Physicochemical Quality of the Water and Heavy Metal Contamination of the Sediment, Water, and Flesh of Some Fish in the Lower Reaches of the Mono River (Benin, West Africa)

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ABSTRACT

This study aimed to assess the physicochemical quality of the water and the heavy metal of the sediment, water, and flesh of two species of fish most commonly consumed by residents in the lower reaches of the Mono River. To this end, four stations (Ahossanou, Codjohoué, Athiémé, Grand-Popo) were selected and surveyed during high water (October to December 2021) and low water (January to March 2022) seasons to measure physicochemical parameters and examine the ichthyofauna in artisanal catches. Water samples were taken to measure the biological oxygen demand (BOD_5), nitrite and nitrate levels. Additionally, samples of sediment, water, and fish flesh were taken to analyze heavy metal concentrations (lead and cadmium). The BOD_5 concentrations exceeded 30 $mg \cdot L^{-1}$, indicating poor water quality. All nitrite and nitrate levels were within acceptable limits (3.28 and 44.28 $mg \cdot L^{-1}$, respectively). The potential ecological risk posed by sediment contamination ranged from low during high water to considerable during low water seasons. Measured lead and cadmium concentrations in the water exceeded permissible limits (0.05 and 0.005 $mg \cdot L^{-1}$, respectively). *Brycinus macrolepidotus* and *Chrysichthys nigrodigitatus* were the most abundant fish species caught in the Mono River. While cadmium levels in the fish flesh were below the WHO/FAO standard (0.05 $mg \cdot kg^{-1}$), lead concentrations exceeded the WHO/FAO standard (0.3 $mg \cdot kg^{-1}$). The study concluded that consumption of fish from the lower Mono River poses health risks to local communities.

Keywords: Cadmium, Heavy metals, Lead, Mono basin, Nitrogen, Organic pollution

INTRODUCTION

The aquatic ecosystems are being increasingly degraded by the negative impacts of human activity and climate change (Erasmus *et al*., 2018). The progression of human economic activities, such as mining and oil refining, pharmaceutical industry, and agriculture, results in discharge of organic waste, heavy metals, and toxic chemicals into the environment (Moruf and Akinjogunla, 2019). These sources of pollution end up in the water through run-off, altering the quality of the biotope (sediment and water), the life of the biocenosis (plankton, invertebrates and vertebrates) and, consequently, the nutritional quality of fishery products (fish, prawns, crabs, gastropods, bivalves, etc.) (Ennouri *et al*., 2013; Erasmus *et al*., 2018; Kondo *et al*., 2021). The accumulation of pollutants in organisms and their transfer along the food chain are more rapid in continental waters (rivers, lakes, lagoons, etc.) than in the oceans (Barnabé, 2022). Unlike the oceans, which have a high capacity for diluting and dispersing pollutants, continental waters have a low capacity for self-purification and concentrate pollutants even in the presence of small sources of pollution. The small size of continental waters and their direct contact with built-up areas and

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agricultural and industrial land facilitate the accumulation of pollutants. Consumption of fish products from continental waters therefore presents a high health risk when there are sources of pollution in the catchment area (Diop *et al*., 2019). In Benin, inland fishing contributes over 63% of national fisheries production (FPD, 2019). It is an income-generating activity for more than 39,000 fishermen (FPD, 2019) and is the country's most important source of animal protein (Rurangwa *et al*., 2014). However, the development of human activities has led to a progressive concentration of heavy metals (such as lead, copper, and mercury), as well as organic and bacteriological pollutants in continental waters (Degila *et al*., 2019). Several studies have revealed the presence of pollutants in high concentrations in some aquatic ecosystems in Benin, namely the Benin cotton basin (Agbohessi *et al*., 2015; Agblonon Houelome *et al*., 2022), Lake Nokoué (Yèhouénou *et al*., 2014; Vodougnon *et al*., 2018), the Cotonou channel (Yèhouénou *et al*., 2014), the Porto Novo lagoon (Vodougnon *et al*., 2018), the Ouémé River (Yèhouénou *et al*., 2014; Attingli *et al*., 2017), etc. The Mono basin, one of the country's most important river systems, is also subject to anthropogenic pressures. The installation of the Nangbéto hydroelectric dam in the middle reaches of the basin and its implementation have had a damaging effect on the Mono River. The retention and sudden release of water from the dam accelerate bank erosion, modify the hydrology of the River (Amoussou *et al*., 2012), alter the quality of the biotope (Chouti and Hounkpêvi, 2018; Adje *et al*., 2021), and disrupt the biology and ecology of living organisms in the environment (Lederoun *et al*., 2021). In addition, there is pollution from agricultural activities (use of pesticides and chemical fertilizers), livestock farming, domestic activities (cooking, washing clothes, and dishes), transport, and tourism (Chouti and Hounkpêvi, 2018; Adje *et al*., 2021). Given these disturbances and threats to this ecosystem, there is a great need for research into the quality of the biotope and the aquatic organisms that are most commonly consumed. Available data on water quality in the basin relate to the coastal lagoon at Grand-Popo (Chouti *et al*., 2017) and a few stations on the Mono River at Grand-Popo in Benin (Chouti and Hounkpêvi, 2018). These studies reported organic and bacteriological pollution of the water in the coastal part of the basin. A study conducted in the lake of the Nangbéto dam on the state of contamination of the biotope revealed contamination of the sediment by heavy metals (cadmium, lead, nickel, copper, chromium, arsenic, and mercury) (Adje *et al*., 2021). However, there is a lack of data on water and sediment quality in other parts of the basin and on the quality of fishery products throughout the basin. As the lower reaches is the final receptacle for pollution from the upper and middle reaches (Kondo *et al*., 2021), and fish is the main source of protein for riverside populations, there is an urgent need to assess the quality of the biotope of the lower reaches and the quality of the flesh of the fish species most consumed by riverside residents. This study aims to assess the physicochemical quality of the water and the concentrations of heavy metals in the sediment, water, and flesh of the most abundant fish species and those most appreciated by residents in the lower reaches of the Mono basin. Furthermore, correlation between fish size and heavy metal concentration was examined. Additionally, the most influential water quality parameter affecting heavy metal concentration was also identified.

