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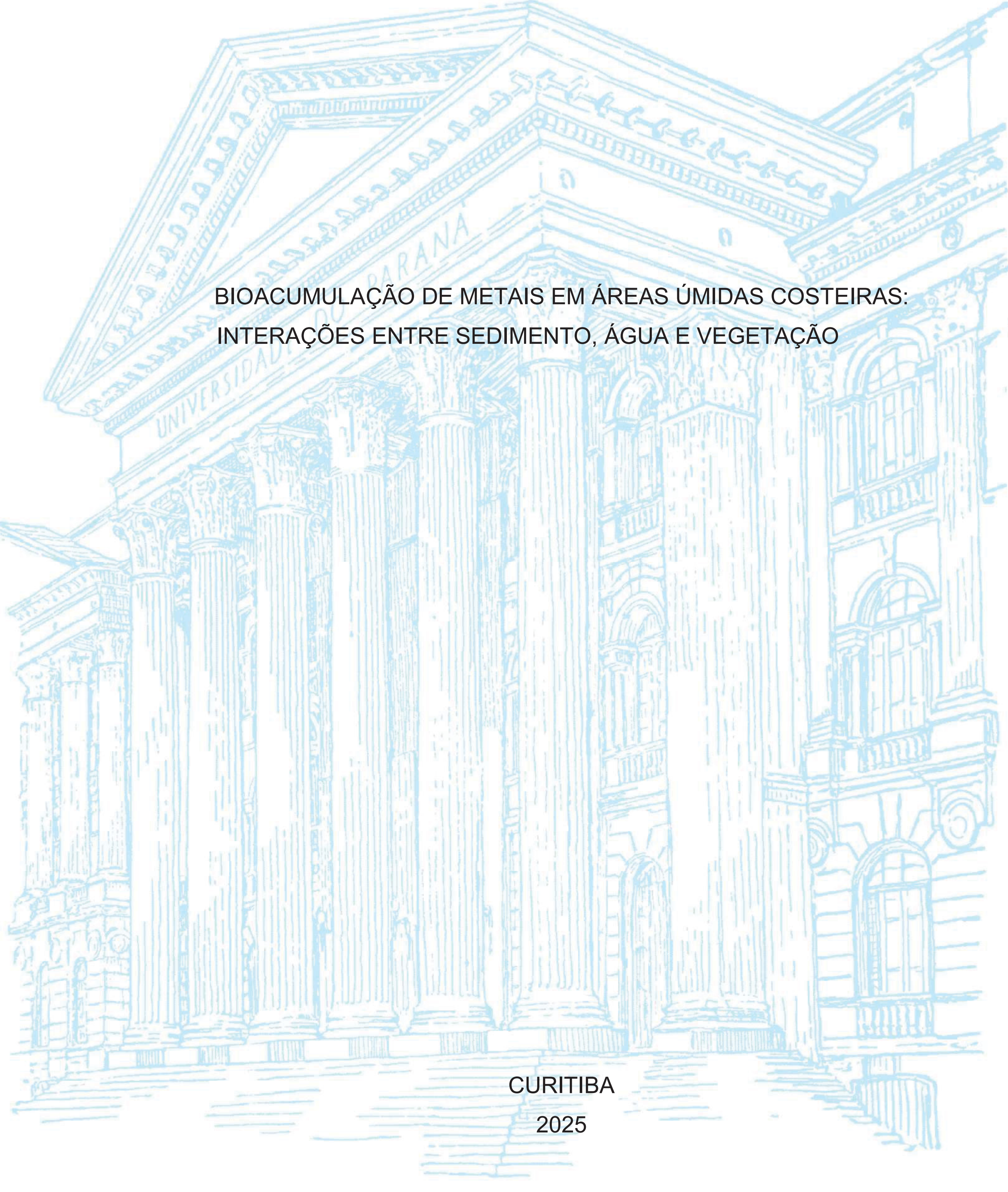
FERNANDA DITTMAR CARDOSO



# BIOACUMULAÇÃO DE METAIS EM ÁREAS ÚMIDAS COSTEIRAS: INTERAÇÕES ENTRE SEDIMENTO, ÁGUA E VEGETAÇÃO

CURITIBA

2025

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# BIOACUMULAÇÃO DE METAIS EM ÁREAS ÚMIDAS COSTEIRAS: INTERAÇÕES ENTRE SEDIMENTO, ÁGUA E VEGETAÇÃO

Tese apresentada ao curso de Pós-Graduação em Botânica, Setor de Ciências Biológicas, Universidade Federal do Paraná, como requisito parcial à obtenção do título de Doutor em Botânica.

Orientador: Prof. Dr. Andre Andrian Padial
Coorientador(a): Prof(a). Dr(a). Alessandra Larissa D’Oliveira Fonseca

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**ATA Nº04**

# ATA DE SESSÃO PÚBLICA DE DEFESA DE DOUTORADO PARA A OBTENÇÃO DO GRAU DE DOUTORA EM BOTÂNICA

No dia seis de maio de dois mil e vinte e cinco às 14 horas, na sala https://teams.microsoft.com/l/meetup-join/19%3a978ec6e51fc04f65be849815d388edba%40thread.tacv2/1746463503979?context=%7b%22Tid%22%3a%22c37b37a3-e9e2-42f9-bc67-4b9b738e1df0%22%2c%22Oid%22%3a%220a9ff6ce-5f47-4861-9df1-bdb5e18799ef%22%7d, Sala virtual, foram instaladas as atividades pertinentes ao rito de defesa de tese da doutoranda **FERNANDA DITTMAR CARDOSO**, intitulada: **BIOACUMULAÇÃO DE METAIS EM ÁREAS ÚMIDAS COSTEIRAS: INTERAÇÕES ENTRE SEDIMENTO, ÁGUA E VEGETAÇÃO**, sob orientação do Prof. Dr. ANDRE ANDRIAN PADIAL. A Banca Examinadora, designada pelo Colegiado do Programa de Pós-Graduação BOTÂNICA da Universidade Federal do Paraná, foi constituída pelos seguintes Membros: ANDRE ANDRIAN PADIAL (UNIVERSIDADE FEDERAL DO PARANÁ), MAURICIO MELLO PETRUCIO (UNIVERSIDADE FEDERAL DE SANTA CATARINA), GISELE CAROLINA MARQUARDT (UNIVERSIDADE FEDERAL DO PARANÁ), IDEL CRISTIANA BIGLIARDI MILANI (UNIVERSIDADE FEDERAL DE PELOTAS). A presidência iniciou os ritos definidos pelo Colegiado do Programa e, após exarados os pareceres dos membros do comitê examinador e da respectiva contra argumentação, ocorreu a leitura do parecer final da banca examinadora, que decidiu pela APROVAÇÃO. Este resultado deverá ser homologado pelo Colegiado do programa, mediante o atendimento de todas as indicações e correções solicitadas pela banca dentro dos prazos regimentais definidos pelo programa. A outorga de título de doutora está condicionada ao atendimento de todos os requisitos e prazos determinados no regimento do Programa de Pós-Graduação. Nada mais havendo a tratar a presidência deu por encerrada a sessão, da qual eu, ANDRE ANDRIAN PADIAL, lavrei a presente ata, que vai assinada por mim e pelos demais membros da Comissão Examinadora.

Curitiba, 06 de Maio de 2025.

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ANDRE ANDRIAN PADIAL
Presidente da Banca Examinadora

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MAURICIO MELLO PETRUCIO
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# TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação BOTÂNICA da Universidade Federal do Paraná foram convocados para realizar a arguição da tese de Doutorado de **FERNANDA DITTMAR CARDOSO**, intitulada: **BIOACUMULAÇÃO DE METAIS EM ÁREAS ÚMIDAS COSTEIRAS: INTERAÇÕES ENTRE SEDIMENTO, ÁGUA E VEGETAÇÃO**, sob orientação do Prof. Dr. ANDRE ANDRIAN PADIAL, que após terem inquirido a aluna e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.
A outorga do título de doutora está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

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Dedico esta tese a todas as mães estudantes que, apesar dos desafios diários, seguem contribuindo para a pesquisa científica e o avanço do conhecimento, jamais abandonando suas famílias. Que sua força e persistência sirvam de exemplo para seus filhos e para outras mães, mostrando que, embora algo possa ser difícil, não é impossível.

