

Trace metal contamination in water, sediments and fish from the Soubré Dam reservoir (Côte d'Ivoire): Bioaccumulation and human health risk assessment

Koné Oumar^{1,*}, Ohou-Yao M.J. Adélaïde¹, Sorho Siaka², Mambo Véronique³

¹Laboratoire des Sciences et Technologies de l'Environnement (LSTE), Université Jean Lorougnon Guedé, Daloa (Côte d'Ivoire), BP 150 Daloa

²Laboratoire des Procédés Industriels et de Synthèse de l'Environnement et des Energies Nouvelles (LAPISEN), Institut National Polytechnique-Houphouët Boigny, Yamoussoukro (Côte d'Ivoire), BP 1313 Yamoussoukro

³Laboratoire des Sciences de l'Environnement (LSE), Université Nangui Abrogoua, Abidjan (Côte d'Ivoire), 02 BP 801 Abidjan 02

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Abstract:

The transfer of trace metal elements (TMEs) from the environment to the food chain is a major concern. This study assessed TME (As, Cd, Hg and Pb) contamination levels in water, sediments, and two fish species (*Oreochromis niloticus* and *Chrysichthys nigrodigitatus*) from the Soubré Dam reservoir and estimated the associated health risks. Samples collected between November 2023 and August 2024 were analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES) for As, Cd and Pb, and by cold-vapor atomic absorption spectrometry (CV-AAS) for Hg. The results showed that the average Hg concentration in water ($6.10 \pm 7.37 \mu\text{g L}^{-1}$) exceeded the quality limit set for raw water intended for drinking-water production according to the Official Journal of the French Republic (OJFR). By contrast, average TME concentrations in sediments remained below the TEC and ISQG thresholds, suggesting a low probability of adverse effects on aquatic organisms. In fish, As (*O. niloticus*: $0.85 \pm 0.69 \text{ mg kg}^{-1}$ and *C. nigrodigitatus*: $0.90 \pm 0.77 \text{ mg kg}^{-1}$) and Pb (*O. niloticus*: $0.55 \pm 0.51 \text{ mg kg}^{-1}$ and *C. nigrodigitatus*: $0.47 \pm 0.44 \text{ mg kg}^{-1}$) exceeded WHO/FAO edibility standards. Assuming that 3% of total As corresponds to the toxic inorganic form (a conservative assumption based on the literature), the total hazard quotient (THQ) for children reached 1.16 and 1.54 for *O. niloticus* and *C. nigrodigitatus*, respectively, indicating a potential non-carcinogenic risk. Cd exposure also resulted in an unacceptable carcinogenic risk ($\text{CR} > 10^{-4}$). These results highlight the need for reinforced environmental monitoring and vigilance regarding water use and fish consumption from the reservoir.

Keywords : Trace metal elements; Water pollution; Sediment contamination; Fish; Bioaccumulation; Human health risk.

* Corresponding author:

Email address: koneoumar9@gmail.com (O. Koné)
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1. Introduction

The pollution of aquatic environments by trace metal elements (TMEs) is a major global problem today [1,2], particularly in the context of climate change. This pollution results primarily from population and urban growth, industrialisation, intensive agricultural practices, and gold mining [3–5]. These factors introduce toxic substances into the environment, compromising the balance of natural ecosystems [6]. Among the major environmental contaminants, TMEs pose serious ecological problems, both because of their ubiquity and their toxicity [7]. Some are purely toxic to living organisms owing to their capacity for bioaccumulation in several animal species, particularly aquatic ones. They also persist in the environment, especially in the sediments of aquatic systems, given their low biodegradability [8]. Unlike organic pollutants, trace metals are practically not subject to biological or chemical degradation and can accumulate along food chains [9]. They are therefore among the chemical substances that pose a danger to the environment and to human health [10]. The consumption of seafood, particularly fish, is increasing significantly worldwide owing to its nutritional quality and its beneficial effects on health [11,12]. The global fish supply has grown at a faster annual rate than the population, rising from 9.1 kg inhabitant⁻¹ year⁻¹ in 1961 to 20.6 kg inhabitant⁻¹ year⁻¹ in 2021 [13]. However, fish consumption can be a significant source of exposure to numerous chemical contaminants present in aquatic ecosystems [14]. In Côte d'Ivoire, the fisheries sector plays a leading role in the economic, social and nutritional spheres. Ivorian national fish production increased from 74 800 tonnes in 2014 to 81 239 tonnes in 2023, and fish is the main source of animal protein and of income for the country [15]. The average Ivorian consumer eats approximately 24.9 kg inhabitant⁻¹ year⁻¹, or 0.068 kg inhabitant⁻¹ day⁻¹, for a population of just over 30 million [16].

The Soubré department has experienced renewed growth in recent years with the construction of new hydroelectric dams (Soubré and Gribo-Popoli). Impoundment of the Soubré dam on the Sassandra River created a reservoir with a surface area of 17.5 km² [17,18]. The Sassandra River watershed is rich in agricultural potential and hosts numerous small-scale artisanal mining operations, both legal and illegal, on land and within the reservoir and river [18]. The excessive use of chemical fertilisers and pesticides (herbicides, insecticides and fungicides) in agriculture, together with ongoing fishing and gold-mining activities, exacerbates pollution and increases the risk of contamination of the reservoir's waters [18,19]. These practices are potentially major sources of environmental pollution, generating chemical pollutants (trace metals, pesticides, etc.) that can degrade aquatic environments [20] and affect the quality of water drawn downstream to supply the population with drinking water. Unfortunately, fish stocks are also exposed to toxic contaminants such as arsenic, cadmium, mercury and lead, which accumulate in their tissues and are transferred through the food

chain to humans [14,15]. This study did not perform any source-tracing investigation or isotopic analysis; therefore, no definitive causal link between specific anthropogenic activities and the measured trace-metal concentrations can be established. The objective of this study was to assess the level of contamination by trace metal elements (arsenic, cadmium, mercury and lead) in the water, sediments and two fish species – one pelagic (*Oreochromis niloticus*) and the other benthic (*Chrysichthys nigrodigitatus*) – of the Soubré dam reservoir, and to estimate the health risks associated with the consumption of these fish.

2. Materials and methods

2.1. Study area

This study was conducted in the Soubré Dam reservoir, located in the Soubré Department, Nawa Region, southwestern Côte d'Ivoire. The reservoir lies between latitudes 5°47' and 5°50' N and longitudes 6°36' and 6°41' W (Figure 1). It covers an area of 17.5 km² (1750 ha) and holds approximately 83 000 000 m³ of water [17]. The reservoir was created following construction of a hydroelectric dam on the Sassandra River [21–23]; it is the last dam built on the Sassandra River upstream of the Gribo-Popoli Dam. The department's climate is generally hot and humid, characterised by four seasons: two rainy and two dry [24,25]. The Sassandra River basin is covered by tropical forest, food crops, and plantations of cocoa, rubber and oil palm. The reservoir constitutes a diverse aquatic ecosystem in which fishing and gold panning are practised throughout. Fishing is carried out by professional migrant fishermen, commonly called “Bozo”, alongside the indigenous Bakoué and Bété communities who live along the river. These fishermen land their catches at the Gnamangui landing stage, established by the Bureau of Aquaculture and Fisheries [23]. The reservoir is subject to considerable human pressure owing to its proximity to the sub-prefecture of Gnamangui; in addition, a large portion of the water body is colonised by aquatic macrophytes (Figure 2).

