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Research article

Evaluation of surface water contamination and its impacts on health in the mining districts of Kambélé and Bétaré-Oya (Eastern-Cameroon)

Ngoa Manga Elisabeth Sylvie [a], Armel Zacharie Ekoa Bessa [b,*], Rigobert-Espoir Ayissi Mbomo [c], Jean Victor Akono [a], Bachirou Dairou [d], Kamtchouing Pierre [a]

[a] *Department of Biology and Animals Physiology, Faculty of Science, University of Yaoundé I, Cameroon*
[b] *Department of Earth Sciences and Environment, Higher Teacher Training College, University of Bertoua, Box 652, Bertoua, Cameroon*
[c] *Department of Biological Sciences, Higher Teacher Training College, University of Yaoundé I, Cameroon*
[d] *Institute for Geological and Mining Research (IRGM), B.P. 4110, Yaoundé, Cameroon*

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ABSTRACT

This study aimed to assess water contamination and associated health risks for populations residing in the mining areas of Kambélé and Bétaré-Oya. Key parameters, including pH, EC, TDS, TSS, and concentrations of metallic elements (Cd, Cr, Fe, Pb and Mn), were measured using established water analysis techniques. The analysis included multivariate statistical assessments, calculation of metal pollution and water quality indices, and health risk determinations, including daily intake (DI) and hazard quotient (HQ). Findings indicate a diverse pH range ($5.26 < \text{pH} < 8.72$), low mineralization ($33.22 < \text{EC}\ (\mu\text{S/cm}) < 179.64$), and elevated TSS content ($22.53 < \text{TSS}\ (\text{in mg/l}) < 271.51$). Metallic elements were observed in the descending order of Fe > Mn > Pb > Cr > Cd. Water quality assessments using the Water Quality Index (WQI) categorized sites as displaying doubtful to very poor quality, notably Woupy (WQI = 719.14) in Kambélé and Mali (WQI = 794.24) in Bétaré-Oya, with Heavy metal Pollution Index (HPI) values exceeding 100. These outcomes highlight consistent chemical degradation of surface water, posing potential risks to local populations' health and well-being. The study emphasizes the critical need for proactive environmental protection measures in mining areas, recommending the adoption of healthy mining practices and effective site reclamation strategies. Furthermore, future studies should consider exposure duration's potential impact on residents' health problems in these areas. Overall, this study contributes significantly to understanding and addressing the intricate interplay between mining activities, water quality, and public health in the Cameroon countryside.

1. Introduction

Access to safe drinking water is fundamental to human health and well-being, yet natural surface water bodies are increasingly contaminated by various pollutants, posing significant health risks to populations [1–3]. Chemical pollution, particularly from metals, has emerged as a prominent concern, warranting extensive research to elucidate its toxicological implications for both the environment and human health [4–7]. In regions where mining activities are prevalent, such as the Kambélé and Bétaré-Oya areas in eastern

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[*] Corresponding author.
E-mail address: armelekoa@yahoo.fr (A.Z. Ekoa Bessa).

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Cameroon, the impact of mining-induced water contamination remains a critical issue.

Mining operations, especially in gold extraction, heavily rely on water, which serves as a primary medium for the transportation and dissemination of mining-related pollutants [3,4,8]. As a consequence, intensified mining activities in these regions have led to significant alterations in the composition of surface water, raising concerns about downstream water quality and potential health risks for local populations. In this context, our study seeks to investigate the ramifications of mining activities on surface water quality in the Kambélé and Bétaré-Oya regions.

While previous research has predominantly focused on soil and sediment contaminations in these areas [3,9–14], limited attention has been given to assessing water chemistry and its health implications [15–18]. Therefore, the specific objective of our study is to establish a comprehensive understanding of the relationship between mining activities and surface water quality, focusing on its impact on the health of local populations in gold mining regions such as Kambélé and Bétaré-Oya.

This investigation will involve evaluating the physico-chemical parameters of surface water, determining the extent of metal pollution through heavy metal pollution and water quality indices, and assessing the health risks posed to local residents by calculating daily intake, hazard quotient, and carcinogenic risk. By employing these methodologies, we aim to contribute valuable insights into the complex dynamics of mining-induced water contamination and its implications for public health in the studied regions. Additionally, a structured questionnaire and survey will be conducted to gather essential data from the sites affected by gold panning activities,

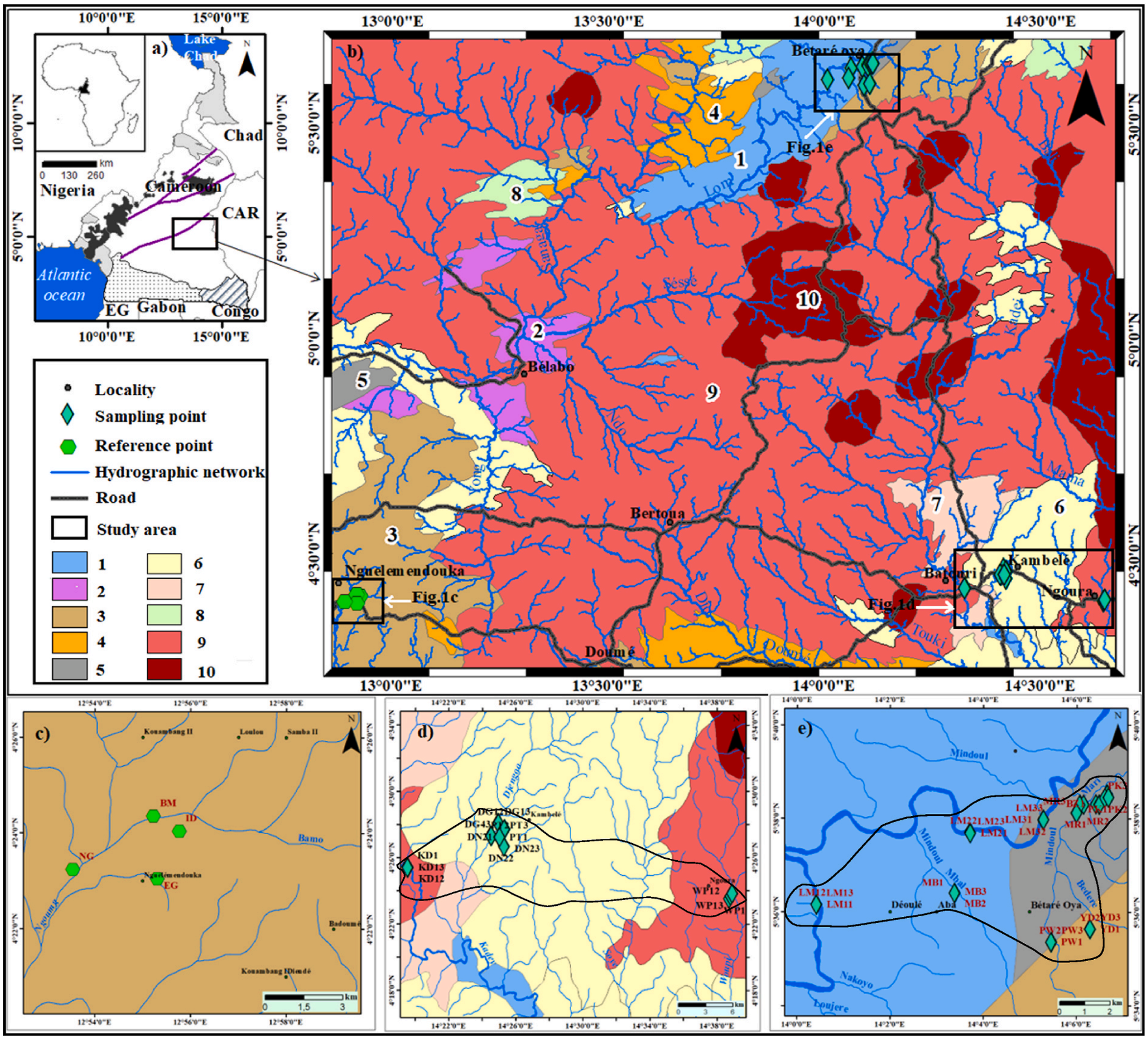

Fig. 1. Location of the study area: a) Cameroon in Africa; b) geological map of Cameroon; c) Reference point from Nguelmendouka; d) Sampling location from Kambele and e) sampling location from Betaré Oya. Geology: 1) Shales; 2) Lower michaschists; 3) Superior gneiss; 4) Inferior gneiss; 5) Micaeous quatzites; 6) Migmatitic gneiss; 7) Orthogneiss; 8) Biotite; 9) Anatexis granites and 10) Syntectonic granites. Black lines in d) and e) represented the boundaries of the study areas.

facilitating a comprehensive analysis of the health risks associated with mining-induced water pollution.

Through our research endeavors, we seek to shed light on the intricate interplay between mining activities, surface water quality, and public health in the context of gold mining regions, ultimately advocating for evidence-based policy interventions and sustainable resource management practices to safeguard the well-being of local communities.

2. Study sites

The study area, located in the eastern region, spans between 2° and 6° North latitude and 12° and 16° East longitude (Fig. 1a–b). Specifically, the research was conducted in the Kambélé and Bétaré-Oya mining districts, chosen for their significant artisanal gold mining activities. The East Cameroon region experiences two climatic units: the tropical climate and the transitional equatorial climate, each characterized by four distinct seasons. Temperature fluctuations range from 11.4 to 25.14 °C, with an annual average of 21.3 °C. The region's vegetation comprises savannah and forest types, with a dendritic hydrographic network governed by the Lom and Kadey basins.

The soils in the study areas consist of red and yellow ferralitic soils belonging to the South Cameroonian domain, which is part of the North Equatorial Pan-African chain. These areas form part of the Precambrian basement of Cameroon, divided into the Congo craton and the Central African fold belt [19]. The metavolcanic rocks in these areas constitute a significant lithological group (Fig. 1b), with syn-to-late collisional calc-alkaline granitoids being widespread. These rocks intrude orthogneiss representing the Palaeoproterozoic basement, which underwent extension and likely dismemberment during the Pan-African event. The basin is characterized by three main units: volcaniclastic shales, metasedimentary rocks, and granites. Shale units are intercalated with quartzites and metaconglomerates, penetrated by granitic plutons [13,16,20].

