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Maria Clara Ferreira Neuenschwander

**CONTAMINAÇÃO POR ELEMENTOS-TRAÇO EM ECOSISTEMAS LÊNTICOS
URBANOS BRASILEIROS: TENDÊNCIAS NACIONAIS E PADRÕES LOCAIS**

Belo Horizonte

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MARIA CLARA FERREIRA NEUENSCHWANDER

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RESUMO

Ambientes lânticos urbanos, como lagos e reservatórios, são especialmente vulneráveis à contaminação por elementos-traço devido a sua característica de baixa hidrodinâmica e, portanto, alta capacidade de retenção de poluentes. Esses contaminantes, provenientes de fontes naturais e antrópicas, oferecem riscos ecológicos e à saúde pública. Sendo assim, investigamos a contaminação por elementos-traço em ecossistemas lânticos urbanos brasileiros a partir de dois enfoques complementares. No primeiro capítulo, realizamos uma revisão sistemática da literatura científica publicada entre 1980 e 2023, com o objetivo de compreender como esses contaminantes são estudados nas diferentes regiões brasileiras, considerando a vasta diversidade geográfica, ambiental e socioeconômica do país. Os estudos foram categorizados de acordo com a região geográfica, bioma, tipo de uso do solo, elementos-traço investigados, matriz analisada e menções às legislações ambientais brasileiras. Observamos uma tendência crescente na produção científica, especialmente entre 2011 e 2023. A maior parte dos estudos foi conduzido predominantemente em áreas industriais e na região Sudeste, em grandes centros urbanos e no bioma Mata Atlântica. Os elementos-traço mais investigados foram Cu, Pb, Cr, Zn e Ni sendo o sedimento a matriz mais frequentemente analisada. No segundo capítulo, analisamos a distribuição espacial de elementos-traço nos sedimentos da Reservatório de Ibirité (Minas Gerais), um reservatório artificial localizado em uma bacia hidrográfica urbanizada, e seus tributários. Foram quantificadas as concentrações de As, Cu, Cd, Cr, Hg, Mn, Ni, Pb e Zn em 22 pontos amostrados em duas campanhas (seca e chuvosa), juntamente com variáveis físicas, químicas e granulométricas dos sedimentos. As concentrações de As, Ni, Cu, Pb e Cr no reservatório ultrapassaram os limites estabelecidos pela Resolução CONAMA nº 454/2012. Nos tributários, observou-se que as concentrações de elementos-traço estiveram associadas ao uso e cobertura do solo, indicando influência direta das atividades antrópicas nas bacias de drenagem. Por outro lado, no reservatório, o uso e ocupação do solo não se mostraram bons preditores da distribuição espacial dos contaminantes, sendo as características sedimentares, especialmente a proporção de sedimentos finos, os principais fatores relacionados às concentrações dos elementos. Os resultados obtidos neste trabalho contribuem para o entendimento da contaminação por elementos-traço em lagoas urbanas e podem subsidiar estratégias de monitoramento e gestão ambiental nesses ecossistemas.

Palavras-chave: metal pesado; lagoa, reservatório; ecossistema urbano; contaminantes inorgânicos; sedimento

ABSTRACT

Urban lentic environments, such as lakes and reservoirs, are particularly vulnerable to trace element contamination due to their low hydrodynamics and, consequently, high capacity for pollutant retention. These contaminants, originating from both natural and anthropogenic sources, pose ecological and public health risks. Therefore, we investigated trace element contamination in Brazilian urban lentic ecosystems using two complementary approaches. In the first chapter, we conducted a systematic review of scientific literature published between 1980 and 2023, aiming to understand how these contaminants are studied across different Brazilian regions, considering the country's vast geographical, environmental, and socioeconomic diversity. Studies were categorized according to geographic region, biome, land use type, trace elements investigated, matrix analyzed, and references to Brazilian environmental legislation. We observed a growing trend in scientific production, especially between 2011 and 2023. Most studies were conducted in industrial areas, mainly in the Southeast region, large urban centers, and the Atlantic Forest biome. The most frequently investigated trace elements were Cu, Pb, Cr, Zn, and Ni, with sediment being the most commonly analyzed matrix. In the second chapter, we analyzed the spatial distribution of trace elements in the sediments of the Ibirité Reservoir (Minas Gerais), an artificial reservoir located in an urbanized watershed, and its tributaries. Concentrations of As, Cu, Cd, Cr, Hg, Mn, Ni, Pb, and Zn were quantified at 22 sampling points during two campaigns (dry and wet seasons), along with physical, chemical, and granulometric characteristics of the sediments. Concentrations of As, Ni, Cu, Pb, and Cr in the reservoir exceeded the limits established by Brazilian Resolution CONAMA n° 454/2012. In the tributaries, trace element concentrations were associated with land use and land cover, indicating a direct influence of anthropogenic activities in the drainage basins. In contrast, in the reservoir, land use and land cover were not good predictors of the spatial distribution of contaminants; instead, sediment characteristics, especially the proportion of fine particles, were the main factors related to trace element concentrations. The results of this work contribute to a better understanding of trace element contamination in urban lakes and may support monitoring and environmental management strategies in these ecosystems.

Keywords: heavy metal; lagoon; reservoir; urban ecosystem; inorganic contaminants; sediment

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INTRODUÇÃO GERAL

A expansão urbana frequentemente ocorre no entorno de corpos d'água, como rios, lagos e lagoas, impulsionada pelas necessidades hídricas e de recursos naturais (Friese et al., 2010; Martinez et al., 2023). Esses ambientes passam a desempenhar múltiplas funções para a população, incluindo o abastecimento de água e alimentos, regulação do microclima, recreação e atividades para geração de renda (Carpenter et al., 2011; Ranta et al., 2021). No entanto, a ocupação intensa e mal planejada do espaço urbano provoca alterações nos processos naturais das bacias hidrográficas como um resultado da impermeabilização do solo, construção de vias pavimentadas e obras de infraestrutura (Friese et al., 2010; Burbank et al., 2022; Martinez et al., 2023). Esses fatores modificam o escoamento superficial, intensificando o transporte de sedimentos e partículas sólidas para os corpos hídricos, por exemplo. Atividades urbanas como o descarte inadequado de esgotos domésticos e os efluentes de indústrias também agravam a degradação da qualidade dos ecossistemas aquáticos devido, por exemplo, ao aumento do aporte de nutrientes, compostos orgânicos e contaminantes (Sun et al., 2017; Macedo et al., 2022).

Ambientes lênticos urbanos, como lagos, lagoas e reservatórios, são especialmente suscetíveis a pressões antrópicas. Por apresentarem baixa hidrodinâmica, longo tempo de residência da água e condições físicas favoráveis à deposição de partículas, esses sistemas funcionam como áreas propícias à retenção de poluentes (Sodrzeieski et al., 2018; Rabello et al., 2018). Os impactos causados pelo uso e ocupação do solo, contribuem para o escoamento de água, sedimentos, nutrientes e substâncias tóxicas provenientes de diferentes fontes (Andrade et al., 2019; Silva et al., 2023). Nesse contexto, os elementos-traço se destacam como contaminantes de interesse ambiental (Sodrzeieski et al., 2018; Rabello et al., 2018; Andrade et al., 2019; Silva et al., 2023).

Os elementos-traço são metais e semimetais naturalmente presentes na crosta terrestre em baixas concentrações, podendo ter origem natural, como o intemperismo de rochas ou atividade vulcânica, ou antrópica, a partir de atividades urbanas, industriais, agrícolas e minerárias (Kabata-Pendias & Mukherjee, 2007). Alguns desses elementos são essenciais aos organismos vivos, como o zinco (Zn), o cobre (Cu), o níquel (Ni) e o manganês (Mn), por participarem de processos fisiológicos fundamentais, como metabolismo celular, respiração e crescimento (Kabata-Pendias & Mukherjee, 2007). Por outro lado, elementos tradicionalmente classificados como não essenciais, como chumbo (Pb), cádmio (Cd), mercúrio (Hg) e arsênio (As), não exercem funções biológicas conhecidas na maioria dos organismos, podendo causar efeitos

adversos mesmo em concentrações muito baixas e representar riscos à saúde humana e à fauna aquática (Kabata-Pendias & Mukherjee, 2007; Andrade et al., 2019). Entretanto, há relatos de organismos capazes de utilizar alguns elementos não essenciais como substitutos na ausência do elemento primário, por exemplo, a utilização de Cd no lugar do Zn pela diatomácea marinha *Thalassiosira weissflogii* sob condições de limitação de Zn (Lane et al., 2000). Ainda assim, mesmo os elementos essenciais podem tornar-se tóxicos quando presentes em concentrações elevadas, acumulando-se nos organismos e causando alterações reprodutivas, fisiológicas e comportamentais (Silva et al., 2023).

Uma vez introduzidos nos ambientes lênticos, os elementos-traço podem ser encontrados em diferentes compartimentos ambientais: dissolvidos na coluna d'água, adsorvidos a partículas em suspensão, acumulados no sedimento ou incorporados à biota aquática (Loureiro et al., 2009; Melo et al., 2012). Entre essas matrizes, os sedimentos se destacam por funcionarem como registro histórico da poluição, além de atuarem como fontes secundárias de contaminação, uma vez que podem disponibilizar elementos de volta à coluna d'água sob determinadas condições ambientais (Andrade et al., 2018; Cunha et al., 2021). Diante dos riscos ecológicos e sanitários associados à presença de elementos-traço em ambientes aquáticos, diferentes órgãos reguladores estabeleceram parâmetros de qualidade ambiental. No Brasil, a Resolução do Conselho Nacional do Meio Ambiente (CONAMA) nº 357/2005, por exemplo, define limites para concentrações de substâncias na água, de acordo com seus usos. Já a Resolução CONAMA nº 454/2012 estabelece valores de referência para elementos-traço em sedimentos, especialmente no contexto de dragagens. A Agência Nacional de Vigilância Sanitária (ANVISA), por sua vez, estipula limites máximos permitidos em alimentos, como o teor de mercúrio em peixes, visando a proteção da saúde pública (Silva et al., 2023). Apesar desses avanços normativos, persistem lacunas relevantes no monitoramento ambiental.

Diante desse cenário, este trabalho teve como objetivo investigar a contaminação por elementos-traço em ambientes lênticos urbanos brasileiros por meio de dois enfoques complementares. No primeiro capítulo, foi realizada uma revisão sistemática da literatura científica publicada entre 1980 e 2023, com o intuito de avaliar aspectos geográficos, ambientais e populacionais relacionados à distribuição dos estudos sobre elementos traço em lagoas urbanas brasileiras. Foram analisados, além dos elementos e as matrizes investigadas, as técnicas de preparo das amostras e equipamentos de detecção utilizados, e a influência de legislações ambientais vigentes sobre as publicações de estudos. No segundo capítulo, aprofundou-se a análise em escala local, por meio do estudo da distribuição espacial de

elementos-traço nos sedimentos de um reservatório urbano inserido em uma bacia hidrográfica com múltiplos usos do solo. O estudo foi realizado no Reservatório de Ibirité (Belo Horizonte, Minas Gerais) e seus principais tributários. Foram avaliadas as concentrações de elementos-traço em sedimentos superficiais, juntamente com variáveis físicas e químicas (pH, condutividade elétrica, porcentagem ou conteúdo de matéria orgânica e granulometria). Os resultados obtidos visam a identificação de zonas críticas de contaminação, contribuindo para o desenvolvimento de estratégias de gestão e monitoramento de ambientes lânticos urbanos, além de ampliar o entendimento sobre a influência dos diferentes usos e ocupação do solo na contaminação por elementos-traço nos sedimentos desses ecossistemas.

Capítulo 1

Research trends on trace element contamination in Brazilian urban lentic ecosystems: the role of environmental and policy factors

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Abstract

Lentic ecosystems are vulnerable to contamination by trace elements, which can accumulate and pose risks to aquatic life and human health. In a large developing country such as Brazil, marked by vast geographic, environmental, and socioeconomic diversity, it is crucial to understand how these factors influence research trends on this group of contaminants. To address this need, we conducted a systematic review of 65 studies published between 1980 and 2023 on Brazilian urban lentic systems, retrieved from Web of Science and Scopus databases. Research output increased sharply after 2011, with 73% of studies published in the last decade. Geographically, half of studies were conducted in the Southeast region, especially in large urban areas within the Atlantic Forest biome, while the North and Central-West together account less than 15%. Industrial zones were the most frequently studied land use, and sediment

was the most common matrix. Copper, lead, chromium, zinc, and nickel were the most frequently reported trace elements, whereas toxic elements such as arsenic and mercury were infrequently studied. This review provides a quantitative synthesis of research on trace element contamination in Brazilian urban lentic ecosystems. The findings highlight critical gaps, including the underrepresentation of North and Central-West regions, the limited use of biological matrices, and the neglect of mercury and arsenic, despite their ecological and toxicological relevance. This study represents the first systematic review of trace element contamination in Brazilian urban lentic systems, providing a comprehensive synthesis of research patterns and critical gaps. In a highly diverse developing country such as Brazil, addressing these gaps is essential to improve ecotoxicological risk assessments, strengthen the integration between environmental monitoring and public health, and guide evidence-based policies for pollution control in vulnerable aquatic systems.

Keywords

Heavy metals, lagoon, urban ecosystem, Brazilian biomes, sediment

Introduction

Ecosystems are shaped by natural and anthropogenic processes, with urbanization being one of the main causes of change (Da Silva et al., 2023). Currently more than half of the global population lives in urban areas, and this proportion is projected to reach nearly 70% by 2050 (United Nations, 2019). In Brazil, urban areas expanded by 2.4 million hectares between 1985 and 2023, reaching 4.1 million hectares (Projeto MapBiomias, 2023). This expansion has transformed landscapes and ecosystems, replacing natural habitats with urban and anthropogenic areas, and affecting ecological processes, ecosystem services, and biodiversity

(Baptista & Rudel, 2006; Ribeiro et al., 2009). Large cities such as São Paulo exemplify this dynamic, where a high population density increases pollutant generation and environmental pressure (Cohen, 2004).

To address the challenges posed by urban growth, development of infrastructure has intensified, including highways, housing, industrial facilities, power plants, and domestic waste disposal systems (Da Silva et al., 2003). These changes modify terrestrial environments and also have significant impacts on aquatic systems, compromising their quality and functionality. Soil impermeabilization, removal of riparian vegetation, and increased domestic and industrial wastewater are anthropogenic activities that lead to greater pollutant input, erosion, and sedimentation in water bodies (Hill et al., 2017).

Aquatic ecosystems can be classified as lentic (lakes, lagoons, ponds, and reservoirs) or lotic (rivers and streams) systems. Lotic systems exhibit continuous water flow and rapid turnover, whereas lentic ecosystems are characterized by low water renewal rates and high water residence times, making them susceptible to environmental changes caused by urbanization (Cardoso-Silva et al., 2018). These environments play crucial ecological roles, including supporting biodiversity, regulating biogeochemical cycles, and providing water resources for human use (Brönmark & Hansson, 2002; Hoverman & Johnson, 2012). However, the depositional characteristics of lentic environments favor pollutant accumulation, leading to high contamination levels in urban environments. They are exposed to nutrients, chemical contaminants, and solid waste, which can disrupt various ecological processes, including water quality, eutrophication, and species extinction (Çelekli & Lekeşiz, 2021). Trace elements, a group of chemical contaminants, are mainly metals and metalloids that naturally occur at low concentrations in the environment (Kabata-Pendias & Mukherjee, 2007). Depending on the element and their levels, they may play essential roles or accumulate, exerting toxic effects that

compromise environmental quality (Kabata-Pendias & Mukherjee, 2007; Sodrzejewski et al., 2018).

Trace elements can be released from natural sources, such as rock weathering and anthropogenic activities, including inappropriate disposal of industrial and domestic waste, urban runoff, and agricultural practices (Melo et al., 2012; Loureiro et al., 2012; Sodrzejewski et al., 2018). The increase in pollutant emissions caused by urbanization intensifies the input of these contaminants into lentic ecosystems. Once introduced, trace elements can remain dissolved in the water column, adhere to suspended particles, or accumulate in sediments (Melo et al., 2012; Rabello et al., 2018). Therefore, they remain in aquatic ecosystems and can be bioaccumulated by organisms, causing reproductive alterations and reducing the survival of aquatic species (Rowe, 2014). Moreover, human exposure, through consumption of contaminated fish or contact with polluted water, can lead to severe health effects, such as kidney damage, neurotoxicity, cancers, and development impairments in fetuses (Cruz et al., 2022). Thus, trace element contamination threatens aquatic biodiversity and human health, requiring continued efforts to monitor and manage these ecosystems.

Given the critical importance of understanding contamination in urban environments, this study investigates trace element contamination in Brazilian urban lentic systems through a systematic review. These ecosystems are exposed to multiple anthropogenic pressures from rapid urbanization, industrial activities, and inadequate waste management, which can lead to the accumulation of trace elements. Considering the risks associated with these contaminants, it is necessary to better understand how they have been studied across different Brazilian regions, considering the country's vast geographic, environmental, and socioeconomic diversity. Moreover, it is also important to understand which trace elements have received research attention to identify potential gaps in monitoring contaminants that may pose significant

ecological and human health risks. We sought to address two main questions: (1) How do geographic, environmental, and population factors influence the distribution of studies on trace element contamination in Brazilian urban lentic systems? (2) How are trace elements distributed in studies on contamination in Brazilian urban lentic systems? We hypothesized that contamination is studied more often in densely populated, industrialized, and impacted regions and biomes. Such analyses are essential for the evaluation and development of effective conservation strategies for vulnerable ecosystems.

Methods

A systematic review was conducted following the PRISMA ("Preferred Reporting Items for Systematic Reviews and Meta-Analyses") guidelines (Page et al., 2021), using Web of Science and Scopus as primary databases. All available databases within Web of Science were searched, covering the title, abstract, and indexing fields in both English and Portuguese, as searches in English did not adequately retrieve articles in Portuguese. Given that the focus of this study was Brazilian ecosystems, the goal was to maximize the inclusion of papers from the region. In Scopus, we searched in titles, abstracts, and keywords exclusively in English, as this approach effectively retrieved articles in both English and Portuguese. This review covers the period from January 1980 to December 2023, a timeframe that coincides with the intensification of urbanization in Brazil (Projeto MapBiomias, 2023).

Keywords were organized into four groups. The first group included the studies location, Brazil, encompassing the names of Brazilian states and biomes in Portuguese and their English equivalents. The second group focuses on trace elements, as defined by Kabata-Pendias and Mukherjee (2007), along with their synonyms. The third group comprised terms related to water

bodies of interest, and the fourth group included terms associated with urban areas. Additionally, we excluded irrelevant terms, such as "hydroelectric plants", "estuaries," and "bays.". Boolean operators (AND, OR, AND NOT) and quotation marks were applied to combine and refine search terms across databases, following best practices for systematic reviews in environmental sciences (Pullin & Stewart, 2006; Haddaway et al., 2016). A complete list of keywords used is provided in the Supplementary Material (Tab. S1).