2.2. Sampling and analysis of water, sediments and fish

2.2.1. Sampling methods

Four water and sediment sampling campaigns were conducted over a seasonal cycle from November 2023 to August 2024. Five sampling sites, comprising twenty sampling points, were selected on the basis of accessibility, the location of likely impact zones (gold-panning sites, plantations, fishing areas), and dam structures (Figure 1 and table 1). Water and sediment samples were collected from the reservoir using motorised canoes. Water samples were collected with a Niskin bottle at a depth of 0.3–0.5 m below the surface. Samples destined for trace-metal analysis were placed in pre-sterilised, labelled 0.5 L polyethylene bottles and stabilised *in situ* with nitric acid (HNO₃) to a concentration of 2% (AFNOR T90-512). For laboratory physicochemical analyses, 1 L polyethylene bottles were used. Sediment

samples were collected at the same locations as the water samples, using a stainless-steel Van Veen grab, taking the top five centimetres of the sediment column. Approximately 200 g of sediment were collected and placed in new plastic containers. Over the four campaigns, 80 water samples and 80 sediment samples were collected. Fish sampling was carried out during two campaigns; the biological material collected consisted of two species, *Oreochromis niloticus* (Linnaeus, 1758) and *Chrysichthys nigrodigitatus* (Lacépède, 1803), commonly known as tilapia and silver catfish, respectively. Both species are frequently caught by local fishermen in

the Soubré dam reservoir and are popular with the local population. Individuals of each species were collected in collaboration with local fishermen immediately after capture, at the landing site in Gnamangui, and packaged in labelled plastic bags. A total of 113 specimens of varying size were collected, including fifty *Oreochromis niloticus* and sixty-three *Chrysichthys nigrodigitatus*. To ensure adequate preservation, water, sediment and fish samples were refrigerated at 4 °C in a cooler and transported to the laboratory for analysis.

Table 1 presents the sampling sites.

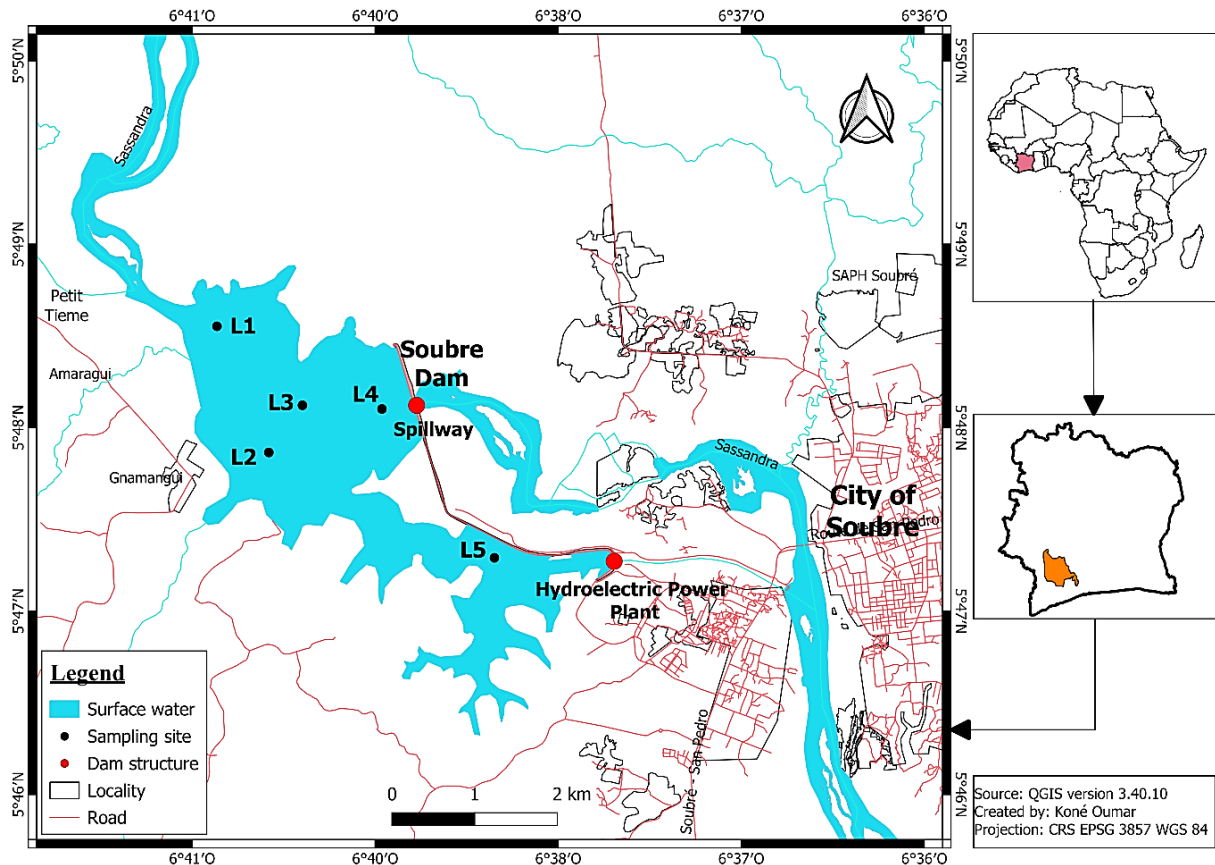


Fig. 1. Map of the study area showing the sampling sites.

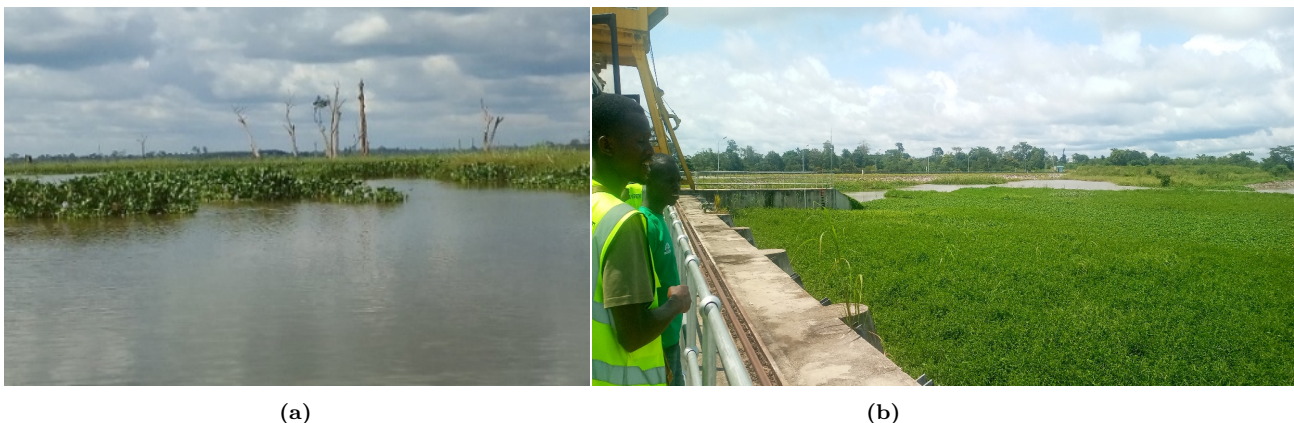


Fig. 2. Views of the Soubré dam reservoir (a) and (b) showing macrophyte proliferation.

Table 1

Sampling sites and their characteristics.

Site	Location	Activities	Sampling points	Latitude	Longitude
L1	Amaragui	Agriculture, fishing, gold panning	4	5°48'40.56"N	6°40'51.29"W
L2	Gnamangui	Gold panning, fishing, agriculture	4	5°47'49.90"N	6°40'30.05"W
L3	Reservoir centre	Gold panning, fishing	5	5°47'57.09"N	6°40'13.84"W
L4	Flood spillway	Tourism, gold panning, fishing	3	5°47'57.31"N	6°39'39.34"W
L5	Power plant	Agriculture, fishing, tourism	4	5°47'0.63"N	6°38'46.09"W

2.2.2. Determination of physicochemical parameters

Temperature and pH were measured *in situ* using a pre-calibrated Mettler Toledo portable multiparameter meter. Electrical conductivity and total dissolved solids were measured using a Jenway 4510 conductivity meter. Turbidity was measured using an Orion AO3010 photoelectric turbidimeter. Dissolved oxygen was determined in the field using the Winkler method. Orthophosphate, ammonium, nitrite and nitrate ions were measured by molecular absorption spectrophotometry according to AFNOR standards NF T90-023 (April 2005), NF T90-015-2 (January 2000), NF T90-013 (November 1985) and NF T90-045 (June 1989), respectively. COD and BOD₅ were determined using the method described by CEAEQ (2016) [26] and standard NF T90-103-2 (February 2017), respectively.