MATERIALS AND METHODS

Study area

The Mono River rises in the Koura Mountains at Alédjo (9°21'N01°27'E) in north-west Benin and drains a catchment area of around 22,000 km^2 (Lévêque and Paugy, 2006) between latitudes 6°10' and 9°00' North and longitudes 0°30' and 1°50' East (Lederoun *et al*., 2018). Most of the basin lies within Togolese territory, but its lower reaches form the natural border between Togo and Benin over a distance of around 100 km. Four stations, namely Ahossanou (06°57'N01°33'E), Codjohoué (06°50'N01°36'E), Athiémé (06°34'N 01°39'E) and Grand-Popo (06°17'N01°49'E) (Figure 1), were selected in the lower reaches based on their geographical location and human activities.

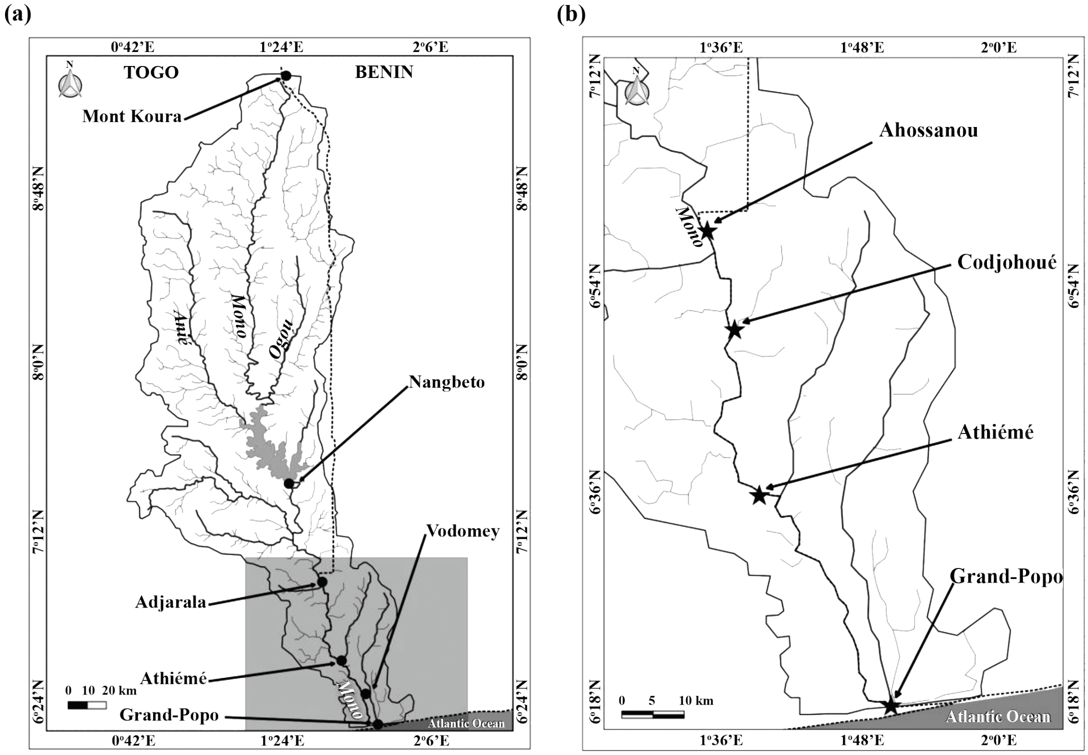

Figure 1. A map showing: (a) Mono River basin, and (b) sampling stations.

Data collection methods

Measurement of physicochemical parameters

The stations were surveyed monthly during high-water (October to December 2021) and low-water (January to March 2022). Water temperature (°C) and pH were measured with a Hanna HI991300 multimeter, dissolved oxygen ($mg \cdot L^{-1}$) with a HI91436-Microprocessor Auto Cal-HANNA oximeter, transparency (cm) and depth (m) with a Secchi disc. Water was sampled seasonally at the stations using the method described by Corriveau (2009) to measure biological oxygen demand (BOD_5), nitrite, and nitrate. BOD_5 was measured using an OxiTop BOD meter through the respirometric method in a chamber thermostated at 20 °C for five days. Nitrite and nitrate, on the other hand, were measured using a Hach Lange DR 2800 spectrophotometer following the method described by Rodier *et al*. (2016).

Fish, sediment and water sampling for lead and cadmium determination

During each sampling event, fish from the artisanal catches were sorted, identified beforehand, counted, and weighed using an electronic balance with a capacity of 2,000 g and a precision of 0.01 g. Two sets of specimens of each species were prepared, with one set being tagged and fixed in 10% formalin. This was done for laboratory confirmation of identification, following the methods outlined in Paugy *et al*. (2003a; 2003b) and Lederoun *et al*. (2018). The other batch was packed, tagged, and stored in a cooler box with ice for metal assay in the laboratory. Two species, identified as consistently present in the study area according to Lederoun *et al*. (2021) and found abundantly in the catches of the current study, were selected for the heavy metals assay. Specifically, one sample of each species was collected during both high-water and low-water seasons at each station. This resulted in a total of 8 samples of each individual species and 16 samples when considering both species combined.

Sediment and water samples were collected once per season at each station. Sediments of 0 to 10 cm deep were scraped by divers using polyethylene containers, placed in polyethylene bags, labeled, and kept in a cool box at 4 °C for transport to the laboratory (Adje *et al*., 2021). Water samples were collected from the water column using sterilized 1 L glass bottles, labeled, and then stored in a cool box at 4 °C for transport to the laboratory. A total of 8 sediment samples and 8 water samples were collected for metal analysis, specifically, 2 sediment samples and 2 water samples per station.

Determination of lead and cadmium

The sediment samples were processed following the methods described by Adje *et al*. (2021) to obtain a 100 mL solution which is used for the assay. For the fish samples, pieces of flesh with skin were taken from the dorsal part and were processed using the methods outlined by Ennouri *et al*. (2013) to obtain a 100 mL solution, which is used for the assay. For the water samples, a 100 mL solution of each sample was taken for the determination of metals. Lead and cadmium concentrations in the flesh with skin of these species, in the sediment, and in the water were determined per station and season using the SpectrAA 110 Atomic Absorption Spectrometer (AAS).

Data analysis methods

Physicochemical parameters

The spatial and temporal variations of the parameters (temperature, pH, dissolved oxygen, depth, and transparency) were presented as mean±SD and the values of nutrients (nitrite, nitrate) and BOD_5 were compared with the standards available to assess the physicochemical quality of the river water (Table 1).