The bibliographic search yielded 1,558 articles, which were imported into the Rayyan reference manager (Ouzzani et al., 2016). Of these 329, were manually excluded as duplicates leaving 1231 for title and abstract screening to ensure alignment with the objectives of this review. Articles were excluded if they: 1) did not address the central theme, 2) investigated water bodies outside the scope of interest, 3) did not analyze trace elements, or 4) were conducted outside Brazil. After the evaluation, 65 articles were selected for review, with each article considered as a report (Fig. S1). We then conducted a full-text review of the remaining articles. This systematic workflow, combining PRISMA guidelines, database-specific search strategies, and digital screening tools, ensures transparency and reproducibility of the method.

During the full-text review of the selected articles, we extracted information to characterize the land-use of research on contamination in Brazilian urban lentic systems. The data collected included: name of the water body, year of publication, journal, state, and city where the study was conducted, analyzed trace elements, matrices, sample preparation methods and detection techniques, land use, and Brazilian regulations cited. When land-use information was not provided it was obtained from other studies on the same water body included in the review or from the Infosnba website (<https://infosnbas.org.br/>). Biome data and classifications of coastal and continental cities were obtained from the Brazilian Institute of Geography and Statistics (IBGE, 2022). City size was determined using population data provided by the IBGE.

The IBGE conducts national population censuses at least once every decade, complemented by official intercensal estimates (e.g., 2018). These censuses and estimates represent the most reliable and comprehensive source of demographic information for Brazilian municipalities. For each study included in our review, we assigned the city size based on the census or estimate in effect in the year of publication, ensuring that the demographic data reflected the period when the study was conducted. Cities were categorized, based on the IBGE criteria, as small population (< 100,000), medium population (between 100,000 and 500,000), or large population (> 500,000).

Results

Systematic Review

A total of 65 articles on the contamination of Brazilian urban lentic systems by trace elements within the defined period from January 1980 to December 2023 were selected for review, with the first publication dating back to 1994. In that year, Huang et al. published an article in *Environmental Geology* that investigated trace elements in the sediments of a lagoon in Rio de Janeiro. Since then, the academic output on the subject has increased, with a notable increase from 2011 to 2023, during which 73% of the articles were published. The year 2019 had the highest number of publications, with nine articles dedicated to this topic (Fig. 1).

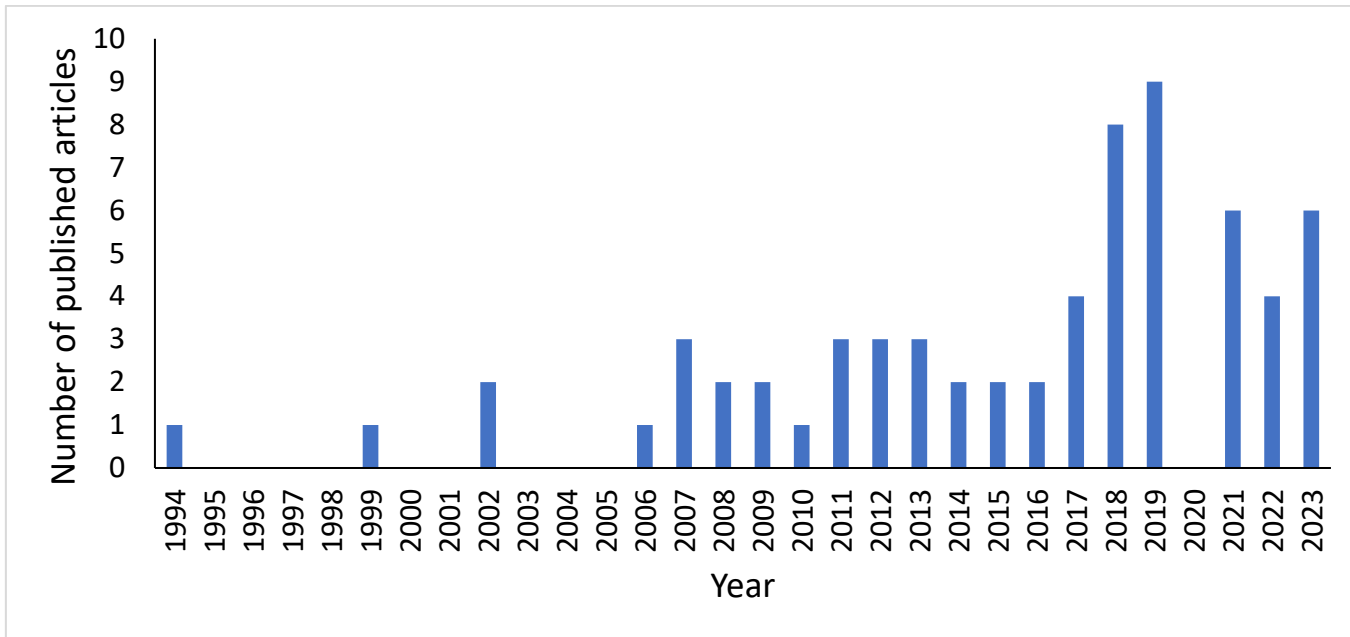


Figure 1. Number of articles published on trace element contamination in Brazilian urban lentic systems from 1994 to 2023. The search covered the period from 1980 to 2023; however, publications began only in 1994, with no records between 1980 and 1993. A correlation test was performed to assess the relationship between publication year and number of publications, showing a Pearson's correlation of $r = 0.72$ ($t(28) = 5.51$, $p < 0.001$).

The journals with the highest number of publications were *Environmental Monitoring and Assessment*, with seven articles, and *Journal of Radioanalytical and Nuclear Chemistry*, with four articles. These journals have impact factors of 3.0 and 1.5, respectively. Additionally, 41 other journals published articles on the topic, with each owning on average 1.32 ± 0.65 papers (mean \pm standard deviation).

Geographical, environmental and population factors

Of the 65 articles analyzed, six investigated lentic systems covering more than one municipality. Among the remaining 59 articles, 62.7% were conducted in large urban centers

(population > 500,000). Medium-sized and small municipalities accounted for 23.7% and 13.6% of articles, respectively.

Among the 65 articles, 56 lentic water bodies distributed across 14 Brazilian states were analyzed. The State of Rio de Janeiro (RJ) stood out with 15 publications (23%), followed by São Paulo (SP) with 12 publications (18.5%), and Rio Grande do Sul (RS) with nine publications (13.9%). Rio Grande do Norte (RN), Santa Catarina (SC), Alagoas (AL), and Sergipe (SE) appeared in only one study. The Southeast region had the highest number of articles (n=33), accounting for 50% of the publications, while the Central-West and North regions had the fewest published articles (n=3 and 6, respectively; Fig. 2).

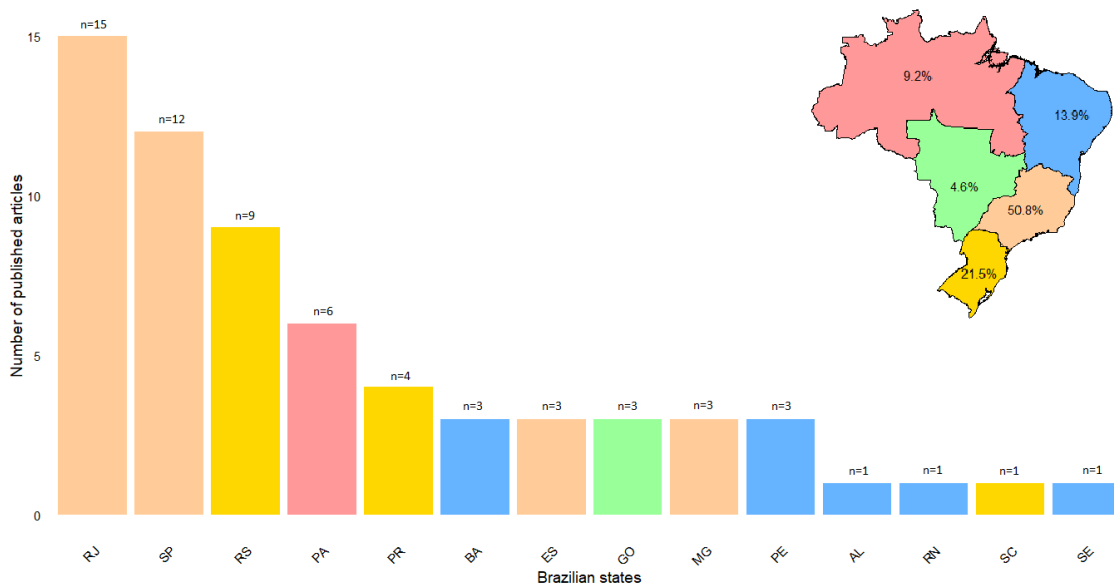


Figure 2. Number of publications on trace element contamination in urban lentic ecosystems between 1980 and 2023 by the Brazilian state. Only 14 of the 26 Brazilian states were mentioned in these articles.

Rodrigo de Freitas Lagoon, located in RJ, was the most investigated ecosystem, with eight published articles corresponding to 12.3% of the total articles. Guaíba Lake in RS was the subject of five articles (7.7%), and Guarapiranga Reservoir in SP was the subject of four (6.1%).

Considering all the lentic systems analyzed in the articles, RS led to the highest number of different systems, followed by RJ and Pará (PA).

The articles covered natural and artificial systems, with 65% being natural and 35% being artificial. Geographically, 51% of the systems were located in continental cities and 49% were located in coastal cities. Most articles (72.3%) were conducted in the Atlantic Forest biome, followed by the Pampa biome (13.8%). Biomes such as Cerrado, Amazon, and Caatinga appeared less frequently at 10.8%, 9.2%, and 6.2%, respectively (Fig. 3). When the study was conducted in an ecosystem in a transition zone between biomes, it was counted as n=1 in each biome. This occurred in eight articles, one of which included both the Atlantic Forest and Cerrado, three combined the Atlantic Forest and Caatinga, and one included both the Atlantic Forest and Pampa. No studies have been conducted on the Pantanal.

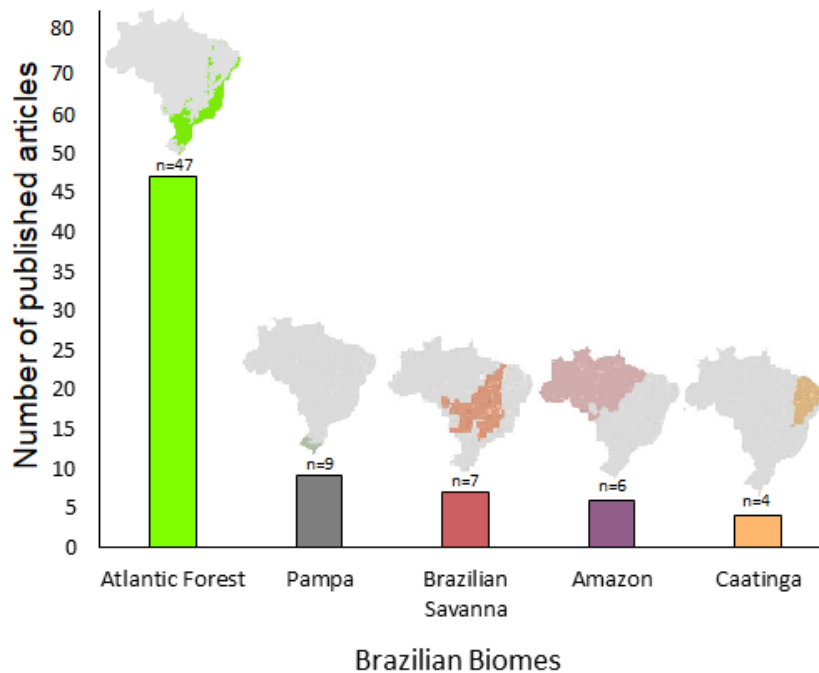


Figure 3. Distribution of the number of articles published on trace element contamination in urban lentic systems between 1994 and 2023 by Brazilian biome.

The articles analyzed lentic systems in areas dominated by industrial activities and were reported in 66.2% of the articles. Agriculture was noted in 52.3% of cases, whereas livestock

farming and mining occurred in 18.5% and 13.8% of cases, respectively. Land use for pasture was the least frequent, occurring in 9.2% of publications.

Trace Elements assessed and their legislation

The trace elements analyzed in the articles on contamination in Brazilian urban lentic systems showed variations in their frequency of occurrence. Cu was the most found element, followed by Pb, Cr, Zn, Ni, Fe, Cd, Mn, Al, Ba, Co and Hg (Table. 1). For these elements, the Southeast region showed the highest number of studies for Zn (n = 31), Cu (n = 30), Pb (n = 29), Cr (n = 28), and Ni (n = 26). The South region recorded the highest number of occurrences for Cr (n = 13), followed by Al, Zn, Ni, Pb, and Cd (n = 11 each). In the Northeast, the most frequently studied elements were Mn and Cu (n = 9 each). The Central-West and North regions recorded a maximum of three studies per element, with no element standing out in either region. Among all the trace elements (list of elements defined by Kabata-Pendias & Mukherjee, 2007), 16 were not reported in this bibliometric research (e.g., Ge, In, Pt, Pd, I).

Table 1. Frequency of studies reporting each trace element in Brazilian urban lentic systems (1994–2023). The table includes only elements reported in ≥ 20 articles.

Trace element	Frequency of studies
Cooper (Cu)	54 (83,1%)
Lead (Pb)	52 (80%)
Chromium (Cr)	52 (80%)
Zinc (Zn)	51 (78,5%)
Nickel (Ni)	45 (69,2%)

Cadmium (Cd)	43 (61,5%)
Iron (Fe)	39 (56,9%)
Manganese (Mn)	35 (53,8%)
Aluminum (Al)	30 (46,2%)
Barium (Ba)	22 (33,8%)
Cobalt (Co)	21 (32,3%)
Mercury (Hg)	20 (30,8%)

Trace elements were mainly analyzed in the sediment samples, with 47 articles (72.3%) assessing this matrix. Of these, 14 analyzed total sediment, 18 fine sediment, and 15 did not classify the granulometric fraction of the analyzed sample. Water was analyzed in 26.2% of the publications, followed by fish, macrophytes, and invertebrates, which appeared in 9.2%, 3.1%, and 3.1% of the articles, respectively. Finally, suspended particles were analyzed in 1.5% of the articles. Among the 65 articles, 58 analyzed only one matrix (sediment, water, or fish). The remaining articles analyzed more than one matrix.

Brazilian legislation regarding trace element contamination in urban lentic systems was mentioned in 33 studies. In Brazil, two institutions deliberate on guidelines regarding environmental contamination by trace elements, Conselho Nacional do Meio Ambiente (CONAMA) and Agência Nacional de Vigilância Sanitária (Anvisa). Resolution CONAMA n° 357/05, which provides guidelines for the classification of water bodies and environmental directives for their management, was mentioned in 12 out of 18 articles that analyzed water, representing 66.7% of them (Fig. 4). Resolution CONAMA n° 454/12, which outlines

guidelines for managing dredged sediments and their disposal, was referenced in 12 out of 47 articles that analyzed sediment (25.5%). The Resolution CONAMA n° 344/04, which sets general guidelines and minimum procedures to evaluate material to be dredged in Brazilian jurisdictional waters, was cited in five out of 47 publications that analyzed sediment, representing 10.6% of them (Fig. 5). In addition, the Anvisa, responsible for regulating and overseeing the quality of products that impact public health in Brazil, including fish for human consumption, was mentioned in four articles. while CONAMA n° 420/09, which establishes guidelines for soil quality assessment and defines reference values for chemical substances in the environment, appeared in two articles and CONAMA n° 430/11, which regulates conditions and standards for the discharge of effluents into water bodies, appeared in one article.

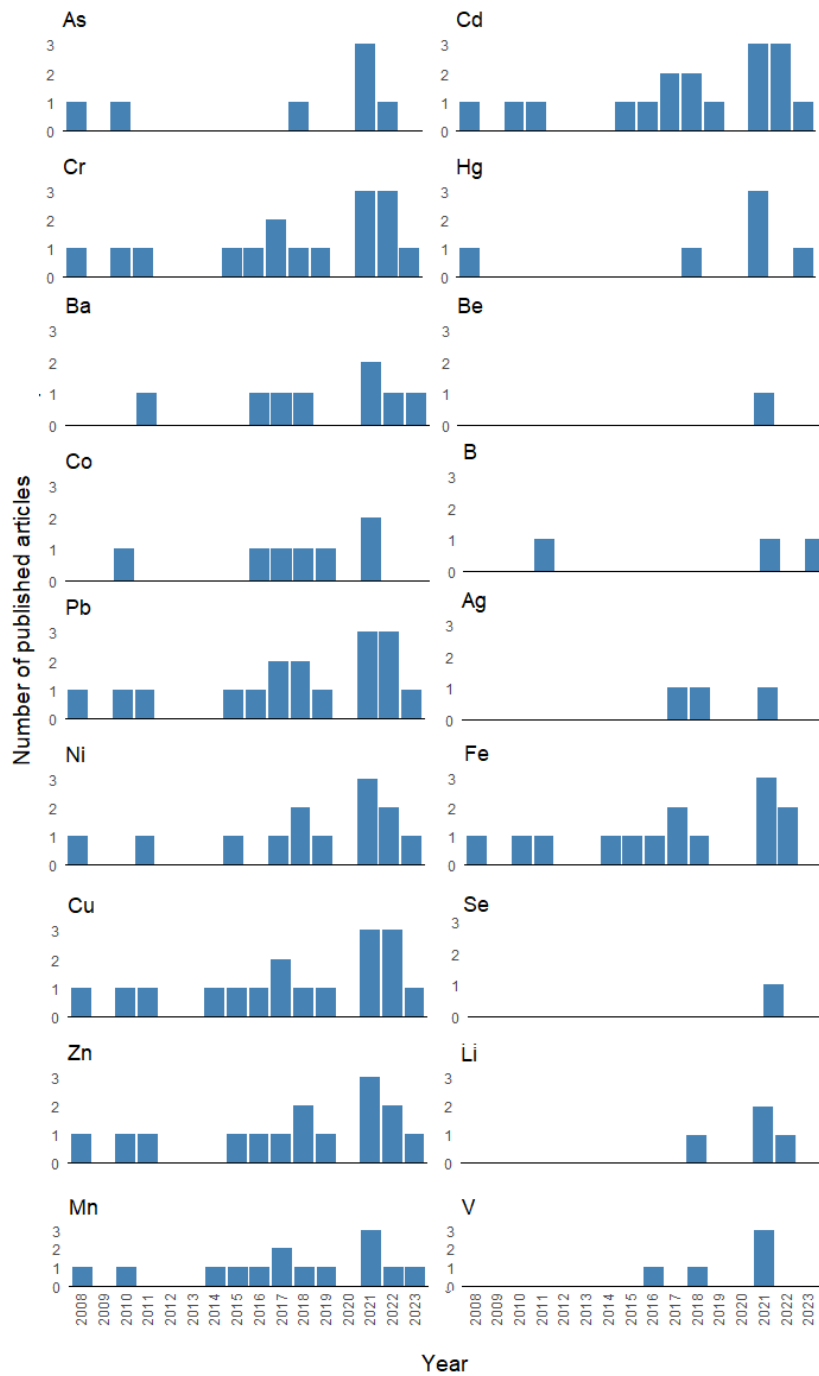


Figure 4. Temporal distribution of publications (2008–2023) on trace element contamination in Brazilian urban lentic systems, focusing on elements regulated by CONAMA Resolution n° 357/05. Each panel represents a specific element and shows the annual number of related publications. Although the literature search covered the period from 1980 to 2023, the earliest relevant article was published in 2008.