2.2.3. Determination of trace elements in water, sediments and fish

Sample preparation and packaging. In the laboratory, water samples were filtered using polytetrafluoroethylene (PTFE) syringe filters with a porosity of 0.45 µm. Before each filtration, the filtration apparatus was cleaned with nitric acid (HNO₃, 1 N) and rinsed thoroughly with distilled water. The filtrates were collected in polyethylene bottles and subsequently acidified with HNO₃ (2%) to a pH < 2 [27]. This step prevents precipitation and adsorption/desorption phenomena, as well as other chemical or biochemical reactions. Sediment samples were air-dried in a dust-free environment, homogenised, ground in an agate mortar, and sieved through 2 mm and 63 µm mesh. The <63 µm fraction was hot-mineralised in microwave PTFE tubes for 25 min: 0.5 g of sediment was mineralised in a PTFE tube with 4 mL of aqua regia (65% HNO₃; 37% HCl; 1:3, v/v) and 3 mL of concentrated hydrofluoric acid (HF, 48%, pure), following AFNOR NF X31-151 (1993) [28]. Neutralisation of the hydrofluoric acid was achieved by adding 4% boric acid [29]. For fish, a piece of fresh muscle was removed with a scalpel and oven-dried at 60 °C to constant mass. Muscle tissue was chosen because it is the tissue most commonly consumed by humans, and because reference guideline values are established relative to muscle concentrations [30]. Samples were finely ground in an agate mortar and stored in plastic bags after cooling; equipment was cleaned before and after grinding each sample. A 0.5 g aliquot of each ground sample was weighed on a Wunder balance and mineralised by closed-vessel microwave digestion (Milestone ETHOS) after addition of 7 mL of 65% nitric acid (HNO₃) and 1 mL of 30% hydrogen

peroxide (H₂O₂). The digestion programme consisted of a gradual temperature rise from ambient to 200 °C over 15 min, followed by a hold at 200 °C for 35 min; microwave power was set at 1200 W, with a maximum allowable pressure of 800 psi (≈5.5 MPa). At the end of the digestion cycle, controlled cooling was carried out for 20 min until a temperature of approximately 60 °C was reached, allowing safe degassing before opening. For mercury determination, 0.5 g of sample was digested at room temperature (22–25 °C) for 96 h in closed PTFE containers with 7 mL of 65% HNO₃ and 1 mL of 30% H₂O₂, with stirring every 12 h using a PTFE rod; blanks were treated identically. Each digest was filtered and diluted to 20 mL with distilled water [3, 15, 31], then stored at room temperature pending analysis.

Measurement of trace metallic elements. Total trace-element concentrations (As, Cd and Pb) in water were measured by inductively coupled plasma optical emission spectrometry (ICP-OES) using an Agilent 5800 spectrometer. Mercury was determined by cold-vapour atomic absorption spectrometry (CV-AAS) using a Shimadzu AA 660 flameless spectrometer at a wavelength of 253.7 nm.

Analytical performance and quality control of the ICP-OES. For each analyte, standard elemental solutions prepared by appropriate dilution of stock solutions were used to calibrate the instrument. The selected wavelengths were 188.980 nm for As, 214.439 nm for Cd, and 220.353 nm for Pb. Limits of detection (LOD) and quantification (LOQ) were estimated from the slope of the calibration curve (a) and the variability of the analytical blank signal (σ), according to $LOD = 3\sigma/a$ and $LOQ = 10\sigma/a$. However, because the analytical blanks gave a near-zero response – reflecting low instrumental noise and good control of the analytical conditions – a conventional statistical calculation based on the blank standard deviation was not feasible, and the limits were therefore treated as theoretical estimates of the method's sensitivity. To account for matrix effects arising from the diversity of the sample types (water, sediment and fish tissue), matrix correction was applied through recovery tests after spiking known amounts of each element into each matrix, allowing verification and correction of potential matrix interferences. The quality and reliability of the analytical data were ensured through rigorous quality assurance/quality control (QA/QC) procedures,

including standardised operating procedures, instrument calibration with certified multi-element standard solutions (Panreac, 100 mg L⁻¹), analysis of blanks, and analysis of replicates. All analyses were performed in triplicate and results are expressed as mean values. Analytical precision, assessed by relative standard deviation (RSD), was below 5% for water samples and below 10% for sediment and fish muscle, indicating good reproducibility. Method accuracy was confirmed by recovery rates of 85–115% across all matrices, validating the use of a single aqueous calibration curve for each element. Accuracy for sediments was verified using certified reference material MESS-4; for fish muscle, method validation used certified reference materials DORM-4 (fish protein) and TORT-3 (lobster hepatopancreas), analysed under the same conditions as the reservoir samples.

2.3. Data processing and statistical analysis

Data were processed using Microsoft Excel 2019 and R (version 4.4.2) within the RStudio environment; Excel was used for data pre-processing and graphing, while statistical analyses were performed in R. Descriptive statistics included the minimum, maximum, mean and standard deviation, together with graphical representation of the distributions. Before comparing means, the normality of distributions and the homogeneity of variances were checked using the Shapiro–Wilk and Levene tests, respectively; when normality was not met, the non-parametric Mann–Whitney test was applied, with a significance threshold of 5% [32, 33]. Spatial data were processed using QGIS (version 3.40.10).

2.4. Determination of trace metal element accumulation in fish

The bioconcentration factor (BCF) and the biota–sediment accumulation factor (BSAF) were used to assess the accumulation of trace metals in both fish species [34–36]. The BCF assesses the concentration of trace elements in fish relative to reservoir water, while the BSAF quantifies their uptake from sediment. Equations 1 and 2 were used to calculate the BCF and BSAF, respectively [36, 37]:

$$\text{BCF} = \frac{\text{Concentration of TME in fish organ}}{\text{Concentration of TME in water}} \quad (1)$$

$$\text{BSAF} = \frac{\text{Concentration of TME in fish organ}}{\text{Concentration of TME in sediment}} \quad (2)$$

2.5. Health risk assessment

To assess the health risks to consumers of fish contaminated with trace metals, the estimated daily intake (EDI), hazard quotient (HQ) and cancer risk (CR) were calculated following the approach of [38].

The estimated daily intake (EDI) is given by Equation 3:

$$\text{EDI} = \frac{C \times Q \times F}{M} \quad (3)$$

where EDI is the estimated daily intake

(mg kg⁻¹ day⁻¹); C is the concentration of the trace element in fish (mg kg⁻¹); Q is the quantity of fish consumed per day (kg day⁻¹); F is the exposure frequency (dimensionless; fish is consumed 7 days per week, hence $F = 1$); and M is the body mass of the target population (kg). In this study, the average concentrations of the four trace elements measured in the muscle tissue of the two fish species were used in the calculations.

The average amount of fish consumed per capita in Côte d'Ivoire is 24.5 kg year⁻¹, or 0.067 kg day⁻¹, according to the Ministry of Animal Production and Fisheries Resources [2]; it is assumed that this amount is consumed every day of the week. The average body mass is 28 kg for children aged 0–15 years and, conventionally, 70 kg for adults, following [38].

The hazard quotient (HQ) relates to the risk of non-carcinogenic (threshold) effects arising from the quantity of metal ingested, and is calculated for the oral route using Equation 4 [39]:

$$\text{HQ} = \frac{\text{EDI}}{\text{ADI}} \quad (4)$$

where ADI (or RfD_o) is the acceptable (oral reference) daily intake (mg kg⁻¹ day⁻¹). If $\text{HQ} < 1$, the occurrence of a toxic effect is very unlikely; if $\text{HQ} > 1$, a toxic effect cannot be excluded and exposed populations may experience adverse health outcomes.

