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RESEARCH ARTICLE

Mercury concentrations in fish and human health assessment in preflood phase of a hydro dam in Teles Pires River, Southern Brazilian Amazon

Liliane Stédile de Matos[1,2,*], Anne Sthephane Arrolho Silva Correa[2,3], Solange Aparecida Arrolho da Silva[1,2], Claumir Cesar Muniz[4,5], and Aurea Regina Alves Ignacio[4,5]

Ingestion of fish is considered the main pathway of human exposure to methylmercury (MeHg), particularly for riverside populations, where fish is the main source of protein. The objective of this study was to estimate concentration of MeHg based on total concentration of mercury in muscles of three species of carnivorous fish: *Boulengerella cuvieri* (bicuda), *Serrasalmus rhombeus* (piranha), and *Hydrolycus armatus* (cachorra), collected from Teles Pires River, Brazil. Furthermore, we calculated human health risk related to MeHg contamination caused by fish consumption. Fish were collected in 20 field campaigns from December 2011 to September 2016 at Teles Pires River, in area of influence of Colíder hydroelectric plant. Risk index (RI) related to ingestion of MeHg through fish intake was calculated considering that MeHg corresponds to around 90% of mercury in fish. There were no significant differences in average mercury concentration between all species: *S. rhombeus* (0.304 mg/kg^{-1}), *H. armatus* (0.229 mg/kg^{-1}), and *B. cuvieri* (0.199 mg/kg^{-1}). RI calculated for sensitive groups (lactating women, breastfeeding infants and children) and RI calculated for general population presented average values, suggesting adverse health effects. This first assessment on MeHg and human exposure to people from Teles Pires River area through fish consumption suggests that mercury concentrations might be posing health adverse effects on people of this sensitive group. Further studies involving more fish specimens and considering fish biological factors are needed to fully understand health risks of mercury exposure to humans in this region.

Keywords: Fish consumption, Carnivores, Risk index, Human health, Tapajós basin

1. Introduction

Mercury (Hg) is a naturally occurring element in earth's crust released by erosion prone rocks and geological movements and is redistributed between and within ecosystems by vegetation and soil or water movements (Sundseth et al., 2017). Anthropogenic mercury sources are mainly comprised of artisanal gold mining, fossil fuel powered power plants, ferrous and nonferrous metal industries, caustic soda manufacturing, waste incinerators, and cement factories (Pirrone et al., 2010). Mercury is also found in agricultural inputs used extensively in agriculture throughout year (Wuana and Okieimen, 2011; Opaluwa et al., 2012; Anim-Gyampo et al., 2013).

In the southern Amazon region, the main anthropogenic sources of mercury are gold mining, agriculture related land use activities, and forest burning (Matos et al., 2018). This area endured intense gold mining activity between 1970s and 1990s, followed by a decline due to reduced gold deposits in the region (Lobo et al., 2016). Logging, agriculture, and cattle ranching, all activities which use fire as a process to create open land, also contribute to erosion of naturally mercury enriched Amazonian soils (Lechler et al., 2000; Cordeiro et al., 2002). Land use activities in the Amazon were significantly accelerated in 1970, when manual workers, colonists, and landowners from the south and southeast regions of Brazil colonized drainage basins (Picoli, 2004). This colonization resulted

[1] Faculdade de Ciências Biológicas e Agrárias-FACBA, Universidade do Estado de Mato Grosso - UNEMAT, Alta Floresta, MT, Brazil

[2] Laboratório de Ictiologia da Amazônia Meridional-LIAM, Universidade do Estado de Mato Grosso - UNEMAT, Alta Floresta, MT, Brazil

[3] Programa de Pós-Graduação em Genética e Melhoramento de Plantas-PGMP, Universidade do Estado de Mato Grosso - UNEMAT, Alta Floresta, MT, Brazil

[4] Faculdade de Ciências Biológicas e Agrárias, Universidade do Estado de Mato Grosso-UNEMAT, Cáceres, MT, Brazil

[5] Laboratório de Ecotoxicologia, Centro de Pesquisa em Limnologia, Biodiversidade e Etnobiologia - CELBE, Cáceres, MT, Brazil

* Corresponding author:
Email: lilistedile@hotmail.com

in increased mercury runoff into rivers as seen in sediments of the Tapajós River (Roulet et al., 2000).

The most recent anthropogenic activity to contribute to mercury release in Amazonian environment is construction of hydroelectric dams, justified on basis that they supply energy needed for economic development (Latrubesse et al., 2017). In Teles Pires River, for example, four hydroelectric plants (HEPs) were recently installed along a 450 km of river extension (Matos et al., 2020). HEP reservoirs, backwater areas, marginal and flood lakes are of concern as regards mercury exposure to wildlife and humans as they present biogeochemical conditions that favor mercury methylation (Lacerda and Malm, 2008). This is because mercury methylation is favored in aquatic environments in Amazonian hydro dams, typically presenting anoxic, suboxic, and slightly acidy waters with high concentrations of dissolved organic matter and intense microbiological activity (Lacerda and Malm, 2008).