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"O maior benefício que a ciência trouxe à humanidade foi a capacidade de compreender as leis da natureza e aplicar esse conhecimento para melhorar nossas vidas” (Linus Pauling, 1901-1994)

## RESUMO

Áreas úmidas marinhas agem como filtros naturais de poluentes provenientes de diversas fontes: oceânicas, terrestres e atmosféricas. Metais pesados provenientes de efluentes de áreas urbanas, assim como resíduos de combustíveis e óleos lubrificantes, podem contribuir para a contaminação dos ecossistemas nessas regiões. A Lagoa da Conceição é uma laguna em Florianópolis, SC, destino de turistas do mundo todo, principalmente em meses de verão, quando a população dobra em tamanho, assim como seus resíduos. A coleta e o tratamento de efluentes domésticos não acompanha o crescimento da região, o que contribui para a queda na qualidade da água do ambiente, que é procurado para a pesca, prática de esportes náuticos, passeios de barco e gastronomia dos restaurantes locais. A situação do corpo hídrico se agravou com o rompimento de uma Lagoa de Evapoinfiltração de Esgotos (LEI), que armazena efluente tratado de uma Estação de Tratamento de Esgotos, cujas substâncias como nutrientes e metais pesados não são removidas pelo tratamento convencional. A barragem da LEI se rompeu em um evento de chuva extrema em 2021, extravasando seu conteúdo de 500.000m³ de efluente para dentro da Lagoa da Conceição, causando estragos materiais e desequilíbrio ecológico na região. Devido à falta de informações a respeito do impacto deste acidente quanto à concentração de metais pesados no ambiente e os riscos associados, este trabalho teve como objetivo avaliar a contaminação a longo prazo, 2 anos após o evento, verificando o teor de metais pesados (Al, As, Cd, Cu, Cr, Fe, Hg, Mn, Ni, Pb e Zn) na água superficial, no sedimento e na vegetação do entorno da Lagoa da Conceição. Avaliou-se também parâmetros de estado trófico da água (N, P), relacionados à contaminação por esgotos. Os resultados indicam uma contaminação sistêmica no local, provenientes de diversas fontes, como tintas antifouling de embarcações, resíduos liberados em marinas e lançamento irregular de efluentes no corpo d’água. Áreas de menor circulação de água e mais urbanizadas foram mais significativas para a contaminação do que o epicentro do acidente dois anos após o ocorrido. O teor de nutrientes esteve dentro dos limites propostos pela legislação brasileira. A vegetação mostrou importante potencial de fitorremediação, reduzindo teores de metais pesados na água superficial. A espécie *Halodule wrightii* foi destaque como acumuladora de metais, seguida da espécie *Panicum racemosum,* que também apresentou alto fator de bioconcentração*. Fimbristylis cymosa*, se mostrou bastante bioacumuladora, sendo uma novidade no campo da fitorremediação, uma vez que também apresenta grande produção de biomassa. Entre as espécies analisadas, *Scirpus* sp. demonstrou tolerância ao mercúrio. As análises estatísticas (PERMANOVA, PCA e GAM) mostraram que a variação da concentração de metais nas plantas foi mais significativa devido à fatores ambientais. A biomassa produzida se mostrou como um fator determinante na escolha de espécies para a fitorremediação. A bioacumulação é influenciada por múltiplas variáveis, sendo condições abióticas e espécie-específicas mais importantes do que a distância do epicentro do acidente, neste contexto.



Palavras-chave: lagoa costeira, metais pesados, nutrientes, efluente, fitorremediação

**ABSTRACT**

Marine wetlands act as natural filters for pollutants from various sources, including oceanic, terrestrial, and atmospheric inputs. Heavy metals from urban wastewater, as well as residues from fuels and lubricating oils, can contribute to ecosystem contamination in these regions. Lagoa da Conceição is a coastal lagoon in Florianópolis, SC, a popular tourist destination, especially during the summer months when the population doubles, along with waste production. The collection and treatment of domestic wastewater have not kept pace with the region's growth, leading to a decline in water quality in an environment sought after for fishing, water sports, boat tours, and local gastronomy. The situation worsened following the rupture of an Evaporation-Infiltration Lagoon (LEI), which stores treated effluent from a Sewage Treatment Plant. Conventional treatment does not remove substances such as nutrients and heavy metals. The LEI dam broke during an extreme rainfall event in 2021, releasing 500,000 m³ of effluent into Lagoa da Conceição, causing material damage and ecological imbalance in the region. Due to the lack of information regarding the impact of this accident on heavy metal concentrations in the environment and associated risks, this study aimed to assess long-term contamination, two years after the event. It evaluated the contribution of the accident to heavy metal levels (Al, As, Cd, Cu, Cr, Fe, Hg, Mn, Ni, Pb, and Zn) in surface water, sediment, and surrounding vegetation of Lagoa da Conceição. The results indicate systemic contamination in the area, originating from multiple sources, such as antifouling paints from boats, waste released from marinas, and the irregular discharge of effluents into the water body. Areas with lower water circulation and greater urban influence showed higher contamination levels than the accident's epicenter. Vegetation demonstrated a significant potential for phytoremediation, reducing heavy metal concentrations in surface water. The species *Halodule wrightii* stood out as a metal accumulator, followed by *Panicum racemosum*, which also exhibited a high bioconcentration factor. *Fimbristylis cymosa* proved to be a strong bioaccumulator, representing a novelty in the field of bioremediation. Among the analyzed species, *Scirpus* sp. demonstrated tolerance to mercury. Statistical analyses (PERMANOVA, PCA, and GAM) showed that metal concentrations in plants varied primarily due to environmental factors. Bioaccumulation is influenced by multiple variables, with the distance from the accident's epicenter not being a determining factor in this context.

Keywords: Bioaccumulation, coastal lagoon, heavy metals, nutrients, effluents, bioremediation

**SUMÁRIO**

# 1 INTRODUÇÃO

## 1.1 ÁREAS ÚMIDAS MARINHAS COMO FILTROS NATURAIS

As áreas úmidas marinhas, localizadas na zona de transição entre a terra e o oceano, são de suma importância para o sequestro de carbono, o ciclo de nutrientes, a manutenção da biodiversidade, além de fornecerem serviços ecossistêmicos como berçários para pesca e proteção contra tempestades (Li et al., 2022; Adaro e Ronda, 2024). Esses ecossistemas incluem marismas, estuários, manguezais, pradarias de ervas marinhas e planícies de maré.

Nestes ambientes, a vegetação favorece a estabilização de sedimentos e linhas costeiras, promovendo a deposição de material particulado, como sedimentos e fitoplâncton (Yu et al., 2002). Desta forma, áreas úmidas marinhas atuam como filtros naturais, retendo materiais oriundos de outros ecossistemas, como metais pesados de fontes terrestres, oceânicas e atmosféricas. Esse papel de fixação é associado especialmente à presença de vegetação aérea e subterrânea, além de solos ricos em matéria orgânica (Li et al., 2022; Adaro e Ronda, 2024). Plantas halófitas ganham destaque devido à sua capacidade de lidar com situações de stress, como em áreas contaminadas (Oliveira et al., 2018).

O potencial de bioacumulação de metais pesados pela vegetação pode ser uma importante tática de remoção de contaminantes da água superficial, como também do sedimento associado, o que reduz a sua disponibilidade e toxicidade para comunidades sujeitas aos seus efeitos. A biorremediação, que envolve o uso de organismos vivos para tratar ambientes poluídos, aproveita a bioacumulação como um mecanismo eficiente de remoção de contaminantes. É uma abordagem sustentável, que evita a geração de poluição secundária, como é caso das remediações química e física. Além disso, pode ser aplicada em ampla escala espacial e de forma contínua ao longo do tempo, permitindo seu uso em diferentes ecossistemas e contextos. Outro fator importante é sua viabilidade econômica, sendo uma solução custo-efetiva, acessível em diversos setores (Sarath e Puthur, 2020).

A fitorremediação é baseada em processos biológicos e características físicas das plantas, englobando diferentes métodos que contribuem para redução da concentração dos poluentes no ambiente, como a acumulação (fitoextração e rizofiltração), dissipação (fitovolatilização) ou imobilização (fitostabilização) (Kaewtubtim et al., 2016). Atualmente, a fitorremediação pode ser aplicada inclusive na remoção de fármacos de águas superficiais, atingindo até 70% de redução de sua concentração e diminuindo os efeitos deletérios das substâncias (Kitamura et al., 2023).

## 1.2 METAIS PESADOS

Metais pesados, caracterizados pela sua alta densidade (superior a 4 $g/cm^3$), são constituintes naturais de minerais, e são continuamente extraídos das rochas para seu uso industrial. Podem estar livres no ambiente provenientes tanto de fontes naturais, em maior proporção, como intemperismo de minerais, erosão e atividade vulcânica, como de fontes antropogênicas, que englobam mineração, fundição, galvanoplastia, uso de pesticidas e fertilizantes à base de fosfato, além da aplicação de biossólidos na agricultura, descarte de lodos, despejos industriais, deposição atmosférica e efluentes domésticos (Ali et al., 2013). Elementos como cromo (Cr), cobre (Cu), chumbo (Pb), zinco (Zn) não podem ser degradados, resultando em sua persistência a longo prazo no ambiente (Suman et al., 2018). Embora não possam ser eliminados, os metais pesados podem ser manejados para minimizar seus impactos ambientais e toxicológicos.

Embora muitos metais sejam essenciais à fisiologia dos seres vivos, como o ferro, fundamental para a respiração celular, a exposição a determinados metais pesados, mesmo em baixas concentrações, está associada a diversos impactos negativos à saúde humana e à biota. O mercúrio (Hg), por exemplo, pode causar ansiedade, depressão, dificuldade de equilíbrio, fadiga, queda de cabelo, insônia, irritabilidade, perda de memória, infecções recorrentes, distúrbios visuais, tremores, explosões de temperamento, úlceras e danos ao cérebro, rins e pulmões (Neustadt e Pieczenik, 2007; Ali et al., 2019). O cromo acima dos limites permitidos pode causar deficiência renal e queda de cabelos; o chumbo também está relacionado à problemas nos rins, e lesões ao sistema nervoso central; o zinco pode causar tontura e fadiga; o cobre tem sido associado a danos no cérebro e nos rins, cirrose hepática, anemia crônica, além de irritação no estômago e nos intestinos; o arsênio (As) pode induzir várias doenças, como conjuntivite, hiperqueratose, doenças cardiovasculares, câncer de pele, distúrbios no sistema nervoso central e vascular periférico (Barra et al., 2000; von Sperling, 2005; Hess e Schmid, 2002; Ali et al., 2019).