The total hazard quotient (THQ) accounts for the combined effects of exposure to several trace elements and was evaluated using Equation 5 [40]:

$$\text{THQ} = \text{HQ}_1 + \text{HQ}_2 + \text{HQ}_3 + \dots + \text{HQ}_n \quad (5)$$

where the subscripts 1, 2, 3, ..., n denote the HQ calculated for each trace element. For $\text{THQ} \leq 1$, there is no risk to consumer health; for $\text{THQ} > 1$, a non-carcinogenic effect may occur and consumption of certain species should be restricted [39].

Cancer risk (CR) refers to the carcinogenic risk associated with characterised trace elements and estimates the probability that an individual will develop cancer as a result of lifetime exposure to the chemical substance. It is determined using Equation 6 [41]:

$$\text{CR} = \text{EDI} \times \text{SF} \quad (6)$$

where SF is the cancer slope factor (mg kg⁻¹ day⁻¹). Following [41], $\text{CR} < 10^{-6}$ indicates a negligible excess individual risk; $10^{-6} < \text{CR} < 10^{-4}$ indicates an acceptable excess risk; and $\text{CR} > 10^{-4}$ indicates an unacceptable excess risk.

In this study, the average TME values estimated in fish muscle were used to calculate EDI, THQ and CR. The inorganic form of As represents 1–10% of total arsenic [3, 42], and only the inorganic form is toxic; inorganic As values were therefore used instead of total As values in the calculations. Here, inorganic As was assumed to constitute 3% of total arsenic [3, 43]. A sensitivity analysis was performed to assess the influence

of the inorganic arsenic fraction on the risk assessment: the proportion of inorganic As was varied between 1% and 10% of total As, and THQ values were recalculated for children and adults exposed through consumption of the two fish species.

3. Results and discussion

3.1. Results

3.1.1. Physicochemical parameters of the water

The physicochemical parameters of the water from the Soubré dam reservoir are summarised in [table 2](#).

The average water temperature (T) is approximately 29.75 ± 1.69 °C: the water is generally warm and neutral, with an average pH of 7.12 ± 0.62 ([Table 2](#)). Electrical conductivity (EC) values indicate very low mineralisation (80.22 ± 9.09 $\mu\text{S cm}^{-1}$ on average), and the average total dissolved solids (TDS) content is 39.63 ± 4.55 mg L^{-1} . Turbidity is relatively high (10.81 ± 8.19 NTU). The reservoir water shows acceptable oxygenation, with an average dissolved oxygen

(DO) concentration of 6.60 ± 1.99 mg L^{-1} . Average concentrations of orthophosphate (PO_4^{3-}), nitrite (NO_2^-) and nitrate (NO_3^-) are low, at 0.05 ± 0.05 , 0.45 ± 0.26 and 1.77 ± 1.01 mg L^{-1} , respectively, whereas the ammonium (NH_4^+) concentration is comparatively high, averaging 5.34 ± 2.09 mg L^{-1} . The chemical oxygen demand (COD) and 5-day biochemical oxygen demand (BOD_5), averaging 83.42 ± 81.02 and 9.70 ± 4.76 $\text{mg O}_2 \text{ L}^{-1}$, respectively, were relatively high. Overall, the measured physicochemical parameters (pH, EC, TDS, DO, PO_4^{3-} , NO_2^- , NO_3^-) remain below the quality limits set for raw water used to produce drinking water, whereas temperature, turbidity, ammonium, COD and BOD_5 exceed the permitted limits.

3.1.2. Concentrations of trace metals in water and sediments

The results of the analyses of trace elements (As, Cd, Hg and Pb) in the reservoir water and sediments are grouped in [table 3](#).

Table 2

Physicochemical parameters of the water in the Soubré dam reservoir (mean $\pm$ standard deviation, minimum and maximum).

Parameter	Mean ($n=80$)	Min–Max	OJFR limit [44]
T (°C)	29.75 ± 1.69	25.87–32.00	< 25
pH	7.12 ± 0.62	6.27–8.59	5.5–9
EC ($\mu\text{S cm}^{-1}$)	80.22 ± 9.09	62.67–110	< 1100
TDS (mg L^{-1})	39.63 ± 4.55	33.33–53.00	≤ 300
Turbidity (NTU)	10.81 ± 8.19	2.23–38.50	≤ 5
DO (mg L^{-1})	6.60 ± 1.99	2.13–10.17	> 5
PO_4^{3-} (mg L^{-1})	0.05 ± 0.05	0.01–0.30	≤ 0.5
NH_4^+ (mg L^{-1})	5.34 ± 2.09	0.61–9.36	≤ 4
NO_2^- (mg L^{-1})	0.45 ± 0.26	0.03–1.34	≤ 0.5
NO_3^- (mg L^{-1})	1.77 ± 1.01	0.13–5.93	≤ 50
COD ($\text{mg O}_2 \text{ L}^{-1}$)	83.42 ± 81.02	18.42–500.36	< 30
BOD_5 ($\text{mg O}_2 \text{ L}^{-1}$)	9.70 ± 4.76	4.00–20.00	≤ 7

T: temperature; EC: electrical conductivity; TDS: total dissolved solids; DO: dissolved oxygen; COD: chemical oxygen demand; BOD_5 : 5-day biochemical oxygen demand; OJFR: Official Journal of the French Republic.

Table 3

Concentrations of trace metals in water and sediment (mean $\pm$ standard deviation, minimum and maximum).

TME	Water	OJFR	Sediment	Thresholds [45]		ISQG [46]
	($\mu\text{g L}^{-1}$, $n=80$)	limit [44] ($\mu\text{g L}^{-1}$)	(mg kg^{-1} , $n=80$)	TEC (mg kg^{-1})	PEC (mg kg^{-1})	(mg kg^{-1})
As	14.10 ± 18.82 (0.00–63.76)	100	0.14 ± 0.19 (0.00–0.90)	9.79	33	5.9
Cd	2.11 ± 3.88 (0.00–21.74)	5	0.20 ± 0.25 (0.00–0.99)	0.99	4.98	0.6
Hg	6.10 ± 7.37 (0.00–31.59)	1	0.09 ± 0.11 (0.00–0.58)	0.18	1.06	0.17
Pb	16.50 ± 25.38 (0.00–95.88)	50	0.11 ± 0.19 (0.00–0.72)	35.8	128	35

TME: trace metal element; OJFR: Official Journal of the French Republic; TEC: threshold effect concentration (below which no toxic effects are expected in benthic organisms); PEC: probable effect concentration (above which toxic effects are likely); ISQG: interim sediment quality guideline (CCME: Canadian Council of Ministers of the Environment).

In the reservoir water, trace-metal concentrations range from $0.00 \mu\text{g L}^{-1}$ (As, Cd, Hg and Pb) to $95.88 \mu\text{g L}^{-1}$ (Pb) (Table 3); in sediments, concentrations range from 0.00 mg kg^{-1} (As, Cd, Hg and Pb) to 0.99 mg kg^{-1} (Cd). In the water, the average Hg concentration ($6.10 \pm 7.37 \mu\text{g L}^{-1}$) exceeds the drinking-water quality limit of $1 \mu\text{g L}^{-1}$, whereas As, Cd and Pb concentrations remain relatively low. In sediments, all average concentrations remain below the TEC and ISQG quality thresholds.

3.1.3. Bioaccumulation of trace metals in fish

Concentrations of trace metals in fish. Average concentrations of trace metal elements in the muscle of *Oreochromis niloticus* and *Chrysichthys nigrodigitatus* are presented in table 4 (wet-weight basis).