Selection of two species

The numerical and weight abundances of each species were calculated to select two of the most abundant species in artisanal catches. Numerical abundance is the percentage ratio of the number of individuals of one species to the total number of individuals of all species. Weight abundance is the percentage ratio of the biomass of individuals of one species to the total biomass of individuals of all species. Two species that are constant in the study area according to Lederoun *et al*. (2021) and abundant in artisanal catches in the present study were selected.

Heavy metal contamination

The potential Ecological Risk Index (ERI) has been used to assess heavy metal contamination of sediments and the risk of its transmission to biocenosis. The ERI was proposed by Häkanson (1980) and is calculated as

$$ERI = \sum_{i}^{n} E_r^i \text{ ; } E_r^i = Tfi \times Cfi \text{ and } Cfi = Cei/Cri,$$

where E_r^i = individual ecological risk index; Cfi = contamination coefficient for metal i; Cei = concentration of metal i in the sample; Cri = concentration of metal i in unpolluted sediments/reference concentration; Tfi = toxicity weight or weighting factor for metal i. The pre-industrial concentrations of lead and cadmium (17.0 and 0.102 $mg \cdot kg^{-1}$) were used as the concentrations of unpolluted sediments (Konan *et al*., 2021). The respective weights assigned to the metals used in the calculations were: cadmium = 30 and lead = 5. When ERI>150, the ecological risk is low; 150≤ ERI<300, the ecological risk is moderate; 300≤ ERI<600, the ecological risk is considerable; and when ERI≥600, the ecological risk is very high.

Table 1. Standard values for organic pollutants.

Elements	Standard values	Reference
BOD_5	30 $mg \cdot L^{-1}$	US EPA (1992)
Nitrite	3.28 $mg \cdot L^{-1}$	US EPA (2004)
Nitrate	44.28 $mg \cdot L^{-1}$	US EPA (2004)

For water, the heavy metal concentrations obtained were compared with environmental quality standards (accepted average concentrations) for watercourses (0.05 and 0.005 mg·L^{-1}, respectively for lead and cadmium) (BE, 2016). Heavy metal concentrations in fish flesh were compared with WHO standards for fish intended for human consumption (cadmium = 0.05 mg·kg^{-1}, lead = 0.3 mg·kg^{-1}) (WHO/FAO, 2019; WHO/FAO/UE, 2021) to assess the quality of their flesh.

Statistical analysis and tests

The one-way analysis of variance (one-way ANOVA) was applied to test the difference between the mean values of each of the physicochemical parameters, metals (in water, sediment, and fish flesh), and ERI in spatial and temporal terms. Where there was a significant difference, post hoc comparisons (Least Significant Difference: LSD) were carried out. Differences were considered significant at the 5% threshold. A principal component analysis (PCA) was carried out using the Factoshiny package, using the mean values of physicochemical parameters and heavy metal concentrations in the water to characterize the stations. A matrix consisting of 10 rows (8 physicochemical parameters and 2 heavy metals) and 4 columns (4 stations) was used. Linear regressions were used to study the correlation between fish size and heavy metal concentration. These analyses were carried out using the R 4.1.3 statistical environment.

RESULTS

Physicochemical parameters

The physicochemical parameters slightly varied during the study period (Table 2). Water temperature varied from 25.50 to 29.20 °C, while pH ranged from 6.51 to 7.44. The dissolved oxygen varied from 5.41 to 8.01 mg·L^{-1}, and the depth was between 0.40 and 4.80 m. Transparency ranged from 24.80 to 79.30 cm, while biological oxygen demand (BOD_5) was between 58 and 270 mg·L^{-1}. The nitrate was between 0.282 and 1.992 mg·L^{-1},

Table 2. Spatial variations of physicochemical water parameters in the lower reaches of the Mono basin.

Parameters	Description	AH	CO	AT	GP
Temperature (°C)	Min–Max	25.50–29.10	25.80–29.20	25.50–27.40	25.80–28.90
	Mean±SD	27.69±1.29^{a}	27.58±1.19^{a}	26.60±0.69^{a}	27.03±1.15^{a}
pH	Min–Max	6.52–7.44	6.80–7.12	6.72–7.22	6.51–7.12
	Mean±SD	7.10±0.34^{a}	6.96±0.11^{a}	6.94±0.21^{a}	6.83±0.20^{a}
Dissolved oxygen (mg·L^{-1})	Min–Max	5.89–7.59	5.41–7.89	5.74–8.01	5.67–6.69
	Mean±SD	6.82±0.62^{a}	6.68±0.98^{a}	6.88±0.97^{a}	6.09±0.39^{a}
Depth (m)	Min–Max	0.56–3.20	0.70–4.30	0.40–3.50	1.00–4.80
	Mean±SD	1.82±1.31^{a}	2.05±1.55^{a}	1.87±1.57^{a}	2.80±1.87^{a}
Transparency (cm)	Min–Max	24.80–78.30	32.80–50.60	28.00–42.90	53.70–79.30
	Mean±SD	46.43±23.00^{ab}	43.18±6.69^{ab}	35.38±6.10^{b}	65.03±9.17^{b}
BOD_5 (mg·L^{-1})	Min–Max	58.00–140.00	110.00–245.00	180.00–270.00	100.00–171.00
	Mean±SD	99.00±57.98^{a}	177.50±95.46^{a}	225±63.64^{a}	135.5±50.20^{a}
Nitrate (mg·L^{-1})	Min–Max	1.383–1.992	1.615–1.905	0.891–1.557	0.282–1.065
	Mean±SD	1.69±0.43^{a}	1.76±0.20^{a}	1.22±0.47^{a}	0.67±0.55^{a}
Nitrite (mg·L^{-1})	Min–Max	0.012–0.855	0.636–1.112	0.384–0.484	0.068–0.394
	Mean±SD	0.43±0.60^{a}	0.87±0.34^{a}	0.43±0.07^{a}	0.23±0.23^{a}

Note: Mean±SD in each row superscripted with different lowercase letters denote significant ($p<0.05$) difference; AH = Ahossanou; AT = Athiémé; CO, Codjohoué; GP = Grand-Popo.

and the nitrite was between 0.012 and 1.112 $mg{\cdot}L^{-1}$. Only transparency varied significantly from one station to another ($p<0.05$; Table 2). The highest transparency values were recorded at Ahossanou (46.43±23.00 m) and Grand-Popo (65.03±9.17 m) (Table 2). A comparison of values between high-water and low-water showed that the differences were significant only for temperature, dissolved oxygen, and water depth ($p<0.05$) (Table 3).