The design of this study employs a case study approach, allowing for a comprehensive comparison of various factors between two distinct cases. Thus, the control site chosen is the town of Nguelemendouka in the department, located between 4°23′ 00″ North Latitude and 12° 55′ 00′ Longitude (Fig. 1c). Established on November 27th, 1952, the commune covers 50 villages across 1068 km^2 and is bordered by the municipalities of Diang to the north, Nyakokombo (Kobdombo) to the south, Doumaintang to the east, and Minta to the west. Presently, sand extraction is the primary underground activity in the area, while the subsoil also contains diamonds, though they are not yet exploited. Nguelemendouka was selected as the control site due to the absence of significant mining activities.

Agriculture predominates in the Nguelemendouka department, with a focus on subsistence farming producing plantains, macabo, and cassava. The harvested crops are sold to buyers from various regions of the country. The area is renowned for its cocoa production, making it one of the major cocoa-producing regions in the country. Notably, cocoa farmers in this locality use agricultural fertilizers to enhance productivity, contributing to the environmental characteristics of the area.

3. Materials and methods

3.1. Sampling and treatment procedures

Samples were collected manually once at a depth of less than 1 m at the riverbed, preferably in areas where the flow velocity was sufficient to ensure proper mixing of solid particles and dissolved materials [17]. The samples were gathered in 1.5 L polyethylene bottles, which had been cleaned with ultrapure acid, rinsed with distilled and MilliQ deionized water, and finally rinsed three times with the sampling water according to standard procedures [21,22]. Subsequently, the samples were stored in coolers to maintain optimal preservation at a temperature of 2 °C. Streams located in close proximity to or within the mining sites in the area, which were utilized for human activities, were selected for sampling.

At each sampling point in every locality, three samples were collected (one triplicate per point). In the Kambélé mining district, a total of 21 samples were collected and distributed among four rivers: Woupy, Ndjiengou (Ndjiengou 1, Ndjiengou 2, Ndjiengou 3, Ndjiengou 4), Derwan 1, Derwan 2, and the main river, Kadey River (Fig. 1d). In the Bétaré-Oya mining district (Figs. 1e), 33 water samples were collected from eight listed rivers: Mali (Mali 1 and Mali 2), Yondéré, Mbal, Mbédiri, Pawara, Pékonoun, Bézédaré, and the main local river, Lom River (Lom 1, Lom 2, and Lom 3). In this area, three samples were taken from each river, except for two in Mali and three from the Lom River.

To ensure an accurate assessment of the impact of mining activities on water quality, identify sources of pollution, evaluate the effectiveness of remediation measures, and ensure statistical validity, the same sampling procedure was followed in the control area. Four rivers: Idoumentchy, Bamo, Egotcha, and Nyong crossing the district were sampled, with three samples taken per river, resulting in a total of 12 samples. In the laboratory, a control sample was created by combining 0.5 L of each individual point to obtain a 1.5 L sample per collecting point. Subsequently, 0.5 L of each individual point sample was combined in a 2 L beaker to constitute the final control area sample. This consolidated control sample was then utilized for subsequent analyses, enabling a comprehensive assessment of water chemistry in the area through a single analysis [23]. The collected samples were transported to the Soil, Plant, Water, and Fertilizer Analysis Laboratory (LASPEE) of the Agricultural Research Institute for Development (IRAD) in Nkolbisson, Cameroon.

3.2. Sample analysis

The analysis of physico-chemical parameters (pH, electrical conductivity, and dissolved solids content) was conducted in situ using the ORION STAR 225 Thermo-Scientific Multiparameter Kit. This analysis adhered to ISO 10523 and NF 27888 standards, as recommended by Rodier et al. [22]. Upon returning to the laboratory, each sample underwent subdivision into two parts. One portion was allocated for the determination of Total Suspended Solids (TSS), and the other for the determination of metals. For the TSS analysis, 50 ml of each sample was weighed using a RAWAG PS 510.R1 precision balance (precision of 0.1 mg) and then heated in an oven at 105 °C for 24 h. The TSS value was derived from the difference in weight before and after drying, expressed as $\mathrm{mg.l^{-1}}$ TSS. The sample fraction earmarked for metallic trace element analysis was filtered with Whatman paper of 4 μm porosity, acidified with a drop of pure nitric acid, and stored at a temperature of 0–4 °C. The experiments were conducted within ten days of sampling. Five metals: Pb, Cd, Cr, Fe, and Mn were selected for this study.

The determination of metal contents was performed using induced coupled plasma with optical emission spectroscopy (ICP-OES) on a PERKIN ELMER model Optima 8000 equipped with Winlab 32 software. Sample handling for analytical purposes adhered to the requirements of standard NF ISO 11885. The analysis in ICP-OES involved the creation of standards to establish a calibration curve, following the method outlined by N'guessan et al. [24]. Calibration ranges were set based on the concentration of the different elements to be measured. To ensure the quality of results, LASPEE is committed to a quality approach, holding ISO/IEC 17025 accreditation since 2005 (certification reviewed in 2017, valid until September 2023). The laboratory upholds quality objectives by recommending the use of reference materials, verification solutions, and high-quality reagents, including distilled and ultrapure water, in the analysis process. Additionally, assays are conducted in three replicates to ensure the repeatability and reproducibility of data, essential elements in method and result validation.

3. 3Estimation of water contamination

3.3.1. Heavy Metal Pollution Index (HPI)

The Heavy metal pollution index (HPI) is a parameter that evaluates the level of water pollution by heavy metals. This method consists of assigning a weight or index (Wi) to each metal according to its contribution to the process of water quality degradation [17,25,26]. The mathematical determination of this index therefore follows a few steps: The determination of the relative weight or index (Wi) attributed to each mineral; this is obtained through the formula below:

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

where k is the constant of proportionality, which in this study is equal to 1 and Si is the standard value of parameter allowed by the WHO standard [27,28]. The second is to calculate values of the sub-indices (Qi) for each parameter; they are obtained using the following formula:

$$Qi = 100 \times Vi/Si \tag{2}$$

where *Vi* is the concentration for parameter in the sample (in μg/L) and *Si* is the permitted limit or standard for this parameter according to WHO standards [27,28]. The next step consists of the calculation of the metal pollution index itself through the following formula:

$$HPI = \sum\nolimits_{i=1}^{n} wi\ Qi \Big/ \sum\nolimits_{i=1}^{n} Wi \tag{3}$$

3.3.2. water quality index

The Water Quality Index (WQI) is a mathematical parameter that, in relation to various water uses, signifies the state of water quality and its potential application for a given purpose. It is expressed as a number between 0 and 100, where 100 denotes excellent water quality and 0 denotes poor water quality [29]. The calculation of the water index involves several steps outlined as follows:

Nature of Water Use: Provencher [29] defined 17 water uses categorized into three types: industrial, social, and ecological. However, our study opts for a general use of water because water at our study sites serves multiple purposes, including recreation, supporting aquatic life, providing food, and industrial use.

Choice of Parameters: The selection of parameters for determining the water quality index is influenced by the nature of water use and site-specific characteristics related to local activities [30]. Physico-chemical parameters, major ions, and metallic trace elements are considered based on the water's nature and can vary from 4 to 12, depending on study objectives [31]. For our study, we followed an open system, as presented by Sultadian [32], considering the knowledge of the study environment. We selected 9 initial elements: pH, EC, TSS, TDS, Fe, Mn, Cr, Cd, and Pb.

Weighting of Parameters: This step involves assigning a relative weight to each parameter, ranging from 0 to 5. The importance of a parameter in representing water quality determines its weight in the calculation [29]. Certain parameters, such as Wi representing the relative weight of each parameter, need determination before finalizing the WQI formula, as obtained by applying a specific formula:

$$Wi = wi \Big/ \sum_{i=1}^{n} wi \tag{4}$$

In this study, we used the relative weights calculated by Rakotondabe et al. [17]. The qi parameter, which indicates the quality score, is determined by the application of the following formula:

$$qi = \frac{ci}{Si} \times 100 \quad (5)$$

With Ci the concentration of each chemical parameter obtained after determination of the samples given here in mg/L and Si the acceptability value or standard value of each parameter proposed by WHO [27] in µg/L in the framework of the food safety of drinking water. The last parameter to be determined here is the SI subindex of the each parameter. It is obtained based on the following formula:

$$SI = Wi \times qi \quad (6)$$

Thus, the WQI is calculated using the following formula:

$$WQI = \sum_{i=1}^{n} SI \quad (7)$$

3.4. Determination of the health risk

In order to better assess the health risk run by the populations living in the mining areas in the East Cameroon region, we evaluated the risks at two levels as follows: non-carcinogenic risks including three parameters: daily intake, health risk and cumulative risk of non-carcinogenic effects. Then we evaluated the carcinogenic risks. Thus, it is important to specify that in the context of this work, only two metals (Pb and Cd) will be involved in determining the health risk.

3.4.1. Determination of the daily intake

Knowing the source of a contamination, exposure assessment consists of estimating the frequency, duration and extent of the exposure. In our case, this is done through the calculation of the daily intake (DI) [33]. In order to arrive at its expression, certain parameters must be defined beforehand, such as: the quantity of the element consumed per individual as well as the body weight of the individuals targeted by the study. Thus, for this study, the average consumption of drinking water is estimated at 2 L per day (i.e. 2 kg/d) for adults and 1.5 L per day (i.e. 1.5 kg/d) for children and it will be considered that the individual consumes this quantity of water in 7 days on the week [34]. It is calculated using the following formula:

$$DI = C \times Q \times F / P \quad (8)$$

where DI: related to the consumption of polluted water (mg/kg/day); C: concentration relative to the polluted water expressed in mg/kg; Q: Quantity of water consumed per day, expressed in kg/day; F: Frequency or rate of exposure (without unit). The average body weight of children aged 0–15 years is 28 kg and that of an adult is conventionally equal to 70 kg according to the US EPA [35].