Trace-metal concentrations in *O. niloticus* range from 0.00 mg kg^{-1} (As, Cd, Hg and Pb) to 2.56 mg kg^{-1} (As), while *C. nigrodigitatus* ranges from 0.00 mg kg^{-1} to 2.74 mg kg^{-1} (As) (Table 4). Mean As and Pb concentrations in both species exceed WHO/FAO edibility standards, whereas Cd and Hg concentrations remain below established limits. Although *C. nigrodigitatus* shows slightly higher mean concentrations for most elements, no significant difference is observed between the two species (Mann–Whitney test, $0.11 \leq p \leq 0.97$) (Table 4), suggesting that both species accumulate broadly

similar amounts of each element studied in their muscle. The order of accumulation of trace elements in both species is $\text{As} > \text{Pb} > \text{Hg} > \text{Cd}$.

Figure 3 shows the distribution of bioconcentration factors (BCF) and biota–sediment accumulation factors (BSAF) of trace metal elements in the two fish species.

Overall, BCF and BSAF values are similar between *C. nigrodigitatus* and *O. niloticus* for all trace metals. BCF values are particularly high (above the threshold of 1), whereas BSAF values are very low (below 1). In reservoir water, the order of trace-metal accumulation in both fish species is $\text{Hg} > \text{As} > \text{Pb} > \text{Cd}$, whereas in sediment the order is $\text{As} > \text{Pb} > \text{Hg} > \text{Cd}$ (Figure 3). In both abiotic compartments, bioaccumulation is high in both fish species for all elements except Cd: the two species accumulate comparatively little Cd from water and sediment, but absorb large amounts of Hg, As and Pb from water, and small amounts of Cd, Hg, Pb and As from sediment.

Health risks associated with fish consumption.

Non-carcinogenic health risks (threshold effects). Table 5 presents the results of the non-carcinogenic risk assessment, grouping the estimated daily intake (EDI) values from which the hazard quotients (HQ) for children and adults were derived for both fish species.

Table 4

Concentrations of trace metals in fish muscle (mean $\pm$ standard deviation, minimum and maximum, mg kg^{-1} wet weight).

TME	<i>O. niloticus</i> (n=50)	<i>C. nigrodigitatus</i> (n=63)	OMS/FAO standard [47, 48]	p-value
As	0.85 ± 0.69 (0.00–2.56)	0.90 ± 0.77 (0.00–2.74)	0.1	0.97
Cd	0.009 ± 0.02 (0.00–0.10)	0.018 ± 0.10 (0.00–0.69)	0.05	0.88
Hg	0.07 ± 0.06 (0.00–0.18)	0.12 ± 0.12 (0.01–0.50)	0.5	0.11
Pb	0.55 ± 0.51 (0.00–1.38)	0.47 ± 0.45 (0.00–1.49)	0.2	0.35

TME: trace metal element; *O. niloticus*: *Oreochromis niloticus*; *C. nigrodigitatus*: *Chrysichthys nigrodigitatus*; p-values > 0.05 indicate no significant difference (Mann–Whitney test).

Table 5

Estimated daily intake (EDI) and hazard quotients (HQ) of trace elements in children and adults for the two fish species.

TMEs	ADI	Children				Adults			
		<i>O. niloticus</i>		<i>C. nigrodigitatus</i>		<i>O. niloticus</i>		<i>C. nigrodigitatus</i>	
		EDI	HQ	EDI	HQ	EDI	HQ	EDI	HQ
As	3×10^{-4}	6.10×10^{-5}	0.20	6.46×10^{-5}	0.22	2.44×10^{-5}	0.08	2.58×10^{-5}	0.09
Cd	10^{-3}	2.15×10^{-5}	0.02	4.31×10^{-5}	0.04	8.61×10^{-6}	0.01	1.72×10^{-5}	0.02
Hg	3×10^{-4}	1.67×10^{-4}	0.56	2.87×10^{-4}	0.96	6.70×10^{-5}	0.22	1.15×10^{-4}	0.38
Pb	3.5×10^{-3}	1.32×10^{-3}	0.37	1.12×10^{-3}	0.32	5.26×10^{-4}	0.15	4.49×10^{-4}	0.13
THQ = $\sum HQ_i$		1.16		1.54		0.46		0.61	

TMEs: Trace metal elements; ADI: Acceptable daily intake ($\text{mg kg}^{-1} \text{ day}^{-1}$); EDI: Estimated daily intake ($\text{mg kg}^{-1} \text{ day}^{-1}$); HQ: hazard quotients.

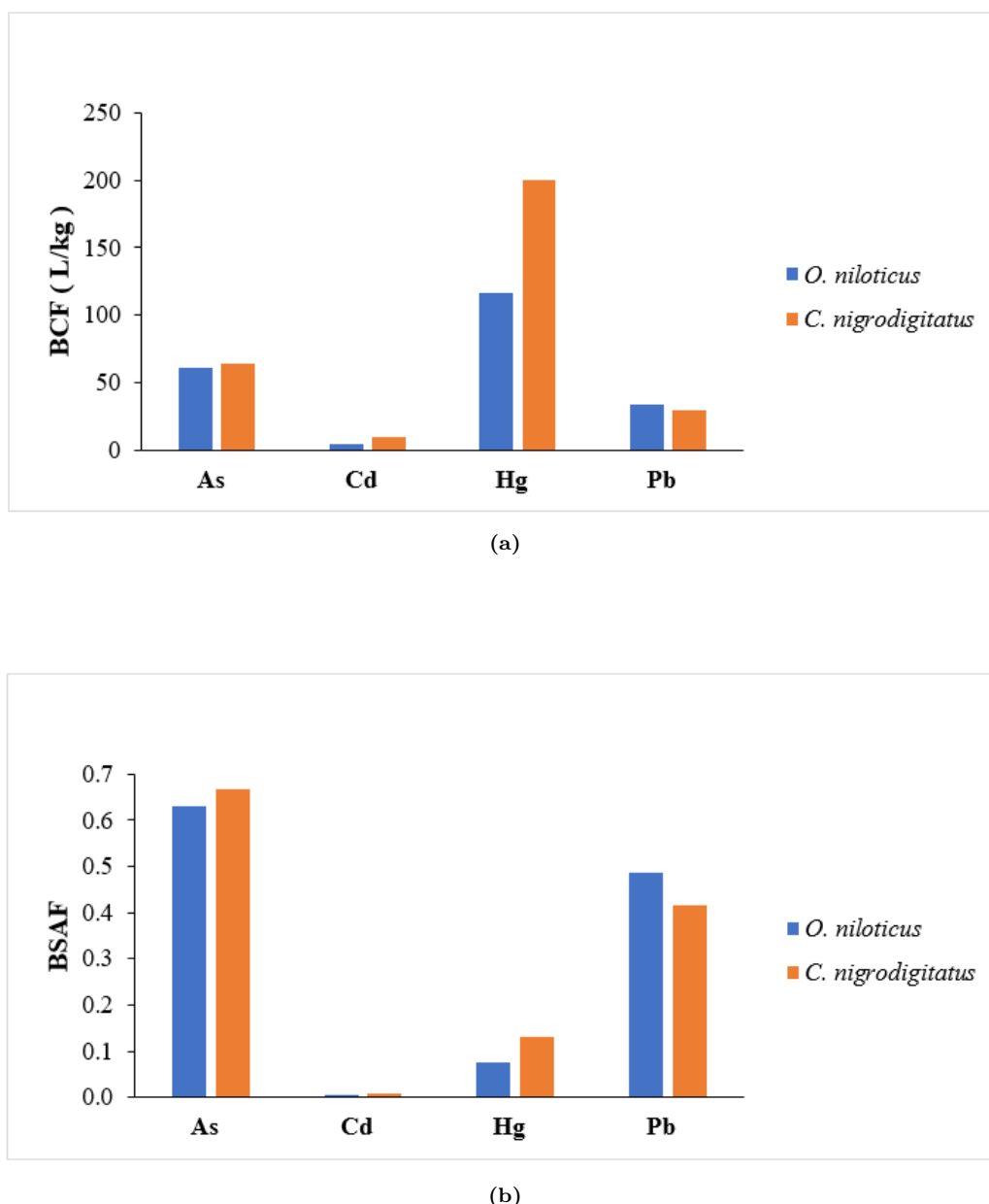


Fig. 3. Distribution of trace metal bioaccumulation factors in *O. niloticus* and *C. nigrodigitatus*: (a) bioconcentration factors (BCF) and (b) biota-sediment accumulation factors (BSAF).