Em plantas, alguns metais também são necessários ao desenvolvimento, como o manganês (Mn), que é essencial para o crescimento e desempenha um papel crucial no ciclo biogeoquímico do nitrogênio, especialmente na redução de nitrato em plantas verdes, onde é comumente encontrado (Chowdhury et al., 2015). O cobre (Cu) é essencial para a fotossíntese, respiração, atividade antioxidante e sinalização hormonal, sendo prontamente absorvido pelas raízes e transferido para organelas como os cloroplastos (Vatansever et al., 2017). No entanto, o excesso de Cu é tóxico e inibe o crescimento (Pasricha et al., 2021).

Assim como o Cu, o zinco é essencial para reações enzimáticas, funcionamento dos cloroplastos, síntese proteica, hormônios de crescimento e metabolismo de carboidratos, frequentemente compartilhando mecanismos semelhantes de absorção (Shaw, 1990; Chowdhury et al., 2015). Embora o zinco seja vital para o crescimento vegetal (Vistosh et al., 1994), níveis excessivos podem prejudicar o metabolismo, induzir danos oxidativos e provocar deficiências de Mn e Cu, prejudicando o desenvolvimento das partes aéreas (Kushwaha et al., 2015).

Segundo Arantes (2016), o alumínio não é utilizado como nutriente, e sua toxicidade pode afetar negativamente as plantas ao inibir o desenvolvimento das raízes e a absorção de água. O cromo (Cr) é um metal pesado não essencial para plantas, e embora baixas concentrações possam promover o crescimento e aumentar a produtividade, níveis elevados podem inibir o crescimento e reduzir a fotossíntese (Nichols et al., 2000).

Atualmente, não se conhece nenhuma função fisiológica do mercúrio (Hg) nas plantas, segundo Rascio et al. (2011). Altos níveis de mercúrio podem provocar efeitos fitotóxicos, como redução da fotossíntese e da respiração, diminuição na absorção de água, comprometimento da síntese de clorofila e danos às sementes, entre outros (Azevedo e Rodríguez, 2012).

O arsênio (As) é um metalóide tóxico, não essencial, sendo frequentemente absorvido pelos vegetais por meio de herbicidas, inseticidas, desfolhantes, preservantes de madeira e água contaminada (Zhao et al., 2009). É amplamente distribuído na natureza, comumente associado a minérios como ouro, cobre e chumbo. Pode ser encontrado em organismos marinhos devido à substituição de nitrogênio e fósforo em vias metabólicas (Barra et al., 2000). A volatilidade do arsênio permite seu transporte a longas distâncias e deposição sobre folhas de plantas (Salomons; Forstner, 1984). O acúmulo de arsênio em plantas depende das concentrações no solo e nos sedimentos (Onken e Hossner, 1995) e pode inibir o crescimento, comprometer a fisiologia e afetar o metabolismo. No entanto, algumas espécies, como *Holcus lanatus*, apresentam tolerância ao arsênio devido às altas concentrações de fitoquelatinas (Hartley-Whitaker et al., 2001). Certas plantas também podem aumentar o acúmulo de arsênio enquanto reduzem sua toxicidade na presença de fósforo (Gomes et al., 2013).

O cádmio (Cd) também é um metal não essencial e sem função biológica conhecida. Apresenta alta mobilidade e solubilidade em água, causando problemas como inibição do crescimento, epinastia foliar, clorose, redução da taxa fotossintética e inibição da absorção de nitrato (Gallego et al., 2012). O cádmio entra no ambiente principalmente por meio de esterco, lodo de esgoto e uso de baterias de níquel-cádmio (Ni-Cd) (Pasricha et al., 2021).

## 1.3 A LAGOA DA CONCEIÇÃO E A MÁ GESTÃO HÍDRICA

A escassez de tratamento adequado dos efluentes domésticos agrava os problemas ambientais e de saúde pública. Os ambientes aquáticos em região urbana no Brasil frequentemente recebem poluentes por meio de lixiviação ou descarte direto de efluentes domésticos, muitas vezes sem tratamento ou com tratamento insuficiente (Cardoso, 2016; Souza, 2020). É o caso da Lagoa da Conceição, localizada na ilha de Santa Catarina, Florianópolis-SC (Figura 1). Trata-se de uma laguna costeira conectada ao oceano pelo Canal da Barra da Lagoa, recebendo influências marinhas, crescimento urbano acelerado e o impacto de uma significativa frota de embarcações de pesca, turismo e transporte de passageiros (Cardoso et al., 2025). É o cartão postal da capital catarinense, com intenso fluxo de turistas nos meses de verão, que buscam esportes náuticos, passeios de barco e a gastronomia e cultura da região. O plano de saneamento básico da Lagoa da Conceição não acompanha sua expansão, afetando a qualidade de vida da população e o equilíbrio ecológico (PMF, 2021).

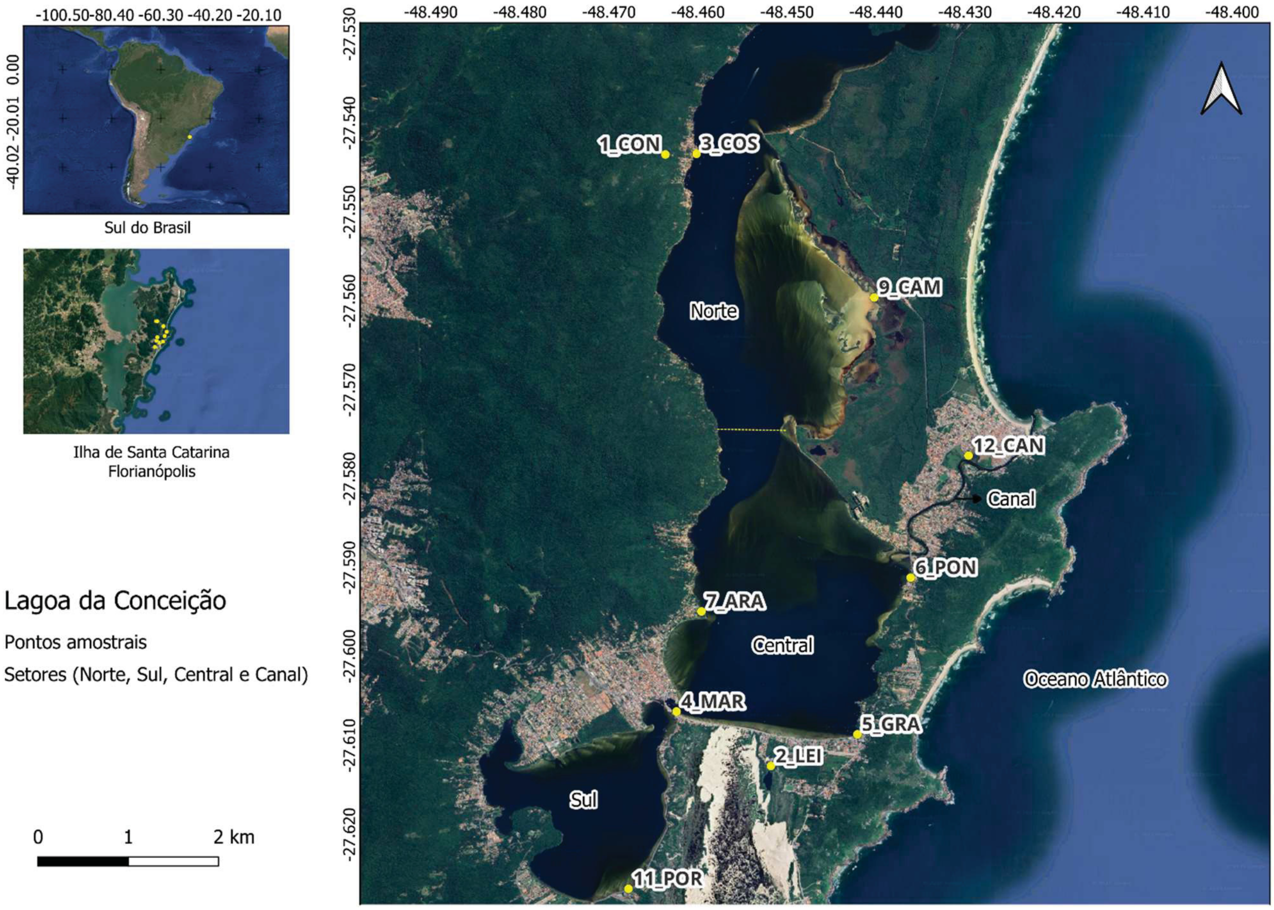


Figura 1. Mapa da área de estudo, Lagoa da Conceição, Florianópolis-SC. Os códigos indicam pontos amostrais onde esta pesquisa foi desenvolvida; para mais detalhes vide seção 2.2 (Materials and Methods, Capítulo 1). Ponto 2-LEI refere-se à Lagoa de Evapoinfiltração.