3.4.2. Non-carcinogenic risk characterization

Risk characterization is an estimate of the incidence and severity of adverse effects that may occur in a human population as a result of exposure to all substances. The risk characterization for threshold effects is expressed as the hazard quotient (HQ) [33]. In order to derive the hazard quotient, the determination of toxicological reference values based on the dose-response relationship is essential. Evaluation of the dose-response relationship: its aim is to define a quantitative relationship between the dose administered or absorbed and the incidence of the effect, from which the toxicological reference values (TRV) or Reference Dose (RfD) are established. For this study, TRVs for the study components will be selected based on [33]. It is calculated for the oral route of exposure (water consumption) as follows:

$$HQ = DI / RfD \quad (9)$$

DI = Daily intake (mg/kg/d); RfD = Reference Dose (mg/kg/d) or TRV. If HQ $<$ 1, the occurrence of a toxic effect is unlikely; If HQ $>$ 1 the occurrence of a toxic effect cannot be excluded.

3.5. Statistical analysis

The statistical method used in this study is multivariate analysis using SPSS software version 29.0.10. It is a method commonly used in the field of water and earth sciences to summarize information from several variables while minimizing the loss of key information from several sampling units and variables. A multivariate analysis is a chain of analysis or groups together statistical tools allowing to conclude on the different origins of a hydro-chemical phenomenon. Thus, in the framework of this work, we have used the following statistical tools: The correlation matrix (CM) which allows to note associations between variables and shows the global coherence of the data set. Principal Component Analysis (PCA) is a multivariate statistical analysis technique that allows data reduction and model deciphering within large data sets. Hierarchical Ascending Classification (HAC): is a technique for classifying data of all types and widely used in the earth sciences. This technique groups together objects that are deemed similar to each other and according to a coefficient of similarity in figure called dendrogram [17]. It is important to specify that we used the ArcGis software 10.4.1, for the realization of the maps presented in this work. A so-called statistical spatial interpolation was carried out for a spatial representation of the water quality as well as to highlight the variations in the concentrations of the different metallic elements of the two sites studied.

3.6. Epidemiology of the profile of health complaints from local residents

In concrete terms, the aim was to evaluate the impact of mining on the local population. The participants were men, women and children, whether or not they were attending school, who were able to provide the information requested. Participants were considered to be healthy and in possession of all physical and mental faculties; to be gold miners or not and to reside in a mining village or on the mining site; for miners, to have been born and raised in the mining village or in a nearby area; to have accepted the conditions of the study and to have signed an informed consent form without constraint. Ineligible persons included those engaged in periodic activities at the site, such as shoppers, as well as other mentally unstable persons and those who refused to sign the informed consent. Ethical considerations guided the recruitment of candidates, which imposed strict respect for the individual, his or her personality and dignity as desired by the National Ethics Committee.

The authors have to precise that before contacting the National Ethics Committee, the study proposal underwent analysis by the health delegation of the Eastern Region, and the team was required to obtain National Research Authorization. The ethical authorization process involved a preliminary review of the study proposal. However, due to the lengthy procedure in our context, we are currently awaiting our authorization. Nonetheless, we have implemented the use of informed consent. Each participant signed an informed consent form, affirming the voluntary nature of their participation in the study. For minors, their legal guardian provided consent on their behalf. A total of 100 local residents responded to the questionnaires per *site. This sample size is crucial as it ensures representative data, minimizes errors, and allows for comprehensive observation of phenomena.*

To achieve our objectives, a questionnaire designed with the SPHINX software was used to collect the various data. This epidemiological survey was held in the control site and the test site. All the information collected was recorded and processed using the SPHINX software. Since this is a case-control study, the data from the test sites were analyzed in relation to the data from the control site, which is the Nguelemendouka site (SM1).

4. Results and discussion

4.1. Physico-chemical parameters of surface waters

In this study, only four physico-chemical parameters were evaluated and analyzed: pH, electrical conductivity, TDS and suspended solids. The summary results of the statistical tests obtained from the different analyses of the two sites are summarized in Table 1 and Fig. 1.

4.1.1. Potential of hydrogen (pH)

The evaluation of Hydrogen potential plays a significant role in the adsorption/desorption processes of trace elements, emphasizing its importance [36,37]. The Hydrogen potential for the control sample is 6.52, indicating that the water at the control site tends to be neutral, aligning with WHO standards. This value is attributed to the quality of the soil, with the entire eastern region characterized by ferralitic soils, influencing the physicochemistry and, consequently, the hydrogen potential of the water flowing through this soil. Regarding Electrical Conductivity, the control sample exhibits low mineralization with a value of 42.02 (μS/cm), consistent with the different mining sites, and this low mineralization is explained by the chemical composition of the soil.

The waters at the Bétaré-Oya site display pH values ranging from 5.94 to 8.72, while those at the Kambélé site range from 5.26 to 8.61 (Table 1; Fig. 2). WHO regulations recommend a pH between 6.5 and 9.5 for drinking water. The waters at both sites exhibit strongly acidic to basic characteristics, influenced firstly by biological activity and, secondly, by soil characteristics. The pH of rivers, varying between 6.5 and 8.5, is influenced by biological activities (photosynthesis, respiration) and the buffering capacity of the water [38]. Additionally, the pH tends towards neutrality for surface horizons in ferrallitic soils, influenced by high rainfall, strong sunshine, and the geographical position of the Eastern Region [39,40]. These values are also associated with the region's geology, consisting of acidic rocks and soils [41,42]. Our results align with previous studies on water contamination in mining areas, such as in southern Togo [33] and the Bétaré-Oya mining area [18]. However, there are slight differences from Mimba et al. [15], who worked in the Lom basin, possibly attributed to variations in the sampling period.

Table 1
Statistical summary of physical and chemical parameters in surface water of the two locality and the control site.

Parameter	Unit	Reference WHO (2011)	Control site Value	Kambélé Locality			Bétaré-Oya Locality		
				Min	Max	Avg.	Min	Max	Avg.
pH	/	6.5–8.5	7.57	5.26	8.61	7.03	5.94	8.72	7.14
CE	μS/cm	1500	97.04	33.22	169.27	100.49	39.60	179.64	77.25
TDS	mg/L	< 1000	95.17	22.00	138.33	79.29	23.25	153.57	60.68
TSS	mg/L	25–40	22.08	22.53	271.51	136.11	50.83	234.7	501.29
Fe	mg/L	0.3	4.406	0.0917	2.5247	1.0271	0.0733	1.2627	0.7395
Mn	mg/L	0.4	0.337	0.0443	0.2830	0.1377	0.0347	0.2830	0.1545
Cr	mg/L	0.05	0.019	0.036	0.087	0.062	0.0223	0.0820	0.0543
Cd	mg/L	0.003	0.521	0.024	0.071	0.052	0.0197	0.0570	0.0402
Pb	mg/L	0.01	ND	0.02	0.20	0.11	0.0257	0.2203	0.1073

ND. not determined.

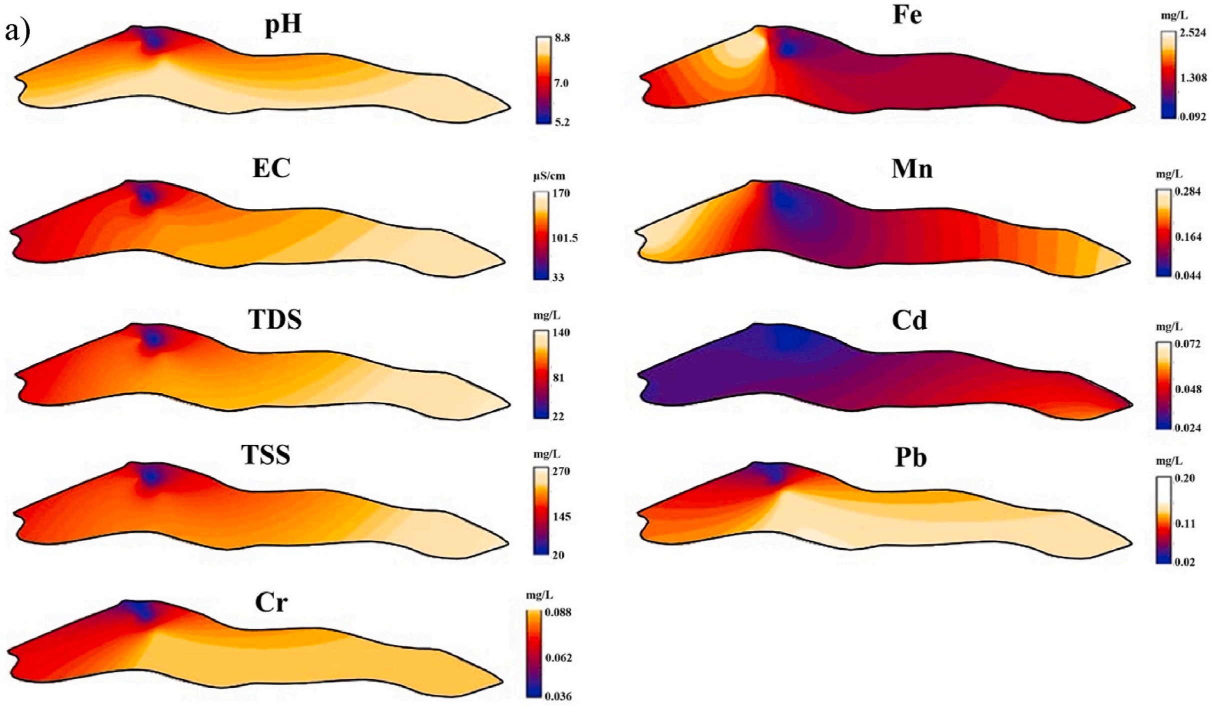

Fig. 2. Spatial distribution of heavy metal concentrations and physical parameters of surface water from a) Kambele and b) Betare-Oya.