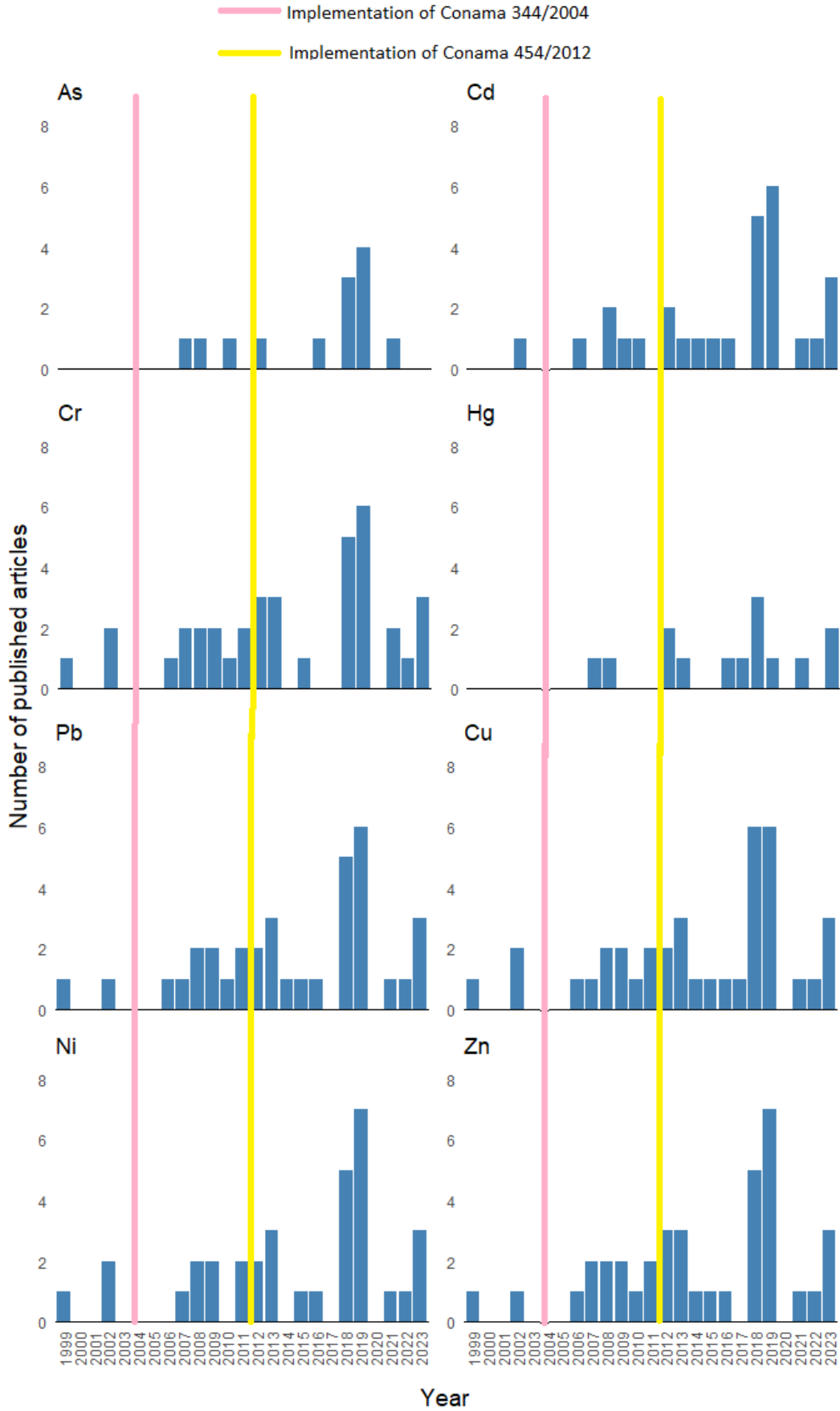


Figure 5. Temporal distribution of publications (1989–2023) on sediment contamination by trace elements regulated under CONAMA Resolutions n° 344/2004 and n° 454/2012 in Brazilian urban lentic systems. Each panel represents a specific element and shows the number of annual publications. Vertical lines indicate the implementation years of the respective resolutions: 2004 (pink) and 2012 (yellow). Although the first relevant study was published in 1989, the literature search spanned from 1980 to 2023.

In the 65 analyzed studies, 76 sample preparation and detection techniques were used, as some studies applied more than one approach based on analytical demands (Table 2; Table 3). Only one article did not indicate the detection technique used, and eight did not specify sample preparation.

Table 1. Sample preparation used in articles on trace element contamination in Brazilian urban lentic systems with their respective frequencies of use (%).

Sample preparation	Frequency of use (%)
Inductively coupled plasma (ICP)	54.0
Flame (F)	13.2
Cold vapor (CV)	6.6
Graphite furnace (GF)	3.9
Instrumental neutron activation analysis (INAA)	3.9
Absence of Gradients and Nernstian Equilibrium Stripping (AGNES)	1.3
Fast atomization injection (FAI)	1.3
Pyrolysis	1.3
No sample preparation required	4.0
Not specified	10.5

Table 2. Detection techniques used in articles on trace element contamination in Brazilian urban lentic systems, with their respective frequencies of use (%).

Detection technique	Frequency of use (%)
Atomic absorption spectrometry (AAS)	31.6
Optical emission spectrometry (OES)	22.4
Mass spectrometry (MS)	18.4
Atomic emission spectroscopy (AES)	14.5
X-ray fluorescence (XRF)	4.0
Atomic fluorescence spectrometry (AFS)	2.6
Chronopotentiometry dissolution	1.3
Gamma spectrometry	1.3
Particle-induced X-ray emission (PIXE)	1.3
Direct mercury analyzer (DMA)	1.3
Not specified	1.3

Discussion

Publication trend

We observed a clear growing trend in studies investigating trace elements in Brazilian urban lentic aquatic ecosystems over the decades. Although our database search began in 1980, the first identified study was published only in 1994. From 2011 and 2023, the number of publications increased, accounting for 73% of all articles, suggesting a growing recognition of the environmental relevance of the topic.

The absence of publications between 1980 and 1993 highlights a historical gap in scientific production that can be attributed to multiple factors. The 1980s, under an authoritarian regime focused on economic growth (Braga, 2020), prioritizes resource exploitation over environmental protection (Oliveira, 2018; Campos & Brandão, 2023). This political and economic scenario, coupled with the repression and censorship faced by the academic community (Braga, 2020), limited both the capacity for research and its dissemination. Another explanation for the absence of studies is the underrepresentation of older works in digital databases (Poisot et al., 2019). Many early studies may only be available in physical archives, limiting their retrieval in digital searches.

From the mid-1980s to the early 1990s, interest in environmental issues began to increase, driven by the strengthening of agreements and regulations (Rocha, 2003; Moura, 2016; Pott & Estrela, 2017). The establishment of governmental bodies like National Environmental Council (CONAMA, 1981) and the National Environmental Fund (FNMA, 1989), along with the ratification of international treaties from the United Nations Conference on Environment and Development, held in Rio de Janeiro, Brazil (1992), created a legal and financial framework that spurred environmental research. These environmental public policies have fostered the growth of environmental research in Brazil, including studies on contamination by trace elements in aquatic ecosystems.

The surge in articles after 2000 is a result of advancements in analytical techniques and increased funding for scientific research in the country (Sidone et al., 2016; Hossain et al., 2021). The publications of studies in 43 journals from various disciplines reflect the need for diverse scientific approaches to investigate trace element contamination. This multidisciplinary approach is essential for a understanding and effective mitigation of pollution impacts.

Thus, we expect publications on trace element contamination in Brazilian urban lentic ecosystems to continue increasing due the growing of environmental pressure and the increasingly evident effects of climate change, such as floods and extreme weather events. Furthermore, the diversity of journals covering the topic suggests that scientific production will remain dispersed across different multiple disciplines, reinforcing the need for integrated approaches to better understand and mitigate contamination impacts on Brazilian urban lentic aquatic ecosystems.

Geographical, environmental and population factors driving research trends

We found that scientific production on urban lentic ecosystems in Brazil is higher in major urban centers, whereas medium- and small-sized municipalities receive less attention. This predominance can be explained by the greater availability of academic infrastructure, technical staff, media visibility, and concentrated investments in these regions (Motta et al., 2002; Albuquerque et al., 2005). The concentration of research is particularly evident in the Southeast and South regions, which historically receive the majority of the country's research funding (Albuquerque et al., 2005; Chiarini et al., 2014; de Moraes Weber, 2018). This unequal distribution is a direct reflection of Brazil's funding structure. For example, in 2009, only seven universities, all located in the Southeast and South regions, accounted for approximately 60% of Brazilian studies published in international journals (Sidone et al., 2016). Three of these leading institutions, all in the state of São Paulo, account for most of this output. The São Paulo Research Foundation (FAPESP) is one of Brazil's leading funding agencies, with a high volume of investment and a prominent role, contributing to the rise of research in the state (Lima, 2023).

Although the North region hosts the Amazon, a biome with high biodiversity and ecological significance, research investment there remains low compared to the other regions of Brazil (Stegmann et al., 2024). Scientific production in this region is often tied to economically strategic sectors, such as mining in Pará (Oestreicher et al., 2017; Sahoo et al., 2023; Lima-Corrêa et al., 2023) and the construction of hydroelectric plants in the Amazon basin (Fearnside, 2006; Tundisi et al., 2014), activities that require environmental studies due to national legislation. Pantanal has also been neglected and no studies were identified, despite the presence of large urban centers within the biome. A possible explanation is that ecological research in the Pantanal has traditionally focused on its natural dynamics, particularly hydrology, biodiversity, land-use change, and conservation (Alho, 2008; Junk et al., 2011; Guerra et al., 2020). As one of the most preserved biomes in the world, with over 80% of native vegetation cover (IMASUL, 2021), scientific attention has been directed primarily toward safeguarding its wetlands, wildlife, and ecological processes, rather than investigating its urban aquatic environments. While this focus is crucial for conservation, it has inadvertently left urban systems underexplored, highlighting a research gap. In contrast, the Atlantic Forest was the most represented biome in the studies, likely due of its high rate of environmental degradation (Ribeiro et al., 2009; Eisenlohr et al., 2015) and greater accessibility for research, given that many academic institutions are located in this region (Sidone et al., 2016). This distribution also reflects the high levels of human occupation and environmental challenges the biome faces, such as deforestation and unregulated land use. The Atlantic Forest is one of the most important biomes in Brazil, renowned for its extraordinary biodiversity, high levels of endemism, and essential ecosystem services such as climate regulation, water supply, and soil protection (Marques et al., 2021; Vancine et al., 2024). Despite its ecological importance, it has been severely degraded by anthropic pressures, including urban expansion, agriculture, and industrial activities, leading to habitat fragmentation and loss of biodiversity (Scarano & Ceotto, 2015;

Lima et al., 2020; Carlucci et al., 2021). These pressures are especially critical in densely populated areas where many of the studied aquatic ecosystems are located. Inequality in study distribution highlights the need for a more balanced allocation of resources to expand research opportunities across the country.

We also observed that these studies were concentrated in industrial and agricultural areas. Industrial processes can release toxic trace elements (Soares et al., 2019; Camargo Filho et al., 2022; Martinez et al., 2023) into aquatic ecosystems affecting biota and human populations, which depend on these water resources. This high exposure risk may drive research in these environments. Additionally, although our study focused on urban areas, several investigated lentic systems are influenced by agricultural land use within their drainage basins (Sodrzeieski et al., 2018; Dórea et al., 2023), possibly due to fertilizer use, which can contaminate soil and water bodies. Agriculture also promotes soil leaching and increases pollutant transport into aquatic systems (Gonçalves et al., 2014; Rashid et al., 2023). Thus, even in a predominantly urban context, contamination of these ecosystems is strongly influenced by multiple anthropogenic sources. The overlap of different human activities underscores the complexity of understanding urban contamination and identifying trace-element sources.

Trace elements assessed and their legislation

The most investigated elements in this review, in descending order, were Cu, Pb, Cr, Zn, Ni, Fe, Cd, Mn, Al, Ba, Co, Hg, and As. Their prevalence in studies of Brazilian urban lentic systems can be attributed to their toxicity, widespread use in industrial products and processes, and availability of well-established analytical techniques for their detection.

Scientific interest in these elements has also been driven by historical contamination events and their impact on human health. Examples include the Minamata accident in Japan, caused by methylmercury contamination (a highly toxic organic form of Hg) and its severe neurological effects, and Itai-Itai disease, also in Japan, related to cadmium poisoning, which damages bone and kidney (Nevado et al., 2010; Nordberg & Nordberg, 2016). Other elements are similarly linked to human diseases, such as high aluminum concentrations, which may lead to kidney dysfunction, whereas prolonged exposure to cadmium, lead, chromium, and nickel is considered carcinogenic (Lino et al., 2018; Matthews et al., 2019). However, even essential elements, such as manganese, can become harmful when they exceed certain concentration limits (Kabata-Pendias & Mukherjee, 2007). Conversely, deficiencies in Zn and Fe can result in growth retardation and anemia, respectively (Nordberg & Nordberg, 2016). The historical significance of these diseases reinforces concerns regarding the impact of exposure to trace elements, driving research on their toxic effects.

The use of trace elements in products and industrial processes has also made them a central research focus (Nordberg & Nordberg, 2016). Since Ancient Rome, lead has been used in the construction of pipelines and aqueducts, as well as in coins and household utensils (Needleman, 2004). Mercury, historically employed in gold mining and various products such as batteries, electrical switches and fluorescent lamps has been banned in several countries because of its toxicity (Pfeiffer et al., 1993; Lacerda & Malm, 2008; Nandiyanto et al., 2023). Other elements, such as copper, chromium, and nickel, also have various industrial applications and still require further studies for a better understanding of their impacts (Swaine, 2000). The frequent use of these elements has led to developing and improving analytical techniques for detecting and quantifying them in various environmental matrices.

Key Matrices in Environmental Contamination Assessment and Analytical Methods

In this review, the most analyzed frequently matrices were sediment and water, both strongly affected by urban, agricultural, industrial, and mining activities. Sediments act as sinks for pollutants, especially in lentic ecosystems, and accumulate and concentrate trace elements over time, making them widely used for environmental contamination assessments (Sodrzeieski et al., 2018; Andrade et al., 2018; Andrade et al., 2019). Their analysis provides insights into parameters influencing metal distribution, such as texture, pH, organic matter, salinity, and dissolved oxygen. In contrast, water is directly available to aquatic organisms and consumed by humans, thus playing a crucial matrix in evaluating contamination exposure. Its selection in studies is linked to both its relevance to public health and its ecological importance, as water analysis reflects the bioavailable fraction of contaminants in the environment (Bucci et al., 2015; Andrade et al., 2018; Silva et al., 2021). Conversely, the lower frequency of studies involving biological matrices, such as fish (9,2%) and invertebrates (3,1%), can be a limitation, as these organisms are key indicators of bioaccumulation and trophic transfer of contaminants (Kasper et al., 2009; Paiva et al., 2022; Saidon et al., 2024). This underrepresentation may be partly explained by the greater complexity of biological sampling and analytical procedures, but it has important implications. Given that fish are a important component of the Brazilian diet (Lopes et al., 2016; Louis et al., 2022; Lopes & Freitas, 2023), the scarcity of studies assessing trace elements in biota raises concerns that human exposure through diet may be underestimated, thereby compromising both ecological risk assessments and food safety considerations.

Environmental legislation appears to be an important driving factor in research on trace element contamination. The presence of CONAMA Resolutions n° 357/05 (water quality), n° 454/12 (management of dredged sediments), and n° 344/04 (assessment of dredged material) in the

reviewed studies suggests that these regulations influence research efforts. A timeline analysis reveals a strong causal link, for example, no studies on trace elements in water from Brazilian urban lakes were found before the 2005 implementation of CONAMA n° 357/05, with publications for this matrix only beginning in 2008 (Figure 4). Similarly, of the 47 studies on sediment, only four were conducted before the 2004 implementation of CONAMA n° 344/04, indicating a significant increase in research after the legislation took effect (Figure 5). While other factors like funding may play an important role, the observed shift in research focus following these legislative milestones is a strong indicator of their influence. In contrast, the inclusion of ANVISA regulations in only four studies highlights the need for further investigation on human exposure through fish consumption. The marginal citation of these regulations underscores how little attention has been given to linking environmental contamination with food safety. This limited adoption may reflect a multicausal disconnection between regulatory agencies and published scientific research, including the lack of specificity of guidelines for lentic ecosystems and the fact that some regulatory reports are not publicly accessible or are stored in databases that are difficult to reach. Bridging this gap is essential to improve the policy relevance of contamination studies and to safeguard both ecosystem integrity and human well-being.

A wide range of sample preparation and detection techniques were employed across the studies, reflecting the diversity of analytical approaches used to assess trace element concentration. Among the equipment used, multi-element techniques, such as Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES), are commonly applied because of their ability to detect multiple elements simultaneously. The detection technique Atomic Absorption Spectroscopy (AAS) is also widely used, typically in combination with specific sample preparation such as flame (FAAS), graphite furnace

(GFAAS), or cold vapor (CVAAS), allowing the detection of individual elements, although not simultaneously. Additionally, X-Ray Fluorescence (XRF) has been used to provide broader elemental screening despite potential limitations in sensitivity for certain elements. Element-specific techniques, such as the Direct Mercury Analyzer (DMA) and Atomic Fluorescence Spectroscopy (AFS), have been applied for mercury analysis, highlighting the toxicological relevance of this element. Although these techniques are limited to specific analytes, they offer high accuracy and require minimal sample preparation.