Composition of the ichthyofauna and choice of two species

The observation of artisanal catches enabled 23 fish species to be inventoried, divided into 17 families and 20 genera (Table 4). The species most represented in terms of numbers of individuals in the catches were *Brycinus macrolepidotus* (18.02% of the total number of individuals of all species), *Labeo senegalensis* (14.85%), *Chrysichthys nigrodigitatus* (13.32%), *L. parvus* (10.85%) and *Pellonula leonensis* (10.72%). The other species contributed less than 5% each (Figure 2a). In terms of biomass, *Distichodus rostratus* (18.90%), *Lates niloticus* (18.17%), *C. nigrodigitatus* (15.68%), *C. gariepinus* (14.03%), and *C. auratus* (9.45%) dominated the fishermen's catches. The other species each contributed less than 5% of the artisanal catch biomass (Figure 2b). As *C. nigrodigitatus* and *B. macrolepidotus* are constant in the study area, according to Lederoun *et al*. (2021), they were selected as abundant species for the determination of lead and cadmium in their flesh.

Heavy metal concentrations (lead and cadmium)

The spatial variations of lead and cadmium concentrations in sediment, water, and flesh of *B. macrolepidotus* and *C. nigrodigitatus* are presented in Table 5 and those temporal are presented in Table 6.

Heavy metal contamination of sediment

The lead concentrations in sediment ranged from 0.850 to 22.206 $mg{\cdot}kg^{-1}$. There was no significant difference between stations ($p>0.05$; Table 5). However, there was a significant difference

Table 3. Temporal variations of physicochemical water parameters in the lower reaches of the Mono river.

Parameters	Description	High-water	Low-water
Temperature (°C)	Min–Max	25.50–29.10	26.80–29.20
	Mean±SD	26.60±1.06[a]	27.85±0.81[b]
pH	Min–Max	6.52–7.42	6.51–7.44
	Mean±SD	6.98±0.23[a]	6.93±0.25[a]
Dissolved oxygen ($mg{\cdot}L^{-1}$)	Min–Max	6.12–8.01	5.41–6.80
	Mean±SD	7.23±0.59[a]	6.00±0.38[b]
Depth (m)	Min–Max	2.40–4.80	0.40–1.20
	Mean±SD	3.54±0.74[a]	0.73±0.26[b]
Transparency (cm)	Min–Max	38.40–78.30	24.80–79.30
	Mean±SD	53.31±12.95[a]	41.69±18.25[a]
BOD_5 ($mg{\cdot}L^{-1}$)	Min–Max	58.00–270.00	100.00–180.00
	Mean±SD	186.00±95.124[a]	132.50±35.94[a]
Nitrate ($mg{\cdot}L^{-1}$)	Min–Max	1.065–1.992	0.282–1.615
	Mean±SD	1.630±0.421[a]	1.043±0.590[a]
Nitrite ($mg{\cdot}L^{-1}$)	Min–Max	0.394–0.855	0.012–1.112
	Mean±SD	0.592±0.201[a]	0.394±0.506[a]

Note: Mean±SD in each row superscripted with different lowercase letters denote significant ($p<0.05$) difference

Table 4. List of species inventoried in artisanal catches in the lower Mono basin.

Families	Species
Polypteridae	*Polypterus senegalus senegalus* Cuvier, 1829
Osteoglossidae	*Heterotis niloticus* (Cuvier, 1829)
Notopteridae	*Xenomystus nigri* (Günther, 1868)
Clupeidae	*Pellonula leonensis* Boulenger, 1916
Cyprinidae	*Labeo parvus* Boulenger, 1902
	Labeo senegalensis Valenciennes, 1842
Distichodontidae	*Distichodus rostratus* Günther, 1864
Alestidae	*Brycinus macrolepidotus* Valenciennes, 1849
Hepsetidae	*Hepsetus odoe* (Bloch, 1794)
Mochokidae	*Synodontis cf. obesus* Boulenger, 1898
Clariidae	*Clarias gariepinus* (Burchell, 1822)
Claroteidae	*Chrysichthys auratus* (Geoffroy Saint-Hilaire, 1808)
	Chrysichthys nigrodigitatus (Lacépède, 1803)
Schilbeidae	*Schilbe intermedius* Rüppell, 1832
	Schilbe mystus (Linnaeus, 1758)
Latidae	*Lates niloticus* (Linnaeus, 1762)
Cichlidae	*Chromidotilapia guntheri* (Sauvage, 1882)
	Coptodon guineensis (Bleeker in Günther, 1862)
	Oreochromis niloticus (Linnaeus, 1758)
	Sarotherodon galilaeus galilaeus (Linnaeus, 1758)
Gobiidae	*Awaous lateristriga* (Duméril, 1861)
Channidae	*Parachanna obscura* (Günther, 1861)
Protopteridae	*Protopterus annectens annectens* (Owen, 1839)

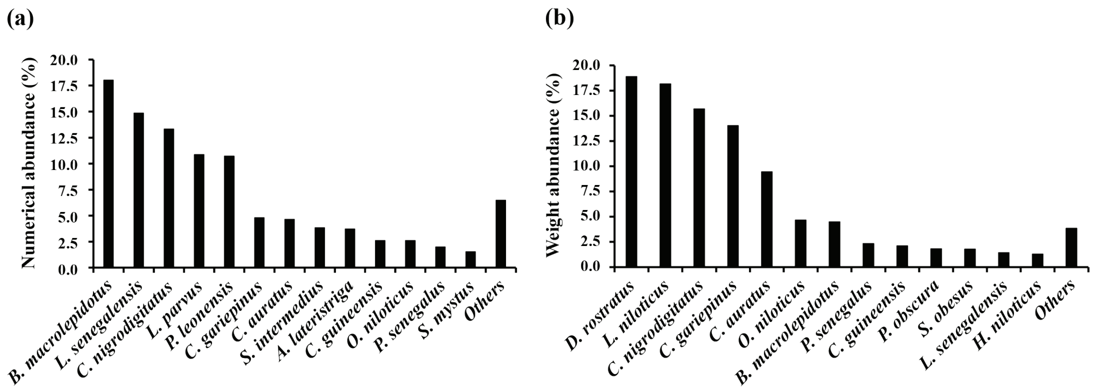

Figure 2. Numerical (a) and weight (b) abundances of species in artisanal catches.

