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Influence of a hydroelectric dam on fish mercury contamination along the Sinnamary River (French Guiana)

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ABSTRACT

The Petit Saut hydroelectric dam and the upstream and downstream areas of the Sinnamary River in French Guiana (Amazon basin) have been studied from 1993 to 2020. The nearly thirty-years-long study of the monitoring of total mercury concentration in fish and the physicochemical survey of the environment made it possible to demonstrate the impact of the flooding of the forest and the role of the hydroelectric dam on the methylation of mercury. Results show that the physicochemical modifications generated by the construction of the dam led to a significant production of methylmercury (MeHg) in the anoxic part of the reservoir and downstream of the river leading to a strong spatio-temporal impact of the dam. Seven species of fishes are studied and their mercury concentrations vary according to many parameters: fish diet, position in the water column, site, lake oxycline level and time.

1. Introduction

The constant growth in world population led to a large increase in the global demand for electrical energy. To bear this need, since 1950, hydroelectric dams of significant sizes are constructed at a frequency of nearly two dams per day which has led today to a total number of 45,000 dams worldwide (<https://www.planetoscope.com/eau-oceans/1677> - June 2023). Hydroelectric dam construction areas are known to provoke large environmental consequences. Some of the major concerns are the impact on river endemic fish species such as (i) the loss of their original habitat (Pestana et al., 2019), (ii) the decrease in their biodiversity (Castello and Macedo, 2016), (iii) the need for the fish to adapt to new food sources (Dominique et al., 2007; De Mérona et al., 2009), and (iv) the disruption of their migration pattern along the river continuum (Fearnside, 2014). Another important consequence of hydroelectric dam construction is its strong disturbance on the physicochemical conditions of the environment. The construction of a dam in tropical forest implies the immersion of the existing forest causing eutrophication of the reservoir (Liua et al., 2012; Abril et al., 2013; Forsberg et al., 2017; Noh et al., 2017) and ultimately leads to the anoxia

of its waters. The severe vegetation decay coupled to the anoxia conditions produces large quantities of methane (Abril et al., 2013), hydrogen sulfide, and methylmercury (Compeau and Bartha, 1985; Barkay and Wagner-Döbler, 2005; Muresan et al., 2008; Ranchou-Peyruse et al., 2009). Chemical characteristics of methylmercury (MeHg) make it easily bioaccumulative which generate high biomagnifications along trophic chains (Kasper et al., 2014; Maury-Brachet et al., 2020) which *in fine* leads to devastating human health risks (Castilhos et al., 2015; Arrifanoa et al., 2018;).

In the mid-1980 s, due to increased electrical energy needs, the French government decided to create a massive hydroelectric dam on the Sinnamary River in the Petit Saut region (French Guiana). Its construction began in 1989 and the impoundment of the reservoir took place in 1994. The Petit Saut reservoir, with its 16 km long and 19 km wide is the largest in France. Its depth reaches 37 m at its deepest, its volume is about 3.5 billion cubic meters and the residence time of its waters is five to six months (Sissakian, 1997). Its impoundment submerged 365 km² of equatorial forest (De Mérona, 2005), and initiated the degradation of its organic matter followed by the production of large quantities of methane, carbon dioxide, and hydrogen sulphide. The

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degradation of the vegetation has led to the formation of a large quantity of biofilm highly loaded with methanogenic and sulphate-reducing bacteria (Dumestre et al., 1997; Galy-Laclaux et al., 1997). Guyanese soils present large quantity of mercury due to both its natural presence in the soils and past and present gold mining activities (Carmouze et al., 2001; Moullet et al., 2006; Dezécache et al., 2017). Physicochemical processes coupled with the presence of mercury in the Sinnamary River (De Mérona, 2005), led to the production of large quantities of MeHg generating fish mercury contamination. Indeed, since the mid-19th century, the Sinnamary region has been under a lot of gold mining activities where gold miners extracted gold from the river by pouring liquid mercury to the water to aggregate gold particles (Le Tourneau, 2020). These illegal gold mining activities increased drastically following the large increase in the gold stock exchange in the 1980 s, as well as the opening of the Petit Saut site after the dam construction in 1998. Nowadays, Saint Elie and Adieu-Vat sites, located on the dam lake banks are still legally exploited still inducing the installation of a large number of illegal sites (Orru, 2001; Le Tourneau, 2020).

In the French legislation, the builder of the dam, here EDF (Électricité de France – a French energy supplier), has the obligation to set up environmental monitoring following the construction of a hydroelectric dam, which led to the creation of the HYDRECO office. From the creation of the dam until 2020, HYDRECO has been supervising a scientific survey on the environmental impacts, caused by the installation of the Petit Saut dam on the Sinnamary basin. This paper is focused on the spatio-temporal variability of total mercury contamination in fishes from different trophic levels located along the Sinnamary continuum.

2. Materials and methods

2.1. Sampling campaigns

From 1993–2020, twice a year, during wet and dry seasons, fish sampling campaign were carried out by the HYDRECO office. From 1998–2006 a research program led by researchers from Bordeaux University (Mercure en Guyane, financed by the CNRS) carried out complementary analyses to supplement the survey carried by HYDRECO. A total number of 57 sites were sampled over the years. Fishes were caught with surface gillnets (25 m long x 2 m high) of different mesh sizes (10, 15, 20, 25, 30, 35, 40, 50, 60 and 70 mm between knots) depending on the type of fish targeted. Two sets of 10 nets were set around 5:00 p.m. and removed between 7:00 a.m. and 10:00 a.m. the following day. In the river, the nets were positioned along the banks in areas of low current. In the lake, the old river bed, the flooded forest edges were sampled above the oxycline level. In addition to the nets, to capture larger fishes like *Hoplias aimara*, traps made of metal hooks about 4 cm long were attached to a tree and left overnight in the water. Fishes caught were measured, weighed, and visually identified (Table Annex 1). Fish muscles were dissected on site and an aliquot of fish muscle (~2 cm × 1 cm) was stored in individually labeled 10 mL sample tubes filled with 4% formaldehyde solution.

This nearly thirty-year endeavor, led to the collection of 180,958 fish belonging to 92 species over the 133 species inventoried in the Sinnamary river (Tito de Moraes et al., 1995; Planquette et al., 1996; Le Bail et al., 2000; Keith et al., 2000; De Merona 2002). Every year, only seven species among the large variety of collected fish were analyzed for mercury concentrations: herbivorous (*Myloplus ternetzi*), benthivorous (*Curimata cyprinoides*), omnivorous (*Leporinus friderici*; *Triportheus brachipomus*), and carnivorous (*Acestrorhynchus microlepis*; *Acestrorhynchus falcatus*; *Hoplias aimara*). These species were selected due to their (i) high abundance, (ii) omnipresence along the river continuum, and (iii) affiliation to various characteristic trophic levels. Additionally, these species are considered sentinel species well suited to evaluate the mercury contamination of French Guiana rivers (Gentès et al., 2017). A total number of 6385 fish samples were analyzed for mercury concentration,

which included 2118 carnivorous, 2095 omnivorous, 1367 benthivorous, and 805 herbivorous (Table 1).

