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Technical Opinion on Dredging, Agitation, and Sediment Mobilization in the Araguaia River to Enable Navigation: Environmental and Human Health Impacts

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Abstract

Dredging and disturbance of sediments in rivers with redox-sensitive conditions, such as the Araguaia River, can pose environmental and health risks, especially in areas with high concentrations of toxic metals like iron and mercury. These metals accumulate in sediments under reducing conditions, and their disturbance can lead to their release into the water column, affecting the food web and human health. The Araguaia River floodplain is composed of alluvial deposits and igneous and metamorphic rocks rich in chromium, nickel, iron, magnesium, and mercury. Land use change, particularly for agriculture, accelerates weathering and the transport of these elements into the river. Sediment dredging disrupts the chemical stability of metals such as iron and mercury, increasing their bioavailability. Mercury, in particular, can be converted into methylmercury, a highly toxic and bioaccumulative form that enters the aquatic food web, impacting fish, wildlife, and humans. Methylmercury biomagnifies through the food chain, posing risks to top predators, including piscivorous birds and humans. Studies show that fish consumption by riverine communities can lead to significant mercury exposure, increasing the risks of neurological damage, cardiovascular disease, and developmental problems in children. Furthermore, dredging can worsen water quality by increasing turbidity and mobilizing other toxic elements such as arsenic and cadmium. The environmental impacts of dredging go beyond immediate contamination, affecting biodiversity, ecosystem resilience, and fisheries, which are vital to local livelihoods. Socioeconomic consequences include food insecurity, income loss for fishers, and increased water treatment costs.

Palavras-chave: Heavy metals, Biogeochemical cycle, Bioaccumulation, Land use, Riparian communities, Watershed management.

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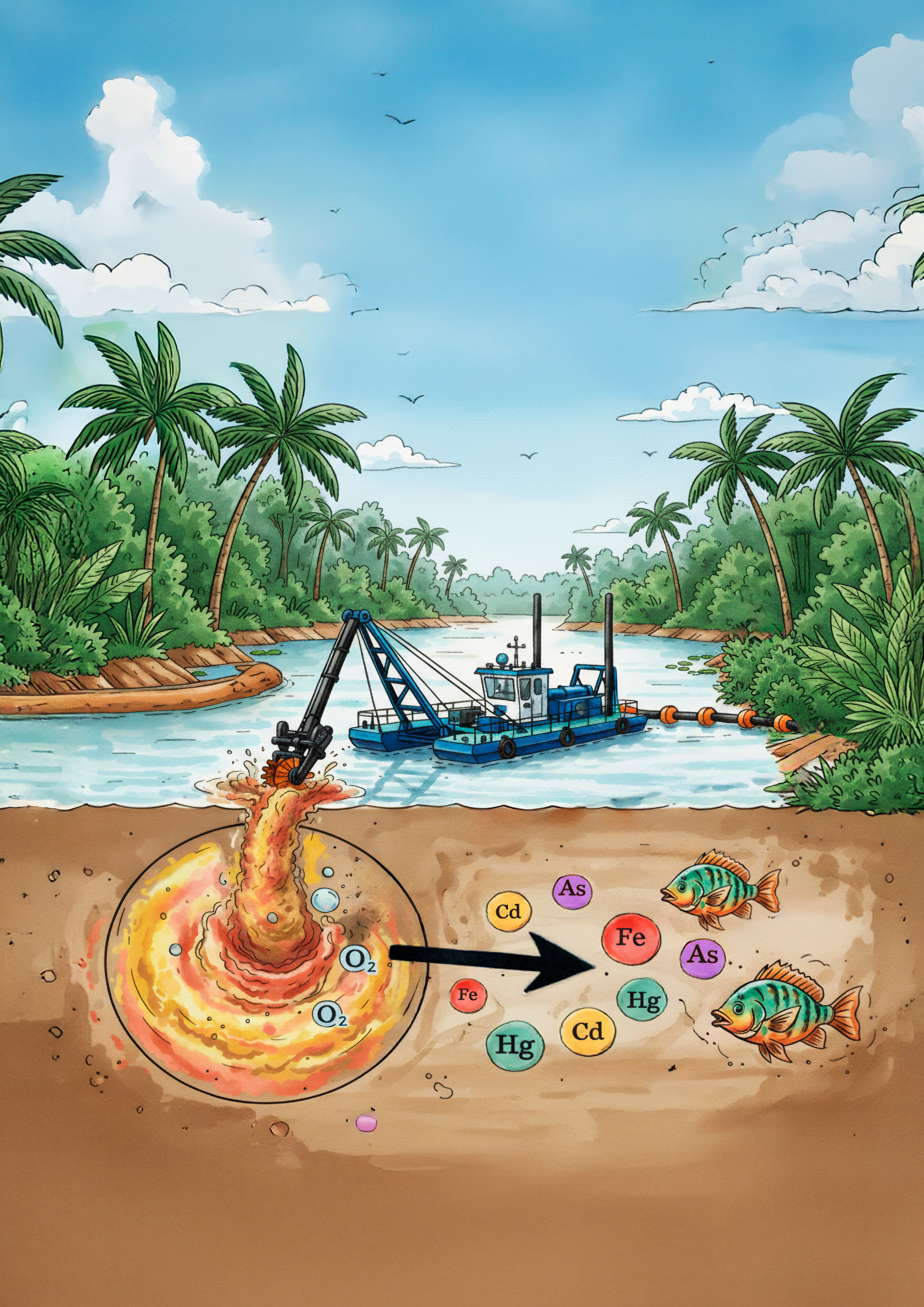