Among mercury forms that are present in aquatic environments, methylmercury (MeHg) incites greatest interest from an ecotoxicological perspective, since it is a neurotoxin and has a tendency to bioaccumulate and biomagnify in trophic chains (Bisinoti and Jardim, 2004). Fish intake is considered the main pathway to human exposure from MeHg, particularly for riverside populations as fish is their main source of protein (Milhomem-Filho et al., 2016). To this end, analysis of fish muscle is a powerful tool to determine risk of mercury transfer to humans who feed on fish. Furthermore, information on MeHg concentrations in fish enables us to assess health risks posed to humans through fish intake (Copat et al., 2012).

In aquatic ecosystems, elemental (Hg^0) and inorganic (Hg^{2+}) forms of mercury are predominant (Verhaert et al., 2019). However, mercury contained in rivers can become more dangerous due to possibility of methylation (MeHg) with action of methanogenic bacteria (Shao et al., 2012). Because MeHg is soluble in fat and well absorbed by biological membranes and digestive tracts of aquatic organisms (Lacerda and Malm, 2008), it is readily absorbed by aquatic biota, bioaccumulating and biomagnifying into aquatic food chains (Porcela, 1994).

Mercury bioaccumulation can vary across ichthyofauna living in same water body, and such differences might be related to life cycle and feeding habits of each species (Hosseini et al., 2013). Organisms at the top of food chain usually present higher mercury concentrations than those at lower trophic levels, even when they inhabit same aquatic system (Campbell, 1994; Kidwell et al., 1995; Voigt, 2004; Terra et al., 2008). According to World Health Organization (WHO, 2006), recommended safety limit for fish consumption is 0.5 mg/kg of mercury. However, in Brazilian Amazon, studies have shown several fish species (carnivores, omnivores, planktivores, and piscivores) above this threshold limit (Kasper et al., 2012; Bastos et al., 2015; Castro et al., 2016; Lino et al., 2018). In Manuel Hydroelectric reservoir on Jamari River, carnivorous fish species presented high levels of mercury concentration upstream (0.545 mg/kg) and downstream of reservoir (1.366 mg/kg; Kasper et al., 2012). In a stretch of river close to Rio Madeira Hydroelectric Complex, mercury concentrations ranged from 0.51 to 1.242 mg/kg (Bastos et al., 2015). In view of this, studies in the Amazon region are necessary to understand whether the consumption of these fish collected in these hydro dam areas in the Amazon may represent a risk to the health of riverside communities and indigenous populations.

Considering the dramatic increase in hydro dam constructions in the Amazon region in the last 20 years and the natural high levels of mercury in the soils, the objective of this study was to establish a background concentration for carnivorous fish species prior to the flooding of Colider Hydro Dam so that future studies after flooding can be compared against. We calculate the concentration of MeHg, based on the total concentration of mercury (THg) in the muscle of different species of carnivorous fish: *Boulengerella cuvieri* (bicuda), *Serrasalmus rhombeus* (piranha), and *Hydrolycus armatus* (cachorra), collected from Teles Pires River. Specifically, we tested the hypothesis that fish species have same THg and MeHg concentrations in their muscle mass. The human health risk associated with MeHg consumption through fish was calculated for different populations in Mato Grosso, so as to assess the health risk consumption that these fish may represent for traditional communities consuming them.

2. Materials and methods

2.1. Study area

Site of this study is Teles Pires River, between municipalities of Colíder and Itaúba in Mato Grosso (**Figure 1**). Fish were collected from Teles Pires River (Mato Grosso), one of the main tributaries of Tapajós River of Brazilian Amazon. A range of land use is known in this region: cattle ranching, agriculture, gold mining, dumping of tannery effluents, and currently, hydroelectric plants are all present in area (Matos et al., 2018). These land use processes make this area highly prone to mercury runoff from soil and consequent deposition into water bodies (Roulet et al., 2000). Furthermore, artisanal gold mining activities using mercury for gold amalgamation processes directly discharged mercury into rivers (Malm et al., 1997). The construction of the Colíder Hydroelectric Plant started in 2011, with the formation of the reservoir at the end of 2017 (Matos et al., 2020); the capture of the specimens of this study was before the formation of the reservoir.

2.2. Fish collection and biometrics

Fish were collected in 20 fieldwork campaigns between December 2011 and September 2016. Considering that predatory top-of-the-chain species provide an integrated view of water body (Flotemersch et al., 2006) and are good models for mercury analysis, we analyzed three species of carnivorous fish: *B. cuvieri* (bicuda), *S. rhombeus* (piranha), and *H. armatus* (cachorra; **Table 1**). Trawls, fixed nets, cast nets, and reel rods were used to capture fish. After capture, fish were euthanized with Eugenol®, following guidelines established by animal ethics council (American Veterinary Medical Association, 2001). Fish samples were packed in Ziploc bags and stored in portable cooler with ice and immediately transported to Laboratório de