2.2. Mercury analysis

Fish muscles were oven dried at 45 °C during 48 h and an aliquot (16 ± 4 mg) was analyzed for total Hg concentration. The analyze was carried out by flameless atomic absorption spectrometry (Varian AA 475 and AMA 254 - SYMALAB France). Over the total length of the survey (1993–2020), analytical technics evolved but intercalibration analyses were conducted in order to avoid potential analytical bias. Detection limit of the instrument was on average $1.4 \pm 0.12 \text{ ng/g}^{-1}$. The validity of the analytical method was verified with three biological reference materials from NRCC-CNRC (Ottawa, Canada): TORT-2 (lobster hepatopancreas), DORM-2 (dogfish muscle), DOLT-2 (dogfish liver), and one from the International Atomic Energy Agency: IAEA407 (fish tissue). Over the duration of the sample analysis, the average recovery percentage of the biological reference materials is $98 \pm 2.98\%$ for N = 725 analyzes. Preliminary studies based on weight measurements in a large number of muscles from different fish species showed that the ratio fw/dw is 5 (data not presented here). Measurements, expressed in dry weight (DW) by the device, are therefore converted into wet weight (WW) following this relationship. All the Hg concentration values for

Table 1

Total number of fishes analyzed in Hg for 7 species and trophic levels as a function of time and study area: Upstream, lake and downstream.

	Upstream	Lake	Downstream	Total
Carnivorous	520	263	1335	2118
<i>Acestrorhynchus</i>	146	159	630	935
1993–1994	1	1	13	15
1995–2000		10	77	87
2001–2007	59	33	296	388
2008–2013	37	75	118	230
2014–2020	49	40	126	215
<i>Hoplias aimara</i>	374	104	705	1183
1993–1994	120	19	111	250
1995–2000	138	26	438	602
2001–2007	62	42	147	251
2008–2013	29	12	8	49
2014–2020	25	5	1	31
Benthivorous	21	685	661	1367
<i>Curimata cyprinoides</i>	21	685	661	1367
1993–1994		1	4	5
1995–2000		34	38	72
2001–2007	19	396	388	803
2008–2013		132	123	255
2014–2020	2	122	108	232
Omnivorous	598	465	1032	2095
<i>Leporinus friderici</i>	395	140	520	1055
1993–1994	17	9	99	125
1995–2000	7	35	126	168
2001–2007	155	35	178	368
2008–2013	91	40	64	195
2014–2020	125	21	53	199
<i>Triportheus brachipomus</i>	203	325	512	1040
1993–1994	7		24	31
1995–2000	2	18	48	68
2001–2007	54	102	244	400
2008–2013	77	109	77	263
2014–2020	63	96	119	278
Herbivorous	399	106	300	805
<i>Mylopus ternetzi</i>	399	106	300	805
1993–1994	25	12	112	149
1995–2000	3	7	87	97
2001–2007	138	22	55	215
2008–2013	106	39	18	163
2014–2020	127	26	28	181
Total	1538	1519	3328	6385

fish muscles presented in this paper are expressed in wet weight.

2.3. Statistical analyses

Descriptive values presented in this study correspond to the mean values of a population and its associated standard error (SE). After validating the normality of the data via a Shapiro test, Wilcoxon-Mann-Whitney test is used to determine the difference between mean mercury concentrations as well as mean standard lengths. If not specified, the significance is calculated at the 95% confidence level.

3. Results and discussion

3.1. Spatial and temporal strategies

The Sinnamary river continuum, with its 262 km of length and 6565 km² of catching basin, is the fifth most important hydrosystem of French Guiana (de Merona, 2005). The Sinnamary hydrosystem, with its dam reservoir, is therefore a complex system, altering both lotic and lentic zones. For the purpose of this study, this region is spatially divided into three areas (Fig. 1): (i) the upstream area with lotic waters, sites located on the Sinnamary river, upstream of the dam lake area, a region supposedly free of gold mining activities, (ii) the reservoir area or lake with

lentic waters, and (iii) the downstream area, sites located downstream the dam, with lotic waters.

Since 1993, surrounding the creation of the dam, the HYDRECO laboratory collected monthly rainfall data and measured oxygen concentration from different depths of the dam reservoir which allowed the determination of the position of the oxycline (transition from oxygenated to anoxic waters). The depth position of the lake oxycline in relation to monthly rainfall dataset from 1995 (reservoir impoundment) to 2020 is presented in Fig. 2. While a significant decreasing trend is observed in the oxycline dataset ($R^2 = 0.2469$) there is no significant trend in the rainfall data ($R^2 = 0.0032$) and therefore no significant relationship exists between the oxycline depth and the rainfall amount variabilities ($R^2 = 0.0077$). In January 2000 an exceptional rainfall event, labelled as a decamillennial flood, occurred. In one event, it rained 800 mm while the maximal rainfall in January during the studied period is 546 mm. This type of rainfall event has strong repercussions on the position of the oxycline. Moreover, to prevent the dam from giving way under the pressure of the water, EDF had to release large quantities of water which caused major disturbances downstream of the dam. The oxycline variability is therefore function of both the aging of lake, the more time passes, the more the biofilm resulting from the submerged leaf mass disappears and degrades, and the occurrence of large precipitations events. Taking into account the position of the oxycline fish