4.1.2. *Electrical conductivity*

The data obtained at the Kambélé site range from 33.22 to 169.27 µS/cm, with 85.8% of the samples meeting WHO standards (1500 µS/cm) for drinking water. Similar results were observed for samples collected at the Bétaré-Oya site, with values oscillating between 39.60 and 179.64 µS/cm (Fig. 2a and b). This outcome aligns with the findings of Krampah et al. [43], who obtained low conductivity values in a study on the hydrochemistry of ground and surface water in Benin. It is also consistent with the results reported by Akil et al. [44] for Oued Guigou surface water in Morocco. The observed low mineralization in these waters can be attributed to the sampling period. The variation in electrical conductivity (EC) of surface waters in East Cameroon is influenced by the chemical signature of the waters, closely tied to the geological formations they drain and the climatic fluctuations present in the study zone [17].

The control sample also exhibits low mineralization with a value of 42.02, consistent with various mine sites. This low mineralization can be attributed to the chemical signature of the soil. The variation in EC of surface water in East Cameroon is intricately linked to the geological formations they drain and the climatic fluctuations in the study area [17]. This finding mirrors the results of Krampah et al. [43], who reported low conductivity values in a hydrochemistry study of ground and surface waters in Benin. It is also in agreement with the outcomes presented by Akil et al. [44] for Oued Guigou surface water in Morocco. Conversely, the data obtained from various mines can be justified by the specific period of sample collection.

4.1.3. *Total Dissolved Solids (TDS)*

The total dissolved matter can be estimated by multiplying the conductivity value with an empirical factor that depends on the nature of dissolved salts and the water temperature. The results obtained from various analyses indicate values ranging from 22.00 to 138.33 mg/L for the Kambélé site (Fig. 2a) and from 23.25 to 153.57 mg/L for the Bétaré-Oya site (Fig. 2a). Importantly, all these values fall within the WHO standard (2011) limits, which recommend optimal Total Dissolved Solids (TDS) levels of less than 1000 mg/L for drinking water. These findings, however, exceed the values reported by Mimba et al. [15], who documented a range of 5.85–69.55 mg/L in the Betaré-Oya area. The disparity can be attributed to the intensity of gold activity during the sampling period. The elevated TDS levels can be explained by increased exploitation of mineralized veins, leading to the release of more particles into the water. Notably, the study area waters carry sediment loads from mining operations and erosion of agricultural land [45].

4.1.4. *Total Suspended Solids*

In Kambélé, Total Suspended Solids (TSS) values range from 22.53 to 271.51 mg/L, with 88.89% of samples exceeding the WHO recommended standards for drinking water (25–40 mg/L). For the Bétaré-Oya site, TSS values fluctuate between 50.83 and 234.7 mg/L, and all samples (100%) surpass the standard for drinking water (Fig. 2b). This high percentage can be attributed to the fact that a significant portion, if not all, of the surface water flowing through the villages of Kambélé and Bétaré-Oya is involved in washing operations during the gold extraction process. The variation in TSS levels can be justified by the intensity of extraction activity in each

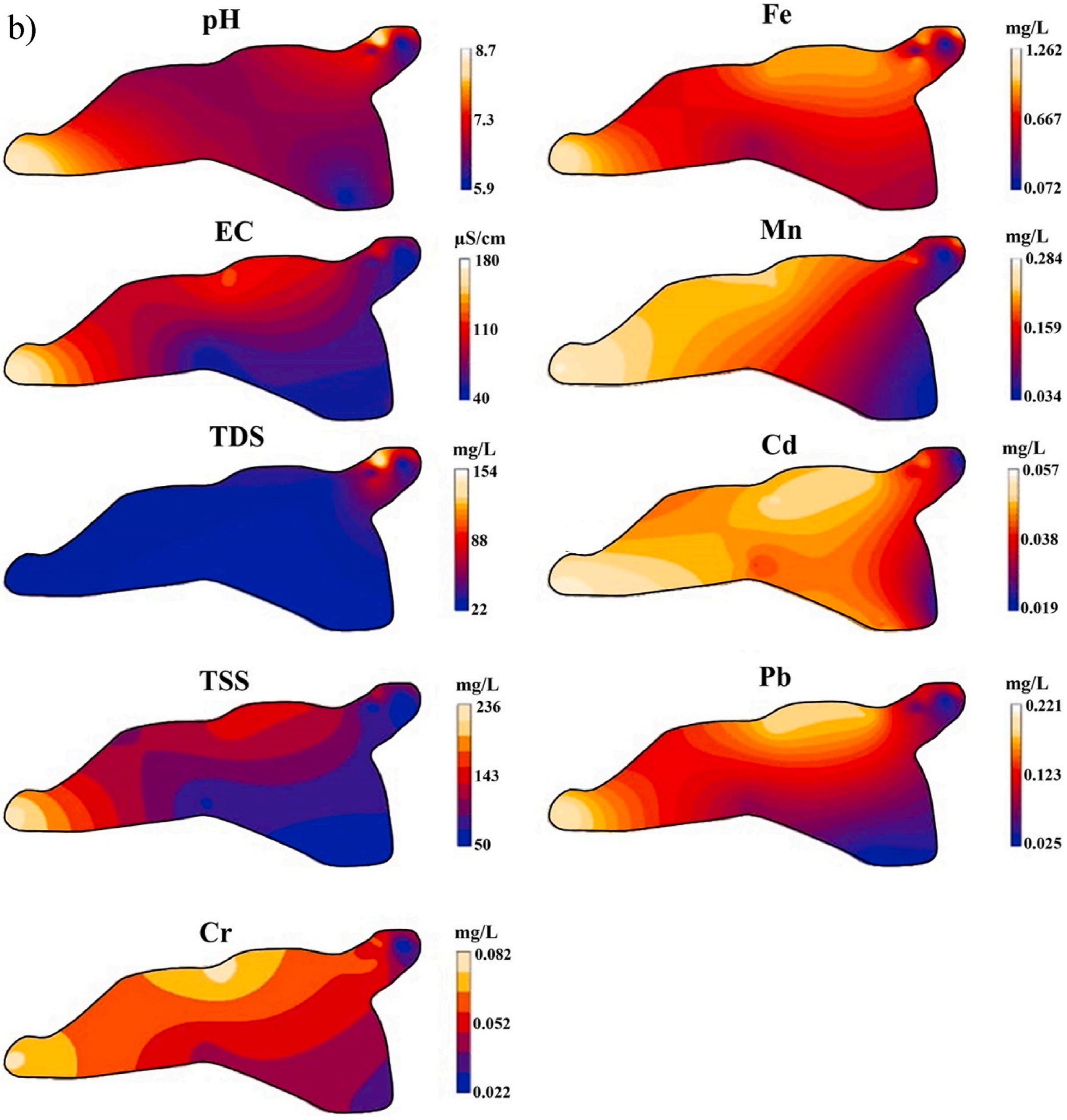

Fig. 2. (*continued*).

watercourse and the quantity of tailings discharged into the water. Consequently, the elevated total TSS values observed in these localities are linked to anthropogenic activities in the area, including gold mining methods that result in deforestation, stripping, soil erosion, excavation and digging of river beds, and the discharge of solid and liquid wastes from gold ore washing. Strong soil leaching with waste rock during rainy seasons also contributes to these elevated TSS levels [18,46]. These findings align with Rakotondrabé et al. [18] and contrast with values obtained by Madzin et al. [47], which can be justified by differences in activity intensity and gold mining methods. Similar to various physicochemical parameters, the control samples exhibit normal values according to WHO standards. This is evident in suspended solids, with a value of 17.08 mg/L. This result is expected, given the absence of surface water activity in the Nguelemendouka area, where only soil drainage during the rainy season influences the suspended solids content.

4.2. *Metals in surface water*

The results pertaining to the metallic element content are outlined in Table 1 and Fig. 2. At the Kambélé site, metal variations are as follows: Fe (0.0917–2.5247 mg/L), Cr (0.036–0.087 mg/L), Mn (0.0443–0.2830 mg/L), Cd (0.0243–0.0713 mg/L), and Pb (0.0237–0.2087 mg/L). Conversely, for the Betaré-Oya site, variations in mg/L are observed as follows: Fe (0.0733–1.2627), Cr (0.0223–0.0820), Mn (0.0347–0.2830), Cd (0.0197–0.0570), and Pb (0.0257–0.2203). The decreasing order of magnitude for these elements in Kambélé's waters is Fe > Mn > Pb > Cr > Cd, with Fe, Pb, Cr, and Cd exceeding WHO drinking water guidelines [27]. Only Mn adheres to WHO acceptability limits for drinking water, applicable to both localities. Variations in metal concentrations from one collection point to another within the same site can be justified by the intensity of ore extractive activity directly linked to tailings discharge at each collection point. These findings align with Rakotondrabé et al. [18] and Bella Atangana [48].

High Fe levels in surface waters are attributed to geological formations in the region [49], where nearly all soils belong to heavily leached ferralitic soil groups under high rainfall. Abundant rainfall causes extensive alteration of primary minerals in parent rocks, resulting in the release of metallic oxides and residual quartz elements into water. Elevated iron levels can also be explained by the concentration of metal ions in the sludge lining river beds, as explained by Eblin et al. [50]. Other metals' high levels may result from intensive mining activity in the region. Gold-bearing rocks, generally reducing, have a strong basicity, while surface water is oxidized and acidic. This physico-chemical difference promotes the destabilization of sulfur-bearing minerals in a reducing environment, leading to increased metal ion mobilization. Acid mine drainage from mine tailings is the main source of this phenomenon in Kambélé and Bétaré-Oya, where several thousand tons of waste rock and tailings are discharged annually from gold extraction operations. Most of these rejections come from the exploitation of sulfide deposits containing gold [51].