Conclusion

This systematic review synthesized the main patterns of research on trace element contamination in Brazilian urban lentic systems. The results indicate a marked spatial imbalance, with studies heavily concentrated in South and Southeast regions, particularly in the Atlantic Forest and densely urbanized and industrialized areas. This reflects both the greater presence of universities and research infrastructure and the contamination pressures associated with urbanization and industry. In contrast, the North, Northeast, and Central-West remain underrepresented despite their ecological relevance. Cu, Pb, and Cr were the most frequently investigated elements, with sediments as the main matrix analyzed. The originality of this review lies in providing a quantitative overview of these research trends. We show that highly toxic elements such as Hg and As remain underexplored and that the limited use of biological matrices represents a major gap in understanding bioaccumulation and ecological and human risks exposure. The frequent citation of environmental legislation, particularly CONAMA resolutions, further suggests that regulatory frameworks have been important drivers of research in this field. Our analysis showed that geographic, environmental, and socio-political trends in trace element research reflected the influence of multiple drivers, including population

density, land use, regional economic development, and environmental characteristics. These socio-environmental, political, and geographic factors shaped where and how studies were conducted, leading to marked spatial and thematic biases in the literature. To our knowledge, this is the first systematic review to explicitly evaluate these drivers in Brazilian urban lentic systems, providing a novel synthesis of patterns and research gaps. Expanding studies to underrepresented regions, incorporating biological matrices more consistently, and aligning research more closely with conservation-oriented legislation will be essential to advance knowledge and protect both aquatic ecosystems and public health in developing countries.

Supplementary materials

Table S1 Search words and synonyms used in the search

Category	Details
Search database	Web of Science, Scopus
Search Strings	(Brazil* OR Acre OR Alagoas OR Amapá OR Amazonas OR Bahia OR Ceará OR “Espírito Santo” OR Goiás OR Maranhão OR “Mato Grosso” OR “Minas Gerais” OR “Mato Grosso do Sul” OR Pará OR Paraíba OR Paraná OR Pernambuco OR Piauí OR “Rio de Janeiro” OR “Rio Grande do Norte” OR “Rio Grande do Sul” OR Rondônia OR Roraima OR “Santa Catarina” OR “São Paulo” OR Sergipe OR Tocantins OR “Distrito Federal” OR Amazônia OR Cerrado OR “Mata Atlântica” OR Pantanal OR Pampa OR Caatinga OR Amazon OR “Atlantic Forest” OR “brazilian savanna”) AND (“trace metal” OR “trace metals” OR “heavy metal” OR “heavy metals” OR “trace element” OR “trace elements” OR element* OR metal* OR semimetal* OR arsenic OR cadmium OR copper OR chromium OR nickel OR zinc OR lead OR mercury OR lithium OR rubidium OR cesium OR beryllium OR strontium OR barium OR lanthanum OR actinum OR scandium OR yttrium OR titanium OR zirconium OR hafnium OR vanadium OR niobium OR tantalum OR molybdenum OR tungsten OR manganese OR technetium OR rhenium OR iron OR ruthenium OR osmium OR cobalt OR rhodium OR iridium OR palladium OR platinum OR silver OR gold OR boron OR aluminum OR gallium OR indium OR thallium OR

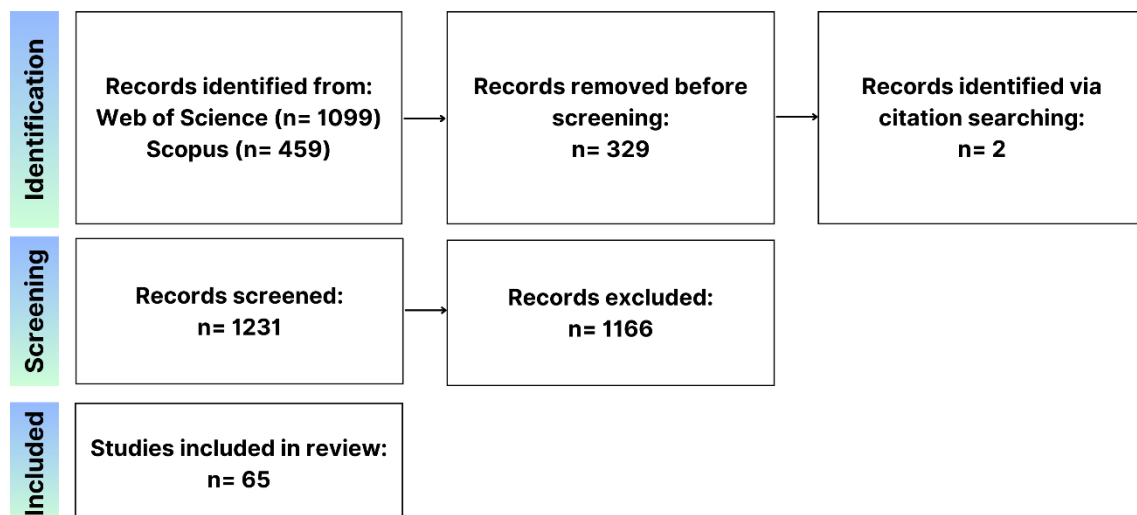
silicon OR germanium OR tin OR antimony OR bismuth OR selenium OR tellurium OR fluorine OR bromine OR iodine) AND (“Dammed river” OR lake* OR reservoir* OR lagoon* OR weir OR pond) AND (urban OR nonrural* OR urbani* OR city OR cities OR town* OR township OR metropolitan OR metropolis OR anthropogenic OR anthropic OR “man-made”) AND NOT (hydroelectric*) AND NOT (estuar* OR bay*).

Research data January 1980 --- December 2023

range

Language English (Scopus/Web of Science) and Portuguese (Web of Science)

Fig. S1 PRISMA flow diagram showing the identification, screening, and inclusion processes of the studies in the systematic review.



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Capítulo 2

Influence of land use and land cover on the spatial distribution of trace elements in sediments of an urban reservoir

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Abstract

Urban water bodies are subject to trace element contamination resulting from different land uses and occupations. The Ibirité reservoir, located in Belo Horizonte (MG), is a highly polluted and eutrophic lentic system situated in a basin under intense urban and industrial pressure. This study evaluated how land use and land cover, as well as sediment properties, influence trace element concentrations in the reservoir and its main tributaries. Two sampling campaigns were conducted in 2024, covering 15 sites in the reservoir and seven in lotic environments. Sediments

were analyzed for grain size, pH, electrical conductivity, and organic matter content, while the concentrations of As, Cd, Cr, Hg, Mn, Ni, Pb, and Zn were determined by ICP-MS after microwave-assisted acid digestion (EPA 3051A). Results showed that contamination in tributaries was mainly explained by land use and land cover, especially ironstone cover and sewage infrastructure, which were associated with high concentrations of Mn, Cr, Ni, Zn, Cd, and Pb. In the reservoir, however, land use and cover had little influence, with grain size, particularly the fine fraction, and physicochemical parameters being the main drivers of element retention. Conductivity showed a positive association with Cr, Cu, Pb, and As, reflecting the influence of urban effluents. Legally, concentrations of As, Ni, Cu, Cr, Zn, and Pb in the reservoir and of Cr, Ni, and Zn in tributaries exceeded the reference values established by CONAMA Resolution n ° 454/2012, indicating environmental risk. These findings highlight the role of tributaries as sources of contaminants, while also emphasizing that, within the reservoir, internal processes such as deposition, fine sediment retention, and organic matter accumulation modulate the distribution of elements. The observed scenario underscores the need for continuous monitoring and integrated basin management strategies to reduce anthropogenic pressures and safeguard the environmental quality of this urban system.

Keywords: inorganic contaminants, lentic ecosystem, elemental determination, heavy metal, ICP-OES

Introduction

Urban population growth is a global trend, placing increasing pressure on aquatic ecosystems (Sun & Lockaby, 2012; Sun et al., 2017). In developing countries such as Brazil, where urban expansion often occurs in an unplanned manner and with infrastructure deficits, the ecological impacts tend to be more severe (Friese et al., 2010; Burbank et al., 2022; Martinez et al., 2023). Urban expansion leads to the replacement of vegetation with impervious surfaces, altering the

hydrological cycle, reducing soil water infiltration, and increasing surface runoff, which intensifies erosion and the frequency of floods (Li et al., 2020).

Urban aquatic environments, such as rivers and lakes, provide essential services to cities, including water supply, microclimate regulation, recreation, and public health promotion (Carpenter et al., 2011; Ranta et al., 2021). However, these ecosystems are exposed to various contaminants from human activities, such as pesticides, pharmaceuticals, and trace elements (Loureiro et al., 2009; Bucci et al., 2015; Perin et al., 2021). The latter, which include metals and semimetals, naturally occur in the environment but can accumulate at high concentrations due to anthropogenic sources, such as industrial effluents, urban runoff, untreated domestic sewage, and improper waste disposal (Sodrzeieski et al., 2018; Rabello et al., 2018; Andrade et al., 2019; Silva et al., 2023).

Several urban activities contribute to the release of trace elements into the environment. Vehicle traffic, for instance, introduces lead (Pb), nickel (Ni), cadmium (Cd), zinc (Zn), and copper (Cu), derived from the wear of tires, brakes, and metallic parts (Charlesworth et al., 2011; Andrade et al., 2019). Agriculture and domestic sewage increase Cu and Zn inputs (Förstner & Wittmann, 2012; Queiroz et al., 2018; Silva et al., 2023), while industrial activities release chromium (Cr), cobalt (Co), Cd, and other toxic metals (Rabello et al., 2018; Gao et al., 2021). Fossil fuel combustion contribute to the presence of mercury (Hg) and Pb in urban environment (Charlesworth et al., 2011; Penteadó et al., 2022). In densely urbanized areas, the combination of high population density, heavy traffic, and land use for industrial, agricultural, and residential purposes intensifies the contamination of aquatic ecosystems. The bioaccumulative nature of these pollutants increases concentrations in organisms over time and relative to their environment, posing risks to both human health and aquatic organisms (Loureiro et al., 2009; Förstner & Wittmann, 2012).

Sediments act as important reservoirs of trace elements (Sodrzeieski et al., 2018; Dórea et al., 2023), reflects natural and anthropogenic inputs within the drainage basin. Chemical compounds released by anthropogenic activities tend to bind to suspended particles and settle into sediments, where they can reach high concentrations (Andrade et al., 2018). The physicochemical characteristics of sediments directly influence the behavior of trace elements, affecting their mobility, retention, and bioavailability (Vezzone et al., 2019; Cunha et al., 2021). Factors such as pH, electrical conductivity, organic matter content, and grain size influence adsorption and precipitation (Loureiro et al., 2009; Friese et al., 2010). In general, higher concentrations are found in finer particles, which have a greater surface area and organic matter content. pH regulates solubility and chemical speciation, while conductivity reflects the presence of dissolved ions, affecting the equilibrium between particles and contaminants (Cunha et al., 2021). Thus, sediments serve as records of pollution and as secondary sources of contamination to the aquatic environment.

Given the importance of understanding the mechanisms regulating trace element contamination in aquatic systems, this study investigated how land use and cover, and sediment properties, influence the concentrations of these elements in a reservoir under urbanization pressure and its main tributaries. We hypothesized that land use and cover contribute distinct contaminant loads to tributaries and the reservoir, that sediment characteristics affect element retention, and that these inputs result in spatial patterns of contamination within the reservoir. By identifying critical contamination zones, our study provides insights that can be applied to the monitoring and management of other urban reservoirs facing similar pressures.

Material and methods

Study area

The study was conducted in the Ibirité Reservoir, located in Minas Gerais, Brazil (20°01'13.39" S; 44°06'44.88" W), popularly known as Ibirité Lagoon. The reservoir was created in 1968 by damming the Ibirité river by Petrobras, the Brazilian state-owned oil company, to supply water for cooling the turbines of the Gabriel Passos Refinery (REGAP) (Mozeto et al., 2014). It currently also supplies the IBIRITERMO thermoelectric power plant, established in 2002 to provide energy to Petrobras.

The reservoir is located among three municipalities: Ibirité, Sarzedo, and Betim, part of the Metropolitan Region of Belo Horizonte, the state capital. The tributaries draining into the reservoir exhibit a wide range of land use types, including residential, industrial, and forested areas, reflecting the heterogeneous landscape and varying degrees of anthropogenic pressure across the watershed (Lanza et al., 2011). The watershed is part of the Paraopeba River basin, a tributary of the São Francisco River (Lanza et al., 2011).

Ibirité Reservoir has historically received substantial amounts of solids, domestic sewage, and industrial effluents, and has been undergoing a silting process that has gradually reduced its flooded area (REGAP Report, 2013; Aquasmart Annual Report, 2025). It has a surface area of approximately 1.6 km², a maximum depth of 18 m, and a usable volume of about 11.7 million m³ (Aquasmart Annual Report, 2025). Bathymetric analyses conducted in 2008 and 2024 revealed a reduction in the reservoir's volume, with the most recent estimate indicating a total lifespan of 91 years (Aquasmart Annual Report, 2025). The longevity of urban reservoirs is directly associated with sedimentation rate, which depends on both the sediment load from the catchment areas and the fraction retained within the reservoir (Barbosa et al., 2011).

The climate in Ibirité is characterized by a rainy season from October to March and a dry season from April to September (INMET, 2024; Fig. 1S). In 2024, the annual average temperature recorded at the local meteorological station (Rola Moça – A555) was 21 °C (INMET). The rainfall regime showed strong seasonality, with accumulated precipitation of 1,031 mm in summer, 842 mm in spring, 296 mm in autumn, and only 1 mm in winter. Notably, October 2024 was the third wettest October in the last 114 years in the region, with an average rainfall of 340.2 mm (INMET, 2024), highlighting the intensity of the onset of the rainy season that year.

Sampling and laboratory analysis

Two sampling campaigns were conducted to account for seasonal variability: one at the dry season (May 2024) and another at the rainy season (November 2024). A total of 22 sites were sampled: 15 within the reservoir (RES01–RES15), six at upstream streams (LOT02–LOT07), and one at downstream stream (LOT08) (Figure 1). All sites were sampled in both campaigns, except RES05 in the second campaign due to the presence of macrophytes that made access impossible.

The lotic sampling points were distributed across different tributaries of the Ibirité Reservoir system (Fig. 1). LOT2 was located in the Pintado stream, downstream from the REGAP refinery; LOT3 in the Palmares stream; LOT4 in a different stretch of the Pintado stream; LOT5 in the Ibirité stream, before its confluence with the Pintado; LOT6 in the Sumidouro stream; and LOT7 in an unnamed stream near a residential neighborhood; LOT8 was positioned downstream of the reservoir, approximately 900 meters from the dam. The watershed is densely urbanized, with high population density and a large number of households (Table S1; Table

S2). Industrial land use is concentrated near LOT2 and LOT4, while other areas include agricultural activity, pasture, and preserved native vegetation, reflecting a heterogeneous landscape with variable anthropogenic influence (Lanza et al., 2011; Aquasmart Annual Report, 2025; Table S1).

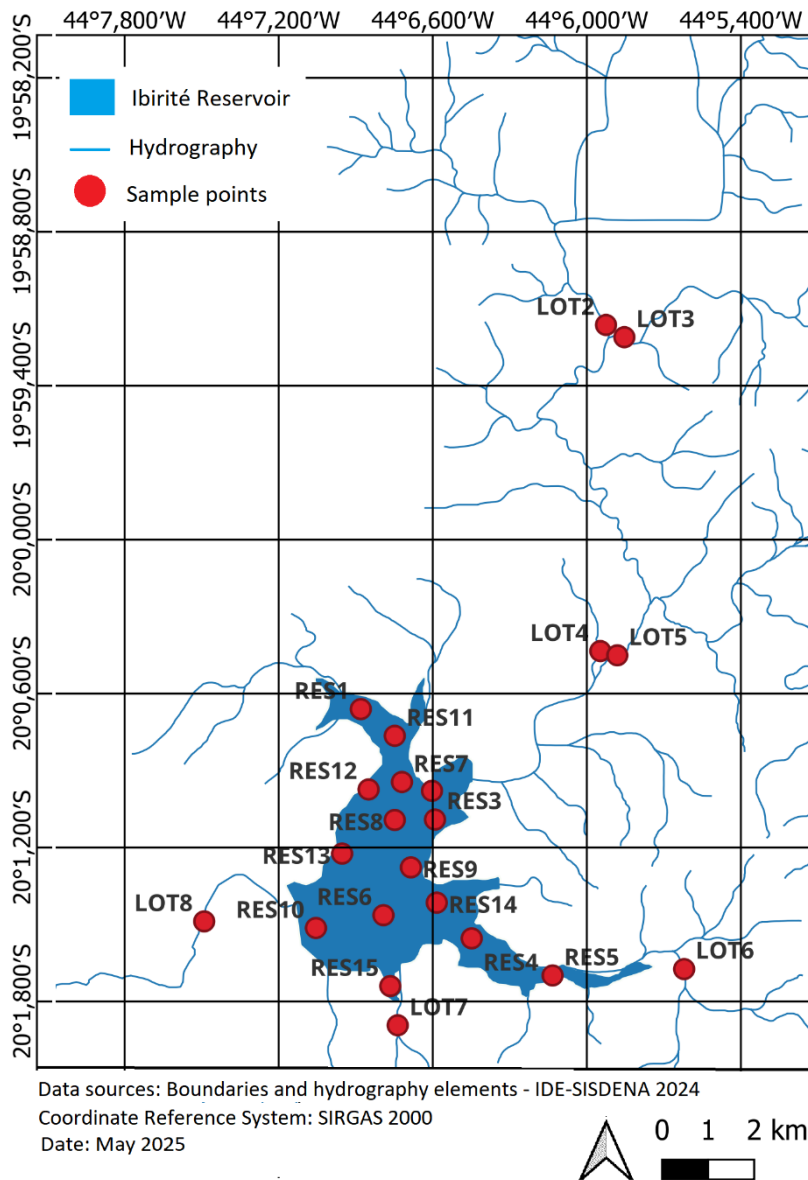


Figure 1. Sampling points in the Ibirité Reservoir and its tributaries (Minas Gerais, Brazil) during the sampling campaigns in May and November 2024. Points labeled RES01 to RES15 correspond to the lentic environment (reservoir), while points LOT02 to LOT08 refer to samples collected in lotic environments (tributaries and downstream area).

Surface sediment samples were collected from the reservoir using a stainless-steel Van Veen grab sampler and from streams using a stainless-steel scoop. Samples were stored in ziplock bags, transported in thermal boxes, and kept frozen until processing. They were dried in an oven at 40 °C, homogenized, and stored in hermetic containers previously decontaminated with HNO₃ 10% (v:v). Approximately 200 g of each sample was reserved for grain size analysis, while the remaining portion was sieved through a 2 mm stainless-steel sieve, and the fraction <2 mm was used for physicochemical and trace element determination.