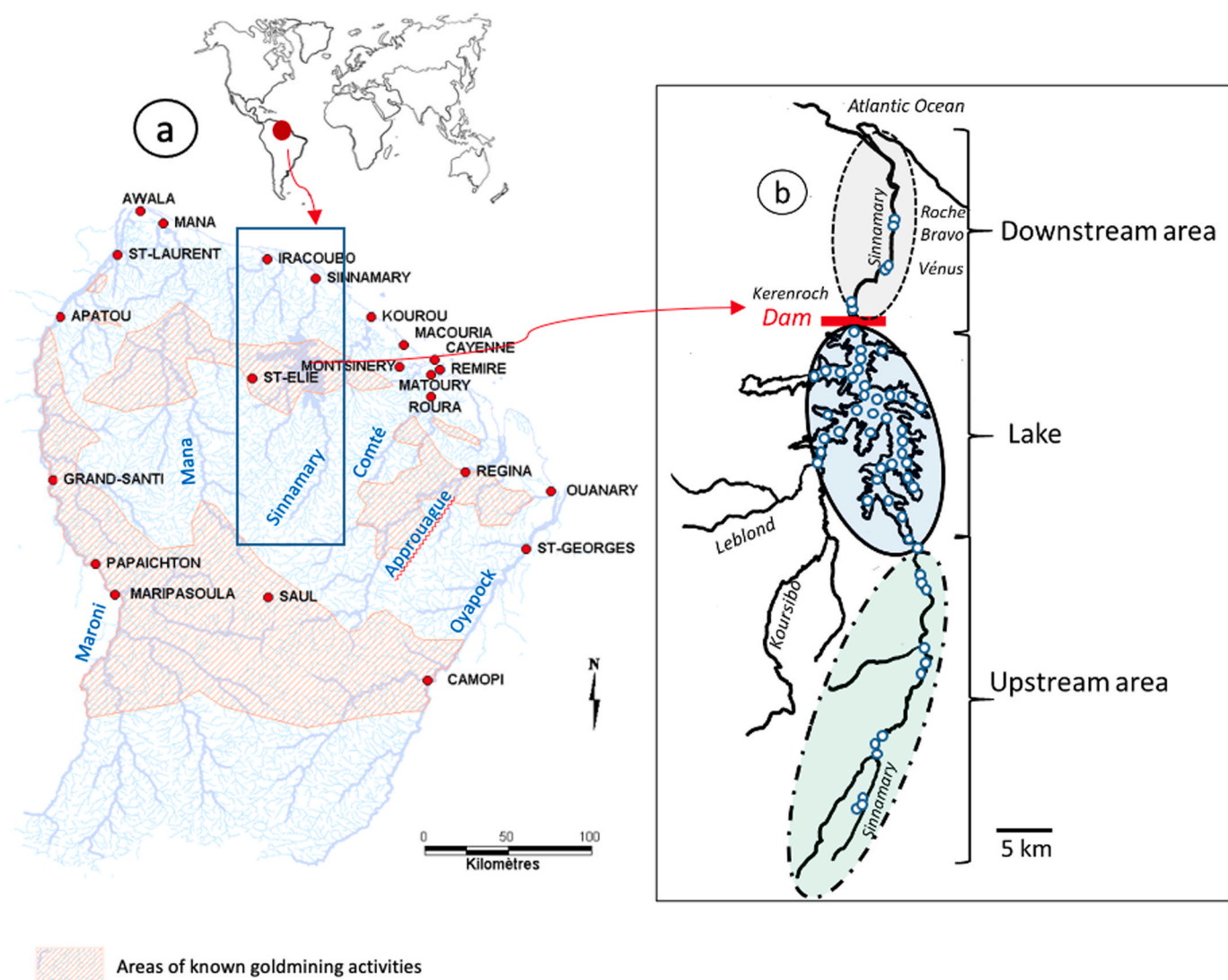


Fig. 1. a. Map of the gold mining activities in French Guiana (Modified from BRGM/RP-55965-FR, September 2007). b. Map of the study area, with the location of the 57 sites (white circles) on the three Sinnamary regions: Upstream, Lake, and Downstream.

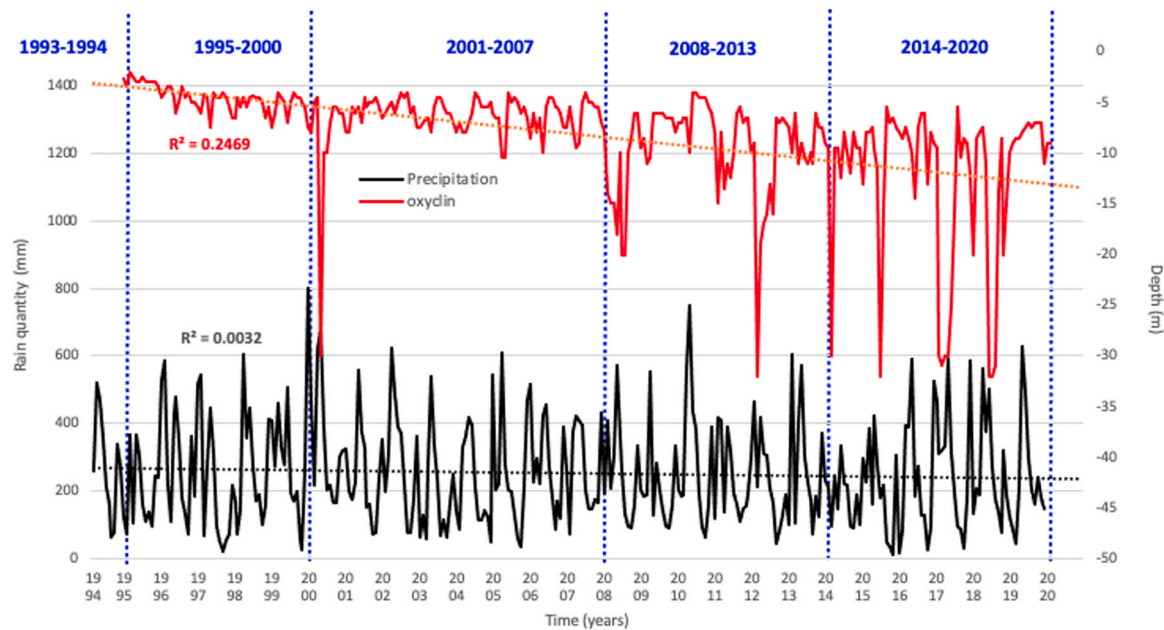


Fig. 2. Monthly rainfall dataset (in black) from 1994 to 2020 in relation to the position of the lake oxycline (in red) from 1995 (dam impoundment) to 2020 (courtesy of HYDRECO GUYANE).

mercury contamination data are separated into five periods: 1) before 1994, it is before the reservoir impoundment 2) from 1995 to 2000, it is right after the reservoir impoundment, the underwater vegetation degradation consumes lake oxygen, 3) from 2001 to 2007, following the decamillennial rainfall event of January 2000, the lake received a large quantity of water which oxygenated the lake and deepened the oxycline, 4) from 2008 to 2013, a large deepening of the oxycline is observed in relation to rainy seasons and to the decrease of the lake biofilm concentration allowing a better oxygenation of the lake, 5) from 2014 to 2020, the deepening of the oxycline is more pronounced and occur every year during the wet season.

In the exposed study, total mercury concentrations in fish will be studied in accordance to the fish trophic level, the spatial location, and the five-oxycline temporal periods described above.

Mercury concentrations in fish of different food diets are not homogeneous neither in space nor time (Fig. 3). Whichever the area is, there is a high difference in mercury concentration means between the four food diets. Carnivorous fish present the highest mercury levels; benthivorous fish are in the second position in a decreasing order for

mercury concentration, both diets exceeding the WHO recommendation (0.5 mg/kg WW; WHO, 1990) fish. Herbivorous fish have the lowest mercury concentrations. Regarding both omnivorous and benthivorous (except the 2001–2007 period), their mercury concentrations have intermediate values but differ between areas. A specific focus is realized on each studied food diet in the sections below.