Table 5 shows that HQ values in children range from 0.02 to 0.96, and in adults from 0.01 to 0.38: all individual HQ values therefore remain below the threshold of 1. The last row of the table, however, shows THQ values above 1 in children and below 1 in adults, indicating a potential risk of non-carcinogenic effects in children. THQ values are ranked as follows: THQ (*C. nigrodigitatus*, child) > THQ (*O. niloticus*, child) > 1 > THQ (*C. nigrodigitatus*, adult) > THQ (*O. niloticus*, adult); THQ values in children are therefore consistently higher than in adults.

The sensitivity analysis (Table 6) shows that increasing the inorganic-As fraction increases THQ values. In children, THQ values remain above 1 even at an inorganic-As fraction of 1%, indicating a persistent potential risk of non-carcinogenic effects. As

the inorganic-As fraction increases from 3% (the assumption used here) to 10%, THQ values rise from 1.16 to 1.63 for *O. niloticus* and from 1.54 to 2.05 for *C. nigrodigitatus*. In adults, THQ values remain below 1 across all tested fractions, suggesting an absence of significant non-carcinogenic risk.

Carcinogenic health risks. Table 7 presents the results of the carcinogenic risk assessment for trace metal elements, expressed as the cancer risk (CR) in children and adults for both fish species.

All CR values for Cd exceed 10^{-4} , except for *O. niloticus* in adults; these values fall in the unacceptable CR range ($CR > 10^{-4}$). By contrast, all CR values for As and Pb in children and adults, and the CR value for Cd in *O. niloticus* in adults, fall within the acceptable range ($10^{-6} < CR < 10^{-4}$).

Table 6

Sensitivity analysis of the total hazard quotient (THQ) for different assumed inorganic-arsenic fractions.

Inorganic As fraction (%)	THQ (children)		THQ (adults)	
	<i>O. niloticus</i>	<i>C. nigrodigitatus</i>	<i>O. niloticus</i>	<i>C. nigrodigitatus</i>
1	1.03	1.39	0.41	0.55
3 (this study)	1.16	1.54	0.46	0.61
5	1.29	1.69	0.51	0.67
7	1.43	1.83	0.57	0.73
10	1.63	2.05	0.65	0.82

THQ = Total Hazard Quotient. Values above 1 indicate potential non-carcinogenic risk.

Table 7

Cancer risk (CR) in children and adults for both fish species.

TME	SF (mg kg ⁻¹ day ⁻¹)	CR (children)		CR (adults)	
		<i>O. niloticus</i>	<i>C. nigrodigitatus</i>	<i>O. niloticus</i>	<i>C. nigrodigitatus</i>
As	1.5	9.15×10^{-5}	9.69×10^{-5}	3.66×10^{-5}	3.88×10^{-5}
Cd	6.1	1.31×10^{-4}	2.63×10^{-4}	5.25×10^{-5}	1.05×10^{-4}
Pb	0.0085	1.11×10^{-5}	9.55×10^{-6}	4.47×10^{-6}	3.82×10^{-6}

TME: trace metal element; SF: cancer slope factor; CR: cancer risk.

3.2. Discussion

3.2.1. Physicochemical characteristics of the reservoir water

The results of the physicochemical parameters measured in the water of the Soubré dam reservoir showed that this water was generally warm, with an average temperature of 29.75 ± 1.69 °C. This value is consistent with the work of [49], which reported that in humid tropical zones, the average water temperature is around 30°C. The high temperatures recorded are likely due to strong insolation during the sampling periods, which could increase the rates of chemical and biochemical reactions. According to [50–54], surface waters are subject to atmospheric influences, particularly variations in air temperature. Overall, the reservoir water exhibited a neutral character ($\text{pH} = 7.12 \pm 0.62$), which would result from the buffering effect due to the presence of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions from the dissolution of carbonate rocks [55]. The reservoir water's pH falls within the recommended range for raw water used in drinking water production, as published in the OJFR [44], and is favorable to fish life [56]. According to [57], pH values between 5 and 9 can be tolerated by most fish; however, they state that a pH below 4 or above 10 is generally unfavorable to aquatic life. The average conductivity, with a value of 80.22 ± 9.09 $\mu\text{S cm}^{-1}$, indicates very low water mineralization [27]. The total dissolved solids (TDS) content was also low. Thus, the reservoir water contains a low amount of dissolved salts [58]. The relatively high turbidity observed in the water (10.81 ± 8.19 NTU) could be associated with the presence of suspended matter, possibly linked to agricultural areas and likely to be brought in by soil leaching. It could also be partly linked to gold panning and fishing activities, which can resuspend bottom sediments, thus

contributing to the increase in particulate load in the reservoir's waters. Throughout the study, although the identified activities constitute potential sources of pollution, no direct causal link can be established in the absence of specific tracing studies. Conductivity and TDS values are within the quality limits published in OJFR [44]. Dissolved oxygen (DO) is an essential parameter for the respiration of aquatic organisms, particularly fish, which require at least 3 to 5 mg L⁻¹ of DO [59]. The average DO content, estimated at 6.60 ± 1.99 mg L⁻¹, reflects acceptable oxygenation of the reservoir waters. This parameter was therefore not a concern overall during the study period. Our temperature, conductivity, and dissolved oxygen values are consistent with those reported by [60] in Lake Buyo, located upstream of our study area, and our pH and dissolved oxygen values are confirmed by those of [57,61] in Lake Alau in Nigeria and the Ouémé River in Benin, respectively. Nutrients such as orthophosphates, nitrites, and nitrates had remarkably low levels (PO_4^{3-} : 0.05 ± 0.05 mg L⁻¹, NO_2^- : 0.45 ± 0.26 mg L⁻¹, NO_3^- : 1.77 ± 1.01 mg L⁻¹), although the reservoir surface showed a proliferation of macrophytes over a large part of the water body, reflecting its enrichment. Regarding ammonium, its average concentration was relatively high at 5.34 ± 2.09 mg L⁻¹. This high value suggests a significant contribution of reduced forms of nitrogen, particularly ammonium, potentially linked to the degradation of organic matter under anaerobic conditions [62,63]. The organic pollution parameters COD and BOD₅, the respective values of 83.42 ± 81.02 mg O₂ L⁻¹ and 9.70 ± 4.76 mg O₂ L⁻¹, were high compared to the quality limits for raw water used for drinking water treatment [44]. This suggests that the water contains a large amount of oxidizable chemical and biochemical compounds. The high BOD₅ value

indicates that microorganisms are involved in the degradation of these compounds by consuming significant amounts of oxygen [11]. COD and BOD₅ values of the same order of magnitude were found by [64] in nine lake catchments in China.