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Introduction

Rivers with redox-sensitive dynamics, such as the Araguaia River in Brazil, are critical zones for the accumulation and potential mobilization of heavy metals. Under anoxic or reducing conditions, sediments often act as long-term sinks for toxic metals such as iron (Fe) and mercury (Hg), stabilizing them through various geochemical processes (Ullrich et al., 2001; Zhuang & Gao, 2013). However, anthropogenic disturbances, especially dredging, can disrupt this balance by exposing anoxic sediments to oxygen, triggering oxidation and the subsequent release of these metals into the water column (Benoit et al., 2001; Driscoll et al., 2007).

This remobilization affects not only the chemical speciation of the metals but also their bioavailability and toxicity. For example, the oxidation of Fe(II) to Fe(III) results in the formation of ferric oxides and hydroxides, which can adsorb and transport other contaminants such as arsenic and cadmium (Warren & Haack, 2001). Mercury, when released from sediments in its elemental or inorganic forms, may be methylated by microbial activity, forming methylmercury (MeHg), a neurotoxic compound capable of bioaccumulation and biomagnification in aquatic food webs (Mason et al., 1996; Clarkson & Magos, 2006).

In redox-dynamic systems such as the Araguaia River, these biogeochemical transformations have significant ecological and public health implications, particularly in regions where fish are a key dietary resource. Therefore, understanding the environmental behavior of sequestered metals and the risks associated with sediment disturbance is essential for developing sustainable watershed management strategies.

Geochemical Risks of Dredging: Metal Release and Biogeochemical Changes in the Araguaia River

The floodplain is primarily composed of Quaternary terraces and alluvial deposits from the Araguaia Formation, with igneous and metamorphic rocks found in the sub-basins of right-bank tributaries (CPRM, 2004). These igneous and metamorphic rocks, derived from mafic and ultramafic minerals, contain high concentrations of chromium (Cr), nickel (Ni), iron (Fe), magnesium (Mg), and mercury (Hg) (Amorosi et al., 2014; Lipp et al., 2020; Moraes et al., 2023). These rocks are present in the tributaries of the Araguaia River watershed (Figure 1), and land-use conversion to agriculture accelerates the weathering and transport of these elements to the main channel and associated lakes (Monteiro et al., 2025). Average Cr concentrations in lake sediments are 3.5 times higher than the safety limit established by CONAMA (Brazil, 2012), posing potential risks to biological communities and human health.

Additionally, in redox-sensitive rivers, metals such as Fe and Hg tend to be sequestered in sediments under anoxic conditions. For example, iron is often present as Fe(II) in reducing environments, where it remains relatively stable (Linnik et al., 2023). Its oxidation can lead to the formation of ferric oxides and hydroxides, which may trap other toxic elements (Root et al., 2007; Feyte et al., 2010; Liu et al., 2013). However, these particles may also become remobilized, increasing water turbidity and complicating the fate of heavy metals (Ullrich et al., 2001). Similarly, mercury is commonly bound in sulfide complexes, such as cinnabar (HgS), or associated with organic matter in reducing conditions, making it less bioavailable (Frieling et al., 2023). Dredging disrupts this balance, exposing buried anoxic sediments to oxygen, triggering Fe(II) to Fe(III) oxidation and the release of mercury in more reactive and toxic forms, such as methylmercury (MeHg) (Benoit et al., 2001; Zhuang & Gao, 2013).