3.2. Carnivorous

There are three carnivorous species: *Acestrorhynchus microlepis*, *Acestrorhynchus falcatus*, and *Hoplias aimara*. Mercury concentrations for both *Acestrorhynchus* species were pooled because they are similar species, they feed on the same preys (Table 2), and no statistical differences were found between their mercury concentration values. Within a same carnivorous species, fish size has an influence on mercury concentration: the longer the fish is, the older it is and therefore the higher its mercury concentration is (Roulet and Maury-Brachet, 2001). Carnivorous fishes caught in the Sinnamary continuum show a large range of size from 5 cm to more than one-meter long; we therefore defined a narrower size range

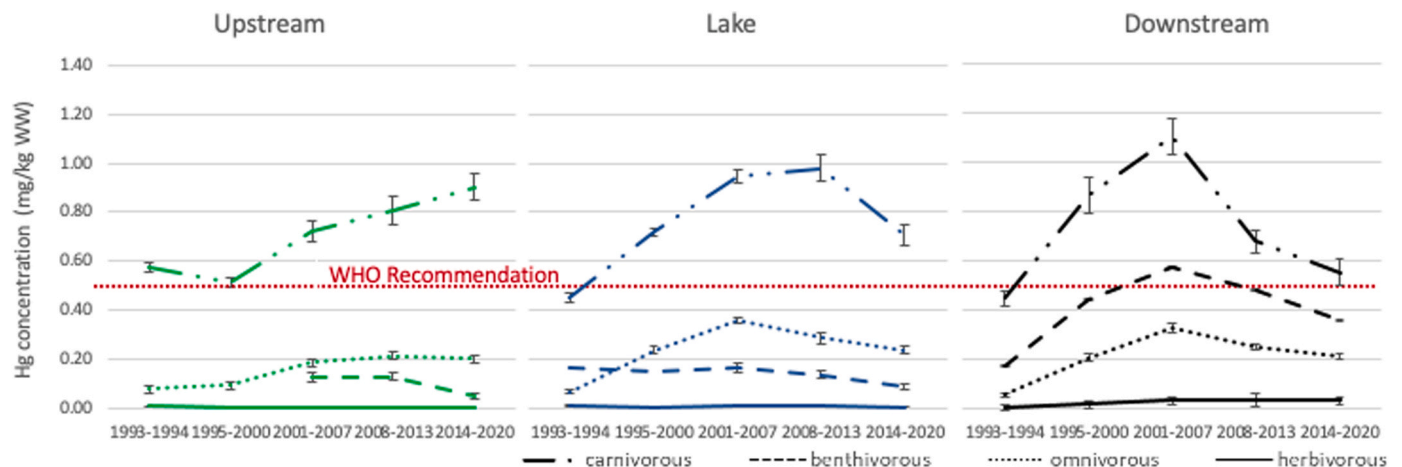


Fig. 3. Total mercury concentration in the four fish diets as a function of the three regions and the five time periods. The red dotted line represents the WHO recommendation limit (0.5 mg.kg⁻¹WW).

Table 2
Diet of the 7 main species studied (in percentage) based on the number of fishes sampled (De Mérona et al., 2009).

	Carnivorous			Benthivorous	Omnivorous		Herbivorous
	<i>Acestrorhynchus falcatus</i>	<i>A. microlepis</i>	<i>Hoplias aimara</i>	<i>Curimata cyprinoides</i>	<i>Leporinus friderici</i>	<i>Triplotheus brachipomus</i>	<i>Myloplus ternetzi</i>
Number	39	30	11	53	78.51	270	167
Plants				3.77	78.51	56.38	97.78
Algae					0.26	0.22	
Terrestrial invertebrate		3.33			6.62	38.78	1.38
Aquatic invertebrate					1.23	1.02	
Plankton				3.21			
Decapod			18.18	1.89	0.19	0.11	
Fishes	100	96.67	81.82		7.99	2.88	
Sediment				91.13	5.2	0.61	0.84

for each species that represent the majority of the fish sizes to facilitate comparison between species of same age at different sites. For *A. microlepis* and *A. falcatus* we only considered fish ranging from 10 to 30 cm and for *H. aimara* fish between 38 and 82 cm (Table 1) as recommended by Gentès et al. (2017).

For *Acestrorhynchus*, mean mercury concentrations and SE are: 0.674 ± 0.401 , 0.847 ± 0.588 , and 0.617 ± 0.470 mg.kg⁻¹ in the upstream, the reservoir, and the downstream areas, respectively (Fig. 4a). Mean mercury concentration levels of *Hoplias* are 0.669 ± 0.374 , 0.746 ± 0.407 , and 1.049 ± 0.485 mg.kg⁻¹ in the upstream, the reservoir, and the downstream areas, respectively (Fig. 4b). Mercury concentration levels of *Hoplias* are globally significantly higher than *Acestrorhynchus*. *Hoplias*

are three times bigger than *Acestrorhynchus* (Planquette et al., 1996), with indeed bigger digestive tracts which allow *Hoplias* to swallow larger preys that are more contaminated in mercury (Depew et al., 2013). Most of the mercury concentration values of both species are above the WHO recommendation value (Table 3). For both species, an increase of the percentage of fishes presenting values higher than the WHO value can be observed along the Sinnamary continuum going from 75% to 100% for *Acestrorhynchus* and from 80% to 94% for *Hoplias aimara*.

