher than those obtained by Koné N. et al.[26] on Lake Kossou, who found higher conductivity during the dry season (77.01 ± 3.84 µS/cm) than in the rainy season (74.25 ± 2.99 µS/cm) in that lake.

The turbidity levels of the waters in the study area are low and show the clarity of these waters. The inconveniences caused by turbidity to users are relative, as some populations are accustomed to consuming more or less turbid water and do not appreciate the qualities of very clear water. However, high turbidity can allow microorganisms to attach to suspended particles. Thus, based on the grid[25], the surface waters of the study area are of average quality during sampling with regard to turbidity.

The waters of the study area are very soft, as they are in the range of 1.2 to 6°f [32]. These measured hardness levels are contrary to those observed by Azonnakpo O. et al.[19] in the Ouémé Delta. The differences in hardness levels observed between this study and that of these authors can be explained by the nature of the ecosystems studied. The hardness values of the waters in the study area are lower than the results found by Adido G.[22]. This difference can be explained by the study period. However, hardness is not subject to a standard, but it can influence taste and detergent consumption; hard water does not lather well, and washing taking place near water bodies means hardness would have an impact on pollution[29].

The concentrations of calcium, magnesium, and chloride ions are below the WHO[29,30] standards for drinking water, which are 100 mg/L for calcium, 50 mg/L for magnesium, and 250 mg/L for chloride. The range of calcium concentrations (15.7 to 65.7 mg/L for groundwater and 15.7 to 17.6 mg/L for river water) is higher than that observed by Kpatchia A.[33] on the Okpara River, which was 10 mg/L, but lower than that obtained by Kpatchia A.[33] in the Ouémé basin. These authors recorded an average of 116.90 mg/L during high water levels and an average of 83.25 mg/L during low water levels.

The chloride ion concentrations are below 10 mg/L in all samples. These values are also lower than those obtained by Kpatchia A.[33] (11.36 mg/L) in June 2014 on the Okpara River. Similarly, the fluoride ion concentration is very low in the waters. Fluoride concentrations are lower if the Ca^{2+} content, originating from gypsum for example, is high. The contact time between rock and groundwater, as well as chemical reactions, determines the F- ion concentrations (equilibrium with fluorite, with Ca^{2+} being dominant).

Fluoride is recognized as an essential element for the prevention of dental caries. However, regular ingestion of water with a fluoride concentration above 2 mg/L[28-30] can lead to problems of skeletal and dental fluorosis. Children are particularly vulnerable to this condition.

At levels above 0.3 mg/L, iron stains laundry and plumbing fixtures[29]. The iron concentrations in the groundwater are below this value. In contrast, these iron levels are 40 to 80 times higher in the river water of the study area. According to Zogo[34], iron-rich waters have an impact on the organoleptic characteristics of water, such as color and taste. Furthermore, surface waters can contain up to 0.5 mg/L of iron, which can originate from the leaching of traversed terrains or industrial pollution[35].

The manganese ion concentration in drinking water is very low. Thus, the detected Mn^{2+} concentration complies with the standard adopted by Benin and the WHO. According to OMS[29], at levels exceeding 0.1 mg/L, manganese present in drinking water supplies can impart an undesirable taste to beverages and can stain sanitary ware and laundry. The presence of manganese in drinking water, like iron, can lead to the accumulation of deposits in the distribution network[29].

Nitrogen compounds (nitrite and nitrate) are two of the main indicators of the water quality of SDG 6.3.2 proposed by the World Bank report[4].

Nitrites are toxic to the human body; their presence in significant quantities degrades water quality[36]. Groundwater contains traces of nitrite, while the ZES river shows low values (0.21 to 0.42 mg/L). These values are consistent with those found by Adido in June 2019 at the Agbado treatment plant. Similarly, these nitrite levels found in the Agbado river corroborate those found by Zinsou H. et al.[37] in the Ouémé Delta. These authors observed nitrite values ranging between 0.004 and 0.13 mg/L. This could be due to the rapid oxidation that transforms them into nitrates.

This might explain, among other things, the slightly higher nitrate values in these waters. The nitrite levels in the waters of the ZES river are below the WHO standard and the beninese drinking water quality standard (3.2mg/L) and the WHO guideline[29] (3mg/L). The Water Quality Assessment System[25] reveals that the water of the ZES river is of acceptable quality and requires simple treatment for nitrite ions.

As for nitrates, their presence in watercourses is due either to the leaching of agricultural land or to the oxidative reactions of ammoniacal nitrogen and nitrites[38]. The highest nitrate value obtained for the groundwater ES1 could be related to its proximity to the cemetery (less than 15 meters). The presence of nitrogen compounds in water is the cause of "blue baby syndrome", which can be fatal, as the infant's body is deprived of the oxygen it needs[4].

However, these nitrate values are below the Maximum Admissible Concentration for potability (50mg/L), with the exception of borehole ES1, which showed a value of 66.36 mg/L. On the other hand, the river waters showed traces of nitrates. This indicates that the waters of the ZES river have excellent class I quality according to SEQ-Eau[25].

The search for pathogenic germs in the water indicated that the waters of sites ES3 and ES6 are contaminated by thermotolerant coliforms and E. coli. All surface waters sampled (R1, R2, and R3) are contaminated by the same germs. The presence of E. coli in water is a sign of fecal contamination.

From a chemical standpoint, it is also noteworthy that the concentrations of major ions such as nitrate, nitrite, total nitrogen, chloride, calcium, and magnesium in the water samples are generally low and below current regulations, except at borehole ES1, where slight nitrate contamination is observed. Indeed, the nitrate concentration recorded at this point is 66.36 mg/L, compared to the current limit value set at 45 mg/L. The same observation is made regarding the hardness and color of the water. In general, the waters are soft and colorless, with a hardness below 20 mg/L (current limit value), except for the surface water with a colorimetry greater than 15 PtCo (current limit value). The colorimetry varies from 319 to 734 Pt, which is >21 to 49 times the current limit value.

The results of the physico-chemical analyses of the sampled waters indicate that only the water from site ES1 has a nitrate concentration above 45 mg/L. The proximity of this traditional well to a market gardening area could justify this high nitrate concentration. Indeed, the consumption of water with a high nitrate concentration leads to methemoglobinemia in infants. Metallic trace elements (As, Cd, Cu, Zn, Hg, Ni, Pb) are dangerous for human health and aquatic life. Thus, above the threshold, they are responsible for numerous diseases. For the groundwater and surface water sampled in this study, all measured values are below the limit that could cause damage to human and aquatic life, except for cadmium.

Furthermore, the measured COD (Chemical Oxygen Demand) and DBO5 (Biochemical Oxygen Demand over 5 days) values are low for the waters. This indicates an absence of organic pollution in these waters.

Regarding hydrocarbons dissolved in water, they can be toxic to aquatic organisms even at very low concentrations. The analyses carried out revealed that total petroleum hydrocarbons are all below the recommended threshold in groundwater.

Conclusion

This work has enabled the development of a comprehensive diagnosis of the pollution status of surface and groundwater in the ZES. Based on the current situation, the results of the physico-chemical and bacteriological analyses of the area suggest poor surface water quality against good groundwater quality. The degradation of the overall quality of surface water is mainly due to microorganisms from leaching discharges via the abusive deposition of fecal matter drained into the rivers. Due to the functional and ecosystem modifications imposed by the creation of an industrial zone, it is urgent to periodically monitor the studied parameters.

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