3.2.2. Levels of trace metal contamination in the reservoir water

Analyses of the reservoir water revealed relatively low average concentrations of trace metals, including As ($14.10 \pm 18.82 \mu\text{g L}^{-1}$), Cd ($2.11 \pm 3.88 \mu\text{g L}^{-1}$) and Pb ($16.50 \pm 25.38 \mu\text{g L}^{-1}$), with the exception of Hg ($6.10 \pm 7.37 \mu\text{g L}^{-1}$), whose concentration exceeded the maximum permitted limit ($1 \mu\text{g L}^{-1}$) for surface water intended for drinking water production, as published in the French Official Journal [44]. This level of Hg contamination of the reservoir water could potentially be linked to an intensification of illegal gold panning activities throughout the reservoir, observed since the advent of the dam. This result is similar to that found by [65], with a mercury concentration in the water exceeding the standard. These researchers also identified illegal mining activities in the studied areas. For them, the presence of mercury in the water suggests the potential of methylation, which produces methylmercury, the most toxic form of Hg. The production of methylmercury, a potent neurotoxin, results from the decomposition of terrestrial organic matter, which leads to increased activity of methylating bacteria [66–68]. This process potentially impacts the bioavailability of mercury [67] for fish and ultimately for humans through fish consumption [69]. Research over the past few decades has shown that reservoirs can raise Hg concentrations in fish [67]. The concentrations of trace elements found in the reservoir are lower than those found by [18] in the same study area, which obtained concentrations of 2.34 mg L^{-1} for As, 0.05 mg L^{-1} for Cd, 0.17 mg L^{-1} for Hg, and 0.64 mg L^{-1} for Pb. These results confirm the presence of TMEs in the aquatic ecosystem. This suggests that the reservoir water, drawn downstream to produce drinking water for the population of the city of Soubré, should undergo appropriate treatment. The presence of TMEs in the reservoir water could potentially be linked to several anthropogenic sources such as agriculture with the excessive use of fertilizers or pesticides, introduced into the waters following the leaching of contaminated land, gold panning and fishing activities [18, 70, 71]. Indeed, farmers, many of whom are illiterate, overuse agricultural inputs such as pesticides and fertilizers to improve their yields. However, some of these products contain low concentrations of trace metals that subsequently end up in the environment [72]. Furthermore, illegal gold mining is rapidly expanding in the study area, particularly since the dam was commissioned. This clandestine activity is widespread throughout the Sassandra River basin, particularly within the reservoir waters [18, 70, 71, 73, 74]. It could cause serious environmental impacts, including soil degradation, disruption of aquatic ecosystems and pollution of reservoir waters with toxic chemicals from gold panning. [75–77]. In

addition, the use of motorized canoes and fishing gear such as plumb nets is likely to influence the concentrations of trace metal elements in the water [78]. In the riverside communities, the banks are regularly used by local populations as open dumps or as watering places for livestock. Furthermore, domestic wastewater from neighboring municipalities is dumped there without prior treatment, possibly contributing to the progressive deterioration of the reservoir's water quality and potentially endangering this aquatic ecosystem [18]. Our results differ significantly from those of [71], conducted downstream in the Sassandra River before the construction of the Soubré Dam. This difference in trace metal concentrations is likely related to the timing and sampling sites, as well as the nature of the waters studied (reservoir and river).

3.2.3. Levels of trace metal contamination in reservoir sediments

The concentrations of the trace elements studied in the sediments were low, with values of $0.14 \pm 0.19 \text{ mg kg}^{-1}$ for As, $0.20 \pm 0.25 \text{ mg kg}^{-1}$ for Cd, $0.09 \pm 0.11 \text{ mg kg}^{-1}$ for Hg, and $0.11 \pm 0.19 \text{ mg kg}^{-1}$ for Pb. This observation is consistent with that of [79] in the Congo, where values fluctuated between 0.01 and 0.04 mg kg^{-1} for Cd and 0.01 and 0.02 mg kg^{-1} for Pb. In our study, all mean concentrations were below the TEC and PEC thresholds. [45] and then to the ISQGs values, guidelines for the protection of aquatic life [46]. This suggests that there would be no potential toxic risk to benthic communities [80]. These results are consistent with those of studies by [81] in Benin, which also obtained As, Cd, Hg, and Pb concentrations below Canadian standards for sediments. In contrast, our values are generally lower than those reported by [82], with average values of 20 mg kg^{-1} for As, 1 mg kg^{-1} for Cd, 0.016 mg kg^{-1} for Hg, and 8 mg kg^{-1} for Pb in the Senegal River basin and its tributaries in Mali. The low levels of trace elements observed in the sediments could be partly explained by the continuous disturbance of the sediment layers within the reservoir, potentially associated with clandestine artisanal gold mining activities. Indeed, dredging-based gold extraction involves the removal of sediments composed of sand, gravel, and mud from the reservoir bottom, followed by their processing to recover gold. This intense mechanical process could promote not only the resuspension of fine particles, but also contribute, to a certain extent, to the release of metallic trace elements initially trapped in the sedimentary matrix towards the dissolved phase. This could potentially reduce concentrations in sediments. Our results are corroborated by those of [83] in Bangladesh and [84] in Colombia. The latter studied in rivers affected by artisanal gold mining. They revealed an increase in the bioavailable fraction of TMEs (Hg, Pb and Cd) within two months. This significant release was potentially attributed to sediment disturbance, promoting the dissolution of TMEs in the water column. The results show that trace metal concentrations in the sediments are generally higher than those in the water. According to [85, 86], sediments act as a sink

for trace metals. This observation could be explained by the physicochemical conditions of the environment, particularly the pH in the sediments. Indeed, an acidic pH promotes the bioavailability of trace elements in solution as well as their mobility along the watercourse. On the other hand, when the pH is basic, TMEs precipitate and accumulate in the sediments, which would be likely to increase their concentrations [79]. The low concentration of trace elements in the sediments was also observed by [19] upstream of our study area. The presence of trace elements in the reservoir water and sediments could pose risks to aquatic organisms and human health [1].

3.2.4. Levels of trace metal contamination in fish from the reservoir

Bioaccumulation of TMEs in fish muscle. The results of toxicological analyses revealed that the average concentrations of trace metals As and Pb in the muscles of *O. niloticus* (As: $0.85 \pm 0.69 \text{ mg kg}^{-1}$ and Pb: $0.55 \pm 0.51 \text{ mg kg}^{-1}$) and *C. nigrodigitatus* (As: $0.90 \pm 0.77 \text{ mg kg}^{-1}$ and Pb: $0.47 \pm 0.45 \text{ mg kg}^{-1}$) were higher than the WHO recommended fish edibility standards [47,48], set at 0.1 mg kg^{-1} for As and 0.2 mg kg^{-1} for Pb. These results indicate that *O. niloticus* and *C. nigrodigitatus* fish from the Soubré dam reservoir have high concentrations of As and Pb. Our results show that trace element levels were generally higher in *C. nigrodigitatus* than in *O. niloticus*, but without a significant difference. This could suggest a similar bioaccumulation capacity in both species, despite their different ecological preferences (pelagic for *O. niloticus* and benthic for *C. nigrodigitatus*). This similarity could be linked, in part, to diffuse contamination of the aquatic ecosystem, affecting both benthic and pelagic habitats. It could also be associated with anthropogenic disturbances, such as the use of dredges and motorized canoes observed throughout the reservoir. This result is consistent with that of [87] who found that *O. niloticus* and *C. nigrodigitatus* accumulated Pb without significant difference, and this is consistent with the findings of [15], who found no significant difference between As and Pb levels in *C. nigrodigitatus* and three other fish species. This observation is also corroborated by [79], who observed no significant difference in Pb and Cd levels in the species studied at two sites. In the work of [88], it was noted that *C. nigrodigitatus* accumulated higher levels of trace elements than *O. niloticus*. The authors [89] emphasized that bioaccumulation depends on the availability of trace elements in the environment, the contamination of which itself remains dependent on several environmental factors. This low variation in trace element levels in fish could therefore be explained by numerous factors, including the physicochemical characteristics of the aquatic biotope and their natural or anthropogenic variations. These factors influence trace element bioavailability via chemical speciation reactions and their transfer and bioaccumulation behavior, in relation to adaptive responses to the main physiological functions (respiration, osmoregulation, nutrition) of aquatic organisms [90].