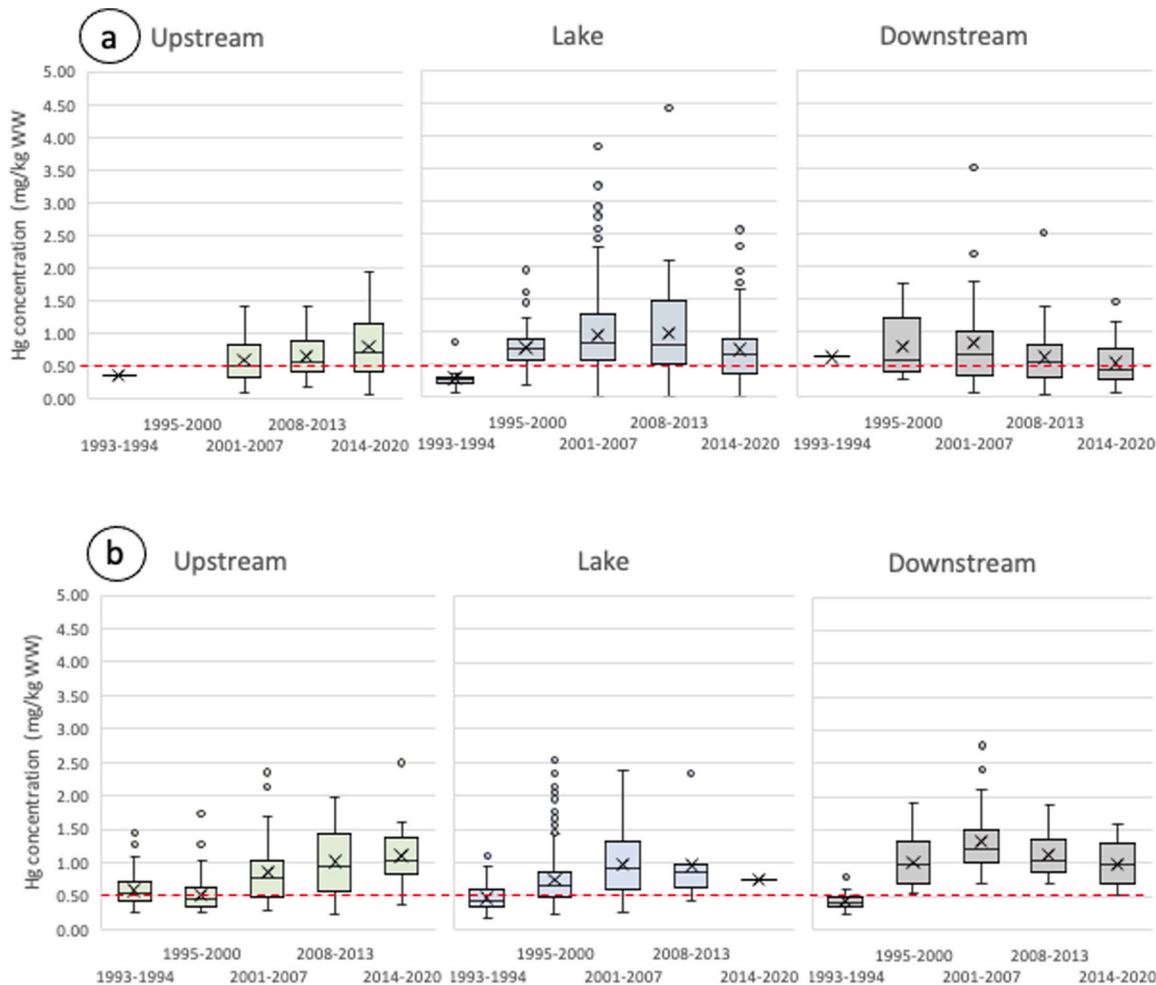


Fig. 4. Total mercury concentration in the two carnivorous species studied (a: *Acestrorhynchus* and b: *Hoplias aimara*) as a function of the three areas and the five time periods. The red dotted line represents the WHO recommendation value (0.5 mg.kg⁻¹ WW; WHO, 1990).

Table 3Percentage of fish above the WHO standard ($> 0.5 \text{ mg.kg}^{-1} \text{ WW}$) depending on the areas concerned.

Diet	Species		Upstream	Lake	Downstream	Total
Carnivorous	<i>Acestrorhynchus</i>	<i>falcatus</i>	75%	87%	100%	88%
	<i>Acestrorhynchus</i>	<i>microlepis</i>				
	<i>Hoplias</i>	<i>aimara</i>	80%	85%	94%	85%
Benthivorous	<i>curimata</i>	<i>cyprinoides</i>	0%	6%	57%	32%
Omnivorous	<i>Leporinus</i>	<i>friderici</i>	17%	32%	12%	24%
	<i>Triportheus</i>	<i>brachipomus</i>	0%	17%	18%	14%
Herbivorous	<i>Myloplus</i>	<i>ternetzi</i>	0%	0%	0%	0%

3.3. Benthivorous

The benthivorous species chosen for the study is *Curimata cyprinoides*. For *Curimata cyprinoides*, mean mercury concentrations and SE are: 0.122 ± 0.087 , 0.149 ± 0.146 , and $0.511 \pm 0.245 \text{ mg.kg}^{-1}$ in the upstream, lake, and downstream areas, respectively (Fig. 5). Due to the lack of data in the upstream area, the mercury contamination is only discussed for the lake and the downstream areas. Mean mercury concentration level in the lake area is significantly lower than in the downstream area. This corroborates the results presented by Dominique et al. (2007) who found that in 2003, downstream fish were ten times more contaminated than lake fish. Furthermore, only six percent of the lake fish present mercury concentration values above the WHO recommendation value compared to 56% in the downstream area (Table 3). This high percentage is mainly influenced by the high levels of mercury concentrations monitored during the 2001–2007 period. After that period a significant decrease in mercury concentration is observed. A similar decrease is observed in the lake area for the same time period. The food diet of *Curimata* fish from the lake is different than the one from the downstream region (Dominique et al., 2007). In the lake area, the presence of the oxycline forces *Curimata* fish to live in the surface water of the lake and therefore feed on plankton. In the downstream area, *Curimata* fish can however feed on the highly contaminated biofilm (Dominique et al., 2007), leading to their high mercury contamination.

3.4. Omnivorous

The studied omnivorous species are: *Leporinus friderici* and *Triportheus brachipomus*. For *Leporinus friderici*, mean mercury concentrations and SE are: 0.197 ± 0.233 , 0.279 ± 0.300 , and $0.215 \pm 0.132 \text{ mg.kg}^{-1}$ in the upstream, lake, and downstream areas, respectively (Fig. 6a). For *Triportheus brachipomus*, mean mercury concentrations and SE are: 0.187 ± 0.127 , 0.269 ± 0.180 , and $0.270 \pm 0.164 \text{ mg.kg}^{-1}$ in the upstream, lake, and downstream areas, respectively (Fig. 6b).

Leporinus friderici presents mercury concentrations in the upstream and lake areas higher than *Triportheus*, especially in the lake area where

32% of the fish have mercury concentrations higher than the WHO value (Table 3). Both omnivorous species present however a similar mercury contamination pattern along the river continuum with mercury concentration values encircling the WHO limit. For the three different regions, both species present a significant increase in mercury concentration between the 1995–2000 and the 2001–2008 periods, following the reservoir impoundment. Mercury concentrations in *Triportheus brachipomus* from the downstream area present high value even before the reservoir impoundment. De Mérona (2009) showed that fish change their diet between the upstream and the downstream zone. Upstream fish are mainly herbivorous while downstream fish feed on invertebrates which would explain the mercury concentration differences.

3.5. Herbivorous

The studied herbivorous species is: *Myloplus ternetzi*. For *Myloplus ternetzi* the mean mercury concentration and SE are: 0.004 ± 0.005 , 0.009 ± 0.011 , and $0.033 \pm 0.017 \text{ mg.kg}^{-1}$ in the upstream, lake, and downstream areas, respectively (Fig. 7a). There is an increasing trend along the Sinnamary continuum with very low values upstream, a slight increase in the lake area and higher values in the downstream area. All the analyzed fish present mercury concentration level below the WHO recommendation (Table 3). We observe however a large shift toward higher mercury concentration values in the downstream area from the 1995–2000 to the 2001–2013 period. *Myloplus* are known to consume riparian plants covered in highly contaminated biofilm (Dominique et al., 2007).