A Lagoa da Conceição é dividida em quatro setores—norte, sul, central e Canal— divididos de acordo com características hidrodinâmicas e morfológicas distintas (Godoy, 2009; Roschild et al., 2021). O setor norte recebe grande aporte de matéria orgânica, principalmente devido aos tributários Rios João Gualberto e Rio Vermelho, que atravessam bairros em expansão demográfica e pouca estrutura de saneamento, totalizando 24% de contribuição hidrológica à Lagoa da Conceição (Fonseca, 2004). A região Central compreende o bairro mais populoso e comercial do entorno da Lagoa, com contribuição significativa de nutrientes dissolvidos proveniente de descarte incorreto de efluentes domésticos, além da entrada da cunha salina proveniente do Canal da Barra da Lagoa (Cabral et al, 2019). A região Sul apresenta pouca hidrodinâmica, com tempo médio de residência da água de 20 dias, confinando uma grande quantidade de nutrientes provenientes da elevada urbanização (Fonseca, 2004). O setor Canal é de alta hidrodinâmica, regida pelo fluxo de marés com dois picos diários, com amplitudes baixas e diferentes, apresentando 2,8 km de extensão e intenso fluxo de embarcações (Godoy, 2009).

A ausência de saneamento adequado não apenas compromete o meio ambiente, mas também expõe a população a riscos de doenças, como infecções gastrointestinais, hepatites e outras enfermidades de veiculação hídrica (Integra, 2021). Greenwhood e colaboradores (2024), verificaram que a contaminação fecal é o principal fator que impede que haja disponibilidade de água potável segura para a população mundial, visto que quase metade da população de regiões de média e baixa renda (aproximadamente 4,4 bilhões de pessoas) não têm acesso a este recurso. A falta de investimentos e infraestrutura adequada no tratamento de efluentes perpetua esse ciclo, reforçando a necessidade de soluções eficazes e sustentáveis para minimizar os impactos na saúde coletiva.

Além da questão de saúde pública, a má gestão hídrica geralmente induz a uma queda de rendimento econômico, perda de potencial turístico, escassez hídrica e alimentícia, e afeta negativamente os ecossistemas aquáticos (Silva et al., 2023). Por exemplo, em muitos ambientes contaminados por efluentes domésticos, a entrada de grandes quantidades de nutrientes, como nitrogênio (N) e fósforo (P), pode levar à eutrofização, favorecendo a proliferação de organismos autótrofos. A decomposição da matéria orgânica, associada ao bloqueio da luz solar, reduz os teores de oxigênio, levando à mortalidade de organismos (Padedda et al., 2019; Dudgeon, 2019).

A CASAN (Companhia Catarinense de Águas e Saneamento) é responsável pela coleta e tratamento de uma parte das águas residuárias produzidas em Florianópolis. Segundo dados do sistema Sanear Floripa, dos 10.821 imóveis avaliados, 75,1% estão irregulares, seja por ausência de caixa de gordura, esgoto conectado na rede pluvial, conexão parcial à rede ou ausência de ligação à rede de esgotos (PMF, 2024). No bairro da Lagoa da Conceição, dos 173 imóveis inspecionados, 76,9% (133) estão irregulares. No Brasil, segundo a Agência Nacional de Águas e Saneamento Básico (ANA, 2024), somente 43% da população têm seu esgoto coletado e tratado, e apenas 39% da carga orgânica é removida das ~9,1 toneladas de efluentes domésticos gerados por dia no país, o que não atinge a taxa de remoção de 60% indicada pela legislação em vigência, proposta pelo CONAMA (Conselho Nacional do Meio Ambiente).

A Lagoa da Conceição é atendida pela Estação de Tratamento de Esgotos (ETE) Lagoa da Conceição, que iniciou suas atividades em 1987, mas só obteve Licença Ambiental de Operação pelo órgão ambiental em 2016 (LAO nº 8457/2016). Esta ETE possui reator anaeróbio do tipo UASB, seguido de tratamento aeróbio com valos de oxidação, e tem capacidade de atender até 30.000 habitantes da região, com vazão média de 50 L/s, recebendo até 75 L/s em momentos de pico, como época de veraneio. Atualmente esta ETE atende uma população de 10.082 habitantes (PMF, 2021)

O efluente final tratado é destinado para uma Lagoa de Evapoinfiltração (LEI), localizada nas dunas da Lagoa da Conceição (Ponto 2-LEI, Figura 1), onde o efluente é disposto para que ocorra sua evaporação e infiltração no solo (Socioambiental, 2021; Burgardt et al., 2021; Orefice, 2014).

O talude natural formado por areia das dunas do Parque Natural Municipal das Dunas da Lagoa da Conceição servia de barragem para uma das Lagoas de Evapoinfiltração (LEI), o qual se rompeu diante de um evento de chuvas extremas, em 25 de janeiro de 2021. De acordo com o Ciram (Centro de Informações de Recursos Ambientais e de hidrometeorologia de Santa Catarina, 2021), no mês do acidente, houve o maior registro mensal de precipitação da região de Florianópolis (recorde mensal absoluto), que chegou a 686 mm. O volume de 500 mil m³ de efluente tratado na LEI foi extravasado em direção à Lagoa da Conceição, afetando várias residências e automóveis, felizmente não provocando perdas humanas diretas (Roschild et al., 2021). Vale ressaltar que o efluente tratado apresentava altos teores de nutrientes (N-P), e substâncias tóxicas que não são removidas pelo tratamento convencional, como metais pesados, que necessitam de tecnologias específicas para sua eliminação (PMF, 2021; Von Sperling, 2005).

No local que se concentrou a lama contaminada proveniente da LEI formou-se um baixio, que foi removido por dragagem pela Prefeitura Municipal de Florianópolis 10 meses após o acidente, reduzindo também a cobertura vegetal que possivelmente estava agindo como fitoremediadora de poluentes que foram carregados para a laguna.

## 1.4 FALHAS NA GESTÃO DE BARRAGENS E DESASTRES AMBIENTAIS

Acidentes com rompimento de barragens, frequentemente associados ao armazenamento de rejeitos de mineração, são registrados em várias regiões do Brasil (ANA – RSB, 2024). O extravasamento dos rejeitos armazenados impacta todos os ecossistemas à jusante da barragem, inclusive a longo prazo (Bowker e Chambers, 2015). Rejeitos com alta concentração de metais podem se depositar no sedimento e, devido aos processos biogeoquímicos naturais, serem ressolubilizados na água superficial, afetando a biota local (Gabriel et al., 2021).

Além da toxicidade intrínseca aos metais, outros processos podem ser desencadeados. Por exemplo, Queiroz e colaboradores (2021) evidenciaram que rejeitos contendo oxihidróxidos de ferro podem atuar são uma fonte contínua de fósforo dissolvido, contribuindo para a eutrofização do ambiente.

O SNISB (Sistema Nacional de Informações sobre Segurança de Barragens), gerido pela ANA, contém o cadastro de barragens de usos múltiplos da água, geração de energia elétrica, contenção de resíduos industriais e de rejeitos de mineração. No entanto, não inclui os dados dos estados de Paraíba, Paraná, Roraima e Santa Catarina. Muitos dos registros de rompimentos nestes últimos estados são encontrados somente no sistema da Defesa Civil ou em fontes jornalísticas.

No levantamento de 2023 do SNISB (RSB, 2024), foram reportados 25 acidentes e 25 incidentes com barragens no Brasil, sem fatalidades mas com danos diversos. O relatório apontou que 92% dos eventos foram relacionados a chuvas intensas, sugerindo que fatores climáticos influenciam significativamente em falhas estruturais, mesmo em barragens bem projetadas e executadas. Devido à tendência ao aumento da frequência e da intensidade dos eventos extremos, de acordo com o

IPCC (2023), é necessário que as estruturas e o monitoramento sejam reforçados continuamente.

Além disso, constatou-se que em 88% dos órgãos fiscalizadores (28 de 32 instituições), a equipe de técnicos com formação especializada é insuficiente para as atividades de fiscalização de segurança de barragens (RSB, 2024). Dentre as principais causas dos rompimentos destas estruturas, destacam-se erros de projeto, problemas geotécnicos da estrutura, falha na gestão dos rejeitos, e falta de monitoramento das estruturas (Werneck, 2019). É evidente que a ausência de fiscalização promove o relaxamento no monitoramento das estruturas e consequente aumento do risco de acidentes.

A Tabela 1 reúne alguns dos últimos casos de rompimentos de barragens no Brasil, sendo dois no município de Florianópolis, envolvendo a mesma companhia de Saneamento. Com exceção dos acidentes de Mariana-MG (2015) e Brumadinho (2019), que ficaram mundialmente conhecidos pela amplitude da catástrofe com as barragens de rejeitos de mineração, os demais acidentes geralmente não foram explorados em artigos científicos, segundo uma busca realizada nos portais de periódicos. Não foram encontrados registros de outros acidentes em Lagoas de Evapoinfiltração.