Mercury Methylation and Transport in the Araguaia River Floodplain

Mercury occurs in various chemical forms: inorganic mercury (Hg^{2+}), elemental mercury (Hg^0), and methylmercury (CH_3Hg^+). Preliminary data from our research group revealed two key patterns regarding mercury transformation and transport in floodplain lakes (Figure 2). Higher Ti/Al ratios in bottom sediments indicate greater weathering and the influx of allochthonous lithogenic detritus (Haberzettl et al., 2008). Total dissolved solids (TDS) and

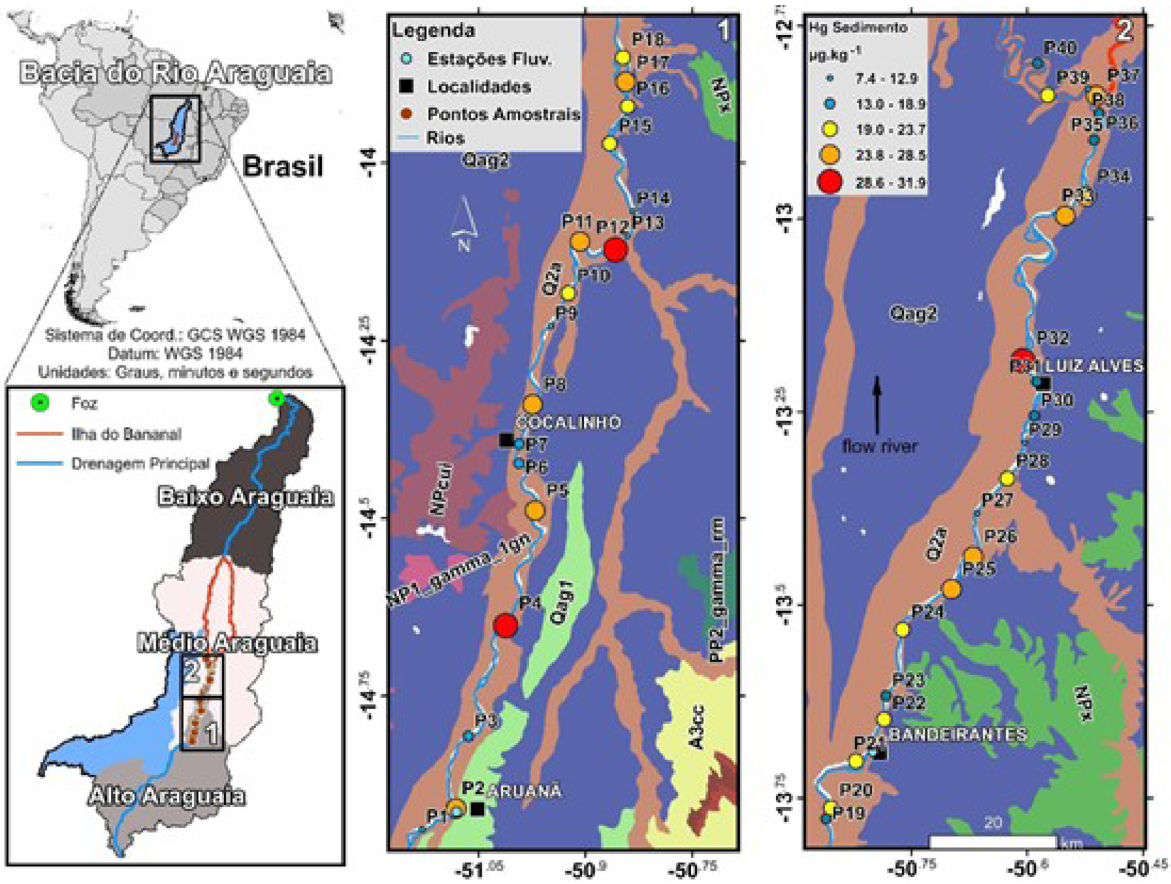

Figura 1. Regional geology and mercury (Hg) concentrations in sediments from the main channel of the Araguaia River.

electrical conductivity (EC) reflect dissolved material concentrations, indicating soil erosion or weathering due to seasonal hydrological changes (Ogwueleka, 2015), and may also signal agricultural impacts (Cruz et al., 2019). As samples were collected during the high-water season, rainfall and lateral water transport likely influenced TDS and EC measurements. Nonetheless, the correlation of these variables with phosphorus and phosphate concentrations reinforces the agricultural footprint, suggesting nutrient leaching from fertilizer use and livestock waste (Bhateria & Jain, 2016).

Conversely, the inverse relationship between MeHg concentrations and the Mn/Fe ratio in sediments, dissolved oxygen (DO), and water pH—as well as the positive association with the proportion of surrounding flooded areas—indicates that reducing conditions promote mercury methylation (DeLaune et al., 2004; Wang et al., 2021). Methylmercury release is of great concern due to its potential for bioaccumulation and biomagnification (Mason et al., 1996). This is a notable issue in the Araguaia floodplain. The ratio of MeHg to total Hg (i.e., all detected forms in a sample) serves as an indicator of methylation activity (Yu et al., 2021). Mercury mobilization through agricultural activity and MeHg production in flooded areas results in MeHg proportions in bottom sediments ranging from 0.9% to 22.1% (mean ± SD: 1.9 ± 3.2%). Thus, changes in inorganic mercury availability, shifts in water physicochemical parameters, and sediment resuspension triggered by dredging can pose substantial risks to biological communities and human populations.