Grain size analysis, used to determine the relative proportions of sand, silt, and clay, was performed using the pipette method, as described by Gee and Bauder (1986). This technique is based on sedimentation principles relating particle settling velocity to size and density in a fluid. After dispersion and removal of organic matter and soluble salts, particles were suspended in a liquid column. At specific intervals, aliquots were extracted from predetermined depths using a pipette to quantify finer fractions (silt and clay), while the sand fraction was determined by sieving.

pH and electrical conductivity were measured following Teixeira et al. (2017). A total of 10 g of sediment were mixed with 25 mL of ultrapure water (Milli-Q®) in 50 mL plastic tubes (1:2.5, m:v). Samples were shaken for 1 min and then left to rest for 30 min. Electrodes were immersed in the liquid phase only to avoid contact with solid particles. After the signal stabilized for at least 10 seconds, the pH and electrical conductivity values were recorded using a potentiometer and a benchtop conductivity meter, respectively.

Organic matter percentage (%OM) was determined by loss on ignition. Three grams of dried sediment were placed in porcelain crucibles, and then ashed in a muffle furnace at 550 °C for 5 h. After cooling, %OM was calculated based on the weight difference before and after ignition.

To determine trace element total concentrations, 0.5 g of dry sediment was subjected to microwave-assisted acid solubilization, following EPA Method 3051A (USEPA, 2007). The procedure was carried out in Teflon vessels using a mixture of 9 mL of HNO₃ and 3 mL of HCl. Digested samples were refrigerated until analysis.

The concentrations of As, Ni, Cd, Cr, Pb, Hg, Zn, and Mn were determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS), while Cu were determined by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). Concentrations were calculated based on calibration curves constructed with multi-element standards, ensuring analytical response linearity within the concentration range of the analyzed elements. The calibration curves showed coefficients of determination higher than 0.995 for all elements. The limits of detection and quantification for each element are presented in Table S2.

Analytical reliability was ensured through validation, including. Certified reference materials of marine sediment (MESS-4, National Research Council of Canada and IAEA-457, International Atomic Energy Agency) with recoveries between 80% to 120% (Table S2), and blank samples in each digestion batch. All analyses were performed in triplicates and the coefficient of variation up to 13% was considered acceptable for reservoir (lentic) samples, and up to 20% for stream (lotic) samples due to higher natural variability.

Trace element concentrations were compared with the thresholds established by CONAMA Resolution n° 454/2012 (Conselho Nacional do Meio Ambiente, 2012), which defines national guidelines for sediment quality assessment. This resolution provides benchmark levels for evaluating ecological risk associated with contaminant presence. Level 1 corresponds to the concentration below which adverse effects on biota are unlikely, while Level 2 indicates a concentration above which adverse effects are more probable. These reference values established by CONAMA n° 454/2012 are based on the Canadian Sediment Quality Guidelines.

Delimitation of drainage basins and their analysis of land use and occupation

To characterize land use and land cover in the study area, that encompassed the entire Ibirité Reservoir basin, high-resolution images from the CBERS-4A satellite were used, acquired in August and December 2023 and in June 2024 (Aquasmart report, 2025). These dates were selected based on low cloud cover and the contrast between dry and rainy seasons. Image preprocessing included the stacking of multispectral bands and their fusion with the panchromatic band, resulting in hybrid images with a spatial resolution of 2 meters and adequate spectral richness to distinguish different land cover types. Subsequently, automatic image registration with a high density of homologous control points was applied to ensure geometric consistency among the scenes, following the procedures described by Lopes et al. (2022).

Image classification was performed using the maximum likelihood algorithm (Maxver), supported by segmentation-based approaches to refine class definitions. From these classification, we derived measurable variables to represent land use and land cover patterns across the basin: dense vegetation (seasonal semideciduous forest and *cerradão*), herbaceous vegetation (grasslands), exposed soil (mining tailings, erosion areas), water bodies, residential areas, industrial areas, agriculture (croplands, pastures, and degraded pastures), and *canga* (lateritic crusts).

For each sampled lotic point (except for the downstream site), the upstream drainage basin was delineated using the ottocoded watershed database provided by IGAM (Instituto Mineiro de Gestão das Águas). Based on these delineations, the percentage of each land cover class within each basin was calculated and associated with the respective sampling point, enabling the evaluation of landscape influence on the aquatic systems (Table S1).

Additionally, data from the 2022 Demographic Census, provided by the Brazilian Institute of Geography and Statistics (IBGE), were used to characterize population and urban infrastructure conditions within the basins. The variables considered included: number of households, number of residents, and the proportion of households with sewage collection, connection to the water supply network, and waste collection services (Table S2). These data provide general estimates, which may differ from conditions observed in the field, particularly regarding sewage coverage. We extracted this information from census tracts, the most disaggregated territorial unit available, each comprising approximately 150 to 350 households. Since tract boundaries do not align perfectly with watershed boundaries, data were weighted proportionally to the area of overlap with each basin. Variables were expressed as coverage percentages or density values, composing a set of socio-environmental indicators associated with each lotic sampling point.

Based on the variables obtained for each drainage basins, the Catchment Disturbance Index (CDI) was calculated, adapted from Ligeiro et al. (2013), to quantify the degree of anthropogenic disturbance. In this formula, we assigned a weight of 4 to residential and industrial areas, 2 to agricultural areas, and 1 to fallow land. Remaining classes (native vegetation, water bodies, canga, exposed soil, etc.) were not included in the calculation.

Data analysis

To investigate the factors associated with trace element concentrations, we performed multivariate analysis in R (v.4.3.2), using the packages: *vegan*, *adespatial*, *ade4*, *Hmisc*, *fields*, *abind*, *ggbiplot*, *ggrepel*, *RColorBrewer*, *openxlsx*, *dplyr*, *geosphere*, and *PerformanceAnalytics*.

Initially, we evaluated collinearity among explanatory variables using Pearson correlation (Table S3). All predictor variables were included and grouped into three categories: (i) sediment granulometry (percentage of sand, silt, and clay); (ii) physicochemical variables (pH, electrical conductivity, and percentage of organic matter); and (iii) proxies for land use and cover within the drainage basin (CDI, percent cover of canga, dense vegetation, herbaceous vegetation, exposed soil, water bodies, residential areas, industrial areas, agriculture, as well as the percentage of households connected to water supply, with solid waste collection and sewage collection, and the density of inhabitants and households per km²). Highly correlated variables ($|r| > 0.70$) were excluded to avoid redundancy in the models.

For the lotic points, we performed variation partitioning to estimate the unique and shared contribution of each group of predictor variables to the trace element composition. Then, we applied a stepwise forward selection procedure to identify the most relevant explanatory variables. All variables were previously standardized (z-score). Based on the selected variables, we conducted a Redundancy Analysis (RDA).

For lentic points, we initially considered the potential spatial influence of tributaries, assuming that areas closer to tributary inflows could be more affected. We calculated geographic distances (in meters) between lentic points and tributary sources using the Haversine formula. Environmental values from tributaries were weighted according to these distances and incorporated into the land use dataset. Following this adjustment, the same procedures used for lotic points were applied: variation partitioning, removal of collinear variables, selection of significant predictors, and RDA.

All significance tests were based on 999 permutations, and adjusted R² values were used to assess model fit and guide variable selection.

Results

Grain size analysis indicated variations in sediment composition between environments and sampling campaigns (Fig. 2). In the reservoir, the clay fraction predominated, followed by silt, in both campaigns. In May, the sediments showed an average of 44% clay and 42% silt, while in November the clay content increased to 54%, and the silt content remained nearly the same at 41%. The sand fraction showed low representation in the reservoir, with 14% in May and 5% in November. At the sites located in lotic environments, including downstream of the reservoir, the sediment composition was predominantly sandy, with an average of 78% in May and 86% in November.

Considering all sample points, the sand and silt fractions showed no differences between the sampling periods ($V = 106$; $p = 0.985$ and $V = 154.5$; $p = 0.181$, respectively). In contrast, clay fraction was higher in November ($V = 35$; $p = 0.0093$). Point RES13 showed, in May, a distinct composition compared to other reservoir points, with a higher proportion of sand and lower proportion of fine particles. However, this pattern was not maintained in the November campaign (Fig. 2).

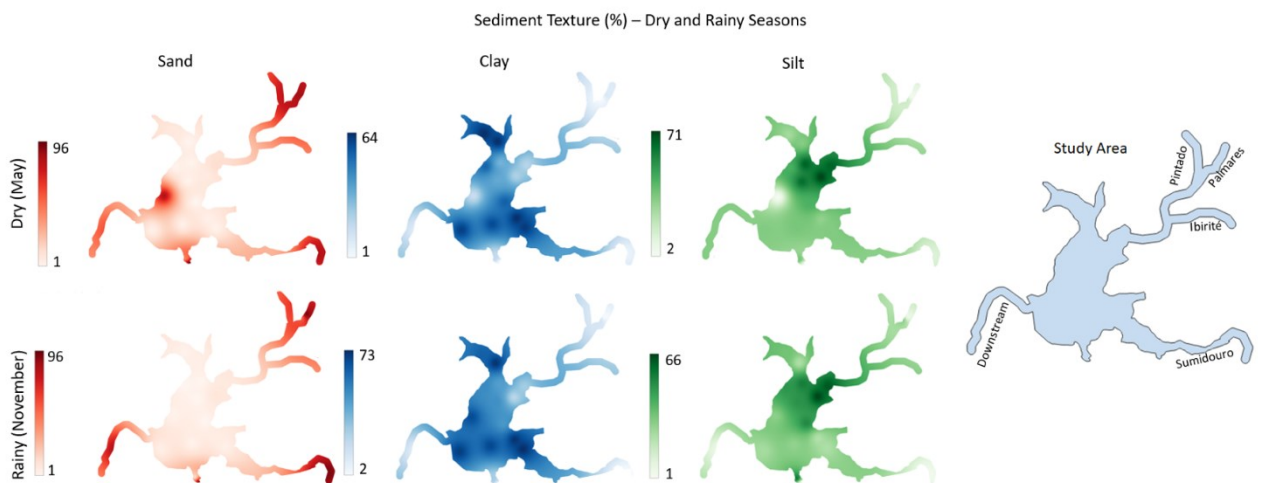


Figure 2. Spatial distribution of grain size fractions in surface sediments of the Ibirité Reservoir in May and November. The maps show the percentage of sand, clay, and silt interpolated using the Inverse Distance Weighting (IDW) method. A predominance of sand is observed in the lotic regions and a higher concentration of clay and silt in the reservoir.

The pH was lower in May (reservoir: 5.24 ± 0.93 ; lotic: 6.65 ± 0.74) than in November (reservoir: 6.11 ± 0.61 ; lotic: 8.26 ± 0.88) (paired t-test, $t = -7.48$; $df = 20$; $p < 0.001$; Fig. 3; Supplementary Table 1). Conductivity was higher in May (reservoir: $1119 \pm 696 \mu\text{S}$; lotic: $324 \pm 232 \mu\text{S}$) than in November (reservoir: $819 \pm 424 \mu\text{S}$; lotic: $143 \pm 87 \mu\text{S}$) (paired Wilcoxon test, $V = 173$; $p = 0.046$; Fig. 3). The %OM showed no significant differences between periods (May: reservoir $17.7 \pm 8.3\%$; lotic $4.4 \pm 3.6\%$; November: reservoir $16.95 \pm 4.6\%$; lotic $2.55 \pm 3.1\%$) (paired t-test, $t = 0.79$; $df = 20$; $p = 0.4378$; Fig. 3).

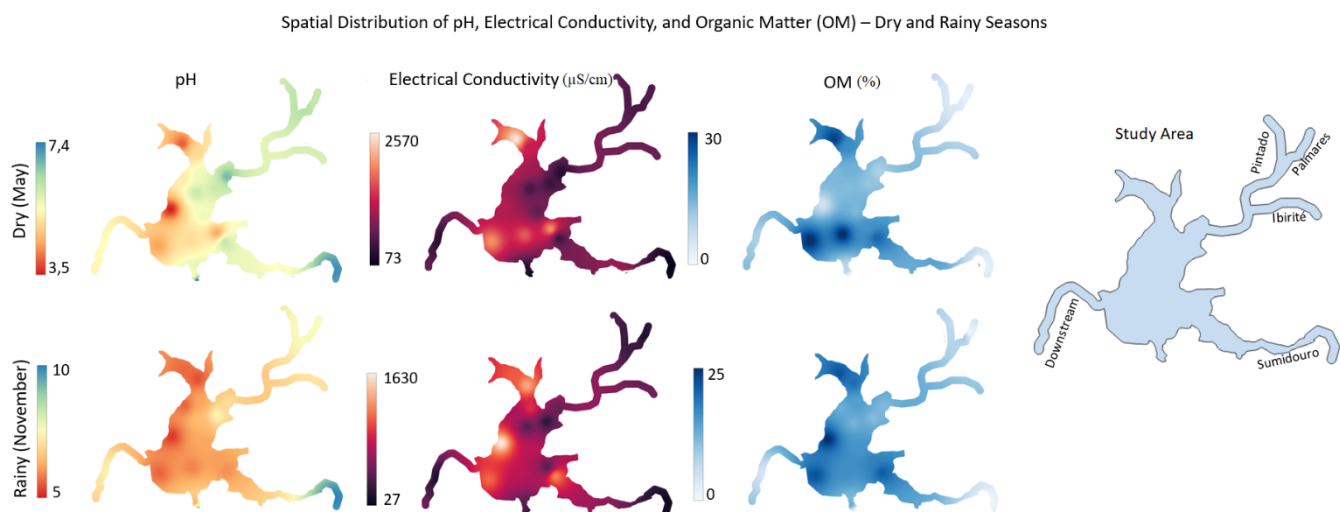
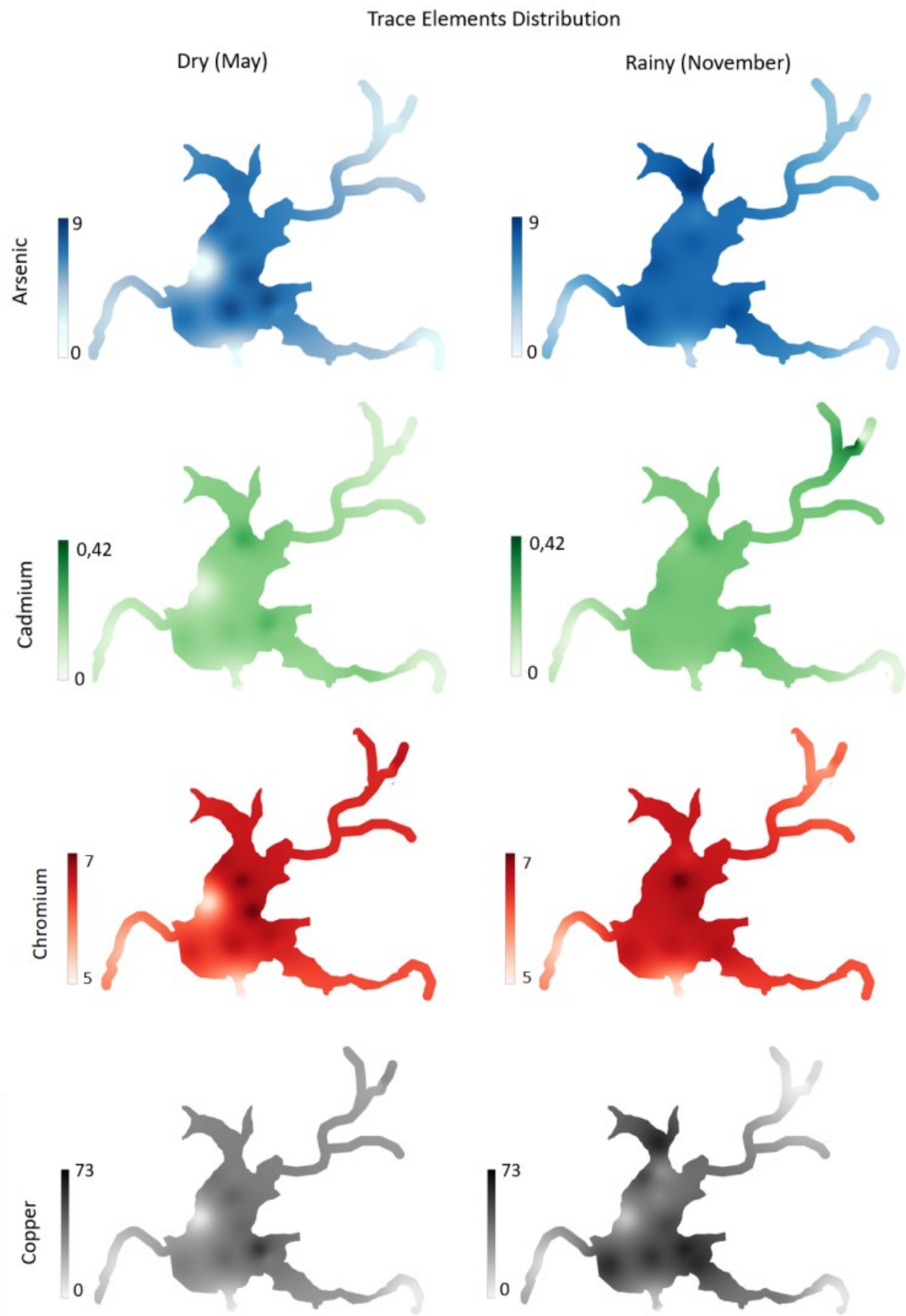


Figure 3. Spatial distribution of pH, organic matter (%) and electrical conductivity ($\mu\text{S}/\text{cm}$) in sediments of Ibirité Reservoir during the May and November campaigns. Maps were generated by spatial interpolation using the Inverse Distance Weighting (IDW) method. Note that the scales of each parameter differ between the sampled months.

Concentrations of trace elements and their seasonal differences in sediments of the Ibirité Reservoir

Among the analyzed elements, only Cd showed a significant difference in concentrations between May and November ($V = 15$, $p = 0.02$), with higher values observed in November (Fig. 4; Table S4). For the other elements, no significant differences were identified between the sampling periods: As ($V = 40$, $p = 0.40$), Ni ($V = 58$, $p = 0.70$), Cr ($V = 37$, $p = 0.35$), Pb ($V = 25$, $p = 0.09$), Zn ($t = -1.4252$; $df = 13$; $p = 0.18$), Mn ($t = -0.0260$; $df = 13$; $p = 0.98$), and Cu ($V = 105$, $p = 0.73$). Hg concentrations were below the quantification limit of the analytical method (0.025 mg/kg) for most samples (Table S5). Difference in trace element concentrations between campaigns are illustrated in Figure 4.