If we zoom into the downstream area, downstream area values come from three different sites: Kerenroch, Roche Bravo and Pointe Combi (Fig. 7b). To be able to compare significantly the three different sites, data were divided into 3 instead of 5 time periods: from 1993 to 2000, from 2001 to 2013 and from 2014 to 2020 (Fig. 7c). A decreasing trend is observed in mercury concentration from the foot of the dam toward the estuary (Fig. 7c), this is due to the tide dilution effect. However, at each site, there is a peak in mercury concentration during the

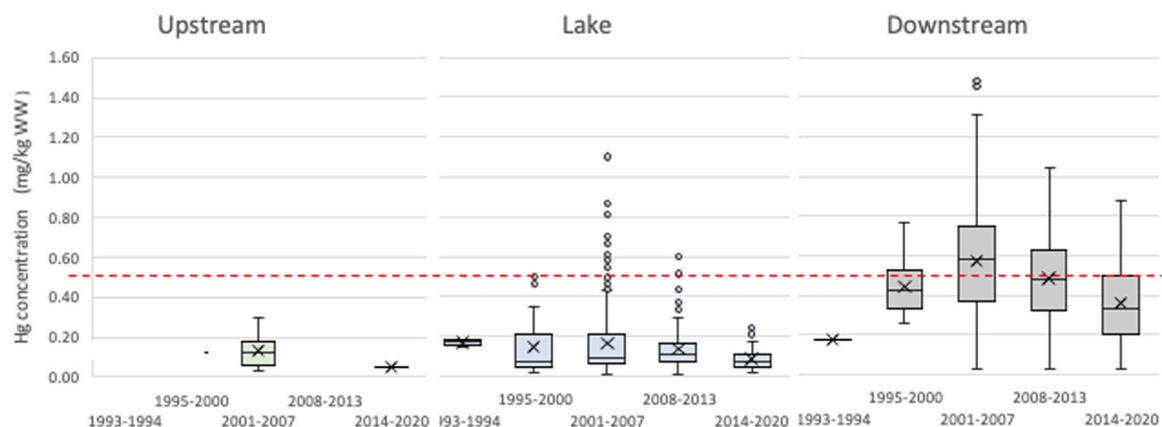


Fig. 5. Total mercury concentration in the benthivorous species *Curimata cyprinoides* as a function of the three regions and the five time periods. The red dotted line represents the WHO recommendation value ($0.5 \text{ mg.kg}^{-1} \text{ WW}$; WHO, 1990).

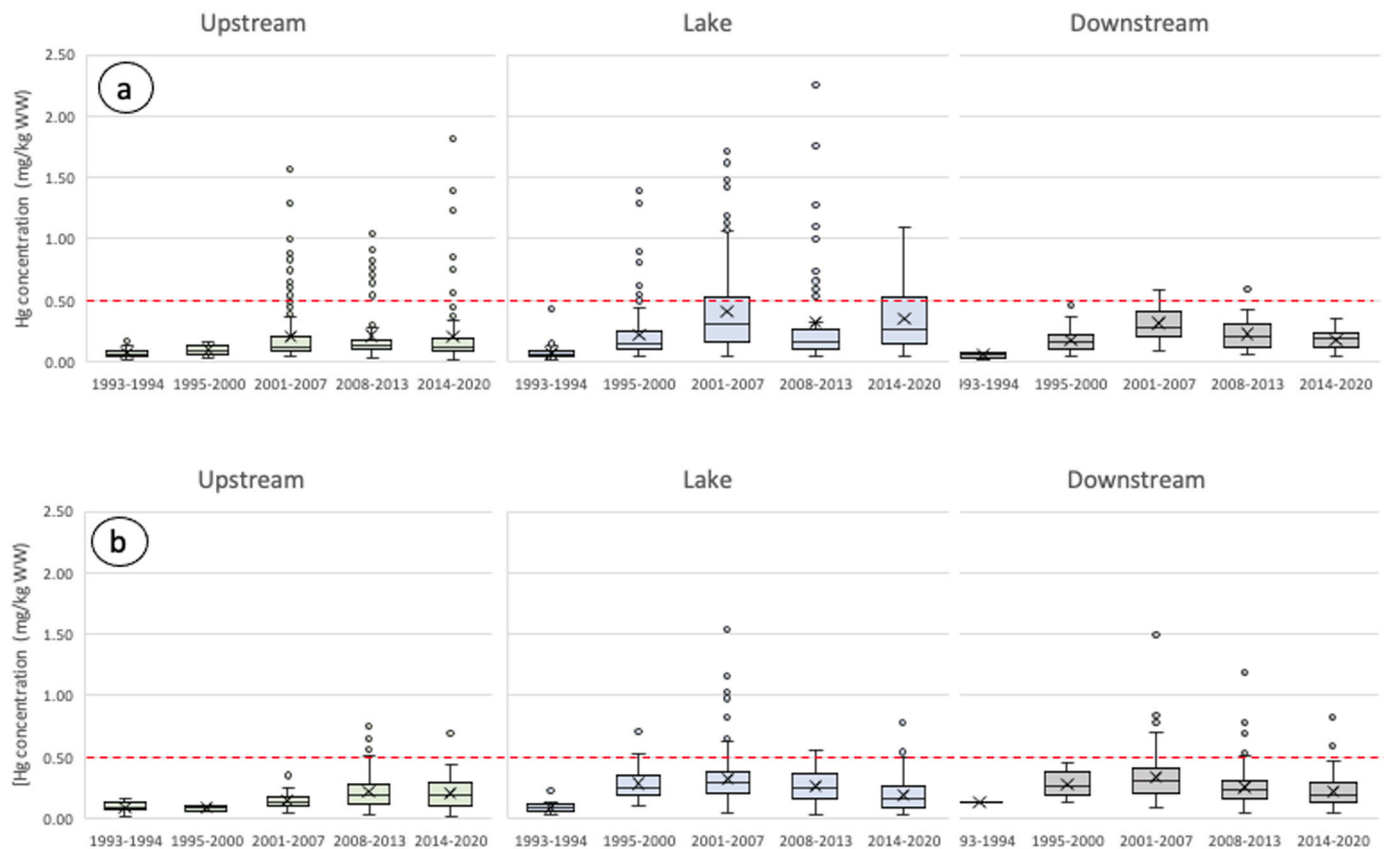


Fig. 6. Total mercury concentration in two omnivorous species: (a) *Leporinus friderici* and (b) *Triportheus brachipomus* as a function of the three regions and the five time periods. The red dotted line represents the WHO recommendation value ($0.5 \text{ mg.kg}^{-1} \text{ WW}$; WHO, 1990).

2001–2013 period.

3.6. Spatial and temporal evolution of the mercury contamination in relation to the reservoir impoundment

As seen previously, the temporal evolution of the dam impoundment had a large influence on mercury concentration values in fish from all trophic levels, however temporal patterns of mercury concentrations are spatially different.

If we focus on the upstream region, mercury concentration starts to increase between the 1995–2000 and the 2001–2007 periods and continues today, especially for the carnivorous and omnivorous species which show a doubling of their mercury concentration (Figs. 4 and 6). The large increase in mercury concentration between the 1995–2000 and the 2001–2007 periods is linked to the dam impoundment and the 2000 flooding event. During the large 2000 flooding event (Fig. 2), the Lake overflowed upstream and contaminated biofilm were transported into the upstream Sinnamary region. However, both *Acestrorhynchus* and *Hoplias aimara* presented, even before the dam impoundment, mercury concentration levels higher than the values found in “Trois Sauts”, a pristine area of the Oyapock river (Maury-Brachet et al., 2020). Additionally, mercury concentration in both the carnivorous and omnivorous species stay high for the remaining of the records (from 2001 to 2020). Those observations cannot be solely due to the dam impoundment. French Guiana is under a lot of pressure regarding illegal gold mining activities that release high quantity of mercury into the atmosphere (Fig. 1a). One hypothesis is that the upstream Sinnamary region receives airborne mercury contamination from nearby illegal gold mining activities on the Approuague and Comté rivers (Fig. 1). There are three meteorological stations, that measure wind, surrounding the upstream Sinnamary region: Maripasoula (to the West); Cayenne airport (to the North), and Saint Georges (to the Est). Wind roses from both

Maripasoula and Cayenne airport indicate a main North East prevailing wind all year long. Saint Georges presents, however, a seasonal pattern with a prevailing East/South-East wind from May to November. It can be therefore assumed that this prevailing wind can bring airborne particles for the nearby illegal gold mining activities on the Approuague and Comté rivers to our upstream Sinnamary region.