Table 5. Spatial variations of lead and cadmium concentrations in sediment ($mg \cdot kg^{-1}$), water ($mg \cdot L^{-1}$), and fish ($mg \cdot kg^{-1}$).

Elements	Description	AH	CO	AT	GP
		Lead			
Sediment	Min–Max	0.870–19.060	0.997–21.405	0.918–22.206	0.850–20.433
	Mean±SD	9.963±12.850^{a}	11.201±14.430^{a}	11.562±15.050^{a}	10.642±13.840^{a}
Water	Min–Max	0.661–0.712	0.638–0.674	0.573–0.740	0.557–0.729
	Mean±SD	0.687±0.036^{a}	0.656±0.025^{a}	0.656±0.119^{a}	0.643±0.122^{a}
Brycinus macrolepidotus	Min–Max	0.603–0.636	0.561–0.588	0.837–0.933	0.855–0.918
	Mean±SD	0.620±0.023^{a}	0.575±0.019^{a}	0.885±0.068^{b}	0.887±0.045^{b}
Chrysichthys nigrodigitatus	Min–Max	0.687–0.738	0.699–0.771	0.831–0.903	0.939–0.981
	Mean±SD	0.713±0.036^{a}	0.735±0.051^{a}	0.867±0.051^{ab}	0.960±0.030^{b}
		Cadmium			
Sediment	Min–Max	0.0424–1.176	0.038–0.579	0.037–0.909	0.033–0.642
	Mean±SD	0.609±0.802^{a}	0.308±0.383^{a}	0.473±0.617^{a}	0.338±0.430^{a}
Water	Min–Max	0.025–0.041	0.020–0.031	0.029–0.036	0.026–0.039
	Mean±SD	0.033±0.011^{a}	0.025±0.008^{a}	0.032±0.005^{a}	0.033±0.009^{a}
Brycinus macrolepidotus	Min–Max	0.003–0.006	0.002–0.002	0.002–0.006	0.002–0.006
	Mean±SD	0.005±0.002^{a}	0.002±0.000^{a}	0.004±0.003^{a}	0.004±0.003^{a}
Chrysichthys nigrodigitatus	Min–Max	0.003–0.006	0.002–0.003	0.004–0.006	0.002–0.009
	Mean±SD	0.005±0.002^{a}	0.003±0.001^{a}	0.005±0.001^{a}	0.006±0.005^{a}

Note: Mean±SD in each row superscripted with different lowercase letters denote significant ($p<0.05$) difference; AH = Ahossanou; AT = Athiémé; CO = Codjohoué; GP = Grand-Popo.

Table 6. Temporal variations of lead and cadmium concentrations in sediment ($mg \cdot kg^{-1}$), water ($mg \cdot L^{-1}$), and fish ($mg \cdot kg^{-1}$).

Parameters	Description	High-water	Low-water
		Lead	
Sediment	Min–Max	0.850–0.997	19.056–22.206
	Mean±SD	0.909±0.065^{a}	20.775±1.356^{b}
Water	Min–Max	0.674–0.740	0.557–0.661
	Mean±SD	0.714±0.029^{a}	0.607±0.050^{b}
Brycinus macrolepidotus	Min–Max	0.561–0.933	0.588–0.855
	Mean±SD	0.754±0.199^{a}	0.729±0.137^{a}
Chrysichthys nigrodigitatus	Min–Max	0.738–0.981	0.687–0.939
	Mean±SD	0.848±0.114^{a}	0.789±0.119^{a}
		Cadmium	
Sediment	Min–Max	0.033–0.042	0.579–1.176
	Mean±SD	0.038±0.004^{a}	0.827±0.273^{b}
Water	Min–Max	0.031–0.041	0.020–0.029
	Mean±SD	0.037±0.004^{a}	0.025±0.004^{b}
Brycinus macrolepidotus	Min–Max	0.002–0.006	0.002–0.006
	Mean±SD	0.004±0.002^{a}	0.004±0.002^{a}
Chrysichthys nigrodigitatus	Min–Max	0.002–0.004	0.003–0.009
	Mean±SD	0.003±0.001^{a}	0.006±0.002^{b}

Note: Mean±SD in each row superscripted with different lowercase letters denote significant ($p<0.05$) difference between seasons ($p<0.05$; Table 6). The highest concentrations were recorded during the low-water period (20.775±1.356 mg·kg^{-1}), while the lowest was measured during the high-water period (0.909± 0.065 mg·kg^{-1}) (Table 6).

For cadmium, the values recorded ranged from 0.033 to 1.176 mg·kg^{-1}. There was no significant spatial difference ($p>0.05$; Table 5). The mean concentration during the low-water period (0.827±0.273 mg·kg^{-1}) was significantly higher than during the high-water period (0.038± 0.004 mg·kg^{-1}) ($p<0.05$; Table 6).

The Ecological Risk Index (ERI) was 182.11±239.54, 94.02±116.78, 142.50±185.80, and 102.42±130.69 at Ahossanou, Codjohoué, Athiémé, and Grand-Popo, respectively (Table 7). There is a spatially significant difference for the ERI ($p<0.05$; Table 7). The ERI values for the low-water period are significantly higher than those for the high-water period ($p<0.05$; Table 7).

Heavy metal contamination of water

The concentration of lead in the water was between 0.557 and 0.740 mg·L^{-1} and that of cadmium between 0.020 and 0.041 mg·L^{-1}. In general, the highest concentrations were recorded during the high-water period and the lowest values were noted during the low-water period for both metals (Table 6, Figure 3). There were no spatially significant differences for either metal ($p>0.05$; Table 5). The concentrations recorded during the high-water period are significantly higher than during the low-water period ($p<0.05$; Table 6) for both metals. All the values recorded are higher than the recognized standard values for the two metals (0.05 and 0.005 mg·L^{-1}, respectively for lead and cadmium) (Figure 3a and 3b).

Table 7. Spatial and temporal variations of Ecological Risk Index of sediment.