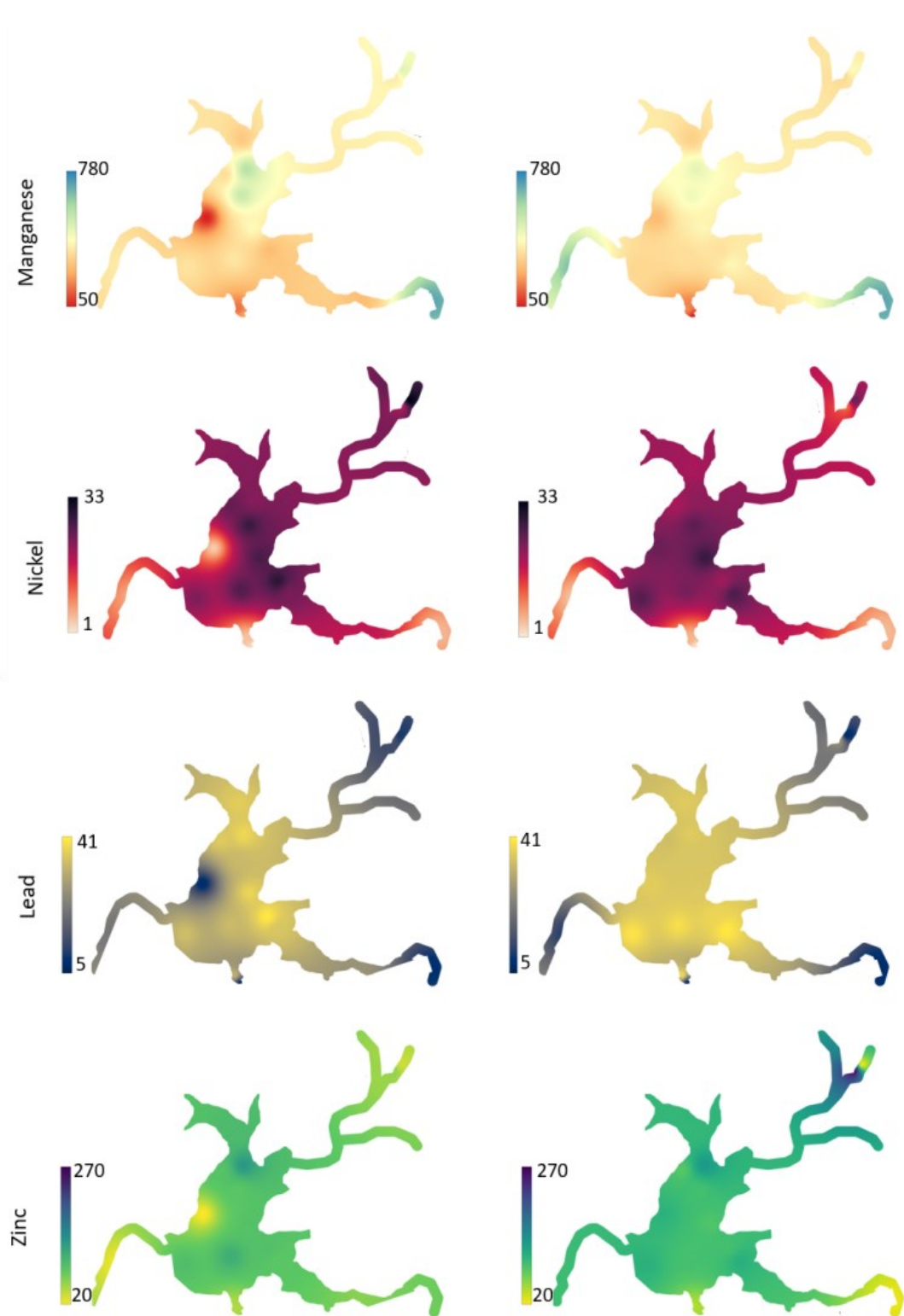


Figure 4. Spatial distribution of trace elements in surface sediments of the Ibirité Reservoir during two sampling periods (May and November). Concentration maps are shown for As, Ni, Cd, Cr, Pb, Zn, Mn and Cu (mg/kg d.w.) across the reservoir, its main tributaries (Ibirité,

Pintado, Palmares, Sumidouro), and downstream. The left column corresponds to the dry season (May), and the right column to the rainy season (November). Note that the scales of each element are the same for both sampling months.

Mercury and Cd concentrations in all reservoir sediment samples were below the Level 1 limit established by CONAMA Resolution n° 454/2012, while Zn exceeded this limit only at point RES07 in both campaigns (Fig. 5; Table S4). Copper, Pb, As, Ni, Zn, and Cr frequently showed concentrations above the Level 1 thresholds, with Cr reaching up to twice the recommended limit (Level 1) in both sampling periods. Point RES15 was the only site not exceeding Ni and Cr limits in November.

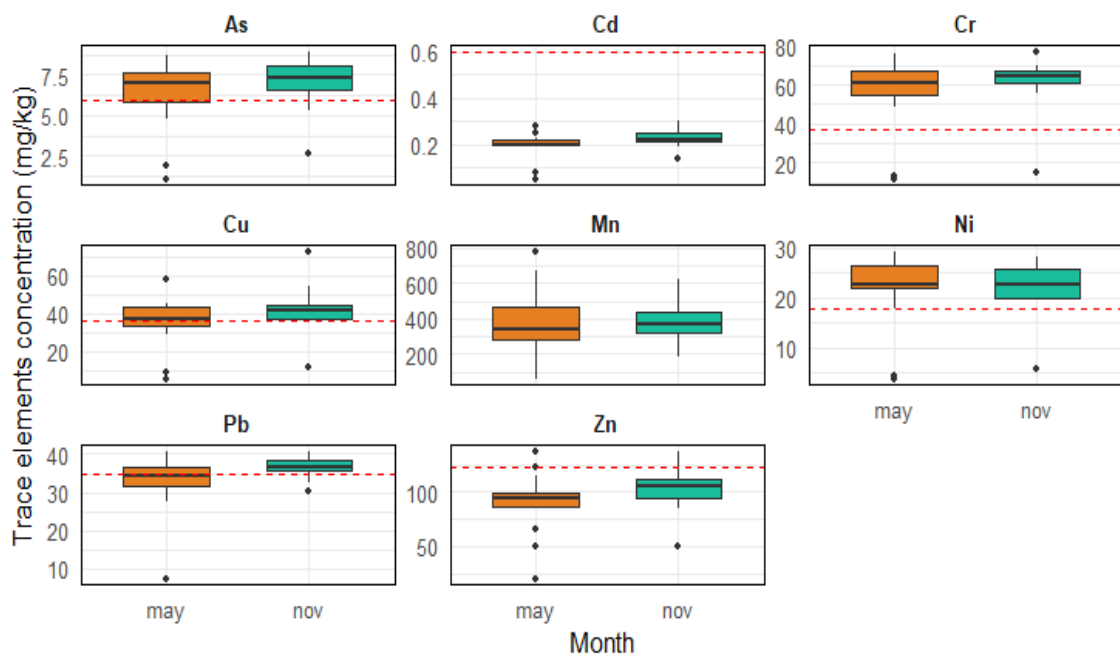


Figure 5. Concentrations of trace elements in the sediments of Ibirité Reservoir (mg/kg, d. w.) collected in May and November (nov) 2024. The dashed red line indicates the reference values established in CONAMA Resolution n° 454/2012 for freshwater environments (Level 1, Metals, and Semimetals).

Sediment samples from the tributaries and downstream sites showed Cr, Ni, and Zn concentrations exceeding the Level 1 limits established by CONAMA Resolution n° 454/2012 for freshwater environments (Fig. 6; Table S6 and S7).

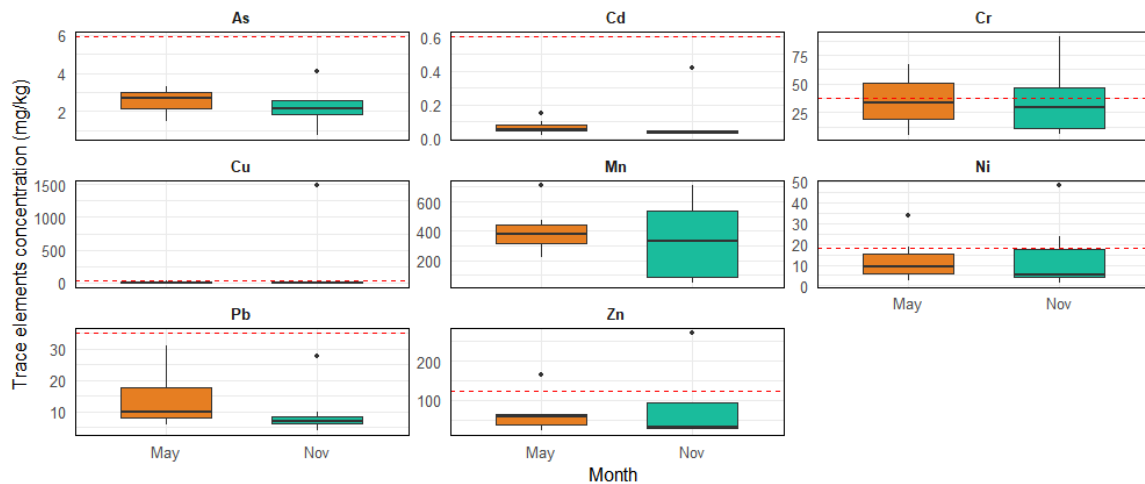


Figure 6. Concentrations of trace elements in the sediments at lotic points (mg/kg, d. w.) collected in May and November (nov) 2024. The dashed red line indicates the reference values established by CONAMA Resolution n° 454/2012 for freshwater environments (Level 1, Metals, and Semimetals).

Land use and cover, and urban infrastructure in the drainage basins

The drainage basins of the lotic sampling points showed variation in land use, vegetation cover, and urban infrastructure. The highest proportions of industrial areas were observed in LOT02 (32%) and LOT04 (23%), while the highest residential coverage was found in LOT03 (28%). In contrast, LOT06 had the lowest percentages of anthropized areas, with only 0.8% industrial and 3.7% residential. Forest cover ranged from 31% (LOT02) to 43% (LOT07), and herbaceous vegetation was most prominent in LOT06 (49%). Canga was more relevant in LOT05 (2.8%), remaining below 0.5% in the other basins. Exposed soil areas reached up to 7% in LOT07.

Agricultural land remained below 4% across all basins, with higher values in LOT05 (3.7%) and LOT03 (2.5%) (Table S1). Population density varied widely, from 62 inhabitants/km² (LOT05) to 2976 inhabitants/km² (LOT03) while household density ranged from 19.7 households/km² (LOT05) to 1010 households/km² (LOT03). Urban service coverage was lowest in LOT05, with only 6% of households served by waste collection, while LOT03 showed over 99% coverage for water supply, sewage, and waste services (Table S2). The Catchment Disturbance Index (CDI) ranged from 23.3 (LOT06) to 164.2 (LOT02). All land use and infrastructure values are relative to the total area of each upstream drainage basin.

Influence of land use, sediment properties, and seasonality on the spatial distribution of trace elements

Variance partitioning analysis revealed that, at lotic sites (Fig. 7), watershed-related variables explained the largest proportion of variation in the composition of trace elements in sediments (39%), followed by physicochemical parameters (24%), seasonality (9%), and granulometry (5%). The interaction between physicochemical parameters and granulometry accounted for 21% of the shared variance. Variance partitioning analysis revealed that, at lotic sites (Fig. 7), watershed-related variables explained the largest proportion of variation in trace element composition in sediments (39%), followed by physicochemical parameters (24%), seasonality (9%), and granulometry (5%). The interaction between physicochemical parameters and granulometry accounted for 21% of the shared variance. This elevated value reflects the strong correlations between variables from these two groups, particularly the high positive correlation between silt and organic matter ($r = 0.96$) and the strong negative correlation between sand and organic matter ($r = -0.99$). Due to this multicollinearity, the model cannot clearly attribute the explained variance to one group or the other, as their effects are intertwined. The residual

variance was 32%. This elevated value is due to strong correlations among variables from these two groups, particularly the high positive correlation between silt and organic matter ($r = 0.96$) and the strong negative correlation between sand and organic matter ($r = -0.99$). Because of this multicollinearity, the model cannot clearly attribute the explained variance to one group or the other, as their effects are intertwined. The residual variance was 32%.

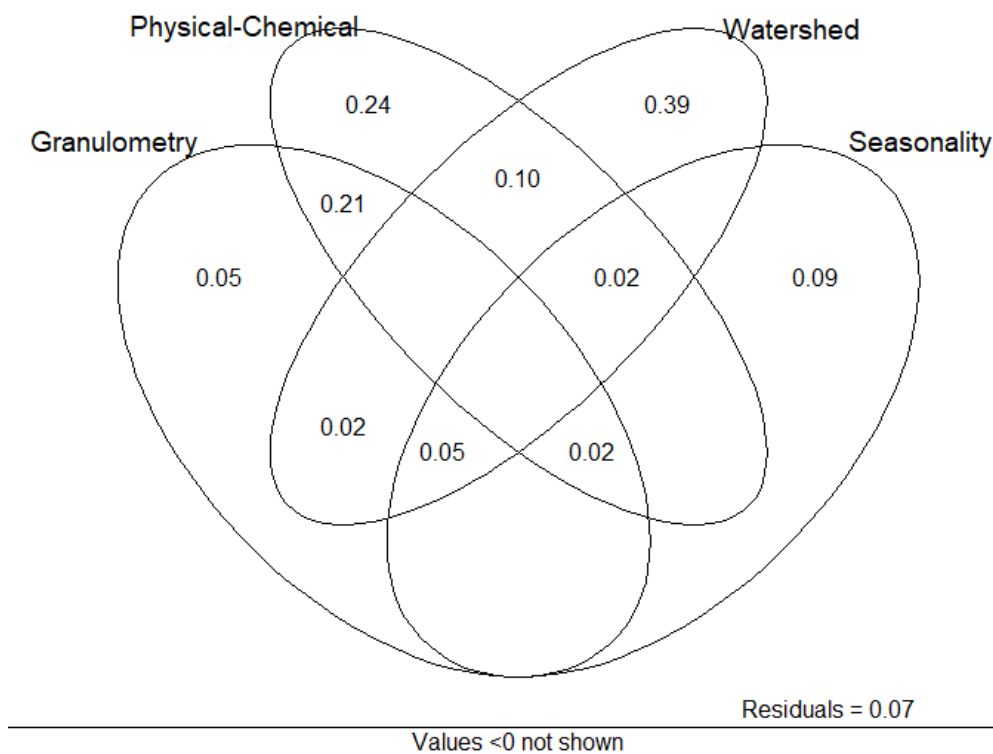


Figure 7. Variance partitioning diagram for lotic samples showing the proportion of variation in sediment trace element composition explained by watershed (0.39), physicochemical (0.24), granulometry (0.05), seasonality (0.09), and their interactions. The high shared variance between physicochemical and granulometry (0.21) reflects strong correlations among their variables (silt and organic matter: $r = 0.96$; sand and organic matter: $r = -0.99$). Residual = 0.07.

Automatic variable selection indicated that, among granulometric variables, only the percentage of clay was significant (adjusted $R^2 = 0.226$; $F_{1,10} = 4.22$; $p = 0.022$). For the

watershed group, canga coverage and sewage collection together explained 22.7% of the variation (adjusted $R^2 = 0.227$; $F_{2,10} = 2.61$; $p = 0.041$).

The RDA with the selected variables (OM, canga, sewage collection, water coverage, and conductivity) explained 82% of the adjusted variance ($R^2 = 0.82$; $F_{5,6} = 11.2$; $p < 0.001$; Fig. 8). Axis 1 explained 54.8% and axis 2 explained 24.2% of the variance. Cadmium, Pb, and Zn were associated with sewage collection and higher organic matter content; Arsenic and Cu with elevated conductivity; and Mn, Ni, and Cr with the presence of canga. Sites LOT03 and LOT04 showed seasonal variations, with higher concentrations during the dry season.

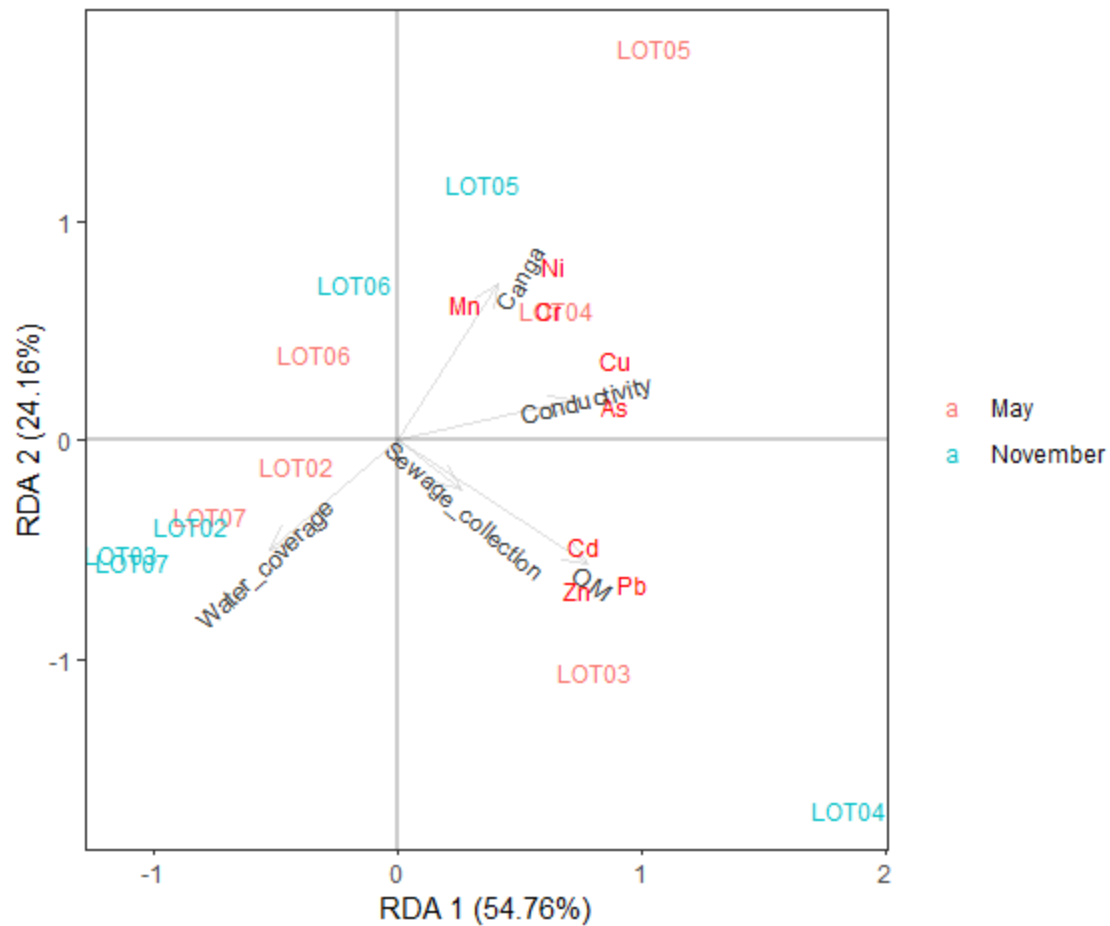


Figure 8. Redundancy analysis (RDA) ordination biplot showing the relationships between trace element concentrations in sediments, environmental variables, and sampling periods at lotic sites. Samples from May are shown in red and from November in blue. Arrows represent explanatory variables; OM = organic matter. RDA1 and RDA2 explain 54.76% and 24.16% of the variation, respectively.