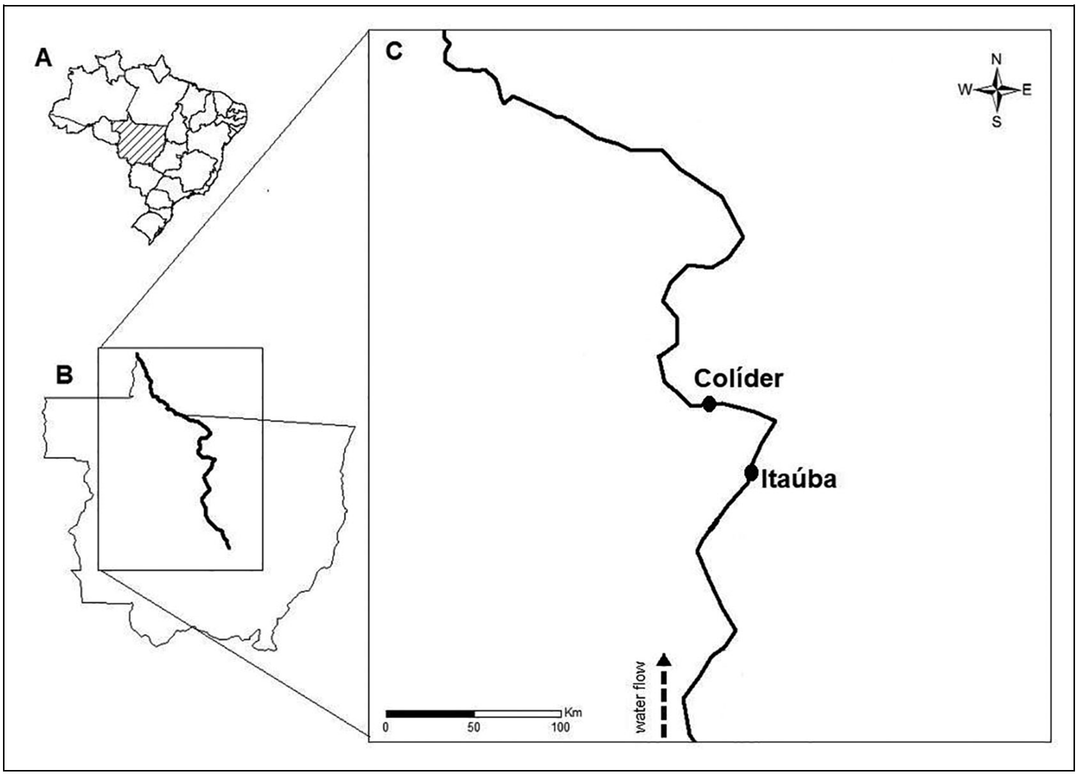

Figure 1. A. Map of Brazil. B. Map of State of Mato Grosso, highlighting Teles Pires River. C. Study Area, with indications to our sampling areas (black dots), between municipalities of Itaúba (11°14'6,36"S e 55°27'6,3"O) and Colíder (10°59'4,49"S e 55°49'25,51"O). DOI: https://doi.org/10.1525/elementa.2021.020.f1

Table 1. Predatory fish species collected from Teles Pires River. DOI: https://doi.org/10.1525/elementa.2021.020.t1

Common Name	Scientific Name	Family	Diet	Reproductive Season	Source
Peixe-cachorra	*Hydrolycus armatus* (Jardine and Schomburgk, 1841)	Cynodontidae	Carnivorous	Flood (migratory)	Goulding (1980)
Bicuda	*Boulengerella cuvieri* (Agassiz, 1829)	Ctenoluciidae	Carnivorous	Flood (migratory)	Santos et al. (2004) and Pereira et al. (2012)
Piranha	*Serrasalmus rhombeus* (Linnaeus 1766)	Serrasalmidae	Carnivorous	Flood (sedentary)	Santos et al. (2006)

Ictiologia da Amazônia Meridional-LIAM at Universidade do Estado de Mato Grosso-UNEMAT. Weight (g), total length (cm), and standard length (cm) for each fish sample were measured and recorded.

Muscle sample (approximately 2 cm^3) was collected from dorsolateral part of fish, from above lateral lines, using stainless steel chirurgical instruments. These tissues were stored at 2 °C until mercury analyses. Voucher specimens were deposited in collection at laboratory LIAM at UNEMAT University Campus Alta Floresta.

2.3. Mercury analysis

Mercury analyses were performed in Laboratório de Ecotoxicologia, Centro de Pesquisa em Limnologia, Biodiversidade e Etnobiologia—CELBE, UNEMAT, Campus de Cáceres. Fish digestion was conducted following method described in Bastos et al. (1998). Approximately 0.5 g (dry or wet weight) of fish muscle and replica were weighted in glass tubes. One milliliter of H_2O_2 (Merck) and 4 ml of H_2SO_4: HNO_3 (1:1 v/v) solution were added and glass tubes were placed in water bath at 60 °C for approximately 30 min. When samples cooled down, 5 ml of $KMnO_4$ 5% solution was added (m/v) to mixture digest and tubes were returned to water bath at 60 °C for 30 min. Once cooled, glass tubes with digests were covered with plastic film and left to rest for approximately 12 h.