	Spatial variations				**Temporal variations**	
	AH	**CO**	**AT**	**GP**	**High-water**	**Low-water**
Min–Max	12.73–351.49	11.44–176.59	11.12–273.88	10.01–194.83	10.01–12.73	176.59–351.49
Mean±SD	182.11±239.54^{a}	94.02±116.78^{b}	142.50±185.80^{ab}	102.42±130.69^{b}	11.34±1.12^{a}	254.15±80.21^{b}

Note: Mean±SD in each row superscripted with different lowercase letters denote significant ($p<0.05$) difference; AH = Ahossanou; AT = Athiémé; CO = Codjohoué; GP = Grand-Popo.

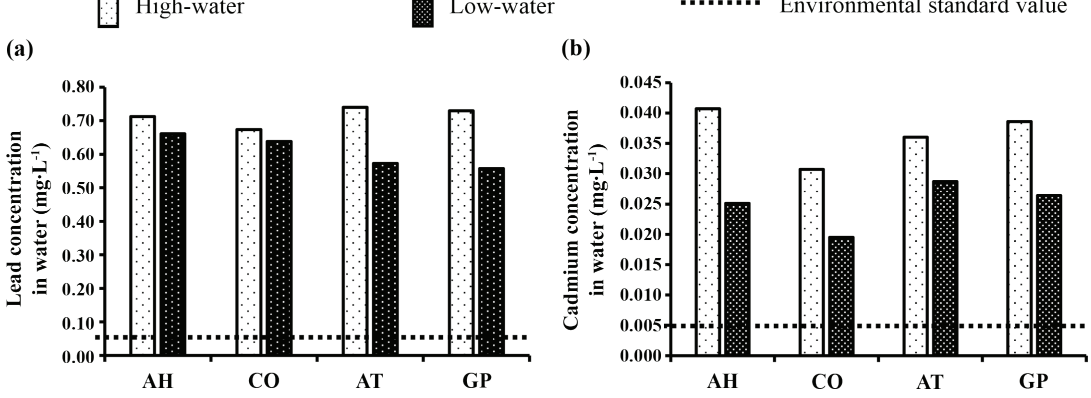

Figure 3. Spatial and temporal variations of lead (a) and cadmium (b) concentrations in water from the lower reaches of the Mono River.

Heavy metal contamination of fish flesh

The lead concentration in the flesh of the fish varied from 0.561 to 0.933 mg·kg^{-1} for *Brycinus macrolepidotus*, while it ranged from 0.687 to 0.981 mg·kg^{-1} for *Chrysichthys nigrodigitatus* (Table 5). For both species, there was a significant difference between the lead concentration values spatially ($p<0.05$; Table 5) whereas the difference was not significant temporally ($p>0.05$; Table 6). The concentration of lead in the flesh was not a function of specimen size (TL) for either species ($r^2<0.3$; Figure 4a and 4b). All the values measured are above the WHO/FAO standard (0.3 mg·kg^{-1}) (Figure 4a and 4b).

For cadmium, the concentrations varied from 0.002 to 0.006 mg·kg^{-1} for *B. macrolepidotus* and from 0.002 to 0.009 mg·kg^{-1} for *C. nigrodigitatus*. There was no significant difference between the cadmium concentration values in the flesh of the two species in spatial terms ($p>0.05$; Table 5). In the case of *B. macrolepidotus*, the concentrations recorded during the high-water period were equal to those recorded during the low-water period ($p>0.05$; Table 6). In the case of *C. nigrodigitatus*, the values recorded during the low-water period were significantly higher than those recorded during the high-water period ($p<0.05$; Table 6). For both species, the cadmium concentration in their flesh decreased with the size (TL) of the specimen ($r^2>0.50$) and all the values recorded remained below the WHO/FAO/EU standard (0.05 mg·kg^{-1}) (Figure 4c and 4d). A comparison of lead and cadmium concentrations between the two species showed that there was no significant difference between species for the two metals ($p>0.05$).

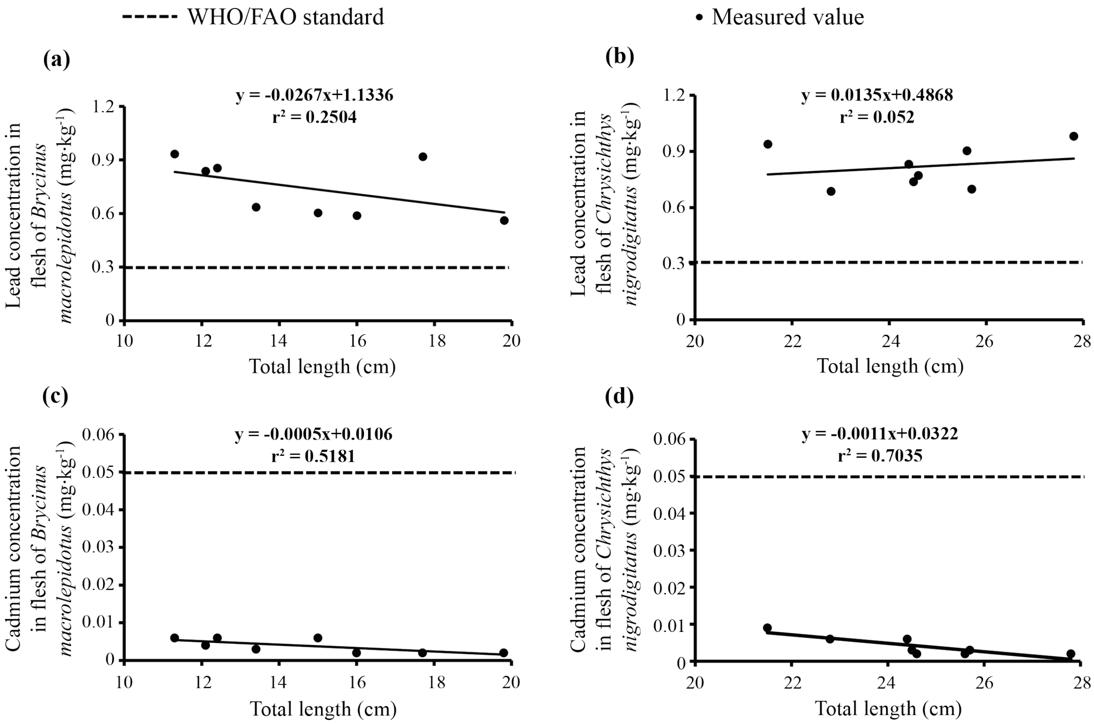

Figure 4. Heavy metal concentrations as a function of total length of fish: (a) lead concentration in the flesh of *Brycinus macrolepidotus*; (b) lead concentration in the flesh of *Chrysichthys nigrodigitatus*; (c) cadmium concentration in the flesh of *Brycinus macrolepidotus*; (d) cadmium concentration in the flesh of *Chrysichthys nigrodigitatus*.