Tabela 1. Alguns acidentes envolvendo rompimento de barragens nos últimos anos no Brasil (Gabriel et al., 2021; Roschild et al., 2021; G1, 2023a,b; Jornal do Comércio, 2024; G1, 2024). *NI: não informado.

| Data do Acidente | Local | Município | Palavras-Chave | Volume extravasado | Impacto No Ecossistema |
|---|---|---|---|---|---|
| nov/15 | barragem de Fundão | Mariana-MG | doenças diarréicas, óxido de ferro e sílica | 43 milhões m³ | Bacia do Rio Doce |
| jan/19 | barragem da mina Córrego do Feijão | Brumadinho-MG | rejeitos de ferro, sílica | 12 milhões m³ | Bacia do Rio Paraopeba |
| jan/21 | barragem ETE-LEI Lagoa da Conceição (Casan) | Florianópolis-SC | esgotos | 500 mil m³ | Estuário da Lagoa da Conceição |
| set/23 | reservatório de água (Casan) | Florianópolis-SC | enxurrada | 2 mil m³ | Bairro Monte Cristo |
| mai/24 | barragem 14 de julho (hidrelétrica-Ceran) | Bento Gonçalves - RS | rompimento parcial, chuvas intensas no RS | NI* | Bacia do Rio Taquari-Antas |

| | | | | | |
|---|---|---|---|---|---|
| ago/24 | represa de água em condomínio | Campo Grande - MS | falta de manutenção, possível negligência | 20 hectares de lâmina d'água | Região de Jaraguari-MS |

O rompimento ocorrido na Barragem 14 de julho, no Rio Grande do Sul, foi propiciado pelas maiores enchentes da história do estado da região Sul, com chuvas levando mais de 385 cidades ao estado de emergência, e mais de 1 milhão de pessoas afetadas (Tabela 1; UOL, 2024). Ou seja, novamente eventos extremos podem ter favorecido a ocorrência de catástrofes como o rompimento da LEI, ocorrido em Florianópolis.

No caso da Lagoa de Evapoinfiltração (LEI) na Lagoa da Conceição, além da precipitação intensa (115,2mm em 24/01/2021) e falha na projeção destes eventos, outras causas do rompimento da LEI foram apontadas por estudos técnicos subsequentes (Burgardt et al., 2021): o solo onde o efluente tratado era disposto estava saturado, reduzindo sua capacidade de infiltração, um problema conhecido pela concessionária responsável; vazão de entrada da ETE estava acima da média desde o dia 18/01/2021, em um período de intensa movimentação de turistas na região, agravado por contribuições irregulares e difusas na rede coletora de esgoto; ausência de adoção das medidas preventivas do Plano de Emergência e Contingência frente ao maior risco associado, em especial o monitoramento das cotas de máximo; ausência de atitude da Concessionária após denúncias de extravasamento da lagoa por moradores dias antes do evento.

Desastres ambientais e acidentes são as principais causas de contaminação metálica em larga escala a partir de fontes antrópicas, como o rompimento da barragem de rejeitos de mineração em Mariana (MG), em 2015 (De Carvalho et al., 2017). A falta de registros centralizados sobre acidentes com barragens, no estado de Santa Catarina por exemplo, compromete a avaliação dos impactos ambientais e a adoção de medidas preventivas. Em relação à Lagoa da Conceição, é provável que o extravasamento da lama de efluente doméstico sem tratamento terciário tenha intensificado a contaminação por metais pesados, tornando essencial o monitoramento do ambiente para entender sua dispersão e riscos ambientais.

## 1.5 JUSTIFICATIVA E OBJETIVOS

Estudos realizados por pesquisadores da UFSC e da FURG em setembro de 2021 indicaram a presença de metais como arsênio, mercúrio, cadmio e chumbo em níveis acima dos limites permitidos em amostras de pescados locais (PES 11, 2021). Esses peixes são parte da dieta da comunidade local, o que coloca em risco a saúde humana e ambiental.

Diante desta contaminação metálica, a vegetação aquática e ripária da Lagoa da Conceição pode desempenhar papel fundamental na biorremediação do ambiente. A presença de plantas halófitas, por exemplo, sugere uma possível adaptação a condições ambientais adversas, devido à sua habilidade de desenvolver tolerância cruzada, isto é, a capacidade de adquirir resistência simultânea a diferentes tipos de estresse abiótico (Carreiras, 2018). Dessa forma, a caracterização florística e a avaliação do teor metálico nas espécies vegetais são essenciais para compreender os processos de bioacumulação e a capacidade das plantas de regular os elementos solúveis e particulados no ambiente.

Além disso, é fundamental avaliar o atual estado de contaminação do ecossistema da Lagoa da Conceição, considerando os impactos de longo prazo do rompimento da barragem da LEI da ETE Lagoa da Conceição e o extravasamento de efluente tratado na laguna. Dados sobre rompimentos e outros acidentes envolvendo lagoas de contenção de esgoto são escassos na literatura, incluindo na homepage da ANA. Essa falta de informações subestima os impactos desses eventos, que, devido ao alto potencial de contaminação da água e do solo, frequentemente apresentam efeitos prolongados. Portanto, tais dados deveriam estar prontamente disponíveis e acessíveis tanto à população quanto aos gestores públicos.

Tendo em vista a necessidade de compreender as consequências deste acidente e averiguar o estado atual da contaminação, foi realizado um levantamento amostral em janeiro de 2023, analisando água, sedimentos e vegetação da Lagoa da Conceição. O objetivo geral deste estudo foi estimar a contaminação metálica na Lagoa da Conceição 2 anos após o impacto de curto prazo da ruptura da barragem da LEI, verificando a influência dos parâmetros físico-químicos do ambiente e avaliando o potencial de fitorremediação natural.

A hipótese testada é de que a vegetação bioacumula os metais pesados, reduzindo sua concentração na água e nos sedimentos, com as maiores concentrações esperadas nas proximidades do epicentro do acidente, caracterizando uma contaminação aguda e pontual. Foram analisados os seguintes elementos: alumínio (Al), arsênio (As), cadmio (Cd), cobre (Cu), cromo (Cr), ferro (Fe), mercúrio (Hg), manganês (Mn), níquel (Ni), chumbo (Pb) e zinco (Zn). Neste estudo, esses elementos foram designados como metais pesados, uma vez que contempla tanto metais como metalóides (IUPAC, 2002), e foram selecionados devido à toxicidade e relevância em estudos anteriores.

Os objetivos específicos foram (1) avaliar a autodepuração do ambiente em relação aos nutrientes dissolvidos (N e P), integrando dados pré-impacto disponíveis na literatura; (2) determinar as concentrações dos metais pesados na água e nos sedimentos nos 4 setores da Lagoa da Conceição, avaliando os riscos ambientais com base na legislação vigente para águas superficiais e diretrizes de qualidade de sedimentos; (3) verificar padrões estatísticos na distribuição dos metais em relação aos compartimentos ambientais analisados; (4) avaliar se a concentração dos metais pesados nas plantas indicam um impacto agudo ou uma contaminação sistêmica, relacionada às fontes antrópicas recorrentes na Lagoa da Conceição.

## 2 CAPITULO 1: “ARSENIC AND HEAVY METALS CONTAMINATION BY EFFLUENT DAM RUPTURE IN A SUBTROPICAL COASTAL LAGOON”

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ABSTRACT

Dam accidents, often resulting from inadequate structural monitoring, pose significant environmental risks. In southern Brazil, the rupture of an evaporation-infiltration lagoon released over 500,000 m³ of treated domestic effluent into a coastal lagoon, raising concerns about potential contamination from nutrients and heavy metals. This study aimed to (1) assess the environment's self-purification capacity regarding dissolved nutrients, (2) determine total heavy metal concentrations in water and sediments throughout the coastal lagoon using inductively coupled plasma mass spectrometry, (3) correlate variables influencing heavy metal availability to identify potential sources, and (4) evaluate environmental risks by comparing concentrations to established water and sediment quality guidelines. Potential sources of contamination included natural origins, boat traffic associated with fuel leaks and antifouling paints, and the irregular discharge of domestic effluents into the lagoon. The results revealed nutrient self-purification and elevated arsenic levels in the water, likely from natural sources. However, manganese and zinc concentrations exceeded water quality limits, while zinc and copper levels were notably high in northern sediments, with no definitive association to the dam's sludge. These findings highlight significant toxicity risks to biota and emphasize the need for continuous monitoring. Mitigation strategies should be implemented, particularly in the most contaminated areas, given the lagoon's intense use for recreation and seafood harvesting. Overall, the results reinforce the threat of pollution to biodiversity, ecosystem services, the livelihoods of fishing communities, and the local economy, emphasizing the importance of this study in guiding management actions amidst significant challenges.

Keywords: heavy metals, arsenic, dam rupture, sewage, estuary

## 2.1 INTRODUCTION

Efficient water resource management is essential for ensuring adequate sanitation conditions, a fundamental aspect of human development that contributes to a life of dignity and quality. Inadequate water management not only impacts public health but also diminishes economic performance, undermines tourism potential, exacerbates water and food shortages, and disrupts the ecological balance of aquatic environments (Silva et al., 2023). The final disposal of treated domestic effluents presents a significant challenge in regions with high population density and unique physiographic characteristics. In Florianópolis, a tropical Brazilian island with a population density of 796.05 inhabitants per square kilometer (IBGE, 2022), the limited availability of suitable effluent disposal options—such as small watercourses or protected areas near river mouths—has necessitated the adoption of evaporation-infiltration lagoons (LEI) as a practical and cost-effective solution. These systems recharge aquifers by utilizing the soil's natural filtration capacity, functioning similarly to intermittent sand filters. Most of the effluents infiltrate into the soil, while a smaller portion evaporates (USEPA, 2006).