Mercury Biomagnification in the Food Web and Potential Human Health Risks

Microbial methylation of mercury in disturbed sediments can significantly increase MeHg levels (Driscoll et al., 2007). MeHg is readily absorbed by phytoplankton and passed through trophic levels via zooplankton and benthic macroinvertebrates to fish (Molina et al., 2010; Lino et al., 2019; Li et al., 2021). As mercury levels rise in fish,

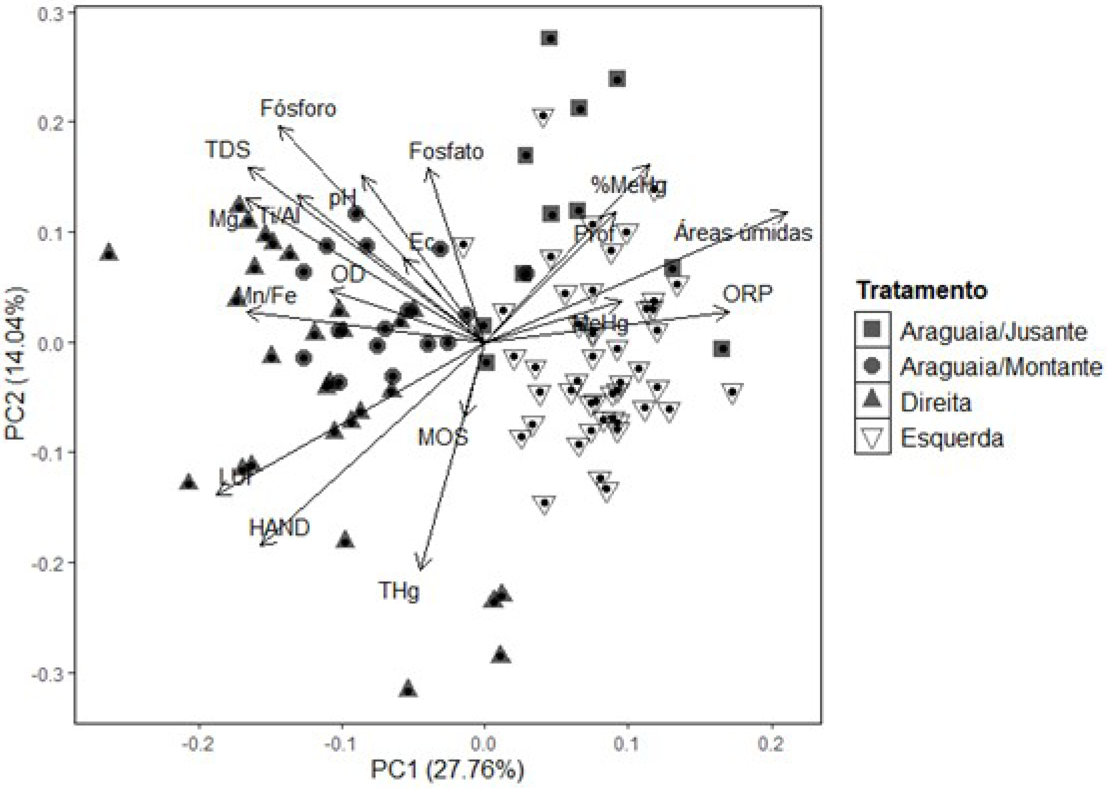

Figure 2. Biplot showing variable and sampling unit ordination based on Principal Component Analysis results. MOS: sediment organic matter. ORP: oxidation-reduction potential. Prof: depth. Ec: electrical conductivity. TDS: total dissolved solids. LUI: land use intensity. HAND: Height Above Nearest Drainage algorithm..

predatory species—such as birds, otters, and cetaceans—accumulate higher mercury loads, leading to toxic effects (Josef et al., 2008; Mosquera-Guerra et al., 2019; Santos et al., 2021). These effects include reproductive failure, neurological damage, and even death in wildlife (Ullrich et al., 2001). Moreover, heavy metal toxicity at lower trophic levels can cascade through ecosystems, reducing biodiversity and altering community structure (Wiener et al., 2003; Zhuang & Gao, 2013).