After 12 h, 1 ml of hydroxylamine was added to digest solution to neutralize oxidizing medium. Final digest volume was set at 13 ml using Mili-Q water. Mercury analyses were performed using an Atomic Absorption Spectrometer with a flow injection system (FIMS—400; Perkin Elmer). Standard reference material DORM-3 from National

Table 2. Consumption classes for risk assessment relating to human health, average fish consumption, definition of each class, and reference. DOI: https://doi.org/10.1525/elementa.2021.020.t2

Consumption Classes	Average Fish Consumption	Definition	Reference
1	0.009 kg/day	Urban population in State of Mato Grosso (Brazil) who rarely consume fish	IBGE (2011)
2	0.03 kg/day	Adult population with sporadic fish consumption	USEPA (2000)
3	0.142 kg/day	Adult population with frequent fish consumption	USEPA (2000)
4	0.340 kg/day	Riverside and indigenous populations in State of Mato Grosso (Brazil)	Passos et al. (2007)

Table 3. Weight (g), body length (BL), average concentration (minimum-maximum) of mercury (THg) and MeHg (mg/kg^{-1}—wet weight) in carnivorous fish species collected from Teles Pires River. DOI: https://doi.org/10.1525/elementa.2021.020.t3

Species	*N*	Weight (g)	BL (cm)	THg (mg/kg)	MeHg (mg/kg)
B. cuvieri	7	556.4–3310.0	21.0–73.0	0.199 (0.020–0.609)	0.179 (0.018–0.548)
S. rhombeus	8	190.0–690.0	17.0–25.0	0.304 (0.087–0.614)	0.274 (0.078–0.552)
H. armatus	6	340.0–9500.0	28.0–75.0	0.229 (0.064–0.529)	0.206 (0.057–0.476)

Institute of Standards and Technology (NIST) was analyzed for every 20 samples to discover quality assurance and quality control. NIST DORM-3 certified THg concentration as 0.382 ± 0.060 mg/kg. Analyses in our lab were recorded as 0.416 mg/kg and 0.352 mg/kg. Replicas had a variation coefficient of less than 15%.

2.4. Estimating human health risk

Human health risk assessment was carried out in accordance with U.S. Environmental Protection Agency (USEPA, 2000). We considered four different consumption rates of *B. cuvieri*, *S. rhombeus*, and *H. armatus* (**Table 2**).

In this study, MeHg concentrations were estimated based on previous studies demonstrating that approximately 90% of THg concentration in fish muscle is present as MeHg (Bloom, 1992; Akagi et al., 1995; Malm et al., 1995; Micaroni et al., 2000; Kehrig et al., 2008). MeHg exposure levels to humans resulting from intake of fish muscle (tissue that is usually consumed) were calculated following MeHg mean daily intake (MDI) equation (FAO, 2006; WHO, 2006, 2008):

$$\mathrm{MDI}\ (\mathrm{mg/kg/day}) = (\mathrm{C} * \mathrm{IR} * \mathrm{FE} * \mathrm{ED})/(\mathrm{BW} * \mathrm{AL})$$

Where:

C = MeHg concentration in fish muscle (mg/kg), minimum and maximum MeHg concentrations were used for each fish species to calculate amplitude,

IR= Average intake rate (**Table 2**),

FE = Frequency of exposure (365 days/year),

ED = Lifetime exposure duration (considered here as 70 years),

BW = Individual body weight (considered here as 70 kg),

AL = Average lifetime (considered here as 70 years × 365 days/year).

Risk assessment deleterious health effects were calculated using risk index (RI), expressed as ratio between MDI and THg oral reference dose (RfD). Note our calculations considered people to be 70 years of age, as a conservative mercury lifetime exposure. RI provides magnitude of human population's exposure in relation to recommended dose. RI was calculated according to the following equation:

$$\mathrm{RI} = \mathrm{MDI}/\ \mathrm{RfD},$$

Where:

MDI = mean daily intake (Calculated in previous paragraph)

RfD = MeHg oral intake reference dose (mg/kg/day) established by WHO (2006, 2008) based on highest MeHg intake level recommended as acceptable for an adult human with a body weight of 70 kg. Values for MeHg oral RfD from Food and Agriculture Organization of United Nations were applied in this study (FAO, 2006), as were those from WHO (2006, 2008).

In this study, two RfD values (WHO, 2006) were used to calculate IR:

- -$\mathrm{RfD}_{(\mathbf{table\ 3})}$ = 0.0003 mg/kg/d for general population;
- -$\mathrm{RfD}_{(\mathbf{table\ 4})}$ = 0.0001 mg/kg/d for sensitive groups (lactating mothers, infants and children).