The absence of an industrial mobilization in Nguelemendouka results in undetectable values for three trace metals (Mn, Cr, Pb). However, higher than normal values are noted for Fe (4.406 mg/L) and Cd (0.521 mg/L). The elevated Fe levels can be attributed to the mineral-rich nature of the entire eastern region, with iron presence resulting from natural factors like wind, gravity, water, and waves affecting primary deposits and rock erosion. The Nyong River, originating precisely in the Nguelemendouka District, flows through a rocky terrain, contributing to the observed Fe levels.

The high Cd concentration in Nguelemendouka can be linked to diffuse sources originating from fertilizers used in agriculture. Given that the Nguelemendouka District is a significant cocoa production area where farmers use a phosphate mineral fertilizer (Special Cocoa) to enhance cocoa tree flowering and production, the pollution of surface water by Cd is due to runoff from agricultural lands. These findings are consistent with the effects of agricultural practices on water quality, where soil infiltration of fertilizers and subsequent runoff contribute to surface water pollution [22,52]. Nguelemendouka, being free of industrial and mining activities, experiences pollution primarily from agricultural practices, emphasizing the importance of monitoring and managing diffuse sources to safeguard water quality.

4.3. Statistical and multivariate analysis

Considering that the two mining villages under investigation are situated in the same region, aggregating the multivariate analysis involved not only utilizing the values from both sites but also conducting a comparative assessment. The primary objective is to characterize and identify diverse sources of pollution. Additionally, the aim is to underscore the similarities or differences among various collection points across the two study sites. Therefore, the focus is on presenting the correlation factors at the collection points of both sites and, via a cluster analysis, examining the distinct similarities between collection points irrespective of the study site.

4.3.1. identification of origins

This analysis utilizes the correlation matrix to explore connections between different parameters, revealing the nature and degree of affinity among them. Initially, we examine the relationships between various parameters within the same site. Table 2 below outlines the connections between different collection points at the Kambélé site. The table indicates a robust and positive correlation among all points and the surface water of the Kambélé mining village, signifying a common pollution source. This connection is more pronounced because all watercourses flowing through the mining village are involved in gold mining activities. For the Bétaré-Oya site, correlations are detailed in Table 3 below. It's noteworthy from this table that there's a strong and positive correlation among the collection points within this work area, suggesting a shared anthropogenic source of pollution in these surface waters.

To supplement these findings, we conducted statistical spatial interpolation to observe the dynamics of physico-chemical and metallic element concentrations. Figs. 3 and 4 depict the evolution of chemical parameters in the localities of Kambélé and Bétaré-Oya,

Table 2

Relationships between the different collection points of the Kambélé site.

Sample	*WP*	*KD*	*DG1*	*DG2*	*DG3*	*DG4*	*DN1*	*DN2*	*KBL*
WP	**1**								
KD	**0.999**	**1**							
DG1	**0.983**	**0.975**	**1**						
DG2	**1.000**	**0.997**	**0.988**	**1**					
DG3	**0.979**	**0.970**	**1.000**	**0.984**	**1**				
DG4	**0.973**	**0.962**	**0.999**	**0.978**	**0.999**	**1**			
DN1	**0.968**	**0.956**	**0.997**	**0.974**	**0.999**	**1.000**	**1**		
DN2	**0.997**	**0.992**	**0.995**	**0.999**	**0.992**	**0.988**	**0.985**	**1**	
KBL	**0.878**	**0.858**	**0.949**	**0.890**	**0.956**	**0.965**	**0.969**	**0.913**	**1**

Correlation is significant at the 0.05 level.

respectively. This analytical approach helps identify two sources of surface water pollution: the fixed anthropic pollution source, represented by direct mining discharge into surface waters following extractive activities enriched with metallic elements (Pb, Cd, Cr). The second source is diffusive anthropogenic pollution, corresponding to a likely mobile source linked to river sediments with a high geo-accumulation of harmful elements, such as metallic elements, considered a secondary source of pollution [53].

Table 4 presents inter-elemental correlations. Notably, a negative correlation between suspended solids particles and Cd indicates their distinct origins. Cd, a metal naturally present in the earth's crust, is released in large quantities due to anthropic actions, such as mining activity in the two study areas. On the other hand, TSS represents all solid particles (mineral and organic) originating from soil erosion (non-native origin) or the river beds themselves (native origin) [54]. The observed TSS percentage can be attributed to road runoff with intense traffic (machinery, vehicles, motorcycles), especially since most collection points are accessible by motorcycle. This road activity generates dust clouds rich in plant particles, depositing them in nearby surface waters. However, a strong linear and positive correlation between metallic elements confirms a positive linear relationship, indicating that these elements generally vary in the same direction. This suggests that environmental degradation in the study areas of the region has a common origin and evolves uniformly. This analysis is complemented by information provided by the PCA.

4.3.2. Principal Component Analysis

As depicted in Fig. 3, the spatial distribution of physico-chemical and metallic parameters on the F1–F2 factorial plane highlights two main positively correlated groups, elucidating distinct processes controlling water mineralization in the Kambélé and Bétaré-Oya zones in Eastern Cameroon. The first group, represented by F2 (13.84%), encompasses the elements TSS, pH, and Fe. This representation suggests geogenic water mineralization. The natural or geogenic mineralization is primarily explained by soil characteristics (ferralitic soils, rock nature, and acidic soils), influencing the movement of Fe and pH variations. Suspended matter is likely associated with soil erosion, leading to solid deposition in surface waters. These mechanisms operate through the soil/water exchange phenomenon.

The second group, represented by F1 (68.14%), includes Pb, CE, TDS, Mn, Cd, and Cr. This significant affinity indicates a shared anthropogenic origin, implying that variations in chemical parameters and metallic elements are influenced by the same geochemical dynamics (washing of gold powder and discharge of mining wastes). This process solubilizes metallic species, a consequence of mining activity in the region, as metals like Mn, Cd, and Pb are primarily leached from mine tailings, gold mine effluents, or materials and products used during exploitation [53].

5. Hierarchical ascending classification analysis (ACH)

Hierarchical Ascending Classification (HAC) was employed in this study to explore similarities among different collection points at various sites and to differentiate them based on their pollution levels. The analysis involved 20 sampling points from the two study sites, considering physico-chemical and metallic parameters. As depicted in Fig. 4, two clusters, A and B, emerged. Cluster A further divided into two non-identical sub-clusters, while Cluster B presented two distinct groups. Cluster A-1 grouped streams that were no longer involved in mining activities during the collection period, points upstream of gold dust washing (DG1 and DN1), and sources of drinking water (DG4 and KBL), among others. These points exhibited pH values ranging from acidic to neutral, and metallic element values tended towards WHO recommendations. The grouping suggests influences from domestic activities near the yards and a reduction in metallic element rates due to the cessation of mining activities, indicating the least polluted watercourses at the two study sites. Cluster A-2 comprised streams located downstream of gold extraction points, representing final receptacles for mining residues. These areas, including KD, LM3, DN2, LM2, LM1, WP, and DG2, were identified as the most polluted in the study. They exhibited high values of TSS and metallic elements, attributed to mining activities and the transport of heavy metals with suspended particles. Cluster B, with two identical branches, included streams ML2, ML1, and PK from the Bétaré-Oya site. This grouping could be explained by specific parameters related to the Mali watershed and its characteristics. Waters in this cluster showed an acidic to basic pH, low electrical conductivity, and low TSS content, indicating natural mineralization. However, high metallic element contents suggested the influence of mining activities, representing a moderately polluted sector.

Table 3

Relationships between the different collection points of the Betare-Oya site.

Sample	*LM1*	*LM2*	*LM3*	*ML1*	*ML2*	*MB*	*PW*	*YD*	*MR*	*BZ*	*PK*
LM1	**1**	**0.976**	**0.967**	0.574	0.563	**0.923**	**0.930**	**0.938**	**0.957**	**0.931**	0.580
LM2		**1**	**0.998**	**0.733**	**0.724**	**0.979**	**0.987**	**0.990**	**0.982**	**0.983**	**0.738**
LM3			**1**	**0.762**	**0.754**	**0.989**	**0.989**	**0.993**	**0.970**	**0.992**	**0.767**
ML1				**1**	**1.000**	**0.839**	**0.819**	**0.811**	0.688	**0.828**	**1.000**
ML2					**1**	**0.831**	**0.811**	**0.803**	0.679	**0.820**	**1.000**
MB						**1**	**0.989**	**0.991**	**0.942**	**1.000**	**0.843**
PW							**1**	**1.000**	**0.976**	**0.992**	**0.822**
YD								**1**	**0.976**	**0.994**	**0.815**
MR									**1**	**0.951**	0.692
BZ										**1**	**0.832**
PK											**1**

Correlation is significant at the 0.05 level.

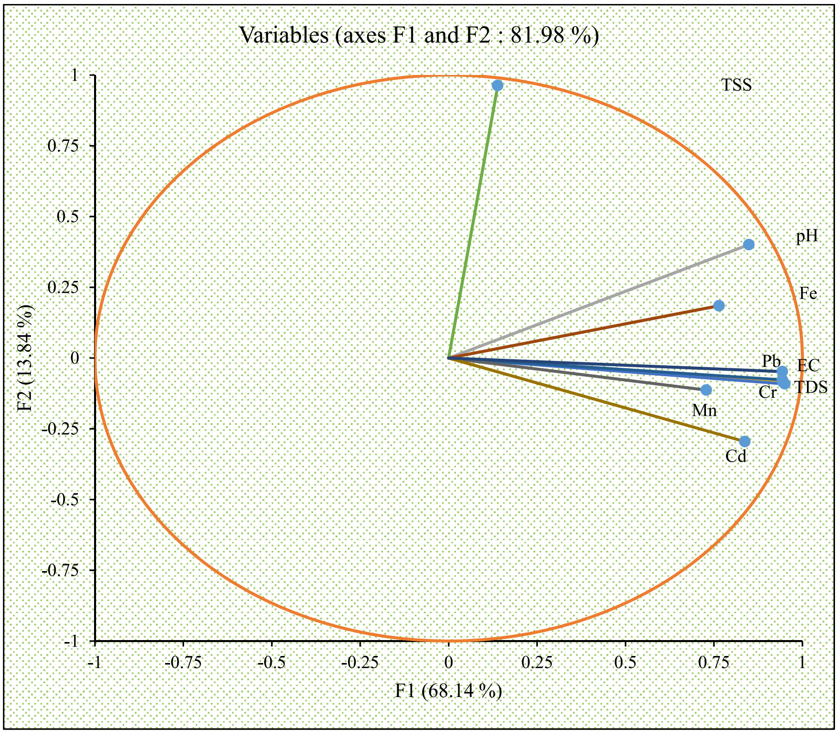

Fig. 3. Spatial distribution of the physico-chemical and metallic parameters.