Methylmercury release into aquatic environments also poses significant public health threats, especially for communities dependent on fish as a primary protein source (Azevedo et al., 2022; Canela et al., 2024; Marchese et al., 2024). In humans, MeHg is especially dangerous for pregnant women and young children, as prenatal exposure may cause developmental delays, cognitive deficits, and motor dysfunction (Clarkson & Magos, 2006). Chronic MeHg exposure through fish consumption has also been linked to cardiovascular diseases and increased risks of neurological disorders such as Parkinson's and Alzheimer's (Guallar et al., 2002).

Our research shows that even relatively low mercury concentrations can lead to elevated health risks due to high fish consumption in riverine populations. For instance, at a low intake rate (50 g/day), predatory species such as croaker (*Plagioscion squamosissimus*), piranha (*Pygocentrus nattereri*, *Serrasalmus* sp.), and dogfish (*Rhaphiodon vulpinus*, *Hydrolycus armatus*) pose a health risk. At average (100 g/day) and high (200 g/day) consumption rates, even non-predatory species widely eaten by local populations, such as *Curimata inornata*, *Psectrogaster amazonica*, sardines (*Triportheus* sp.), and *Hemiodus* sp., become risky (Figure 3).

Although official data on fish consumption in Araguaia communities is lacking, a late-1990s study found that fish comprised only 10% of dietary protein in the Araguaia population—unlike the Amazon and Negro rivers, where fish was the main protein source (Begossi et al., 2000). However, a recent study showed that 85% of 75 artisanal fishers in the Middle Araguaia (Tocantins) consumed fish three to seven times per week (Mendes-Filho et al., 2020). Silva et al. (2019) also noted the importance of fish protein for the Karajá Indigenous communities of the Middle Araguaia.

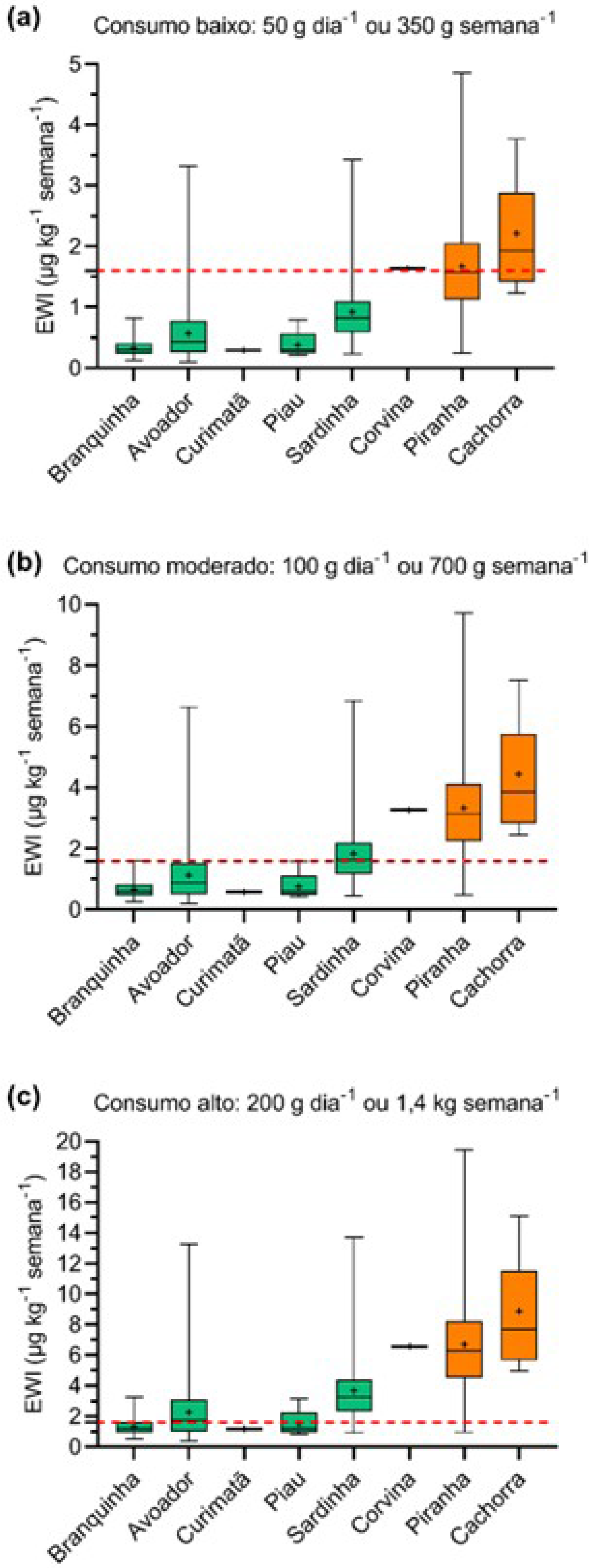

Figura 3. Estimated Hg intake via fish consumption. Species listed include: *Curimata inornata*, *Psectrogaster amazonica*, *Anodus* sp., *Hemiodus* sp., *Prochilodus nigricans*, *Laemolyta* sp., *Leporinus* sp., *Triportheus* sp., *Plagioscion squamosissimus*, *Pygocentrus nattereri*, *Serrasalmus* sp., *Rhaphiodon vulpinus*, *Hydrolycus armatus*.