Characterization of stations: Relationship between physicochemical parameters and heavy metals

The Principal Component Analysis of the physicochemical parameters and lead and cadmium concentrations in the water is shown in Figure 5. The first two axes express 80.01% of the total inertia of the data set. Only these two axes were used in the expression of the analysis. The first axis divides the stations into two groups: one made up of the Ahossanou, Codjohoué, and Athiémé stations, and the second made up of Grand-Popo. The Axis 2 route also divides the stations into two groups. The first group is formed by Ahossanou and Grand-Popo, and the second by Athiémé and Codjohoué. In summary, three groups of stations were identified: Group 1: Ahossanou, Group 2: Codjohoué and Athiémé, and Group 3: Grand-Popo (Figure 5a). The projection of physicochemical and metallic parameters shows that the Ahossanou station (group 1) is characterized by high values for temperature, lead, pH, and nitrate. The Codjohoué and Athiémé stations (group 2) are characterized by high values for BOD_5, nitrite, and dissolved oxygen. Group 3 (Grand-Popo) is characterized by high-water depths and transparency and, to a smaller extent, high cadmium values (Figure 5b).

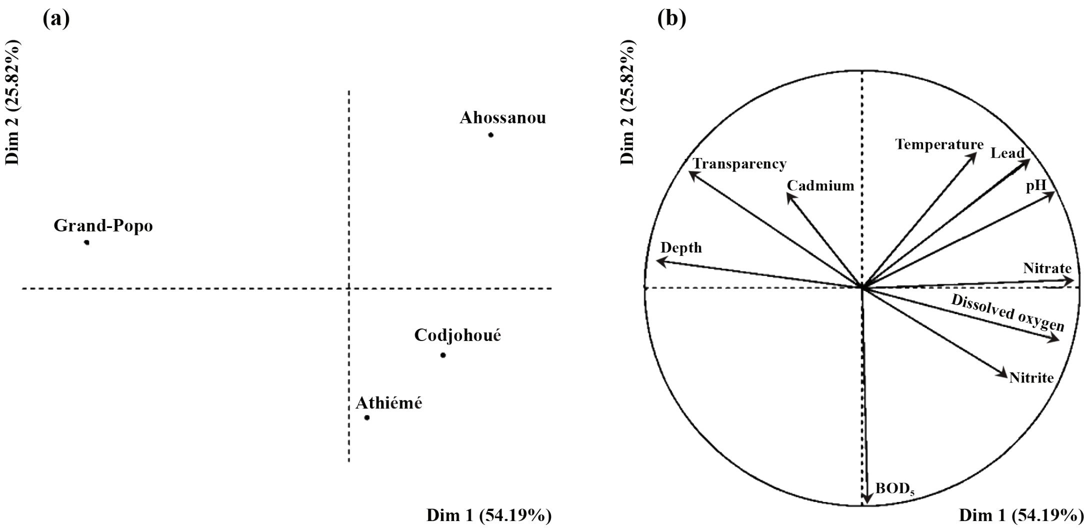

Figure 5. Principal Component Analysis of physicochemical and metallic parameters of water in the lower reaches of the Mono River: Abiotic typology of stations (a); Characterization of groups of stations with water parameters (b).

DISCUSSION

The physicochemical parameters of the water (temperature, pH, dissolved oxygen, depth, biological oxygen demand, nitrite, and nitrate) in the lower reaches of the Mono River (Benin, West Africa) did not vary significantly from a spatial point of view, except water transparency, whose values in Grand-Popo were significantly different from those in Athiémé and Codjohoué. As the stations selected for this study are all downstream of the Nangbéto hydroelectric dam, the absence of significant variation in the other physicochemical parameters can be attributed to the strong renewal of water by the dam's water release phenomenon (El morhit *et al*., 2008; Amoussou *et al*., 2012). In terms of time, there were no significant differences between high and low-water values other than for temperature, dissolved oxygen, and water depth. The highest temperatures were recorded in the low-water period, while the highest values for depth and dissolved oxygen were recorded in the high-water period. These variations can be explained by the hydrological regime (alternating high-water and low-water) of the Mono basin (Amoussou *et al*., 2012; Chouti and Hounkpêvi, 2018). The biological oxygen demand (BOD_5), nitrite, and nitrate are often used to characterize the pollution status of surface waters (Ifé, 2010). All BOD_5 values (58 to 270 $mg \cdot L^{-1}$) are above 30 $mg \cdot L^{-1}$, which is the value above which surface water is said to be of poor quality for aquatic biodiversity (US EPA, 1992). About nitrite, the value above which aquatic biodiversity is threatened is 3.28 $mg \cdot L^{-1}$ (i.e. 1 $mg\text{-}N \cdot L^{-1}$) (US EPA, 2004). All recorded values (0.012 to 1.112 $mg \cdot L^{-1}$) are below this standard. For nitrate, all values measured (0.283 to 1.992 $mg \cdot L^{-1}$) remained below the standard 44.28 $mg \cdot L^{-1}$ (10 $mg\text{-}N \cdot L^{-1}$) (US EPA, 2004). In general, the highest values for all three pollutants were recorded at the Athiémé and Codjohoué stations, which are located in the most agricultural areas of the basin (rice and cotton growing) (Baglo, 2022). As agriculture is well known as a source of organic pollution of surface waters (Pinay *et al*., 2017; Chouti and Hounkpêvi, 2018; De Kinkelin and Petit, 2018), the high organic pollution at these stations would come from residues of agricultural inputs and organic matter drained by runoff water.