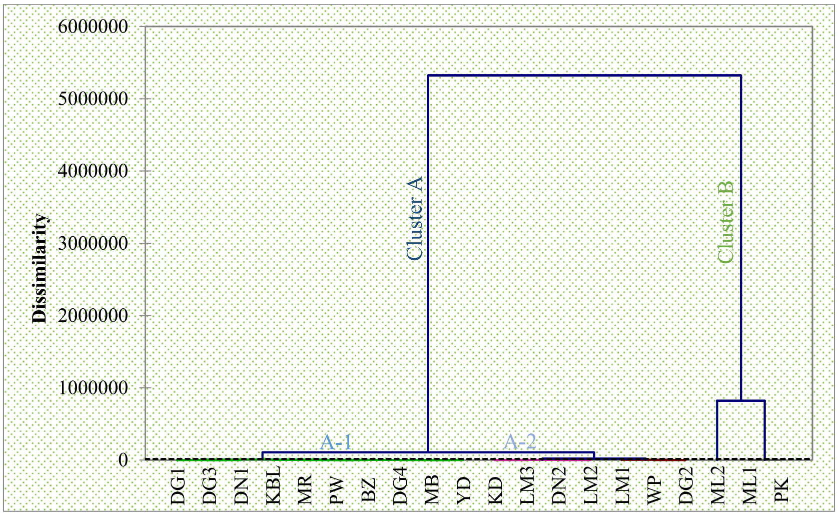

Fig. 4. Hierarchical Ascending Classification. Lengend of rivers: DG. Ndjiengou; DN. Derwan; MR. Mbédiri; PW. Pawara; BZ. Bézédaré; MB. Mbal; YD. Yondéré; KD. Kadey; LM. Lom; WP. Woupy; ML. Mali; PK. Pékonoun.

Multivariate analyses revealed that both sites, Kambélé in Batouri and Bétaré-Oya, shared identical environmental pollution of a mining nature, with variations based on the intensity of gold mining activities. Despite different extraction methods at each site, such as alluvial mining in Kambélé and vein deposits in Bétaré-Oya, the environmental pollution was consistent. The mining activities expose the population to health risks, emphasizing the need for effective control measures.

5.1. Determination of the intensity of water pollution

The intensity of water pollution was determined using two pollution indices: the Heavy Metal Pollution Index (HPI) and the Water Quality Index (WQI).

Table 4
Dynamic Correlation of all parameters.

Variable	pH	*CE*	*TDS*	*TSS*	*Cr*	*Fe*	*Mn*	*Cd*	*Pb*
pH	1								
CE	**0.744**	1							
TDS	**0.765**	**0.986**	1						
TSS	**0.466**	0.058	0.035	1					
Cr	**0.738**	**0.873**	**0.842**	0.091	1				
Fe	**0.653**	**0.701**	**0.722**	0.201	**0.661**	1			
Mn	**0.586**	**0.593**	**0.629**	0.010	**0.698**	0.408	1		
Cd	**0.598**	**0.809**	**0.791**	−0.112	**0.850**	**0.524**	**0.513**	1	
Pb	**0.784**	**0.855**	**0.873**	0.080	**0.905**	**0.673**	**0.722**	**0.756**	1

Correlation is significant at the 0.05 level.

5.1.1. *Heavy metal pollution index*

The HPI (Heavy Metal Pollution Index) is a parameter indicating the extent of metal involvement in water quality degradation. In this study, the calculation of this index considered all analyzed metals. Table 5 displays the HPI values for the localities of Kambélé and Bétaré-Oya.

For the Kambélé site, HPI values range from 546.51 to 1700.95, while for Bétaré-Oya, the values span from 489.65 to 1195.80. These values are further justified by the fact that, except for Mn, all metals (Fe, Cr, Mn, Cd, and Pb) contributing to this index exceed the WHO guideline standard [27]. It's noteworthy that HPI is primarily influenced by the hazardous nature of different elements in the organism. Consequently, metals like Pb and Cd contribute significantly to determining this pollution, overshadowing Fe's high value [55]. These values provide insight into the environmental condition shaped by the activities occurring within it. In both Kambélé and Bétaré-Oya sites, there's evident release of metallic elements into the environment, particularly into water surfaces used for human activities.

These findings can be attributed to soil and sediment contamination by metallic elements originating from mining activities. Previous studies, such as those by Mimba et al. [16] and Tehna et al. [10] in Bétaré-Oya, and Edith-Etakah et al. [56] in Batouri, have uncovered soil and sediment pollution. The chemical composition of surface water is intricately tied to the nature of the land it traverses [57]. Geological characteristics significantly influence water's chemical composition. The continuous contact between water and the ground, where it stagnates or flows, establishes equilibrium through the transfer or exchange of compounds and metallic elements from the soil to the water. Water, in its course, dissolves various elements constituting the land [57,58]. Additionally, human activities in water bodies, such as gold powder washing and direct discharge of mining waste into the water, contribute to the chemical contamination of surface waters.

5.1.2. *Water quality index*

Water possesses a mystical influence on us, serving as a source of purification, healing, and relaxation. It is the lifeblood of the Earth, yet it can also succumb to pollution, transforming from a life-giving force into a source of death [58]. In an era marked by desertification, drought, erosion, deforestation, and global warming induced by pollution, water and the environment emerge as two

Table 5
HPI in surface water obtained with physical and chemical parameters in surface water.

Kambélé			
Sampling point	Wi	Wi*Qi	IPM
Woupy	0.55	1030.15	1873.01
Kadey	0.55	769.83	1399.70
Ndjengou 1	0.55	515.11	936.57
Ndjengou 2	0.55	935.52	1700.95
Ndjengou 3	0.55	781.44	1420.81
Ndjengou 4	0.55	511.83	930.60
Derwan 1	0.55	690.36	1255.21
Derwan 2	0.55	930.83	1692.43
Kambélé	0.55	300.58	546.51
Bétaré-Oya			
Lom 1	0.55	657.69	1195.80
Lom 2	0.55	618.53	1124.60
Lom 3	0.55	795.32	1446.05
Mali 1	0.55	603.25	1096.83
Mali 2	0.55	645.38	1173.42
Mbal	0.55	546.58	993.79
Pawara	0.55	561.45	1020.82
Yondere	0.55	269.30	489.65
Mbediri	0.55	353.73	643.15
Bezedare	0.55	303.95	552.63
Pekomoun	0.55	303.61	552.02

interconnected challenges crucial to humanity's evolution [59].

The Water Quality Index (WQI) serves as a parameter defining the potential for water use. Our analyses reveal that all samples from the two sites fall into three water quality categories: doubtful, poor, and very poor. At the Kambélé site, the breakdown is as follows: water of doubtful quality (11%), poor quality water (22%), and very poor quality water (67%) (Fig. 5a). For the Bétaré-Oya site, the distribution is: poor quality water and water of doubtful quality each representing 18%, and very poor quality water constituting 64% (Fig. 5b). This figure underscores that the runoff waters traversing the two study sites are unsuitable for vital human activities such as cooking, eating, cleaning, or bathing, given the mining context characterized by elevated levels of trace elements responsible for water quality deterioration. Our findings align with those of Yadav and Jamal [60], who reported WQI values ranging from 779.85 to 19719.84 while assessing surface water quality in a mining area in India.

In the Kambélé locality, the spatial distribution (Fig. 6a) highlights the rivers Djengo (sections 2 and 3), Derwan, and Kadei as the most polluted. The Water Quality Index's spatial distribution in the Bétaré-Oya locality (Fig. 6b) reveals that the Mari and Lom rivers are the most polluted. Moreover, water degradation follows a downstream trend for both study sites. The upstream, less affected by punctual pollution or no longer engaged in gold panning activities, may experience decreased metallic element levels over time with the influx of new water. Reduced Total Suspended Solids (TSS) rates may cause soil/water exchange inputs to migrate and settle in