Environmental and Socioeconomic Consequences

The environmental consequences of dredging go beyond immediate ecological damage. Sediment destabilization can degrade habitats, especially for benthic organisms that rely on stable substrates (Day et al., 1995; Zweig & Rabeni, 2001). Sediment resuspension may also smother habitats, reducing benthic species abundance and diversity—key contributors to nutrient cycling and food web dynamics (Adámek & Maršálek, 2012). Over time, this loss may compromise ecosystem resilience and reduce the river's ability to filter pollutants (Millennium Ecosystem Assessment, 2005).

From a socioeconomic perspective, fisheries degradation due to heavy metal contamination can severely affect communities reliant on fish for food and income. Loss of biodiversity and ecosystem services such as water purification and fish productivity can increase water treatment costs and create food security challenges (Mergler et al., 2007).

Final Considerations and Management Recommendations

Dredging and sediment agitation in redox-sensitive rivers with high iron and mercury concentrations pose serious environmental and public health risks. The release of toxic metals—particularly methylmercury—can disrupt aquatic ecosystems through food web biomagnification and cause long-term neurological and reproductive harm to both wildlife and humans.

Given this context, sediment dredging should be avoided unless absolutely necessary and justified by robust environmental impact assessments, with the adoption of less intrusive techniques. As an alternative, precautionary management strategies should be implemented, prioritizing the preservation of natural sedimentation and stabilization processes. This includes conserving and restoring riparian vegetation to reduce erosion and strictly controlling land use along the Araguaia River margins and tributary sub-basins.

Moreover, permanent environmental monitoring programs are recommended, focusing on sediment, water, and aquatic biota quality to detect early signs of geochemical instability or increased metal bioavailability. The maintenance of natural processes, combined with preventive management strategies, represents the safest and most sustainable approach to safeguarding the ecological integrity of the Araguaia River and the health of populations dependent on its resources.

References

Adámek, Z., & Maršálek, B. (2013). Bioturbation of sediments by benthic macroinvertebrates and fish and its implication for pond ecosystems: a review. *Aquaculture International*, 21(1), 1-17

Amorosi, A., Guermandi, M., Marchi, N., & Sammartino, I. (2014). Fingerprinting sedimentary and soil units by their natural metal contents: a new approach to assess metal contamination. *Science of the Total Environment*, 500, 361-372.

Azevedo, L. S., Pestana, I. A., Nascimento, L., Oliveira, R. C., Bastos, W. R., & di Beneditto, A. P. M. (2022). Risk of exposure to Hg and pesticides residues in a traditional fishing community in the Amazon: a probabilistic approach based on dietary pattern. *Environmental Science and Pollution Research*, 1-10.

Begossi, A., Hanazaki, N., & Peroni, N. (2000). Knowledge and use of biodiversity in Brazilian hot spots. *Environment, Development and Sustainability*, 2(3), 177-193.

Benoit, J. M., Gilmour, C. C., & Mason, R. P. (2001). The influence of sulfide on solid-phase mercury bioavailability for methylation by pure cultures of *Desulfobulbus propionicus* (1pr3). *Environmental Science & Technology*, 35(1), 127-132.

Bhateria, R., & Jain, D. (2016). Water quality assessment of lake water: a review. *Sustainable Water Resources Management*, 2, 161-173.

Brasil (2012). Resolução CONAMA nº 454, de 1º de novembro de 2012. Estabelece as diretrizes gerais e os procedimentos referenciais para o gerenciamento do material a ser dragado em águas sob jurisdição nacional.

Canela, T. A., Monteiro, L. C., Cabral, C. D. S., Ximenes, F. D. S., Oliveira, I. A. D. S., Bernardi, J. V. E., ... & Bastos, W. R. (2024). Mercury in fish and human hair and estimated dietary intake in a riverside community of the Madeira River Basin in the Brazilian Amazon. *Toxics*, 12(3), 208.

Clarkson, T. W., & Magos, L. (2006). The toxicology of mercury and its chemical compounds. *Critical Reviews in Toxicology*, 36(8), 609-662.