Overall, the results show that bioconcentration factors (BCF) were similar in *C. nigrodigitatus* and *O. niloticus*, and the same was true for biota–sediment accumulation factors (BSAF). Thus, both fish species accumulated similar amounts of trace elements, which corroborates the equal concentrations of each trace element in these species. This trend was also observed by [88]. In both fish species, high bioaccumulation of trace elements (As, Hg, and Pb) was noted, with the exception of Cd. The low bioavailability of Cd was noted in the work of [88]. In this study, the two species accumulated similar amounts ($0.11 < p < 0.97$), confirmed by the BCF and BSAF values, which were close between species for each trace element studied. The high accumulation of trace elements in fish in reservoir water (5 L kg^{-1} for Cd in *O. niloticus* to 200 L kg^{-1} for Hg in *C. nigrodigitatus*) indicates direct absorption via the gills and skin [91]. In sediments, the accumulation of trace elements in fish was very low (0 for Cd in *O. niloticus* to 0.63 for As in *C. nigrodigitatus*), which confirms that sediments act as traps for trace elements, although they are less bioavailable than water. This result is reinforced by the work of [92] and [11], in which the species had significantly more trace elements accumulated in the sediments compared to water. The BCF values were all above the threshold 1 for all the trace elements studied. This suggests a significant bioconcentration of these elements and therefore their transfer from the water into the fish organisms [19,93]. Both fish species are contaminated, regardless of their trophic level. This contamination depends on species-specific factors and environmental conditions. Indeed, the concept of bioaccumulation stems from several mechanisms acting simultaneously or with time lags. For the same chemical species, bioaccumulation can vary considerably depending on the aquatic organism considered, the age of the individuals, sex, diet, habitat, environmental variables (pH, temperature, etc.), the properties of the contaminant, etc. [34]. The BCF results showed that the four trace elements are bioconcentrated from concentrations in the surrounding water, unlike the sediments. This is normal given that sediments act as traps for trace metals, reservoirs where trace metals accumulate in alkaline waters [94]. This study highlights the ability of these fish species to bioaccumulate trace metals even when their concentrations in the abiotic environment where the fish are found are low [35]. Previous studies have shown that trace metals can persist in fish tissues due to their lack of biodegradation, which can lead to human exposure through the consumption of contaminated fish [3,4,31,95–99]. Our results are consistent with those of [15,78,79,88], who reported high levels of Pb or As in their work. Authors such as [81] attributed this to the natural availability of As in their study area. According to [100], the high As concentrations in the organs could be explained by a significant capacity for As enrichment in the aquatic environment. Furthermore, a high absorption capacity in tilapia species would contribute to its accumulation in their organs [101]. It is necessary to recognize that the level of trace element contamination in fish generally reflects the level observed in

their biotope [102]. The use of chemical inputs such as fertilizers and pesticides (herbicides, fungicides, and insecticides) in cocoa, coffee, and rubber plantations located throughout the watershed, as well as the use of mercury during gold amalgamation, fishing activities involving lead-weighted nets, and fuel residues discharged into the reservoir, could represent potential sources of trace metal elements in the different matrices of the aquatic environment. Thus, agricultural, gold panning and fishing activities could potentially promote the contamination of water, sediments and fish.

Human health risks linked to fish consumption.

The results of the non-cancer health risk assessment indicate that in two populations (children and adults), the HQ values were all less than 1 in the two fish species for each TME studied. This suggests that the occurrence of a toxic effect linked to each trace element is very unlikely [103]. On the other hand, the THQ values in children for both species are greater than 1, considering 3% of total As representing inorganic As, the most toxic fraction [3, 43]. This result indicates that the consumption of each of the two species of fish from the reservoir by children could lead to non-carcinogenic toxic effects on their health, due to the accumulation of the TMEs studied [41]. These effects would be more critical if the proportion of inorganic As (3%) considered was higher. The results of the sensitivity analysis show that increasing the proportion of inorganic arsenic leads to higher THQ values, with higher risk estimates when the fraction considered increases up to 10%. However, THQ values in children remain above 1 even for a low inorganic arsenic fraction (1%), indicating the persistence of a potential risk of non-carcinogenic effects. These results show that, although the risk assessment is sensitive to the assumed inorganic-arsenic fraction, the overall conclusion of the study remains unchanged. On the other hand, in adults, these results do not generate any non-carcinogenic health risk. This result is in agreement with those of [104] with a THQ greater than 1 in children. According to [105], children's heightened vulnerability to the toxic effects of TMEs is attributable to their low body weight and physiological immaturity. The results of the carcinogenic health risk assessment show CR values greater than 10^{-4} (unacceptable CR) for Cd, in children for the two fish species studied and in adults for *C. nigrodigitatus*. This indicates a clear carcinogenic risk in children through the consumption of both fish species, and in adults through consumption of *C. nigrodigitatus*. This same result was found in the work of [106], however [107] found an acceptable limit for Cd. Taken together, these results provide clear evidence of a non-carcinogenic risk in children, arising from the combined action of all the TMEs studied, and of a carcinogenic risk arising from exposure to Cd through the consumption of *O. niloticus* and *C. nigrodigitatus* in children, and *C. nigrodigitatus* in adults. Therefore, the regular consumption of these two fish species could be a worrying factor [2, 11, 79, 106]. As, especially inorganic As, is a Group 1 carcinogen according to the International Agency for Research on

Cancer (IARC). It is a neurotoxin constituting a global health problem [108]. It can cause skin manifestations, vascular diseases and visceral cancers [40, 109]. Like As, Pb is also a major toxic substance for human health. It is classified in group 2A according to the IARC. Its accumulation in fish is very dangerous, because children are very sensitive to its chronic poisoning called lead poisoning [2]. Pb poisoning can cause health problems in fish and humans. It can lead to serious fetal brain damage, kidney, circulatory and nervous system diseases, prostate cancer and reduced fertility in humans [70, 88, 110–112]. Cd is a cumulative toxin, group 1 carcinogen according to the IARC, which has no recognized biological role in the human body. Chronic and long-term exposure to Cd has been associated with a number of adverse health consequences, including impaired kidney and liver function, reduced reproductive capacity, cancers, bone disorders, respiratory problems, and cardiovascular disease [113–115]. As for exposure to Hg, even in small amounts, it can lead to serious health problems, particularly in children's development in utero and during infancy, childhood, and early and middle adolescence [116]. Humans are most commonly exposed to methylmercury (organic form), which is frequently present in relatively high amounts in aquatic organisms, including fish. However, the risk of exposure to elemental Hg also exists. Mercury toxicity affects the lungs, skin, eyes as well as the nervous, cardiovascular and excretory systems. Symptoms of mercury poisoning include deterioration of the nervous system, motor system disorders, hearing problems, speech problems, tremors and headaches [114].

4. Conclusion

This study assessed the level of contamination by the trace metal elements As, Cd, Hg and Pb in the water, sediments and two fish species, *Oreochromis niloticus* and *Chrysichthys nigrodigitatus*, from the Soubré dam reservoir. The results reveal the presence of these four trace metal elements in all three compartments, with concentrations sometimes exceeding recommended limits. In the reservoir water, the average mercury concentration is higher than the limit value for raw water used for drinking water production, published by the Official Journal of the French Republic (OJFR). As for the sediments, the average concentrations are very low and comply with the TEC, PEC, and ISQGs aquatic life quality standards. The average arsenic and lead concentrations in the muscles of the two fish species, *Oreochromis niloticus* and *Chrysichthys nigrodigitatus*, exceed the edibility limits recommended by the WHO/FAO. The bioaccumulation of trace elements is identical in both fish species, and the bioconcentration factors (BCF) are also high, above threshold 1 for the trace elements studied. As, Pb, and Hg are the trace elements that accumulate the most in the studied species, while Cd is the least bioavailable. The health risk assessment reveals that the total hazard quotient (THQ) values are above threshold 1 in children, and the cancer risk (CR) is greater than 10^{-4} for Cd, considering 3% of total As representing inorganic As, the most

toxic fraction. These results highlight the importance of strengthening environmental prevention and management actions in the Sassandra River watershed. These could include, for example, reducing potential sources of pollution, particularly by raising farmers' awareness of more environmentally friendly agricultural practices using biological inputs, as well as implementing regular monitoring of the quality of aquatic ecosystems. Furthermore, this study opens up perspectives for further research on other locally consumed fish species, as well as on different metabolic organs such as the liver and kidneys, in order to improve the understanding of the distribution and dynamics of bioaccumulation of trace metal elements in the Soubré dam ecosystem.

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