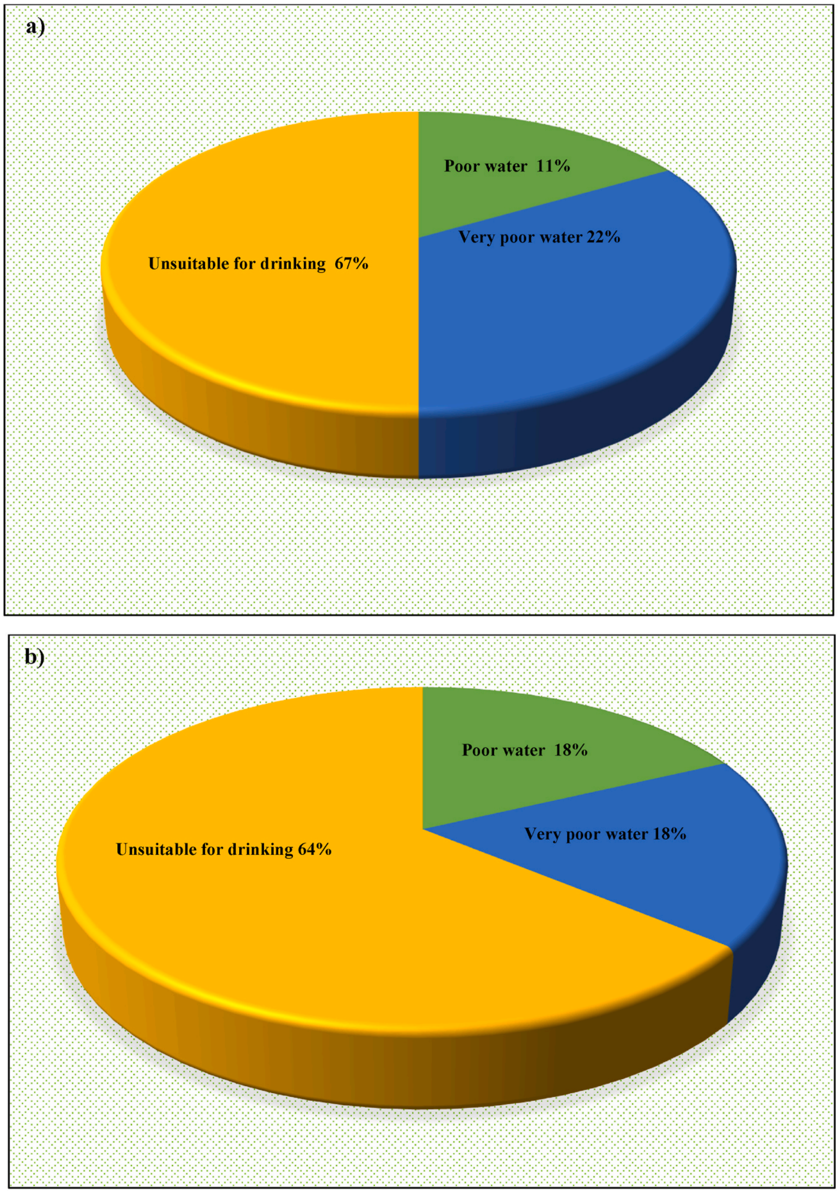

Fig. 5. Graphical data representation of WQI in gold mining area of: a) Kambele and Betare-Oya. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sediments, potentially reversing WQI values at these sites [47]. Sediment composition and their geo-accumulative capacity for water chemicals, even years after mining cessation, contribute to explaining the enduring water quality degradation downstream of the sites, where upstream surface waters become the final recipients of observed pollution in the localities.

5.2. *Determination of the health risk incurred by the local population*

The pollution of aquatic environments by trace metal elements (TMEs) has emerged as a significant global challenge, driven by the escalation of industrial activities and rapid urbanization. This metallic pollution leads to a deterioration of water quality, posing a

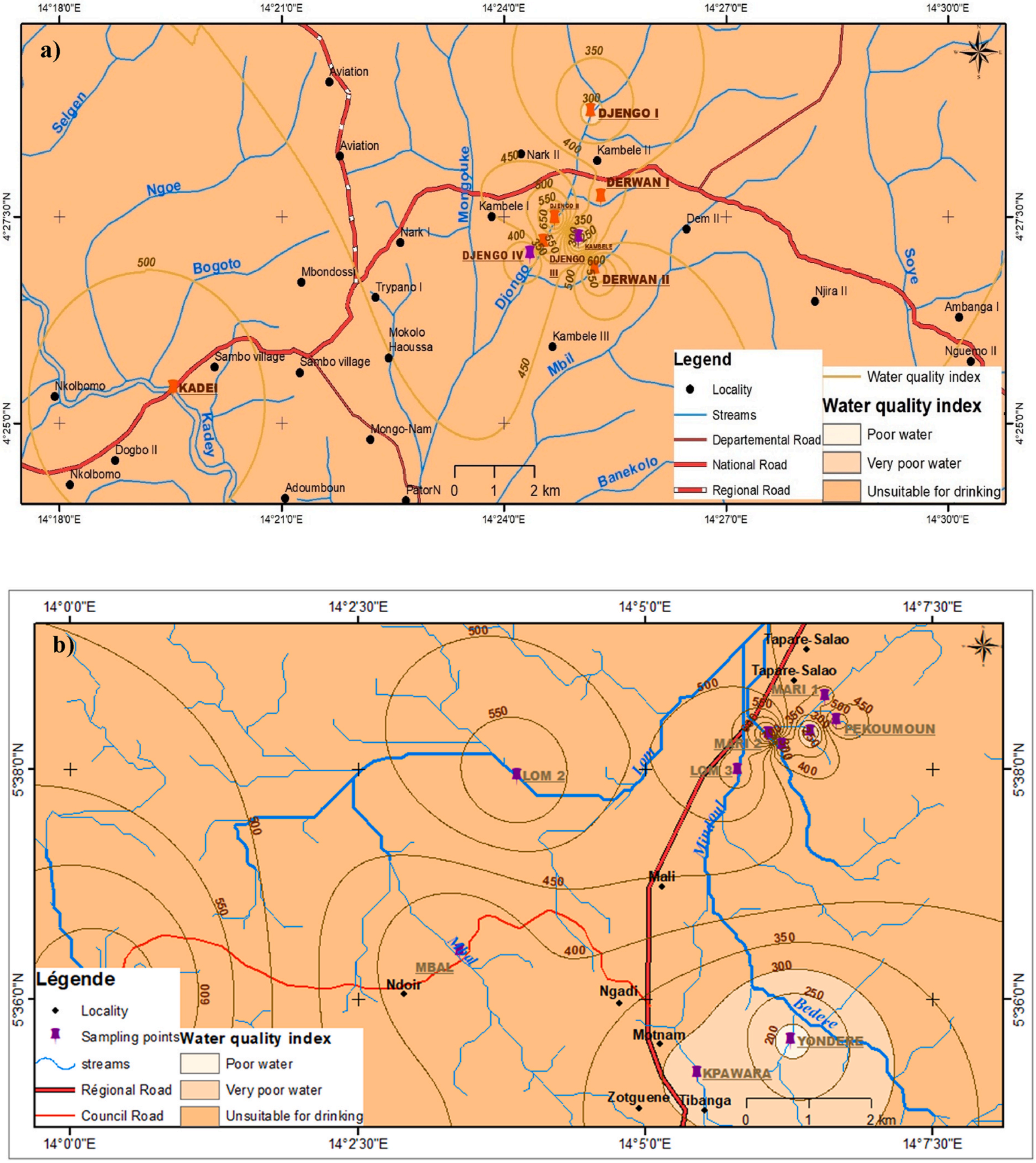

Fig. 6. Spatial distribution of WQI in a) Kambele and b) Betare-Oya gold mining areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

threat to the survival of aquatic organisms and humans alike. Notably, TMEs are a cause for concern due to their non-biodegradable nature and the potential toxic effects they can induce when accumulating in organisms at elevated concentrations.

This study employs various methodologies to assess whether the population faces risks by residing in these mining areas. The evaluation involves determining the daily dose of exposure, calculating the hazard quotient, and assessing all non-carcinogenic effects caused by the presence of these trace metal elements. These measures aim to provide insights into the potential health risks associated with living in proximity to areas impacted by mining-related water pollution.

5.2.1. Determination of the daily intake (DI)

Risk is defined as the process of estimating the occurrence of an event and the probability of adverse effects on human health during a given time or period. In this study, the Daily Intake (DI) was calculated specifically for the metallic elements Cd, Cr, and Pb due to their non-biodegradable nature, which renders them potentially toxic to the human organism. The evaluation was conducted for both adults and children to provide a comprehensive understanding of the most vulnerable population segments. The calculated Daily Intake (DI) values for each site, metal element, and population group are presented in Table 6.

The results reveal that the different populations in these areas experience a high daily dose of exposure to the metallic elements (Cr, Cd, and Pb) compared to the reference DI values, which are set at 0.0005 μg/kg/d for cadmium and chromium and 0.0014 μg/kg/d for lead [61], and this is observed in both sites. Kambélé emerges as the site posing the greatest risk to the population, with children being the most exposed segment compared to adults, likely due to their active growth process, making them more vulnerable. These findings underscore the real health risks faced by the populations residing in the mining areas of Kambélé and Bétaré-Oya. Thus, the concentrations of cadmium, chromium, and lead in the samples align with these elements being identified as the most hazardous metals in the area according to this study.

5.2.2. Determination of the hazard quotient (HQ)

The Hazard Quotient (HQ) serves to assess the potential risk to human life associated with the ingestion of chemical substances following exposure. The results of the conducted analyses are presented in Table 7, displaying the various HQs for the three metals considered in the health risk assessment. A HQ value exceeding 1 indicates a potential danger to the health of populations. Upon examination of the table, it is evident that there is no danger associated with the ingestion of Cr at both sites, as evidenced by an HQ below 1. The values of 0.955 for the Kambélé site and 0.876 at Bétaré-Oya suggest a potential danger for adults in both locations, particularly since even minimal doses of Pb pose a risk to human health. This risk is already apparent in the younger population of both sites, with an HQ of 1.791 for children in Kambélé and an HQ of 1.642 for those in Bétaré-Oya. In the case of Cd, the HQ related to the ingestion of this metal exceeds 1 for both sites and all populations, indicating an increased danger, particularly for children. While Cr currently does not present any health hazards in the study area, Cd and Pb constitute real dangers of varying degrees to the health of populations living in the mining areas of eastern Cameroon. These results on health risks differ from those obtained by Togbe et al. [62] in their evaluation of health risks related to Pb, Cd, and As in Lake Ebrié in Côte d'Ivoire, and this disparity can be attributed to differences in the nature or origin of the water pollution studied.