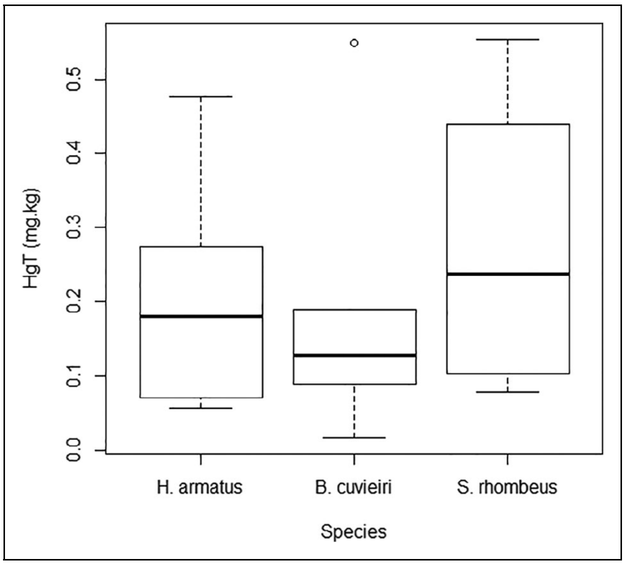

Figure 2. Box plots referring to concentrations of THg (mg/kg) found in species of carnivorous fish collected from Teles Pires River. DOI: https://doi.org/10.1525/elementa.2021.020.f2

RI values < 1.0 indicate that human exposure is below threshold value in which negative health effects may occur, while an RI $\geq$ 1.0 indicates that a given human population might be at risk of adverse health effects from MeHg through fish consumption (FAO e WHO, 2006).

2.5. Statistical analyses

Statistical analyses were performed using statistical software R v. 3.6.3 (R Core Team, 2020, https://cran-r.c3sl.ufpr.br/). Kruskal-Wallis H-test was used to determine whether there were statistically significant differences between estimated MeHg concentrations among fish species.

3. Results

3.1. Total mercury

Total mercury and MeHg data are presented in **Table 3**. We collected and analyzed seven specimens of *B. cuvieri*, eight of *S. rhombeus*, and six of *H.* armatus (**Table 3**). Weight of collected *B. cuvieri* specimens ranged between 556.4 and 3310 grams, while *S. rhombeus* ranged between 190 and 690 grams and *H. armatus* varied between 340 and 9500 grams (**Table 3**, individual data for all specimens analyzed are presented as supplementary material).

There were no significant statistical differences between THg concentrations in analyzed species (Kruskal-Wallis, level of 5% probability, $P = 0.65$; **Figure 2**). Highest average concentrations of THg were found in *S. rhombeus* (0.304 mg/kg^{-1}), followed by *H. armatus* (0.229 mg/kg^{-1}) and *B. cuvieri* (0.199 mg/kg^{-1}). There were no significant differences among these concentrations (**Table 3**). Average MeHg concentrations in muscle of analyzed species were below 0.5 mg/kg limit, recommended by WHO (2008).

3.2. MeHg estimation and human health risk assessment

RI values for consumption of *B. cuvieri*, *S. rhombeus*, and *H. armatus* are presented in **Tables 4** and **5**, according to amplitude of MeHg concentrations estimated for four different fish consumption ranges defined in this study (**Table 2**). **Table 4** shows RI values based on 0.0003 mg/kg/day/MeHg oral RfD for general population defined by WHO (2006). In **Table 5**, RI calculations were based on most restrictive oral RfD of 0.0001 mg/kg/day/MeHg indicated for sensitive groups defined by WHO (2006).

Using as an oral RfD of 0.0003 mg/kg/day/MeHg, our results show that amplitude RI > 1 only for two classes of consumers: Adult population with frequent fish consumption (142 g/day) and Riverside and indigenous populations in State of Mato Grosso (Brazil) (342 g/day; **Table 4**).

When calculated for sensitive groups (oral RfD of 0.0001 mg/kg/day/MeHg), RI values were greater than 1 (RI < 1) for all consumer classes, except for urban population in State of Mato Grosso (Brazil) that rarely consumes fish (9 g/day) in **Table 5**.

4. Discussion

4.1. Total mercury in fish from Tele Pires River

In this study, average mercury concentrations were *B. cuvieri* (0.199 mg/kg), followed by *H. armatus (*0.229 mg/kg) and *S. rhombeus* (0.304 mg/kg; **Table 3**). In this study, we analyzed three species from top-of-the-chain fish, and generally these species have higher concentrations of mercury than those of lower trophic levels (Voigt, 2004; Terra et al., 2008). Thus, differences in mercury accumulation found in these fish species in this study may be related to morphological differences, life cycle, and food items of each species (Goulding, 1980; Terra et al., 2008). Because bioaccumulation, defined as increase in mercury concentrations over life of an organism, may not be the main factor that explains increase in mercury concentrations in Amazonian fish (Pouilly et al., 2012), studies on diet of these species show that in Teles Pires River basin these species are piscivorous predators of small caracids (Dary et al., 2017).