In the reservoir (Fig. 9), granulometry explained the largest proportion of variation in trace element composition (22%), followed by physicochemical parameters (3%) and land use (2%). Seasonality alone did not explain any variation. Interactions, mainly between granulometry and physicochemical parameters, explained 31%, with residual variance at 32%.

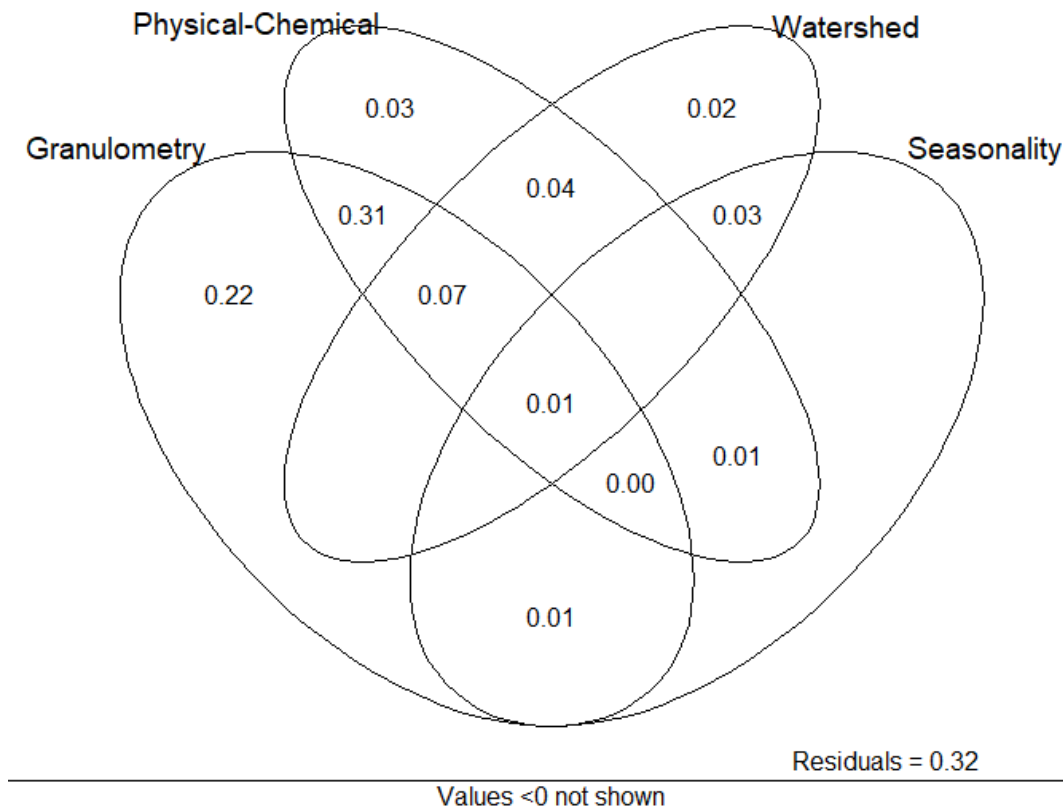


Figure 9. Variance partitioning diagram for lentic samples showing the proportion of variation in sediment trace element composition explained by granulometry (0.22), watershed (0.02), physicochemical (0.03), and their interactions. The high shared variance between physicochemical and granulometry (0.31) reflects strong correlations among their variables. Residual = 0.32. Values < 0 are not shown.

Variable selection identified %sand and %silt as the most relevant predictors, explaining 58% of the variance ($R^2 = 0.58$; $F_{2,11} = 20.4$; $p < 0.001$). In the land use group, %canga and %agriculture explained 10.5% ($R^2 = 0.11$; $F_{2,11} = 2.65$; $p = 0.032$).

The RDA with %sand, %silt, %canga, conductivity, and pH explained 68% of the variance ($R^2 = 0.68$; $F_{5,8} = 12.7$; $p < 0.001$; Fig. 9). Axis 1 explained 55.6% and axis 2 explained 12%. Cd, Pb, Zn, Ni, Cr, Cu, and As were positively associated with silt, conductivity, and canga; Hg with conductivity; and Mn with silt and canga. The sandier sites (RES15, RES13, and RES04)

had the lowest concentrations. RES13 exhibited seasonal variation, with higher concentrations during the rainy season, where the association with sand was negative.

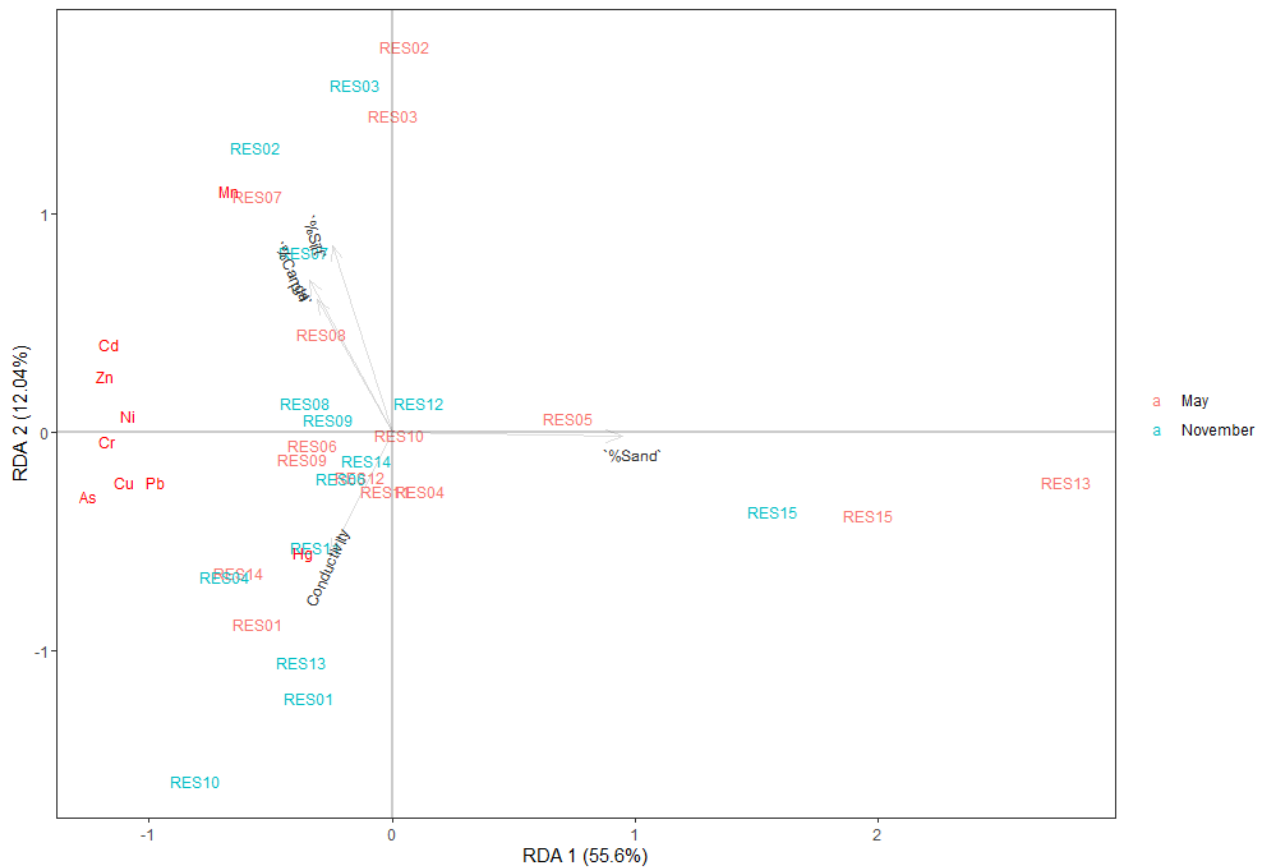


Figure 10. Redundancy analysis (RDA) ordination biplot showing the relationships between trace element concentrations in sediments, environmental variables, and sampling periods at lentic samples. Samples from May are shown in red and from November in blue. Arrows represent explanatory variables. RDA1 and RDA2 explain 55.6% and 12.04% of the variation, respectively.

Discussion

Influence of land use on the distribution of trace elements

The results indicate that contamination by trace elements in sediments is driven by different factors in the Ibirité Reservoir and its tributaries. In the tributaries (Fig. 7), the composition of trace elements was mainly explained by land use and land cover variables (39%), whereas in the reservoir (Fig. 9), their contribution was minimal (2%), with sediment granulometry playing a predominant role (22%).

At lotic sites, *canga* coverage and sewage collection infrastructure were the most influential watershed land use predictors. The presence of *canga* was associated with elevated concentrations of Mn, Cr, and Ni, particularly at points LOT04 in May and LOT05 in November. This pattern reflects the geochemical composition of *canga* itself, a ferruginous formation rich in iron and manganese oxides that naturally contains these elements (Silveira et al., 2020). Ni and Cr accumulation has also been reported in *canga* vegetation (Silva, 1992). Nevertheless, it is important to consider that areas with high *canga* coverage were negatively correlated with waste collection, and population density, reinforcing its role as an indicator of less urbanized areas (Fig. S3). However, *canga* can also function as a natural diffuse source of elements to aquatic systems through weathering and surface erosion (Skiryicz et al. 2014; Prado et al., 2023). The watershed contributing to point LOT05 had the highest *canga* coverage and the lowest population and households densities, consistent with the observed results. In the case of LOT04, although the watershed had high industrial coverage and intermediate urbanization compared to other basins. Yet, this point presented a strong association of Mn, Cr, and Ni with *canga*, suggesting that local geology rather than urban factors, was the main driver of sediment composition.

In contrast, sewage collection infrastructure is typically associated with urbanization, which often results in greater domestic pollutant loads entering water bodies. Therefore, it serves as

an indicator of anthropogenic pressure on the watershed, reflecting the impact of human activity on sediment contamination. In this study, this variable was strongly correlated with residential areas, and associated with elevated concentrations of Zn, Cd, and Pb in sediments at point LOT03, further supporting the influence of urban density on the observed contamination patterns. These elements, commonly used in urban products and processes, can reach water bodies through domestic sewage (Jordão et al., 2005; Touzani et al., 2023). For instance, Zn is frequently found in personal care and cleaning products, such as shampoos, toothpaste, and detergents (Ayenimo et al., 2010), Cd is present in batteries and PVC plastics (Gazano et al., 2009; Andrade et al., 2019), and Pb has sources, including construction materials, electrical cables, batteries, and historically, as a gasoline additive (Gazano et al., 2009; Rabello et al., 2018; Gao et al., 2021).

Point LOT03 showed the highest Zn concentrations among lotic sites during dry season (Fig. S5). Its watershed has the highest population density and residential occupation (Fig. S2), which likely explains the substantial contaminant input at this location. However, this association was not observed in November, possibly due to increased rainfall-driven flow and dilution, that redistributed pollutants, reducing their sediment concentrations, a pattern also reported in the literature (Ettler et al., 2008; da Silva et al., 2023; da Silva et al., 2024). Even so, the site continued to show urban influence, as it remained associated with water surface coverage. In this context, water supply network was positively correlated with urbanization-related variables such as waste collection, households and inhabitants density, acting as an indicator of densely populated areas.

Water supply network was also associated with points LOT02 and LOT07, which shared similar characteristics, with greater anthropogenic influence and lower *canga* coverage (Fig. 8). But in contrast, despite being located in urbanized areas, these points did not show high concentrations

of trace elements in the sediments (Fig. 8; Table S7). This pattern may be linked to differences in sanitation infrastructure, drainage characteristics, or the manner in which effluents are routed in the watershed. It is also possible that elements at these upstream areas remain in suspension in the water column and deposit only downstream in the reservoir. Since this study focuses on the sediment compartment, such hydrological dynamics may explain the observed spatial distribution of trace elements. It is possible that these stretches do not receive direct inputs from sewage or other point sources of contamination, functioning instead as flow-through areas with less deposition of particulate material.

In the reservoir, Mn remained associated with areas influenced by *canga* coverage. However, overall, land use and cover had limited influence on trace element concentrations in this environment. The low explanatory power of these variables suggests that, unlike in tributaries, other factors were more important in shaping the distribution of contaminants (Fig. 9). While tributaries contribute to the reservoir's contamination, as they transport elements from their respective basins, their contributions are not directly associated spatially with land use patterns, likely because once elements enter the reservoir, they undergo dispersion and redistribution. Hydrodynamic conditions, including reduced flow velocity and longer water residence time, promote mixing and homogenization of sediment across sites (Friedl & Wüest, 2002; Ishikawa et al., 2021). As a result, the spatial signal of watershed characteristics becomes blurred within the reservoir. Similar patterns have been observed in other lentic systems, where tributary inputs lose their spatial distinctiveness due to internal hydrodynamics and sedimentation processes (e.g., Friedl & Wüest, 2002; Bing et al., 2019).

Role of sediment properties and environmental parameters in contaminant distribution

In the reservoir (Fig. 9), granulometric composition, particularly the proportion of sand and silt, was the main factor explaining the spatial distribution of trace element, accounting for 22% of the variation. An additional 31% was explained by the intersection between granulometry and physicochemical parameters, suggesting a strong interplay between sediment texture and environmental conditions. At lotic sites (Fig. 7), physicochemical characteristics were more influential (24%), followed by the intersection with granulometry (21%) and granulometry alone (5%).

Sand was negatively associated with the concentration of all analyzed elements in lentic ecosystem, especially at points RES13 (May) and RES15 (both May and November), indicating lower contaminant retention in sandy areas. These two sites displayed a distinct pattern compared to the rest of the reservoir, with RES13 in May showing the highest sand percentage recorded in the reservoir (Fig. 2). Located near the shoreline, this site may be more exposed to localized erosion and direct input of coarse sediments. However, this pattern was not observed in RES13 in November, suggesting that the change in sediment composition was temporary and linked to local processes. Seasonal variation at RES13 also revealed increased trace element concentrations coinciding with a decrease in sand content, reinforcing the association between fine sediments and contaminant accumulation.

Overall, reservoir sites showed stronger associations with the silt fraction, suggesting a homogenization and retention process within the water body. The dam reduces flow velocity, facilitating deposition of suspended materials (Schleiss et al., 2016; Guo et al., 2020). The predominance of fine particles reinforces the reservoir's role as a sediment accumulation zone (Schleiss et al., 2016). This observed distribution reflects the influence of hydrodynamic energy on deposition: in lentic systems, reduced flow favors the settling of fine particles, while in lotic environments, higher flow and constant water renewal keep these particles suspended and

promote accumulation of sand (Friedl & Wüest, 2002; Ishikawa et al., 2021). In the Ibirité Reservoir, this pattern was confirmed by the predominance of clay and silt (up to 54% and 42%, respectively), while sediments at lotic sites were mostly sandy (up to 86%). Over time, this leads to continuous accumulation of silt and clay at the bottom, while outflowing water carries lower sediment loads. In the reservoir, this process is already evident, particularly in the arm receiving input from the Ibirité Stream, where visible sediment accumulation has reduced the flooded area.

Organic matter content was positively correlated with silt and negatively correlated with sand (Table S3), highlighting the importance of fine particles in organic matter retention. In lentic environment, concentrations of all analyzed trace elements correlated positively with organic matter. In the lotic ecosystem, this relationship was site-specific. At LOT03, the tributary site with the highest proportion of fine particles, organic matter content was also elevated and positively associated with Cd, Pb, and Zn, again reinforcing the role of fine sediments in trace element retention. Conversely, at LOT06, organic matter showed negative correlations with these elements. The high organic matter content observed in the reservoir is mainly linked to abundant biomass of aquatic macrophytes, which contributes organic material to the sediments (Aquasmart Annual Report, 2025). The decomposition of this biomass releases ions and nutrients, altering parameters such as pH and conductivity (Yan et al., 1996; Wang et al., 2012; Carmo et al., 2016; Lee et al., 2019). In contrast, in the tributaries, higher flow velocity limits both organic matter accumulation and fine sediment deposition, reducing their influence on trace element dynamics (Ferreira et al., 2020; Zhang et al., 2023).

Human activities such as hillside occupation, lack of erosion control, untreated surface runoff, and the expansion of informal settlements significantly contribute to the transport of fine sediments, especially during the rainy season (Loureiro et al., 2009; Fonseca et al., 2011; Dórea et al., 2023). These sediments, rich in silt and clay, have high adsorption capacity, favoring the

retention of trace elements at the bottom of the reservoir (Meng et al., 2014; Wang & Zhang, 2021). Although land use and cover were not directly associated with trace element concentrations in the reservoir sediments in the present study, they play a key role in the generation and transport of both sediments and contaminants that continuously supply the system (Toledo, 2014). Thus, the effects of urbanization are expressed in a diffuse and persistent manner, influencing environmental quality even in areas that appear less impacted.

Among physicochemical parameters, electrical conductivity was a key factor influencing trace element concentrations. In the reservoir, conductivity was higher, especially in the dry season, and positively associated with Cr, Cu, Pb, and As (Fig. 10), notably at RES01, RES04, RES13, and RES14. In contrast, Cd, Zn, and Ni showed weak associations with conductivity, suggesting a greater influence of sediment characteristics. In the tributaries, conductivity was lower and declined during the rainy season, with variable effects on trace element concentrations: LOT04 showed positive associations with As and Cu, while LOT02 and LOT07 showed negative ones, indicating distinct localized processes.

Conductivity reflects the ionic load of water and is commonly linked to domestic and industrial effluents, leaching from urban surfaces, and general water quality degradation (Chapman, 2021). In the reservoir, higher conductivity likely results from the accumulation of dissolved ions originating from urban runoff and untreated wastewater, with low water renewal and evaporation during the dry season intensifying solute concentrations (Piratoba et al., 2017). Conversely, in the tributaries, greater discharge and water renewal promote ion dilution, particularly during the rainy season, leading to reduced conductivity and, consequently, lower mobility of some trace elements (Piratoba et al., 2017).

Sediment trace element levels in comparison with environmental guidelines

Sediment samples showed elevated concentrations of trace elements throughout the sampled periods. In the reservoir, concentrations of As, Ni, Cu, Cr, Zn, and Pb exceeded the Level 1 reference values established by CONAMA Resolution n° 454/2012, with Cr levels reaching up to twice the legal limit in both seasons (Fig. 5). In the tributaries, concentrations of Cr, Ni, and Zn also surpassed regulatory thresholds (Fig. 6).

The recurrent presence of elevated trace element concentrations in sediments raises serious environmental concerns. These elements do not degrade in the environment and remain available for long periods, with potential for bioaccumulation in aquatic organisms and food webs (Melo et al., 2012; Rowe, 2014; Rabello et al., 2018). This scenario poses risks to both aquatic fauna and human populations, especially in contexts where informal fishing still occurs (Kabata-Pendias & Mukherjee, 2007).