For the Lake region, the mercury concentration data present a bell-shaped pattern. There is a large increase in the mercury concentration following the 1994 dam impoundment. A consequence of the dam impoundment is the rise of the lake oxycline in the water column which favors the production of methylmercury and therefore the Hg contamination of lake fish (Coquery et al., 2003; Dominique, 2006; Muresan Paslaru, 2006). Between the 2008–2013 and the 2014–2020 periods, a decrease in mercury contamination is observed. Once the vegetation that has been submerged during the dam impoundment has been fully degraded, the anoxic conditions are progressively disappearing which is observed with the deepening of the oxycline (Fig. 2). The lake conditions are therefore getting better (less methylmercury production) and fish are becoming with time be less and less contaminated. A positive consequence of the dam impoundment is the creation of a permanent-like flood conditions in the lake area. This permanent rise in the water level was accompanied by an increase in nutrients levels which was beneficial for certain species of lake-riverbank fish, which then proliferates (De Mérona, 2005).

The story of the downstream area is a bit more complex; the dam impoundment had two major impacts on the fish concentrations. There is an increase in mercury concentration from the 1993–1994 to the 1995–2000 period. During the construction of the dam, there were a resuspension of the sediments containing high levels of mercury from both legal and illegal gold mining actives along the Sinnamary river continuum (Carmouze, 2001; Laperche et al., 2007, 2008). In 1995, the conditions of the downstream Sinnamary were anoxic which led EDF to

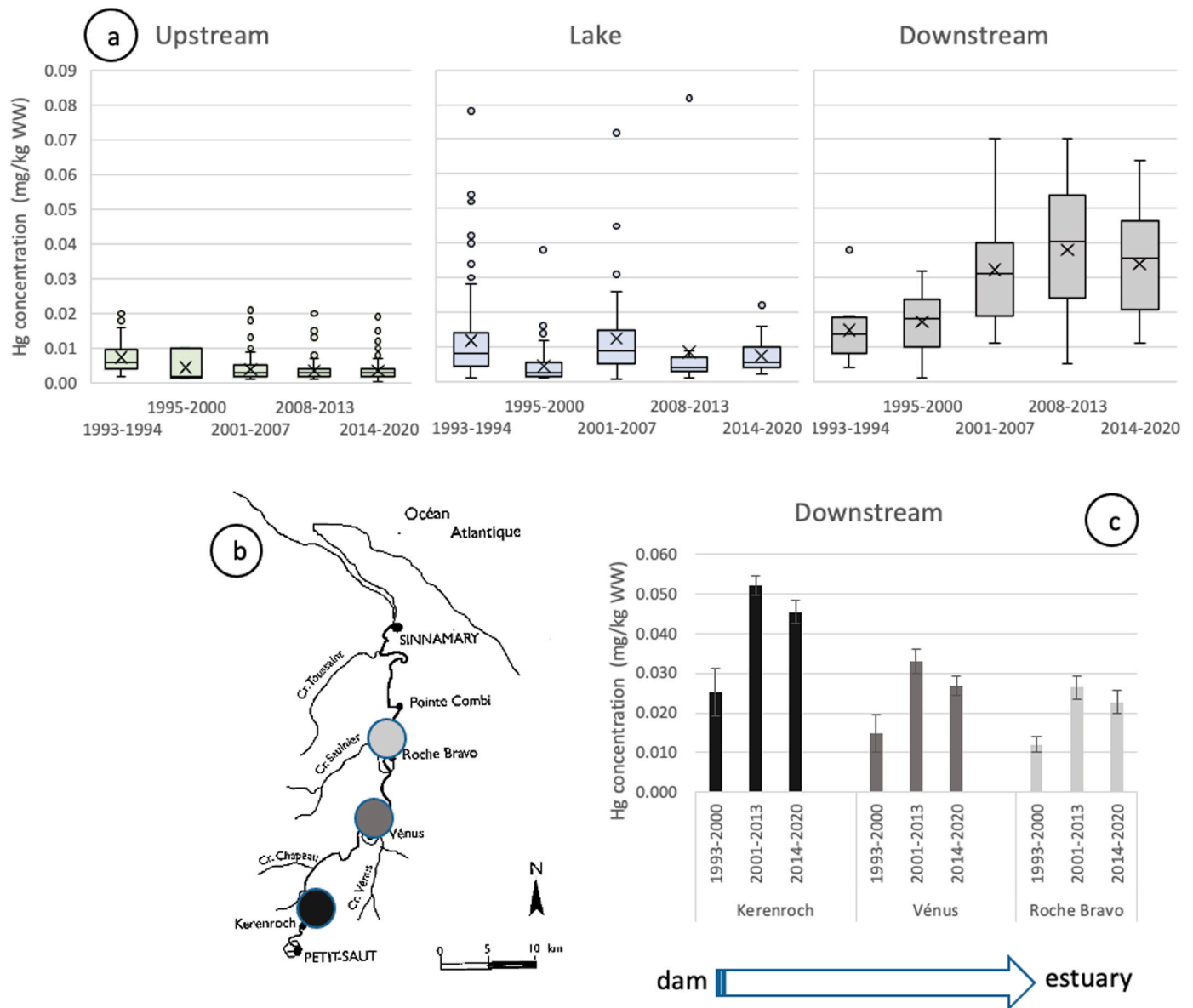


Fig. 7. Total mercury concentration in the herbivorous specie *Myloplus ternetzi* as a function of (a) the three regions and five time periods (b and c) in the three downstream sampling zones.

install a device to artificially oxygenate the river to allow viable conditions for the aquatic species. The second large increase in mercury concentration, observed for all the species, took place between the 1995–2000 and the 2001–2007 periods. The January 2000 large flooding event (Fig. 2), that transported highly contaminated biofilm in methylmercury from the lake region into the upstream Sinnamary region, had also consequences on the downstream area. This flooding event threatened to break the dam, therefore EDF opened the dam valves which are located at the bottom of the dam. The opening of the valves created an enormous wave that scraped the bottom of the downstream river and destroyed the benthic fauna and flora. Moreover, degraded vegetation from the bottom of the lake was also released into the downstream region creating a large production of methane, sulphureous hydrogen, and methylmercury (Muresan Paslaru, 2006; Abril et al., 2013). Higher levels of mercury contamination are observed in both herbivorous and benthivorous species in the downstream area where those species feed on the highly contaminated biofilm. A decrease in mercury concentration can be observed from the 2008–2013 period to today, leading to conclude that the conditions are improving.