However, a more detailed study in Xingu River showed that for *B. cuvieri*, the most important food items are *Geophagus* sp. and *Leporinus* sp, and for *H. armatus*, they are *Cichla melaniae* (Barbosa et al., 2018). Piranhas are fish with a tooth structure adapted to pull pieces (scales, fins, muscle) from their prey (Piorski et al., 2005), allowing them to feed on larger fish. Although not significantly different, the slightly higher mercury concentrations found in *S. rhombeus* in the present study is likely a result of differences in the feeding behavior of these three predatory species. A study on biomagnification of mercury in trophic structure of ichthyofauna in Amazon basin suggests that top chain species may be associated with several trophic webs within an ecosystem (Azevedo-Silva et al., 2016). Species *B. cuvieri* would be feeding on small non-carnivorous fish, *H. armatus* would be feeding on small carnivorous fish, and *S. rhombeus* feeding on large fish that have higher levels of mercury due to bioaccumulation. However, these differences in mercury concentration

Table 4. Amplitude of adverse health effects risk index (RI) calculated for four classes of fish consumers, based on oral reference dose of 0.0003 mg/kg/day/MeHg. DOI: https://doi.org/10.1525/elementa.2021.020.t4

Species	Urban Population in State of Mato Grosso (Brazil) that Rarely Consumes Fish	Adult Population with Sporadic Fish Consumption	Adult Population with Frequent Fish Consumption	Riverside and Indigenous Populations in State of Mato Grosso (Brazil)
B. cuvieri	0.007–0.234	0.025–0.782	0.121–3.705	0.291–8.872
S. rhombeus	0.033–0.236	0.111–0.782	0.527–3.732	1.262–8.937
H. armatus	0.024–0.204	0.081–0.680	0.385–3.218	0.922–7.706

Risk index values were calculated based on amplitude of MeHg concentrations estimated in fish collected from Teles Pires River, described in **Table 3**.

Table 5. Amplitude of adverse health effects risk index (RI) calculated for four classes of fish consumers, based on oral reference dose of 0.0001 mg/kg/day/MeHg for sensitive groups (lactating women, breastfeeding infants and children). DOI: https://doi.org/10.1525/elementa.2021.020.t5

Species	Urban Population in State of Mato Grosso (Brazil) that Rarely Consumes Fish	Adult Population with Sporadic Fish Consumption	Adult Population with Frequent Fish Consumption	Riverside and Indigenous Populations in State of Mato Grosso (Brazil)
B. cuvieri	0.023–0.704	0.077–2.348	0.365–11.116	0.874–26.617
S. rhombeus	0.100–0.709	0.334–2.365	1.582–11.197	3.788–26.811
H. armatus	0.073–0.612	0.244–2.040	1.156–9.656	2.768–23.120

Risk index values were calculated based on amplitude of MeHg concentrations estimated in fish collected from Teles Pires River, described in **Table 3**.

in fish of same trophic level are difficult to explain, as there are many factors that may have influenced, or perhaps it would be, synergistic effect of all these factors, requiring further studies on this.

However, one main difference between species analyzed in present study can be migratory fish and sedentary fish. Fish from lentic systems have mercury contents about four times higher than fish from same trophic level in lotic systems, with same concentration of MeHg in water (USEPA, 2010). In the present study, sedentary species *S. rhombeus* (piranha) showed higher concentrations of mercury than migratory *H. armatus* and *B. cuvieri*. Piranhas' preference for lentic environments is already well known (Agostinho and Júlio, 2002). Species H. armatus and B. cuvieri are fish from lotic environments, as they perform long annual reproductive migrations *(*Goulding, 1980; Santos et al., 2004). This is possibly the best explanation for differences in mercury concentrations found between *S. rhombeus* (piranha), *H. armatus*, and *B. cuvieri* fish.

Mercury concentrations in fish from Tapajós basin (in which Teles Pires River is part of) vary between studies, most likely as a result of collection site relating to anthropogenic activities, including gold-digging, deforestation, and agriculture (**Table 6**). For *B. cuvieri*, on Teles Pires River in a preserved area (Castilhos et al., 2012), and on Rio Roosevelt belonging to Madeira River basin (Dos Anjos et al., 2016) in an area with deforestation and gold-digging, studies showed higher concentrations of mercury compared to data from present study (**Table 6**). There are studies showing higher mercury concentrations than present study for *H. armatus* with its counterpart *Hydrolycus scomberoides* in Tocantis River in an area with gold-digging and deforestation (Milhomem-Filho et al., 2016), in Tapajós River in an area with gold-digging, deforestation and agriculture (Bidone et al., 1997), on Teles Pires River in an area with gold-digging and deforestation (Uryu et al., 2001). However, other studies have lower concentrations of mercury than those in present study for *H. armatus*, in Teles Pires River in an area with deforestation, gold-digging, and agriculture (Matos, 2018) and in a preserved area (Castilhos et al., 2012; **Table 6**). And for *S. rhombeus*, we also found studies with higher concentrations of mercury in Tapajós River in an area with deforestation, gold-digging, and agriculture (Da Silva et al., 2006) and lower concentrations in Tapajós River in an area with deforestation, gold-digging, and agriculture (Bidone et al., 1997), on Teles Pires River in a preserved area (Castilhos et al., 2012) and in an area with gold-digging and deforestation (Uryu et al., 2002; **Table 6**). These variations in mercury concentration in ichthyofauna can be explained by seasonal migrations of fish, introducing food variations not only temporal but also spatial (Goulding, 1980). Dynamics of Tapajós basin, due to seasonal flooding process, can cause changes in fish feeding and facilitate development of favorable conditions for MeHg production (Roulet et al., 2000). The effects of hydro dams on the increased