However, despite being considered safer than tailings dams, which store hazardous mining waste, evaporation-infiltration lagoons present their own set of risks (Kumar & Singh, 2019). These systems can accumulate toxic substances that are not effectively removed during the earlier stages of conventional sewage treatment. Inadequate management of these lagoons can lead to the contamination of soil and groundwater, posing long-term environmental and public health risks (Kumar & Singh, 2019). Therefore, evaporation-infiltration lagoons represent a unique environmental hazard due to their potential to facilitate the gradual leaching of heavy metals and toxic contaminants into groundwater systems. This contamination can persist for decades, resulting in widespread soil and water pollution, as highlighted by studies such as Lottermoser (2010) and Johnson & Hallberg (2005).

The recent rupture of an evaporation-infiltration lagoon dam in southern Brazil exemplifies significant environmental risks. This rupture likely elevated metal concentrations due to the uncontrolled release of inadequately treated sewage, along with other hazardous substances, adversely affecting downstream ecosystems and resulting in substantial economic, social, and ecological damage. Contaminants such as arsenic, cadmium, mercury, and lead can accumulate in sediments and later resuspend, posing threats to local biota and leading to irreversible health effects, including neurological damage, organ dysfunction, and an increased risk of cancer (Balali-Mood et al., 2021; Gabriel et al., 2021). This specific evaporation-infiltration lagoon is part of the “Lagoa da Conceição” Sewage Treatment Plant (STP), which has been operational since 1987 and was officially licensed in 2016 (LAO nº 8457/2016). Serving a population of up to 30,000 residents, the STP is situated in “Lagoa da Conceição”, Florianópolis (SC), a coastal lagoon that attracts international tourists, particularly during the summer months, for water sports and artisanal fishing.

On January 25, 2021, following an extreme rainfall event, the natural sand slope acting as a dam for the lagoon collapsed, releasing approximately 500,000 $m^3$ of effluent into “Lagoa da Conceição”. This incident caused damage to several homes and vehicles; however, no direct human casualties were reported (Roschild et al., 2021). The released effluent contained elevated levels of nutrients (nitrogen and phosphorus) and toxic substances, including heavy metals, which were not adequately removed by conventional sewage treatment methods (Aquino et al., 2013; Santos et al., 2022).

In addition to the extreme rainfall event and inadequate planning for such occurrences, subsequent technical studies identified other causes for the rupture, primarily related to a lack of oversight and monitoring (Burgardt et al., 2021). The absence of consistent monitoring resulted in structural weaknesses in the dam, ultimately leading to its failure. As noted by Bowker & Chambers (2015), there is no global regulatory framework with the authority or capacity to prevent an estimated $6 billion in future losses from similar dam failures. Eight months after the “Lagoa da Conceição” incident, a technical report (PES 11, 2021) found concentrations of heavy metals in fish samples that exceeded legal limits, indicating potential contamination of other organisms within the food web. The sampled fish, which are omnivorous and carnivorous, feed on phytoplankton, microalgae, zooplankton, zoobenthos, and smaller fish, suggesting that local populations consuming these fish could be exposed to the harmful effects of these pollutants. Furthermore, in addition to the direct impacts of the disaster, this aquatic ecosystem faces ongoing challenges such as rapid population growth, expanding urbanization, heavy boat traffic, waste deposits, and the continuous influx of untreated or inadequately treated domestic effluents (Cardoso, 2016; Souza, 2020; Roschild et al., 2021).

Given the long-term pollution likely caused by the rupture of the natural slope at the LEI-STP and the subsequent overflow of treated effluent, it is critical to assess the current contamination status of the ecosystem. Despite the significant potential for water and soil contamination from such incidents—often involving numerous substances harmful to human health—the impact of these events remains under-evaluated, with essential information frequently inaccessible to the public and policymakers, including the ANA (Brazilian National Water and Basic Sanitation Agency) website. This study aims to evaluate the environmental status of "Lagoa da Conceição" through water and sediment sampling conducted in January 2023, two years after the rupture and release of toxic sludge into the environment. The analysis incorporates pre-impact data obtained from previously published studies. The objectives include: (1) assessing the self-purification capacity of the environment concerning dissolved nutrients (nitrogen and phosphorus); (2) determining the total concentrations of heavy metals (aluminum, arsenic, cadmium, copper, chromium, iron, mercury, manganese, nickel, lead, zinc - Al, As, Cd, Cu, Cr, Fe, Hg, Mn, Ni, Pb, Zn hereafter) in the water and sediments across the four sectors of "Lagoa da Conceição"; (3) identifying potential sources of heavy metals in this aquatic environment; and (4) evaluating the environmental risks associated with these metals by comparing their concentrations with current water and sediment quality regulations.

## 2.2 MATERIALS AND METHODS

### 2.2.1 Study area

"Lagoa da Conceição", a picturesque destination in the city of Florianópolis (SC), located in southern Brazil, is a lagoon ecosystem situated within an urban environment. It is positioned at coordinates 27.60353° S and 48.45355° W, covering an area of 20.3 km² with a maximum depth of 8.89 m. The lagoon can be divided into four sectors—North, South, Central, and Channel—which exhibit distinct physical-chemical, sedimentary, biological, and hydrodynamic characteristics. The lagoon is connected to the ocean by a 2.8 km canal, characterized by high hydrodynamics due to flood and ebb tides, with a medium to fine sand grain size. Consequently, this lagoon experiences a microtidal regime, featuring two daily tidal peaks of low and variable amplitudes, with meteorological tides prevailing. Winds predominantly originate from the north and south, significantly impacting the northern and southern sectors (Godoy, 2009).

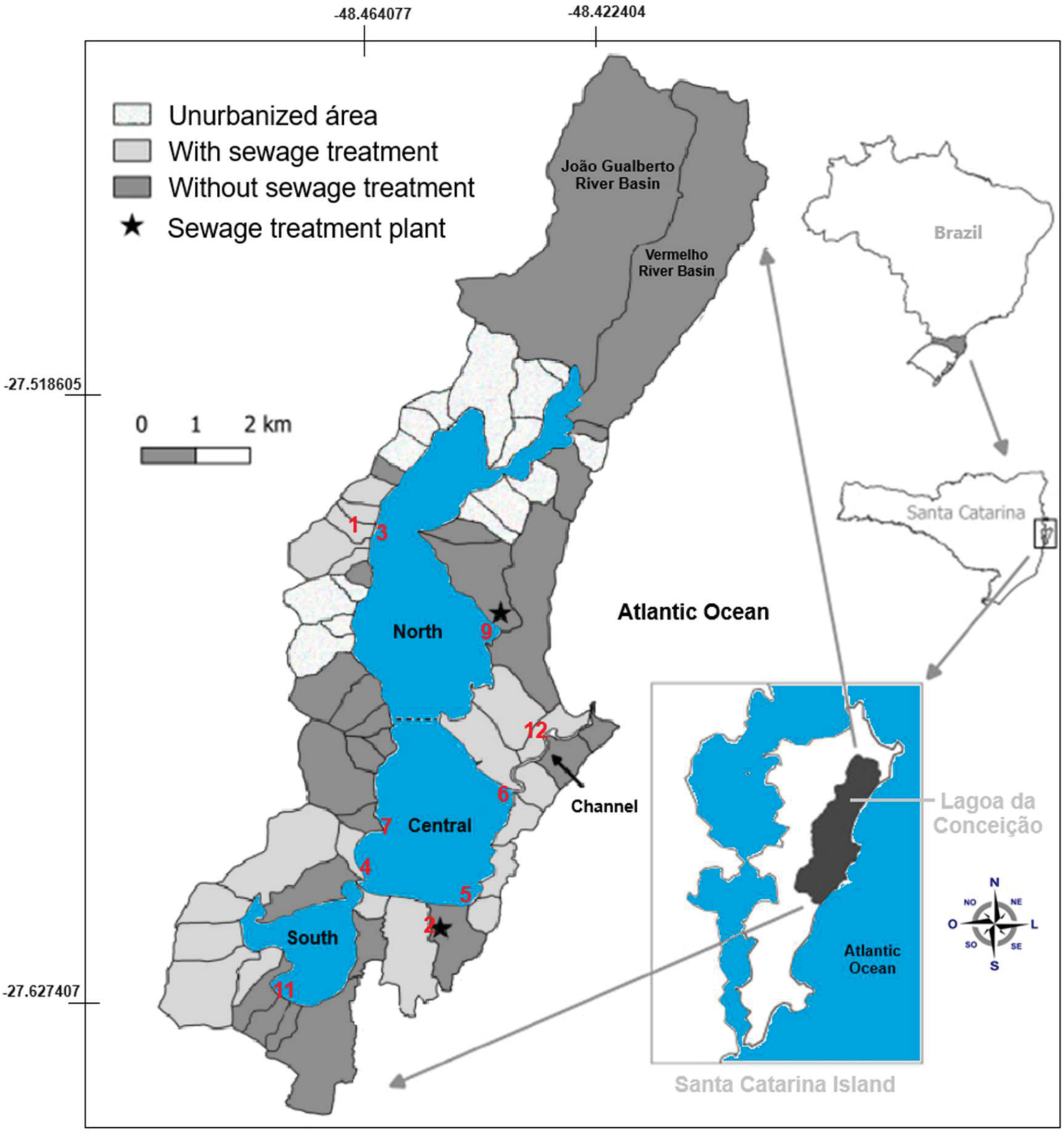


Figure 1. Map of "Lagoa da Conceição", illustrating the four sectors that divide the lagoon (North, Central, South, and Channel). The numbers indicate the sampling points, with names listed in Table 1. Sampling Point 2-LEI marks the location of the sewage treatment plant where

the dam rupture occurred. Local descriptions are provided in Table 1 of the Supplementary Material 1.