CPRM – Serviço Geológico do Brasil (2004). Mapeamento Geológico do Brasil. Disponível em: https://www.sgb.gov.br/

Cruz, M. A. S., Gonçalves, A. D. A., de Aragão, R., de Amorim, J. R. A., da Mota, P. V. M., Srinivasan, V. S., ... & de Figueiredo, E. E. (2019). Spatial and seasonal variability of the water quality characteristics of a river in Northeast Brazil. *Environmental Earth Sciences*, 78, 1-11.

Day, K. E., Kirby, R. S., & Reynoldson, T. B. (1995). The effect of manipulations of freshwater sediments on responses of benthic invertebrates in whole-sediment toxicity tests. *Environmental Toxicology and Chemistry*, 14(8), 1333-1343.

DeLaune, R. D., Jugsujinda, A., Devai, I., & Patrick Jr, W. H. (2004). Relationship of sediment redox conditions to methyl mercury in surface sediment of Louisiana Lakes. *Journal of Environmental Science and Health, Part A*, 39(8), 1925-1933.

Driscoll, C. T., Han, Y. J., & Chen, C. Y. (2007). Mercury contamination in forest and freshwater ecosystems in the northeastern United States. *Bioscience*, 57(1), 17-28.

Feyte, S., Tessier, A., Gobeil, C., & Cossa, D. (2010). In situ adsorption of mercury, methylmercury and other elements by iron oxyhydroxides and organic matter in lake sediments. *Applied Geochemistry*, 25(7), 984-995.

Frieling, J., Mather, T. A., März, C., Jenkyns, H. C., Hennekam, R., Reichart, G. J., ... & Van Helmond, N. A. G. M. (2023). Effects of redox variability and early diagenesis on marine sedimentary Hg records. *Geochimica et Cosmochimica Acta*, 351, 78-95.

Guallar, E., Sanz-Gallardo, M. I., & van't Veer, P. (2002). Mercury, fish oils, and the risk of myocardial infarction. *The New England Journal of Medicine*, 347(22), 1747-1754.

Haberzettl, T., Kück, B., Wulf, S., Anselmetti, F., Ariztegui, D., Corbella, H., ... & Zolitschka, B. (2008). Hydrological variability in southeastern Patagonia and explosive volcanic activity in the southern Andean Cordillera during Oxygen Isotope Stage 3 and the Holocene inferred from lake sediments of Laguna Potrok Aike, Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 259(2-3), 213-229.

Josef, C. F., Adriano, L. R., De França, E. J., de Carvalho, G. G. A., & Ferreira, J. R. (2008). Determination of Hg and diet identification in otter (*Lontra longicaudis*) feces. *Environmental Pollution*, 152(3), 592-596.

Li, C., Xu, Z., Luo, K., Chen, Z., Xu, X., Xu, C., & Qiu, G. (2021). Biomagnification and trophic transfer of total mercury and methylmercury in a sub-tropical montane forest food web, southwest China. *Chemosphere*, 277, 130371.

Lino, A. S., Kasper, D., Guida, Y. S., Thomaz, J. R., & Malm, O. (2019). Total and methyl mercury distribution in water, sediment, plankton and fish along the Tapajós River basin in the Brazilian Amazon. *Chemosphere*, 235, 690-700.

Linnik, P., Osadchyi, V., Osadcha, N., & Linnik, R. (2023). Redox potential as an important characteristic of the chemical and biological state of surface waters. *Chemistry and Ecology*, 39(6), 640-672.

Lipp, A. G., Roberts, G. G., Whittaker, A. C., Gowing, C. J., & Fernandes, V. M. (2020). River sediment geochemistry as a conservative mixture of source regions: Observations and predictions from the Cairngorms, UK. *Journal of Geophysical Research: Earth Surface*, 125(12), e2020JF005700.

Liu, R., Altschul, E. B., Hedin, R. S., Nakles, D. V., & Dzombak, D. A. (2014). Sequestration enhancement of metals in soils by addition of iron oxides recovered from coal mine drainage sites. *Soil and Sediment Contamination: An International Journal*, 23(4), 374-388.

Marchese, M. J., Gerson, J. R., Berky, A. J., Driscoll, C., Fernandez, L. E., Hsu-Kim, H., ... & Bernhardt, E. S. (2024). Diet choices determine mercury exposure risks for people living in gold mining regions of Peru. *Environmental Research: Health*, 2(3), 035001.

Mason, R. P., Reinfelder, J. R., & Morel, F. M. M. (1996). Uptake, toxicity, and trophic transfer of mercury in a coastal diatom. *Environmental Science & Technology*, 30(6), 1835-1845.

Mendes-Filho, O. R., Figueiredo, E. S. A., de Araújo Silva, K. C., & Cintra, I. H. A. (2020). Caracterização dos pescadores que integram o acordo de pesca na região do médio rio Araguaia, Tocantins, Brasil. *Research, Society and Development*, 9(7), e529974516-e529974516.