Table 6. Average THg concentrations (mg/kg wet weight) in species of fishes in Amazon basin reported in literature. DOI: https://doi.org/10.1525/elementa.2021.020.t6

Species	THg Concentration	Location	Possible Hg Source	Investigator and Year
Serrasalmus sp	0.100	Tapajós river	Gold-digging, deforestation and agriculture	Bidone et al. (1997)
Hydrolycus tatauaia	0.180	Teles Pires river	Gold-digging, deforestation and agriculture	Matos (2018)
Hydrolycus sp	0.193	Teles Pires river	Preserved area	Castilhos et al. (2012)
Boulengerella cuvieri	0.199	Teles Pires river	Gold-digging, deforestation, and agriculture	This study
B. cuvieri	0.205	Teles Pires river	Preserved area	Castilhos et al. (2012)
Hydrolycus armatus	0.229	Teles Pires river	Gold-digging, deforestation and agriculture	This study
Serrasalmus sp	0.240	Teles Pires river	Preserved area	Castilhos et al. (2012)
Serrasalmus sp	0.259	Teles Pires river	Gold-digging and deforestation	Uryu et al. (2002)
Hydrolycus scomberoides	0.275	Tocantis river	Gold-digging and deforestation	Milhomem-Filho et al. (2016)
Serrasalmus rhombeus	0.304	Teles Pires river	Gold-digging, deforestation and agriculture	This study
S. rhombeus	0.383	Tapajós river	Gold-digging, deforestation and agriculture	Da Silva et al. (2006)
B. cuvieri	0.600	Roosevelt river	Gold-digging and deforestation	Dos anjos et al. (2016)
H. scomberoides	0.690	Tapajós river	Gold-digging, deforestation and agriculture	Bidone et al. (1997)
H. scomberoides	1.650	Teles Pires river	Gold-digging and deforestation	Uryu et al. (2001)

production of MeHg and bioaccumulation in fish are not fully understood in the Amazon yet. The results of this study provide a baseline for THg and MeHg prior to flooding, to which future studies can be compared against to establish increased rates in Hg bioaccumulation after damming the Teles Pires River.

The effect of hydro dam construction on mercury methylation, bioaccumulation in fish, and exposure to humans is of concern in the Amazon. Approximately 80% of the hydroelectric reservoirs in South America had MeHg levels in predatory fish above the limit (0.5 mg/kg^{-1} WHO, 2006) desirable for human consumption (Pestana et al., 2019). Several of these reservoir are located in the Amazon (Malm et al., 2004; Dominique et al., 2007; Kasper et al., 2012; Kasper et al., 2014). In the Manuel Hydroelectric on the Jamari River, an average 1.366 mg/kg MeHG was reported of carnivorous fish downstream and 0.545 mg/kg upstream the dam (Kasper et al., 2012). Particularly for the Teles Pires River, methylation of mercury is further favored by the historical of anthropogenic activities and the recent implantation of a hydroelectric complex, consequently increasing Hg exposure to humans who consume fish from this river.

The average mercury concentration in fish analyzed in the present study is below limit of 0.5 mg/kg^{-1} recommended by WHO (2006) for fish intake. However, four individual samples have exceeded the WHO recommended mercury limit: two *S. rhombeus* (0.514 and 0.659 mg/kg^{-1}), one *B. cuvieri* specimen (0.609 mg/kg^{-1}), and one *H. armatus* (0.529 mg/kg^{-1}; supplementary material). Although this study comprises a small *n*-sample, the mercury concentrations analyzed provide a unique data set of mercury concentrations in fish prior to damming the Teles Pires River for the formation of the Colíder Hydroelectric Reservoir. These results can be used as a baseline to compare mercury concentrations in fish after damming the river, to better understand the increase ratio of MeHg in fish, and consequently on humans consuming fish collected in this region.

In 2011, construction of Colíder Hydro dam began, filling reservoir in August 2017 with an area of about 182 km^2, about 65% of reservoir area was forest, and only 70% of this area had its vegetation removed (COPEL, 2018; Matos et al., 2020). Vegetation that has been submerged after filling reservoir can increase concentration of dissolved organic matter in reservoir. Hydroelectric reservoirs in the Amazon region are extremely favorable environments for mercury methylation, as this process is favored in anoxic or suboxide, slightly acidic aquatic environments, with high concentrations of dissolved organic matter and intense microbiological activity (Lacerda and Malm, 2008). Elemental mercury (nonpoisonous) is naturally present in Amazonian soils, having millions of years of existence. Amazonian soils have accumulated mercury received from rain over time due to volcanic eruptions (Fearnside, 2019). The problem of methylation in mercury in this reservoir is aggravated by the fact that the Colíder Hydro dam is immediately downstream of another hydroelectric plant (Matos et al., 2020), Sinop Hydro dam, and this is considered a gigantic environmental problem in several aspects (Fearnside, 2019). Thus, in the Colíder Hydro dam, there may be a considerable increase in concentrations of MeHg, due to sum of MeHg generated in its reservoir and that originating from Sinop Hydro dam reservoir, because in many cases (Malm et al., 2004; Kasper et al., 2012; Kasper et al., 2014), ichthyofauna downstream is more contaminated with MeHg than that upstream. Results of this research can serve as a database, so that in future, research on effect of flooding of hydro dam can be compared.