In the northern region, there is a significant fluvial contribution characterized by a grain size of fine sand, silt, and clay, where the main tributaries of “Lagoa da Conceição”—the “João Gualberto” River and the “Vermelho” River—discharge. These rivers receive a substantial organic load due to the inadequate sanitation network in the area, which is continually experiencing urban growth (Cury et al., 2017). The central sector is characterized by a grain size of fine sand and gravel and is subject to saline water intrusion from the channel. This intrusion, combined with the nutrient load from the largest tourist and commercial area of “Lagoa da Conceição” and the processes of organic matter decomposition, frequently generates anoxic zones beginning at a depth of 3 meters (Cabral et al., 2019). Within this region, located in the “Lagoa da Conceição” Municipal Natural Park (PNMDLC), is the STP whose effluent line ruptured, releasing effluent into the lagoon in January 2021. This sector connects to the southern sector via a 3-meter-wide canal. The southern sector exhibits low hydrodynamics, with a water residence time of up to 20 days, along with significant urbanization and drainage canals that may be contaminated by domestic effluents (Burgardt et al., 2021).

According to the geological map of Santa Catarina Island (Tomazzoli & Pellerin, 2014), the geological framework in the “Lagoa da Conceição” region is primarily composed of the “Ilha Granite”, which dates back to the Neoproterozoic era. This granite consists of syenogranites and monzogranites, characterized by phenocrysts of potassium feldspar. These minerals are Al silicates that include sodium, potassium, calcium, and occasionally barium. Furthermore, the region features Pleistocene Marine Coastal Deposits, which are composed of fine sandy sediments that exhibit a reddish-yellow hue due to the presence of Fe oxides and hydroxides, and were deposited under marine influence (Tomazzoli & Pellerin, 2014).

The “Lagoa da Conceição” STP has an average flow rate of 50 liters per second (L/s), with the capacity to reach up to 75 L/s during peak periods, such as the summer season. The STP utilizes several stages of effluent treatment: preliminary treatment (screening and sand removal), biological treatment (UASB reactor followed by activated sludge, oxidation ponds, and a secondary clarifier), and disinfection using chlorine gas (PMF, 2019). Approximately 76% of the properties surrounding the lagoon have irregular sewage connections, either lacking a connection or being only partially connected to the sewage network (PMF, 2022).

The natural slope created by the sand dunes in the “Lagoa da Conceição” Municipal Natural Park acted as a dam for one of the Evaporation-Infiltration Lagoons (LEI), which breached during an extreme rainfall event. According to EPAGRI/CIRAM (2021), January 2021, the month of the incident, recorded the highest monthly precipitation ever documented for the Florianópolis region, totaling 686 mm (see Figure 1 in Supplementary Material 1)

2.2.2 Water and Sediment Sampling

Water and sediment sampling was conducted at ten strategically selected locations in “Lagoa da Conceição” (see Figure 1 and Table 1; local descriptions in Table 1 of the Supplementary Material 1). These locations encompass the four sectors of the lagoon—northern, southern, central, and channel areas—that may be affected by the effluent plume resulting from the lagoon rupture, as well as other potential sources of nutrient and metal contamination in the aquatic system. These sources include stormwater channels influenced by urban runoff (Points 5-GRA, 7-ARA, 11-POR), gas stations and marinas where lubricating oils and fuels are present (Points 4-MAR, 6-PON), areas directly impacted by treated effluents from sewage treatment plants (Points 2-LEI, 9-CAM), and sites where boat maintenance occurs for fishing and transportation, potentially introducing antifouling paints that contain high levels of heavy metals such as Cu and Zn (Points 3-COS, 12-CAN). The sampling was conducted two years after the dam accident, on January 26 and 27, 2023, during a dry period (see Figure 2 in Supplementary Material 1) (INMET, 2024).

The geochemical background of the region was evaluated through the collection and chemical analysis of samples from a control site (Point 1-CON), which was selected to represent the natural concentrations of the study parameters within the geological and sedimentological matrix. This control site was chosen in an area free from anthropogenic contamination. For comparative purposes, pre-impact data were obtained from scientific articles, as well as data on nutrient concentrations in “Lagoa da Conceição” from studies conducted by the research group at the Didactic Laboratory of Chemical and Biological Oceanography (LADOC-UFSC) in January and February 2021, which remain unpublished.

Sediment samples play a crucial role in assessing long-term contamination due to their high adsorptive capacity, which is influenced by factors such as texture, grain size, chemical composition, pH, and the characteristics of the inorganic solid phase. Sediment was collected from 11 sampling locations, including the 10 previously described sites and an additional site at "Shoal" (coordinates: -27.608637, -48.451333), where contaminated sludge from the LEI had accumulated. This sludge was dredged and removed by the Municipal Government of Florianópolis 10 months after the incident. The samples were collected using shovels, stored in plastic bags, and frozen until heavy metal analysis could be conducted.

### 2.2.3 Nutrients, Physical and Chemical Parameters of Surface Water

Surface water samples were collected in duplicate from “Lagoa da Conceição” using a Van Dorn bottle. In the field, parameters such as temperature, pH, salinity, and dissolved oxygen (DO) were measured. Immediately after each collection, the samples were preserved and stored until they arrived at the laboratory. The following parameters were determined: total alkalinity was measured using a titrimetric method, while silicates, phosphates ($PO_4^{2-}$), ammonium ($NH_4^+$), and nitrate ($NO_3^-$) were analyzed using a UV-Vis spectrophotometer through the colorimetric method, following the protocols described by Grasshoff et al. (1983) at the Laboratory of Chemical and Biological Oceanography of the Federal University of Santa Catarina (UFSC). Blanks underwent the same analytical procedure, and the analyses were performed in triplicate.

### 2.2.4 Heavy Metals in Surface Water

The analytes (Al, As, Cd, Cu, Cr, Fe, Hg, Mn, Ni, Pb, and Zn) will be referred to as heavy metals in this article, as this term encompasses both metals and metalloids

(IUPAC, 2002). These elements were selected due to their toxicity and the availability of previously published data. The analyses were conducted at the Determinations Laboratory II of the Biological Sciences Institute at the Federal University of Rio Grande (ICB/FURG). Metals were extracted from water samples using acid digestion assisted by a microwave oven, following the methodology outlined in Environmental Protection Agency (EPA) 3015A (USEPA, 2007a). The quantification was performed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS PLASMAQUANT® MS, Analytik Jena, Jena, Germany) in accordance with the EPA 6020 method (USEPA, 2014).

### 2.2.5 Laboratory Procedures for Sediment Samples

The organic content was determined using the loss-on-ignition method, in which dry sediment samples were incinerated in a muffle furnace at 550°C for a minimum of four hours (Dean, 1974). Particle size distribution was assessed through sieving for sand to granule fractions (>0.063 mm), following the methodology proposed by Folk & Ward (1965). The Wentworth scale (1922) was employed for grain size classification.

### 2.2.6 Heavy Metals in Sediment

Heavy metals (Al, As, Cd, Cu, Cr, Fe, Hg, Mn, Ni, Pb, and Zn) in the sediment were analyzed at the Determinations Laboratory II of ICB/FURG. The available fraction of metals in the sediment was extracted using microwave-assisted acid digestion, in accordance with the EPA 3051A methodology (USEPA, 2007b). The elements were quantified using ICP-MS, following the EPA 6020 method (USEPA, 2014).

### 2.2.7 Quality Assurance and Quality Control - QA/QC procedures

The quality assurance and quality control for analyses were based on regular assessments of method blanks, spiked matrices, and, whenever available, reference materials and certified reference materials processed alongside the samples (Wade &

Cantillo, 1994). The limit of detection (LOD) was defined as three times the standard deviation (SD) of the blank signals (3 × SD; n = 10). The limit of quantification (LOQ) was established as ten times the SD of the blank signals (10 × SD; n = 10). The limits of quantification and detection for water and sediment samples are detailed in the Supplementary Material (1). Analyses of Sediment Reference Material for trace metals (MESS-4) and Freshwater Reference Material for trace metals (SLRS-6) from the National Research Council of Canada (NRC - CNRC) were conducted. The analytical results of the quality control samples demonstrated good agreement with the certified values, with recoveries ranging from 95.3% to 97.5% for metals studied in sediments and from 91.1% to 93.5% for water samples. Procedural analyses were performed in triplicate to ensure the representativeness of the data.