The determination of lead and cadmium concentrations in sediment and water revealed that the lower reaches of the Mono basin are contaminated with heavy metals. All values of lead (0.557 to 0.740 $mg \cdot L^{-1}$) and cadmium (0.020 to 0.041 $mg \cdot L^{-1}$) recorded in the water are above the limit values for these metals in rivers and water bodies (0.05 and 0.005 $mg \cdot L^{-1}$, respectively for lead and cadmium) for the protection of the environment and aquatic biodiversity (BE, 2016). The highest concentrations were recorded during the high-water period and the lowest during the low-water period. As for sediment, the concentrations varied from 0.850 to 22.206 $mg \cdot kg^{-1}$ for lead and from 0.033 to 1.176 $mg \cdot kg^{-1}$ for cadmium. The overall mean concentrations of lead and cadmium recorded in the sediment (10.842 and 0.432 $mg \cdot kg^{-1}$, respectively) are significantly higher than those recorded by Adje *et al*. (2021) in the Nangbéto Dam Lake in the same basin (4.835 and 0.055 $mg \cdot kg^{-1}$, respectively). These results show the accumulation of heavy metals in the lower reaches of the Mono basin. The heavy metals originating from pollution sources in the upper and middle reaches would be drained downstream (the lower reaches), where they would be added to local pollution to produce high concentrations of heavy metals (Blanc *et al*., 2005; Damy, 2011; Moruf and Akinjogunla, 2019). The phenomenon of water releases from the Nangbéto Dam, responsible for high erosion in the basin (Amoussou *et al*., 2012), would facilitate this accumulation of metals in the lower course (Kondo *et al*., 2021). High-water velocity in a river encourages bank erosion, releasing particles (including organic matter, metals, etc.) that move with the current and are deposited downstream, contributing to the accumulation of pollutants in the lower reaches where water velocity is low (ha Dang, 2011; Baglo, 2022).

The assessment of sediment pollution status is based on the calculation of indices rather than a comparison of metal concentrations against reference values (Adje *et al*., 2021; Konan *et al*., 2021). The potential Ecological Risk Index (ERI) was used for this purpose. In the low-water period, the ERI was between 150 and 300 for Codjohoué, Athiémé, and Grand-Popo, while it was over 300 at Ahossanou, indicating that the ecological risk is considerable at Ahossanou and moderate at the other stations. In the high-water period, the ERI was below 150 for all stations, indicating a low ecological risk. Spatially, sediment at the Ahossanou station is more contaminated with heavy metals than at the other stations. This can be explained by the high level of anthropogenic activity at Ahossanou. Indeed, the Ahossanou station is the site of choice for the illicit transport of smuggled petroleum products (gasoline and kerosene) and agri-food products from Benin to Togo. Some gasoline cans are buried in the water in the event of police checks, thus increasing the risk of contamination of the ecosystem by oil spills (Biney *et al*., 1994). Contrary to Adje *et al*. (2021), who concluded that contamination of the sediment of Lake Nangbéto by trace metals was negligible, the present study reports the presence of metallic pollution in the sediment and water of the Mono River. The contamination of sediment is higher in low-water than in high-water, while that of water is higher in high-water than in low-water: this is the phenomenon of settling. The input of pollutants by runoff and the stirring up of sediment when rainfall arrives during high-water explain the high concentrations of metals in river water during high-water (Tahiri *et al*., 2005). The absence of rain during low-water favors settling and explains the high sediment contamination and low metal concentrations in the water (Tahiri *et al*., 2005; Adje *et al*., 2021).

A Principal Component Analysis performed on the mean values of physicochemical and metal parameters in the water revealed that the Codjohoué and Athiémé stations are characterized mainly by high BOD_5 and nitrite values, probably due to the development of agricultural activities in the areas where these stations are located. The Ahossanou station stands out from the others for its high lead and nitrate concentrations, probably due to the increased transport of agro-industrial products (fuel and food) and people at Ahossanou. As for the Grand-Popo station, it is characterized by depth, transparency, and cadmium. The high depth and transparency may be linked to manual dredging activities in the lagoon part of the Mono basin (close to the Grand-Popo station) (Lalèyè *et al*., 2022), while the cadmium is thought to come from domestic effluents (batteries, cement, and paint residues) from the town of Grand-Popo (Biney *et al*., 1994).

A total of 23 fish species, divided into 17 families and 20 genera, were inventoried in the artisanal catches. All these species have already been reported in the study area by Lederoun (2015) and Lederoun *et al*. (2021). According to Noppe and Prygiel (1999), the choice of species for a fishery product quality study must take into account both the representativity of the species at the scale of the study area and their abundance in the area. The species *Brycinus macrolepidotus* and *Chrysichthys nigrodigitatus* are constant in the study area according to Lederoun *et al*. (2021) and abundant in the artisanal catches of the present study. They were therefore selected for the determination of lead and cadmium in their flesh. The concentrations of cadmium in the flesh of *B. macrolepidotus* (between 0.002 and 0.006 $mg \cdot kg^{-1}$) and *C. nigrodigitatus* (between 0.002 and 0.009 $mg \cdot kg^{-1}$) were all below the WHO/FAO standard for fish for human consumption (0.05 $mg \cdot kg^{-1}$) (WHO/FAO/UE, 2021). As for lead, the concentrations in the flesh ranged from 0.561 to 0.933 $mg \cdot kg^{-1}$ for *B. macrolepidotus* and from 0.687 to 0.981 $mg \cdot kg^{-1}$ for *C. nigrodigitatus*. All values recorded were above the WHO/FAO standard for fish for human consumption (0.3 $mg \cdot kg^{-1}$) (WHO/FAO, 2019). It was concluded that the consumption of fish from the lower reaches of the Mono River poses a contamination risk to the health of consumers.

CONCLUSION

This study has highlighted organic pollution of the water, metallic pollution of the sediment and water, and contamination of the flesh of *Brycinus macrolepidotus* and *Chrysichthys nigrodigitatus* by lead and cadmium in the lower reaches of the Mono basin. The level of organic pollution is highest at stations located in areas with a high level of agricultural activity (Athiémé and Codjohoué), while metallic pollution is highest in areas with a high level of anthropogenic pressure (Ahossanou and Grand-Popo). The contamination of sediment is higher during the lower water period. The concentrations of cadmium in the flesh of both species are below the WHO/FAO standard, while those of lead are above the standard. This study concludes that the consumption of fish caught in the lower reaches of the Mono basin poses a health risk to consumers.

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