5.2.3. Epidemiology of common reasons for medical consultations

It is noteworthy that the two control sites exhibit similarities in the various reasons for seeking medical attention (i.e., the reasons for consulting a doctor are virtually the same). In order of occurrence, the primary reasons include abdominal pain, fever, asthenia, headache, chest pain, anemia, joint pain, and sexually transmitted infections (STIs) (Fig. 7). Lead, cadmium who present health risk are in this study, are able to affect cellular functioning by disrupting numerous metabolic pathways and physiological processes. Studies demonstrate its role as a catalyst for lipid peroxidation reactions, generating free radicals, such as ROS and NO production activity inducing inflammatory reactions. All this physiology reactions influencing or contributes to hypersensitivity in the nervous system, reproductive functions, blood system [63–65]. Sexually Transmitted Infections (STIs) are more prevalent in the control site (22.40%) due to the mixing of traders and a sexually active youth, leading to the proliferation of STIs. In the mining site, 12% of consultations for STIs can be attributed to the presence of young people engaging in uncontrolled sexual activity. However, STIs do not appear in the top 5 reasons for consultations, possibly because individuals engage in risky behaviors in larger cities after selling precious metals.

Other health issues, such as epigastralgia, eye problems, and skin rashes, are reported but in small percentages. Epigastralgia and eye problems result from oxidative stress induced by TMEs in mining sites, while in the control site, aging contributes to physiological system issues, especially in the ocular system. Skin rashes in mining sites are justified by chromium contamination, leading to dermatitis. The low prevalence of these clinical signs in both sites may be due to their neglect, not constituting valid reasons for medical consultation.

Table 6
Determination of the daily intake.

Site	Kambélé			Bétaré-Oya		
Elements	Cr	Cd	Pb	Cr	Cd	Pb
DJE Kid (μg/kg/d)	0.0033	0.0027	0.0062	0.0029	0.0021	0.0057
DJE Adult (μg/kg/d)	0.0017	0.0014	0.0033	0.0015	0.0011	0.0030

Table 7
Determination of the hazard quotient.

Site	Kambélé			Bétaré-Oya		
Elements	Cr	Cd	Pb	Cr	Cd	Pb
QD Kid	0.002	5.591	1.791	0.001	4.314	1.642
QD Adult	0.001	2.982	0.955	0.001	2.301	0.876

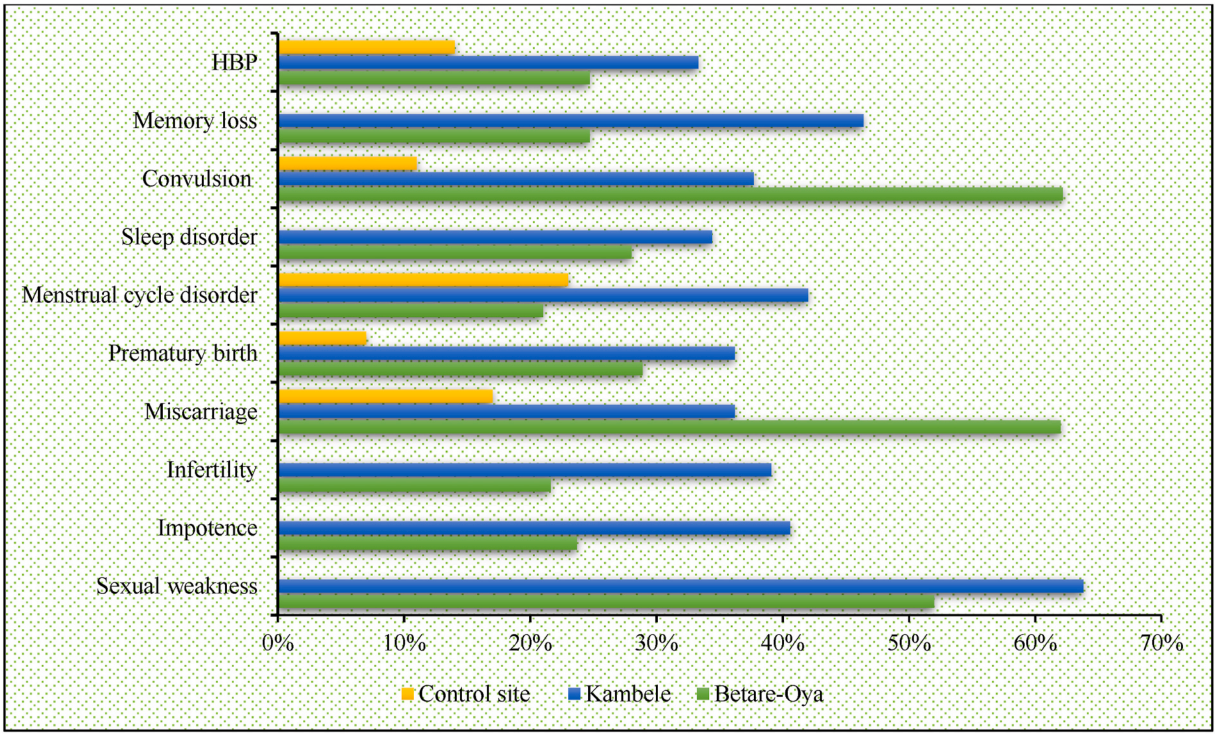

Fig. 7. Analysis of specific medical symptoms in study areas and control site.

5.3. *Epidemiology on specific health problems*

Our organism resembles a tree of cells arranged in a system, where a biological system is defined as a collection of organs or a cellular network functioning for a specific physiological purpose. Consequently, the organism, crucial for its growth and physiological balance, consists of primary systems whose malfunction not only jeopardizes the individual's vital prognosis but also poses a threat to the survival of the human species. Notable among these systems are the nervous, reproductive, and endocrine systems. Therefore, when a pathogen, toxic substance, or any other factor disrupts the semiotics of these primary systems, it becomes a genuine and urgent health concern.

In this study, specific health issues were investigated to draw conclusions regarding the peril posed by various mining sites, comparing them to a control site. The results reveal that major health pathologies encountered in both mining sites encompass nine conditions, including high blood pressure, memory loss, convulsions, sleep disorders, menstrual cycle disorders, premature birth, miscarriage, infertility, impotence, and sexual weakness. The elevated incidence of these pathologies, categorized as major in this study, can be attributed to the pollution of the living environment by trace metal elements (TMEs). Among the various metals responsible for pollution in mining areas, lead is acknowledged as the most perilous.

Lead alters cellular functioning by disrupting numerous metabolic pathways and physiological processes. Studies demonstrate its role as a catalyst for lipid peroxidation reactions, generating free radicals and influencing reproductive functions. High blood lead levels are linked to occurrences such as abortions, pre-term deliveries, and alterations in sperm, affecting male and female fertility. Lead also interferes with calcium homeostasis, impacting cellular and molecular processes. Notably, neurological disorders like irritability, sleep disorders, anxiety, memory loss, confusion, and asthenia have been observed in both adults and children.

Controversy exists regarding the increase in blood pressure due to elevated lead levels, with some studies suggesting a positive correlation. The shared lifestyle and diet in the two mining sites contribute to the presence of the same pathologies. Differences between the sites can be explained by variations in mining intensity, characterized by the degree of metal pollution and hazard quotient observed.

In the control site, five major pathologies were identified: convulsions and high blood pressure, with the first three signs (miscarriage, menstrual cycle disorder, and premature birth) potentially arising from infections and sexually transmitted diseases. Cases of convulsions in various sites may be attributed to tropical diseases like malaria, facilitated by environmental conditions. The prevalence of high blood pressure in the control site, potentially associated with the absence of mosquitoes in the fields, may be linked to the elderly population. Aging, characterized by structural modifications of the arterial wall, rigidification of collagen, and alterations in arterial vasomotricity, contributes to an increase in systolic blood pressure with age.

6. Conclusion

This study sought to elucidate the environmental ramifications induced by mining operations and assess the associated risks for the local populations in the Kambélé and Bétaré-Oya regions of eastern Cameroon. This study has delved into various facets of mining-induced pollution, ranging from physico-chemical parameters to health risk assessments, all with the aim of comprehensively understanding the challenges faced by local populations. We have distill our research findings into some key points.

1 Our analysis delved into physico-chemical parameters, metallic contamination, water quality, and health risk assessments, aligning with the predefined objectives set forth in the introduction. The investigation revealed fluctuations in pH attributed to mining activities, while EC and TDS were linked to the diverse rock composition and prevalent mining dynamics. Notably, the concentrations of Fe, Pb, Cr, and Cd exceeded WHO recommendations, underscoring a substantial pollution issue.
2 The shared pollution characteristics in both Kambélé and Bétaré-Oya, irrespective of administrative divisions and extraction methods, indicated an overarching problem detrimental to all human activities dependent on the water sources in these localities.
3 The health risk assessment unveiled a genuine threat to the population regarding the ingestion of Pb and Cd, particularly posing high risks for children. The imperative need for environmental safeguarding was emphasized, advocating for responsible mining practices that prioritize methods and products with minimal risk to both the environment and human health.
4 Crucially, the conclusion underscores the direct correlation between the intensity of mining, levels of Trace Metal Elements (TMEs) in water, hazard quotient, and observed health issues in the local population. This substantiates the claim that unregulated mining operations, lacking plans for site reclamation post-exploitation, pose severe threats to the well-being of inhabitants, as evident in the Kambélé and Bétaré-Oya sites in the East Cameroon region.

To enhance this study, it is crucial to evaluate anions and cations as they provide additional parameters for assessing water quality, including the water quality index, metal enrichment index, and geologic index. Additionally, determining the lead blood concentration for local residents is essential, as it can be correlated with health risks identified through epidemiological investigations. Moreover, adherence to mining code regulations regarding environmental and personal protection is imperative. It is essential to completely avoid the use of hazardous chemicals like mercury and cyanide, as well as chemical fertilizers in agriculture, to mitigate heavy metal pollution. Natural fertilizers offer a safer alternative, promoting food production and environmental health. Proposing zinc extraction practices for mining activities can further reduce environmental and health risks associated with extraction processes.

Data availability statement

Data is available upon request to the corresponding author.

CRediT authorship contribution statement

Ngoa Manga Elisabeth Sylvie: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Armel Zacharie Ekoa Bessa:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rigobert-Espoir Ayissi Mbomo:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Formal analysis, Conceptualization. **Jean Victor Akono:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation. **Bachirou Dairou:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation. **Kamtchouing Pierre:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization.

Declaration of competing 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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Appendix A. Supplementary data

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