Mergler, D., Anderson, H. A., & Chan, L. H. M. (2007). Methylmercury exposure and health effects in humans: A worldwide concern. *Ambio*, 36(1), 3-11.

Millennium Ecosystem Assessment. (2005). Ecosystems and human well-being: Wetlands and water synthesis. *World Resources Institute*.

Molina, C. I., Gibon, F. M., Duprey, J. L., Dominguez, E., Guimarães, J. R. D., & Roulet, M. (2010). Transfer of mercury and methylmercury along macroinvertebrate food chains in a floodplain lake of the Beni River, Bolivian Amazonia. *Science of the Total Environment*, 408(16), 3382-3391.

Monteiro, L. C., Vieira, L. C. G., Bernardi, J. E. V., Pereira, T. A. M., Costa-Júnios, W. A., Silva, W. P., ... & Bastos, W. R. (2025). Combined effects of land use and geology on potentially toxic elements contamination in lacustrine sediments from the Araguaia River floodplain, Brazilian Savanna. *Environmental Monitoring and Assessment*, 197, 693

Moraes, L., Bernardi, J. V. E., de Souza, J. P. R., Portela, J. F., Vieira, L. C. G., Sousa Passos, C. J., ... & Dorea, J. G. (2023). Sediment Mercury, Geomorphology and Land Use in the Middle Araguaia River Floodplain (Savanna Biome, Brazil). *Soil Systems*, 7(4), 97.

Mosquera-Guerra, F., Trujillo, F., Parks, D., Oliveira-da-Costa, M., Van Damme, P. A., Echeverría, A., ... & Armenteras-Pascual, D. (2019). Mercury in populations of river dolphins of the Amazon and Orinoco basins. *EcoHealth*, 16, 743-758.

Munthe, J., & Hultberg, H. (2004). Mercury in aquatic ecosystems. In *Encyclopedia of Environmental Health* (pp. 511-519). Elsevier.

Ogwueleka, T. C. (2015). Use of multivariate statistical techniques for the evaluation of temporal and spatial variations in water quality of the Kaduna River, Nigeria. *Environmental Monitoring and Assessment*, 187, 1-17.

Root, R. A., Dixit, S., Campbell, K. M., Jew, A. D., Hering, J. G., & O'Day, P. A. (2007). Arsenic sequestration by sorption processes in high-iron sediments. *Geochimica et Cosmochimica Acta*, 71(23), 5782-5803.

Santos, A. N. D., Recktenvald, M. C. N. D. N., de Carvalho, D. P., Puerta, E. L. B., de Sousa-Filho, I. F., Dórea, J. G., & Bastos, W. R. (2021). Mercury in birds (aquatic and scavenger) from the Western Amazon. *Environmental Research*, 201, 111574.

Silva, L. G., de Lima, S. C., & Nazareno, E. (2019). O povo Karajá de Aruanã-GO/Brasil: Turismo, território e vida indígena. *Tempos Históricos*, 23(1), 216-240

Ullrich, S. M., Tanton, T. W., & Abdrashitova, S. A. (2001). Mercury in the aquatic environment: A review of factors affecting methylation. *Critical Reviews in Environmental Science and Technology*, 31(3), 241-293.

Wang, J., Shaheen, S. M., Jing, M., Anderson, C. W., Swertz, A. C., Wang, S. L., & Rinklebe, J. (2021). Mobilization, methylation, and demethylation of mercury in a paddy soil under systematic redox changes. *Environmental Science & Technology*, 55(14), 10133-10141.

Warren, L. A., & Haack, E. A. (2001). Biogeochemical controls on metal behavior in freshwater environments. *Earth-Science Reviews*, 54(3-4), 261-320.

Wiener, J. G., Krabbenhoft, D. P., Heinz, G. H., & Scheuhammer, A. M. (2003). Ecotoxicology of mercury. In *Handbook of Ecotoxicology* (pp. 409-463). CRC Press.

Yu, C., Xu, Y., Yan, Y., Xiao, W., Liu, M., Cheng, M., ... & Wang, X. (2021). Mercury and methylmercury in China's lake sediments and first estimation of mercury burial fluxes. *Science of the Total Environment*, 770, 145338.

Zweig, L. D., & Rabeni, C. F. (2001). Biomonitoring for deposited sediment using benthic invertebrates: a test on 4 Missouri streams. *Journal of the North American Benthological Society*, 20(4), 643-657

Zhuang, J., & Gao, X. (2013). Environmental fate and behavior of toxic heavy metals in sediment. *Environmental Science and Pollution Research*, 20(6), 4079-4094.

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