Additionally, right after the January 2000 flooding, in the upstream area, the total number of fish species has fallen by more than half, and a proliferation of species that modified their food diet such as *Myloplus ternetzi* and *Curimata cyprinoides* (De Mérona, 2005; Dominique, 2007) was observed.

4. Conclusions

The transformation from a river-forest ecosystem into a lake ecosystem cannot be without any consequence for the natural environment. The Petit Saut dam impoundment had indeed led to serious environmental consequences. On average, all the species presented in this study present a significant increase in their mercury contamination levels following the dam impoundment. However, there are differences between trophic levels with 75–100% of the carnivorous fish presenting mercury concentration values above the WHO value, 57% for the downstream benthivorous, 32% of the omnivorous and 0% of the herbivorous. These fish mercury concentration levels may pose a risk to human health. Dam impoundment has broken the natural seasonality of

the Sinnamary river that was alternating between high level during the rainy season and low level the rest of the year. This has favored some species such as benthivorous and herbivorous species presented in this study in regard of some others, depending of the adaptability of their food diet. While mercury contamination levels are species-dependent they also vary both spatially and temporally. We observe an increase in fish mercury concentrations from the dam impoundment to the 2002–2007 period followed by a slow decrease toward present. Dam impoundment still has a large effect on the Sinnamary continuum but it appears that the impact of the dam is diminishing over time. Those environmental consequences could have been avoided by both removing the forest before the impoundment and positioning the dam’s valves, which are currently located at the bottom of the dam, to a higher position which will prevent the contaminated biofilm from the anoxic region to reach downstream area. Unfortunately, as long as illegal gold mining activities will be largely present in French Guiana the problem of mercury contamination will still exist.

CRediT authorship contribution statement

Régine Maury-Brachet Conceptualization, Methodology, Writing – original draft preparation, **Émilie P. Dassié** Writing – original draft preparation, **Alexia Legeay** Writing – review & editing, **Patrice Gonzalez** Writing – review & editing, **Agnès Feurtet-Mazel** Writing – review & editing, **François Gourand**, Investigation, **Yannick**

Dominique, Investigation and **Régis Vigouroux** Funding acquisition, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Annex 1. Mean and standard error of biometry data including weight and standard length from the different fish species per time period

Species and periode	Upstream					Downstream					Lake				
	N	Standard length (cm)		Weight (g)		N	Standard length (cm)		Weight (g)		N	Standard length (cm)		Weight (g)	
		Mean	SE	Mean	SE		Mean	SE	Mean	SE		Mean	SE	Mean	SE
<i>Acestrorhynchus</i>	146	15.92	0.3	56	4	159	14.95	0.3	49	4	630	17.08	0.2	77	3
1993–1994	1	20.00	0.0	112	0	1	24.00	0.0	264	0	13	20.79	0.4	165	33
1995–2000						10	23.00	0.8	175	20	77	21.84	0.4	160	9
2001–2007	59	16.22	0.4	62	8	33	14.29	0.6	43	7	296	16.32	0.3	66	3
2008–2013	37	16.61	0.6	64	9	75	14.33	0.3	39	4	118	17.50	0.4	72	4
2014–2020	49	14.94	0.4	41	4	40	14.44	0.5	36	4	126	15.20	0.4	48	3
<i>Curimata cyprinoides</i>	21	15.92	0.2	111	5	685	14.70	0.1	107	3	661	17.22	0.1	154	3
1993–1994						1	16.00	0.0	101	0	4	21.63	0.5	341	41
1995–2000						34	18.60	0.4	170	9	38	18.97	0.6	219	23
2001–2007	19	15.79	0.2	109	5	396	15.22	0.2	124	4	388	16.30	0.1	137	3
2008–2013						132	13.96	0.2	85	5	123	18.61	0.2	176	5
2014–2020	2	17.15	0.1	135	3	122	12.73	0.2	61	3	108	18.17	0.2	163	6
<i>Hoplias aimara</i>	374	56.43	0.5	4180	111	104	55.93	1.2	4109	279	705	56.28	0.3	4120	87
1993–1994	120	56.43	0.9	4213	224	19	48.53	1.3	2334	232	111	54.68	1.1	4216	300
1995–2000	138	56.56	0.8	4258	185	26	69.02	2.4	6869	625	438	56.33	0.4	4115	107
2001–2007	62	53.17	1.0	3495	183	42	51.91	1.4	3539	331	147	57.50	0.7	4113	139
2008–2013	29	58.63	1.6	4466	324	12	53.71	3.6	3407	805	8	54.36	2.0	3400	334
2014–2020	25	61.15	1.9	4962	379	5	55.08	4.6	2979	474	1	46.00	0.0	2311	0
<i>Leporinus friderici</i>	395	19.95	0.3	241	13	140	28.57	0.6	751	33	520	25.03	0.3	543	23
1993–1994	17	29.07	1.7	831	170	9	30.44	2.3	946	194	99	33.78	0.5	1257	52
1995–2000	7	23.71	2.5	322	124	35	30.40	0.7	818	57	126	27.77	0.6	660	45
2001–2007	155	19.19	0.5	219	15	35	28.69	1.1	757	57	178	21.01	0.3	271	16
2008–2013	91	20.07	0.5	215	16	40	24.83	1.3	556	63	64	20.55	0.4	214	15
2014–2020	125	19.34	0.4	203	13	21	31.65	1.1	915	71	53	21.05	0.5	241	17
<i>Mylius ternetzi</i>	399	12.60	0.2	105	4	106	15.78	0.4	207	14	300	17.85	0.2	266	9
1993–1994	25	19.58	0.4	333	18	12	18.68	0.5	290	22	112	19.14	0.2	310	12
1995–2000	3	18.50	1.3	285	48	7	20.06	1.3	397	72	87	20.88	0.2	343	14
2001–2007	138	12.77	0.2	109	6	22	14.72	1.0	193	33	55	15.33	0.6	203	18
2008–2013	106	11.49	0.2	70	5	39	15.38	0.6	184	20	18	11.88	0.9	92	19
2014–2020	127	11.83	0.2	82	5	26	14.78	0.7	164	22	28	12.03	0.6	90	13
<i>Triportheus brachipomus</i>	203	16.65	0.2	84	2	325	20.40	0.2	170	4	512	18.17	0.1	113	2
1993–1994	7	19.21	0.6	127	11						24	23.05	0.4	228	12
1995–2000	2	21.25	0.3	139	6	18	20.59	0.6	158	17	48	19.90	0.2	145	5
2001–2007	54	15.45	0.2	70	3	102	19.94	0.3	169	7	244	18.00	0.1	109	3
2008–2013	77	16.93	0.2	86	3	109	20.94	0.3	179	8	77	17.64	0.2	100	3
2014–2020	63	16.91	0.4	87	6	96	20.23	0.3	165	8	119	17.19	0.2	94	3
Total	1538	26.04	0.5	1124	52	1519	20.12	0.3	455	32	3328	26.89	0.3	1043	33

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