Comparable contamination patterns in sediments have been documented in other Brazilian urban aquatic systems. In the Billings Reservoir (São Paulo), concentrations of Hg, Cr, Ni, Pb, Cu, and Zn frequently exceeded PEL thresholds (above which harmful effects are likely to occur), suggesting biological risks similar to those observed in Ibirité (Hortellani et al., 2013). In Paranoá Lake (Brasília), urban land use was the main driver of contamination, with sediments enriched in Pb (Franz et al. 2013). In the Pampulha Lagoon (Minas Gerais), anthropogenic enrichment of Cr, Cu, Ni, and Zn in sediment was associated with intense industrial activity, confirming the persistent contamination of this urban system (Friese et al. 2010). In Lake Guaíba (Rio Grande of Sul), although no elements exceeded CONAMA guidelines, elevated concentrations of Zn, Cu, Ni, and Pb were observed near urban stream outflows (Andrade et al. 2018). A key difference in this system lies in sediment texture, which was predominantly sandy (Andrade et al. 2018). The lower metal retention capacity of sandy sediments may explain the comparatively lower concentrations, a pattern consistent with sand-rich sites in the Ibirité

Reservoir, such as RES13 and RES15. These findings reinforce the importance of sediment texture in modulating trace element accumulation and bioavailability.

The scenario observed in Ibirité is especially concerning given the reservoir's historical role as a location for fishing and leisure for the local population. Despite current prohibition, informal fishing still occurs, exposing individuals to potential health risks. Elevated concentrations of Cr, Ni, and Pb in sediments raises concerns about chronic exposure through the consumption of contaminated fish (Dhanakumar et al. 2015; Rubalingeswari et al. 2021). Beyond direct health risks, the degradation of sediment quality compromises essential ecosystem services, including recreation, subsistence fishing, and water regulation, that are particularly critical in densely populated urban areas.

The findings highlight a systemic issue involving multiple sources and actors, underscoring the need for coordinated and integrated watershed management. The concentrations observed in the sediments exceed thresholds established by Brazilian legislation for dredging activities (CONAMA n° 454/12), suggesting environmental risk and the need for continuous investigation. Although these benchmarks are not direct indicators of ecological or human health impacts, they offer a reference value for assessing sediment quality and informing management strategies. Addressing this situation requires joint efforts by the company responsible for the reservoir, public agencies, and local governments, especially considering the influence of upstream urban inputs. Measures such as sediment monitoring, remediation, and preventive actions across the basin are essential to avoid further degradation. Without such collaboration, contamination will persist, reducing ecosystem resilience and compromising environmental quality for the surrounding population.

Conclusion

This study revealed that the distribution of trace elements in the Ibirité system is influenced by different factors in lotic and lentic environments. In the tributaries, concentrations were strongly associated with land use and land cover within the drainage basins, highlighting the role of urbanization and industrial activities as primary sources of contamination. In contrast, the reservoir did not exhibit a spatial pattern consistent with basin occupation. Areas near tributary inflows did not present higher concentrations of elements, contradicting our hypothesis. Instead, sediment characteristics, particularly the proportion of fine particles, were the main factors associated with trace element accumulation in the reservoir.

Although land use was not a direct spatial predictor in the reservoir, the influence of the watershed remains evident. Tributaries impacted by anthropogenic activities act as entry points for pollutants, which, once discharged into the reservoir, disperse and settle under lentic conditions. This process results in more homogeneous concentrations and low seasonal variability, reflecting a system with chronic contamination.

The contamination of the Ibirité reservoir by trace elements is closely linked to unplanned urbanization in the municipality, characterized by irregular land occupation and insufficient infrastructure, such as absence of sewage collection networks and adequate treatment systems. This scenario facilitates the continuous discharge of pollutants into the aquatic environment, resulting in the accumulation of nutrients, organic matter, and persistent contaminants.

The findings highlight the need for public policies aimed at integrated watershed management, with priorities including land-use planning, restoration of degraded areas, and expansion of sanitation services. Furthermore, identifying the main factors associated with contamination, including land use, sediment granulometry, and physicochemical parameters, provides valuable support for environmental monitoring and planning, contributing to more effective strategies for impact mitigation and ecosystem service conservation.

Supplementary materials

Figure S1. Monthly variation in precipitation (mm) during the year 2024, recorded by the INMET weather station (code A555), in the Serra do Rola-Moça State Park, Ibirité, Brazil.

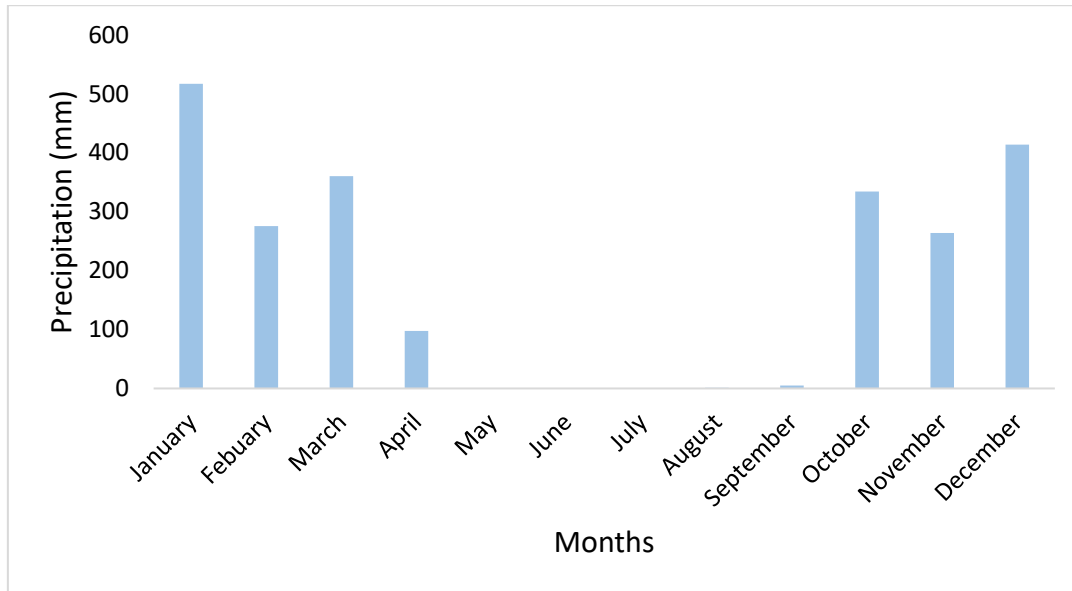


Table S1. Percentage of land use and land cover in the contributing basins of sampling points LOT02 to LOT07 in the Ibirité Reservoir. Values represent the proportion (%) of each basin area classified as residential, industrial, agricultural, pasture, exposed soil, water, and vegetation classes. The "Vegetation" category includes canga, forest, and low vegetation. Sampling point LOT08 was not included as it is located downstream of the reservoir.

Sample point	Canga	Herbaceous vegetation	Industrial area	Residential area	Dense vegetation	Exposed Soil	Water bodies	Fallow land	Agriculture
LOT02	0.5	19.4	31.9	8.5	30.6	6.8	0.7	0.7	1.0
LOT03	0.4	19.8	10.3	27.7	36.9	1.7	0.2	0.7	2.5
LOT04	0.4	19.6	23.3	15.1	34.5	4.6	0.5	0.6	1.4
LOT05	2.8	30.0	5.3	23.9	30.8	1.7	0.3	1.6	3.7
LOT06	0.2	48.5	0.8	3.7	41.5	0.7	0.7	2.5	1.5
LOT07	0.1	22.6	6.1	17.8	43.5	7.0	0.1	0.6	2.3

Table S2. Socio-environmental indicators for each lotic sampling site, based on 2022 Demographic Census (IBGE). Values represent household and population densities (households/km² and residents/km²) and the percentage of households with sewage collection,

water supply, and waste collection services. Data were obtained from census tracts and spatially weighted according to the proportion of each tract overlapping the corresponding watershed.

Sample point	Number of households/km ²	Number of residents/km ²	Households with sewage collection	Water supply network	Waste collection services
LOT02	73.2	208.4	95.3	51.8	19.2
LOT03	1010.2	2975.7	99.9	99.9	83.3
LOT04	117.7	407.9	98.8	38.9	31.6
LOT05	19.7	61.7	99.5	33.1	6.2
LOT06	924.7	2673.6	84.8	68.2	53.7
LOT07	375.6	1099.7	97.4	76.7	52.9

Table S3. Significant Pearson correlations ($p \leq 0.01$) between land use and land cover variables, urban infrastructure, and sediment characteristics at the sampling sites. Only correlations with $|r| \geq 0.70$ are shown. CDI: Catchment Disturbance Index

Variable 1	Variable 2	Correlation (r)	p-value
Herbaceous vegetation	Industrial área	-1.00	0
Waste collection	Number of residentes/km ²	1.00	0
Waste collection	Number of households/km ²	1.00	0
Number of residentes/km ²	Number of households/km ²	1.00	0
Canga	Dense vegetation	-0.94	0
Residential areas	Sewage collection	0.94	0
Sand	Silt	-0.92	0
Water supply network	Waste collection	0.89	0
Water supply network	Number of residentes/km ²	0.89	0
Water supply network	Number of households/km ²	0.89	0
Herbaceous vegetation	Cdi	-0.89	0
Industrial area	CDI	0.89	0
Organic matter	Sand	-0.85	0.001
Residential areas	Water bodies	-0.77	0.003
Residential areas	Agriculture	0.77	0.003

Canga	Water supply network	-0.77	0.003
Canga	Waste collection	-0.77	0.003
Canga	Number of residentes/km ²	-0.77	0.003
Canga	Number of households/km ²	-0.77	0.003
Exposed soil	Fallow land	-0.71	0.009
Water bodies	Agriculture	-0.71	0.009
Dense vegetation	Waste collection	0.71	0.009
Dense vegetation	Number of residentes/km ²	0.71	0.009
Dense vegetation	Number of households/km ²	0.71	0.009
Dense vegetation	CDI	-0.71	0.009
Organic matter	Silt	0.71	0.01
Electrical conductivity	Canga	0.71	0.01

Table S4. Concentrations of trace elements (mg/kg d.w.) in the Ibirité Reservoir in May 2024. Values in bold exceed the LEVEL 1 thresholds established in CONAMA Resolution n° . 454/2012. LQ = Limit of Quantification

Sample points	As	Cd	Cr	Cu	Mn	Ni	Pb	Zn	Hg
RES01	8.71	0.227	63.9	45.2	343	27.0	34.2	123	0.073
RES02	5.78	0.211	56.0	33.4	780	22.1	30.1	95	<LQ
RES03	5.83	0.229	53.4	34.0	673	22.8	31.1	100	<LQ
RES04	6.35	0.199	58.4	38.6	289	23.3	35.4	86	<LQ
RES05	4.81	0.204	48.7	29.1	271	17.8	27.4	66	<LQ
RES06	8.18	0.208	65.8	42.9	360	26.3	33.9	114	<LQ
RES07	6.92	0.280	63.6	36.7	567	22.2	38.4	137	<LQ
RES08	7.34	0.197	74.7	44.2	531	28.1	33.6	87	<LQ
RES09	7.97	0.199	75.9	43.7	406	27.0	37.8	92	<LQ
RES10	7.06	0.200	57.7	36.9	354	22.8	34.3	96	<LQ
RES11	7.23	0.200	61.3	36.2	296	22.4	36.7	99	<LQ
RES12	7.37	0.202	68.2	40.0	343	24.7	36.5	89	<LQ
RES13	1.07	0.052	13.0	5.2	59	3.8	7.3	20	<LQ
RES14	8.19	0.253	68.3	57.8	269	29.3	40.8	94	<LQ

RES15	1.85	0.083	11.6	8.2	159	4.3	32.2	50	<LQ
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Table S5. Analytical parameters: detection (LD) and quantification (LQ) limits, blanks (mean \pm standard deviation; n), and recovery (mean \pm standard deviation; n) of reference materials MESS-4 and IAEA-457 by trace elements.

Element	LD (ug/g)	LQ (ug/g)	Blank (ug/L)	Mess-4 (%)	IAEA-457 (%)
As	0.13	0.42	1.353 \pm 0.033 (15)	97.7 \pm 1.0 (3)	112.2 \pm 3.3 (2)
Cd	0.01	0.03	0.005 \pm 0.002 (15)	104.6 \pm 3.2 (3)	180.0 \pm 2.2 (2)
Cr	0.24	0.81	0.112 \pm 0.065 (15)	-	115.9 \pm 1.6 (2)
Cu	2.65	8.83	-0.001 \pm 0.001 (12)	94.6 \pm 1.0 (3)	97.4 \pm 1.5 (2)
Mn	0.35	1.16	2.798 \pm 0.093 (15)	98.7 \pm 4.9 (3)	92.9 \pm 0.5 (2)
Ni	0.19	0.63	0.008 \pm 0.018 (15)	89.4 \pm 5.3 (3)	89.8 \pm 0.2 (2)
Pb	0.09	0.28	0.045 \pm 0.023 (15)	90.2 \pm 6.0 (3)	100.3 \pm 1.8 (2)
Zn	6.60	21.90	1.356 \pm 1.759 (15)	92.8 \pm 3.0 (3)	93.0 \pm 0.6 (2)
Hg	0.02	0.07	0.984 \pm 0.037 (15)	103.6 \pm 2.1 (3)	112.8 \pm 13.1 (2)

Table S6. Concentrations of trace elements (mg/kg d.w.) in the Ibirité Reservoir in November 2024. Values in bold exceed the LEVEL 1 thresholds established in CONAMA Resolution n° 454/2012. LQ = Limit of Quantification. No sample was collected at point RES05 during this campaign.

Sample point	As	Cd	Cr	Cu	Mn	Ni	Pb	Zn	Hg
RES01	8.12	0.242	60.6	41.0	298	19.6	38.0	108	0.082
RES02	6.50	0.286	68.5	42.2	608	27.7	32.7	123	<LQ
RES03	5.29	0.300	55.6	36.6	620	20.8	30.4	113	<LQ
RES04	8.28	0.256	67.7	44.9	397	26.5	40.7	112	0.068
RES06	7.38	0.216	66.0	40.1	342	23.5	39.4	94	<LQ
RES07	6.54	0.271	58.1	35.5	472	21.5	36.4	137	<LQ
RES08	7.74	0.212	76.9	45.0	446	25.4	35.5	94	<LQ
RES09	7.14	0.220	69.6	41.6	397	28.2	36.1	88	<LQ
RES10	8.20	0.226	65.3	73.0	326	25.8	40.0	111	0.083
RES11	8.95	0.209	64.1	54.1	312	19.6	36.4	104	<LQ

RES12	6.89	0.188	63.5	37.1	422	19.6	34.5	85	<LQ
RES13	7.92	0.233	63.5	42.3	265	24.3	36.8	110	0.068
RES14	7.27	0.214	66.1	38.2	348	20.5	38.0	95	<LQ
RES15	2.61	0.138	15.0	11.5	187	5.7	38.5	50	<LQ

Table S7. Concentrations of trace elements (mg/kg d.w.) at the lotic points (tributaries and downstream of the Ibirité Reservoir) in May and November 2024. Values in bold exceed the LEVEL 1 thresholds established in CONAMA Resolution n° 454/2012. LQ = Limit of Quantification. Hg values are not presented, as all measurements were below the LQ.

Sample point	Campaign	As	Cd	Cr	Cu	Mn	Ni	Pb	Zn
LOT 2	May	2.24	0.044	13.1	3.5	412	4.2	5.8	59
LOT 3	May	2.71	0.148	33.5	12.9	272	9.4	30.8	164
LOT 4	May	2.70	0.100	54.3	21.7	363	18.6	14.7	63
LOT 5	May	3.31	0.055	66.7	33.7	476	33.6	10.0	39
LOT 6	May	2.02	0.057	16.2	3.9	713	6.8	7.8	<LQ
LOT 7	May	1.46	0.022	6.4	2.2	222	2.5	8.1	<LQ
LOT 8	May	3.40	0.055	21.1	7.5	375	6.2	20.9	22
LOT 2	Nov	0.75	0.027	9.0	3.0	124	4.4	5.6	34
LOT 3	Nov	<LQ	0.025	5.1	1.4	49	1.5	3.9	<LQ
LOT 4	Nov	4.11	0.420	29.1	30.0	328	10.6	27.8	272
LOT 5	Nov	2.56	0.038	45.7	21.2	407	24.0	7.0	27
LOT 6	Nov	1.80	0.048	46.6	4.5	712	5.2	7.0	27
LOT 7	Nov	<LQ	<LQ	6.0	1.5	59	1.4	6.8	<LQ
LOT 8	Nov	2.14	0.039	14.2	5.5	674	3.6	9.8	<LQ

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Conclusão Geral

Este estudo contribuiu para o entendimento da contaminação por elementos-traço em ambientes lênticos urbanos brasileiros por meio de uma abordagem integrada em escalas nacional e local. A revisão sistemática evidenciou que a produção científica sobre lagos e lagoas urbanas concentra-se em regiões e biomas mais densamente povoados e industrializados, indicando que fatores geográficos, ambientais e populacionais influenciam fortemente a distribuição dos estudos. Observou-se também que os elementos mais investigados incluem tanto elementos essenciais quanto não essenciais, e que os estudos frequentemente aplicam múltiplas técnicas de preparo e detecção, refletindo a complexidade e diversidade metodológica do monitoramento ambiental. A análise do efeito de legislações ambientais revelou uma influência parcial sobre a condução dos estudos, sugerindo lacunas no cumprimento ou na eficácia das normas vigentes.

Em escala local, o estudo do Reservatório de Ibirité e seus tributários mostrou que a distribuição espacial de elementos-traço nos sedimentos é fortemente modulada pelo uso e cobertura do solo nas áreas drenadas, especialmente nos ambientes lóticos. No reservatório, entretanto, a heterogeneidade espacial das concentrações indicou que processos internos, como deposição sedimentar e características físico-químicas dos sedimentos, podem superar o efeito direto das contribuições dos tributários. Sedimentos finos e com maior teor de matéria orgânica destacaram-se como principais acumuladores de elementos-traço, reforçando seu papel como indicadores de contaminação e como potenciais fontes secundárias de poluição.

De forma geral, os resultados demonstram que a contaminação por elementos-traço em ambientes lênticos urbanos é resultado da interação entre pressões antrópicas externas e processos internos do ecossistema, sendo modulada por fatores geográficos, usos do solo, características físico-químicas e granulometria dos sedimentos. Essas evidências reforçam a

necessidade de monitoramento contínuo e de estratégias de gestão integradas que considerem a diversidade de escalas espaciais e a complexidade dos processos que regulam a distribuição de contaminantes, visando proteger os serviços ecossistêmicos e a saúde humana.

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