4.2. RI for fish consumption

This research presents risks of adverse health effects for two distinct groups: general population and sensitive groups (lactating, infants, and children), according to oral RfD for each group indicated by WHO (2006, 2008). For each group, four classes of fish consumption were calculated, ranging from 9 g/day to 340 g/day (**Table 2**). For four classes of fish consumption within general population group, RI ranged from 0 to 8 (**Table 4**). Only for classes "Urban population in State of Mato Grosso (Brazil) that rarely consumes fish" (9 g/day) and "Adult population with sporadic fish consumption" (30 g/day), amplitude of RI < 0, is there indication that there is no health risk. For general population (except sensitive groups), including four consumption classes presented in this research, consumption should be at most about 210 g fish per week, or 840 g per month, as up to this intake limit of fish, our results suggest that there is no risk of adverse effects on health (**Table 4**).

Limit of 0.5 mg/kg^{-1} (WHO, 2006) considers a 60 kg person with a weekly intake of 250 g of fish, reaching an intake of 0.3 μg of MeHg per kg of body weight per day. For sensitive groups (e.g., lactating women, breastfeeding infants, and children), WHO guidelines recommend maximum intake of 0.1 μg of MeHg per kg of body weight per day. In this study, for four classes of fish consumption within sensitive groups, RI ranged from 0 to 26 (**Table 5**). Only for class "Urban population in State of Mato Grosso (Brazil) that rarely consumes fish" (9 g/day) amplitude of the RI < 0, there is an indication that there is no risk to health. This suggests that people belonging to sensitive group are at greater risk of adverse health effects from mercury poisoning. Therefore, for people in sensitive group, a maximum consumption of 200 g of fish per month is recommended.

Mercury contamination in humans mainly occurs through food intake. Due to the fact that MeHg is a fat soluble, the higher the levels of MeHg in muscle of fish, the greater the chances of contamination in humans, if consumption of fish is in large quantities or frequently. The high RI (0.291–26.811) calculated for class 04 (Riverside and indigenous populations in State of Mato Grosso, Brazil) in both groups (general population and sensitive groups) is in agreement with the fish consumption rate reported for three indigenous ethnic groups (Mundurukus, Kayabis, and Apiakás) living in the Teles Pires River region. A daily intake of 340 g of fish, including carnivorous species, was reported for these three indigenous groups (Passos et al., 2007; Fany, 2011). Mercury measurements of human hair have shown that 60% of an indigenous Kayabi population had mercury concentrations in hair above the acceptable limit of 10 ppm established by the WHO (Klautau-Guimarães et al., 2005). This is particularly the case for the fishermen colony in the Teles Pires River, the site of this study, which houses 250 professional fishermen whose fish intake and commerce are their main food and income sources.

This pilot study on risk of mercury exposure for traditional communities through fish consumption indicates that further studies are needed to establish with greater precision health effects posed upon these communities. Considering the great nutritional value of fish meat, we suggest that consumption of fish is preferably for noncarnivorous fish. Future studies should consider other fish species commonly consumed in the area and consider biological factors (fish size and diet) in health assessment for human consumption.

5. Conclusion

Almost every fish species analyzed (*S. rhombeus*, *B. cuvieri*, and *H. armatus*) presented MeHg concentrations below that recommended for human consumption by WHO, but, considering that region consumes high quantities of fish, the population's daily MeHg intake can exceed the recommended threshold. Risk indices indicate that for sensitive groups (lactating mothers, infants, and children), consumption of these fish species is only safe in an amount of approximately 200 g per month, and for other consumers, approximately 1,000 g per month can be ingested. However, benefits provided by intake of omega-3 fatty acids present in fish are extremely important. Thus, consumed species, intake frequency, and amount of fish ingested must be taken into account in order to balance benefits and risks of regular fish consumption. Considering high nutritional value of fish meat, we suggest that populations in the study region should choose to consume noncarnivorous fish.

As already presented in the present study, methylation of mercury in aquatic environments is intensified with formation of reservoir lakes as part of hydroelectric plants. Considering that fish analyzed in this research were collected before the formation of reservoir lake for hydroelectric plant Colíder Hydro dam, results presented here can serve as a database for monitoring concentration of MeHg in ichthyofauna of Teles Pires River.

Data accessibility statement

Results presented are based on original data sets provided as the Supplemental Data file.

Supplemental files

The supplemental files for this article can be found as follows:

Supplemental Data. Database used in this manuscript. xlsx

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Competing interests
The authors have no competing interests to declare.

Author contributions
Conception, design and basic idea of manuscript. Wrote article: MLS.

Collections and biometrics of analyzed fish. Creation and maintenance of database: CASAS.

Project coordinator who raised financial resources to carry out this research: SSAA.

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