### 2.2.8 Water Quality Guidelines

The water sample data were compared with the reference values established by CONAMA Resolution No. 357 of 2005 (National Environment Council of Brazil), which outlines the classification of water bodies and the environmental guidelines for their categorization. Class 1 brackish water was considered for the sampling points in "Lagoa da Conceição", while freshwater was designated for Point 1-CON ("Costa da Lagoa" Waterfall). Additionally, CONAMA Resolution No. 430/2011, which addresses effluent discharge standards, was utilized to evaluate the samples from Point 2-LEI.

### 2.2.9 Sediment Quality Guidelines

The concentrations of heavy metals in sediment were compared with specific quality guidelines for coastal and marine sediments aimed at protecting aquatic life, as outlined by the National Oceanic and Atmospheric Administration (NOAA). These guidelines provide threshold values for both organic and inorganic substances. They are based on the Threshold Effect Level (TEL), which represents the upper limit below which no adverse effects on the biological community are observed, and the Probable Effect Level (PEL), which indicates the levels at which adverse effects on the biological community are likely to occur (Buchman, 2008). CONAMA Resolution No. 454/12 addresses dredged sediments and is the only regulation in Brazil that establishes maximum contaminant levels for sediments, as there is no specific legislation for controlling substances in river, reservoir, and lake beds. This resolution is based on NOAA parameters, with TEL and PEL indices corresponding to "Level 1" and "Level 2" of CONAMA, respectively.

### 2.2.10 Data Analysis

Overall Spatial Patterns

We conducted a Principal Coordinate Analysis (PCoA; Gower, 1966) using Euclidean distance matrices derived from standardized tables of heavy metal concentrations in water and sediment to explore overall spatial patterns. The sampling points were classified into four sectors—North, South, Central, and Channel—along with a control site for comparative analysis.

Correlation Diagram of Surface Water Parameters

Correlation values were calculated for the parameters analyzed in the field and in the surface water, including depth, electrical conductivity, temperature, dissolved oxygen, pH, alkalinity, nitrate, ammoniacal nitrogen, silicates, phosphate, and heavy metals. Microsoft Excel 2021 was utilized to compute the correlation matrix. The correlation diagrams were generated using the EzCorrGraph application (Campos & Licht, 2020), employing a significance level of 99% and a critical correlation index of 0.63.

Partitioning of Metals between Solid and Liquid Phases

To evaluate the mobility and retention capacity of metals in both the aqueous and particulate phases, the partition coefficient (Kd) was calculated using the method proposed by Feng et al. (2017):

$$Kd = Cs/Cd$$

where Cs represents the metal content in the solid phase (sediment) measured in mg/kg, while Cd denotes the concentration of the metal in the dissolved phase (water) expressed in µg/L.

## 2.3 RESULTS AND DISCUSSION

### 2.3.1 Nutrients, Physical and Chemical Parameters of Surface Water

The results of the in situ analyses of the water's physical and chemical parameters are presented in Table 2 of the Supplementary Material (1). The salinity data ranged from 0.08 ppm to 24.18 ppm, reflecting the lagoon's compartmentalization into the Southern, Central, and Northern sectors, as well as the “Barra da Lagoa” Channel. This study observed alkalinity values ranging from 0.1 to 3.81 mmol/L. Based on the narrow range of pH results, it can be inferred that there is little risk of imbalance in the neutralization reactions within the water column. The concentration of dissolved oxygen (DO) ranged from 4.3 mg.L$^{-1}$ (2-LEI) to 11 mg.L$^{-1}$ (1-CON). The low DO level at Point 3-COS (5.7 mg.L$^{-1}$) suggests high organic matter consumption in the region and restricted water circulation.

The nutrient analyses of the water column are presented in Table 1. These analyses may reveal an anthropogenic signature in the water. The highest concentrations of nitrogen and phosphorus were detected in the effluent from the Evapo-infiltration Lagoon (Point 2-LEI), as anticipated, since the STP does not effectively remove these elements from domestic effluent. The effluent discharged into “Lagoa da Conceição” on January 25, 2021, exhibited nutrient concentrations that far exceeded legal limits—up to 30 times the permissible phosphorus levels and 5,000 times the allowable ammonium levels as stipulated by CONAMA legislation. Excess nutrients are the primary drivers of the eutrophication process in aquatic environments, resulting in reduced oxygen concentrations (anoxia and hypoxia), harmful algal blooms, fish mortality, decreased biodiversity, and a decline in recreational water quality (Cury et al., 2017).

Table 1. Concentration of orthophosphate ($PO_4$), nitrate ($NO_3$), ammonium ($NH_4$), and silicates in water samples from “Lagoa da Conceição”. Points 8 and 10 were excluded due to inaccessibility, leaving 10 sampling locations from Point 1 to 12. Limits established by CONAMA Resolutions.

| SAMPLING POINT | LOCATION DESCRIPTION | SECTOR | $PO_4^{2-}$ MG.L$^{-1}$ | $NO_3$ MG.L$^{-1}$ | $NH_4$ MG.L$^{-1}$ | SILICATES MG.L$^{-1}$ |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| **1-CON** | "Costa da Lagoa" Waterfall | Control | 0.024 | 0.098 | 0.079 | 42.421 |
| **2-LEI** | LEI | Central | 0.657 | 3.246 | 18000.0 | 10.039 |
| **3-COS** | "Costa da Lagoa" | North | 0.035 | 0.062 | 0.074 | 4.883 |
| **4-MAR** | "Marina" | Central | 0.029 | 0.038 | 0.068 | 3.353 |
| **5-GRA** | "Gravatá Trail" | Central | 0.029 | 0.029 | 0.099 | 4.226 |
| **6-PON** | "Brigde of Channel" | Central/ Channel | 0.028 | 0.005 | 0.083 | 2.610 |
| **7-ARA** | "Canto dos Araçás " | Central | 0.025 | 0.031 | 0.071 | 4.016 |
| **9-CAM** | "Rio Vermelho" Campground | North | 0.028 | 0.046 | 0.131 | 5.056 |
| **11-POR** | "Porto da Lagoa" | South | 0.029 | 0.155 | 0.044 | 15.170 |
| **12-CAN** | Mangrove | Channel | 0.031 | 0.004 | 0.061 | 4.192 |
| **MAXIMUM** | | | 0.657 | 3.246 | 18000.0 | 42.421 |
| **MINIMUM** | | | 0.024 | 0.004 | 0.044 | 2.610 |
| **CONAMA 357/2005 BRACKISH WATER (CLASS 1)** | | | 0.124 (Ptotal) | 0.4 | 0.4 | - |
| **CONAMA 357/2005 FRESHWATER*** | | | 0.02 (Ptotal) | 10 | 3.7 | - |
| **CONAMA 430/2011 EFFLUENT**** | | | - | - | 20 | - |

*For Point 1-CON **For Point 2-LEI.

The Brazilian National Resolution CONAMA No. 357/2005 establishes guidelines for permissible concentrations of physical and chemical parameters in fresh and brackish waters designated for recreational and fishing activities. Two years after the dam rupture, the sampled locations exhibited nutrient concentrations within the allowable limits set by this resolution. Sampling Point 1-CON was established as the geochemical background of the lagoon, with virtually no anthropogenic activity in this area of the study. Due to the intense water-rock interaction at this site, which features a waterfall, the highest concentration of silicates (42,42 mg.L-1) in the study was observed.

Point 9-CAM, located near the "Rio Vermelho" Campground in the northern sector of the lagoon, exhibited the highest concentration of $NH_4$ in the study, with the exception of the effluent site (Point 2-LEI). The "Barra da Lagoa" STP (Figure 1) is situated in proximity to this area. According to the sanitation company (CASAN, 2021), the plant does not discharge treated effluent directly into the lagoon; instead, it applies the effluent to pre-established nearby soil. However, through leaching or groundwater percolation, some of this effluent may still reach “Lagoa da Conceição”. This location also experiences limited water circulation (Figure 3, Supplementary Material 1), influenced by tidal patterns. Furthermore, the substantial amount of vegetation and the decomposition of organic matter in this shallow area contribute to the elevated concentration of ammoniacal nitrogen at this site.

The results align with findings from other studies conducted in the region (Figure 2), which indicate that the water in “Lagoa da Conceição” was already in a state of alert, particularly regarding nitrate concentrations, even before the rupture of the treated effluent dam from STP-LEI in January 2021 (Cury et al., 2017; Koch-Dias, 2007). Approximately 10,000 residents of “Lagoa da Conceição” are connected to the sewage network (CASAN, 2022), while over 50% of the remaining population disposes of their domestic effluent untreated or uses septic tanks, often under inadequate conditions, which illegally discharge into the lagoon via emissaries. Consequently, nutrient inflows routinely occur in the lagoon due to this insufficient sewage coverage.

A review of historical data indicates that a self-purification process may be occurring in “Lagoa da Conceição”, as natural fluctuations in water parameters have been observed over time (Figure 2). This process could be associated with both dilution and the assimilation of elements by local biota, even over short periods (e.g., between January and February 2021). Water circulation driven by tidal currents may also contribute to the mobilization of substances within the water column; however, this is a slow process due to the presence of the Channel and areas with limited mixing (see Figure 1, Figure 3 Supplementary Material 1). Additionally, self-purification processes influenced by salinity may also play a significant role (Vidal et al., 2019).

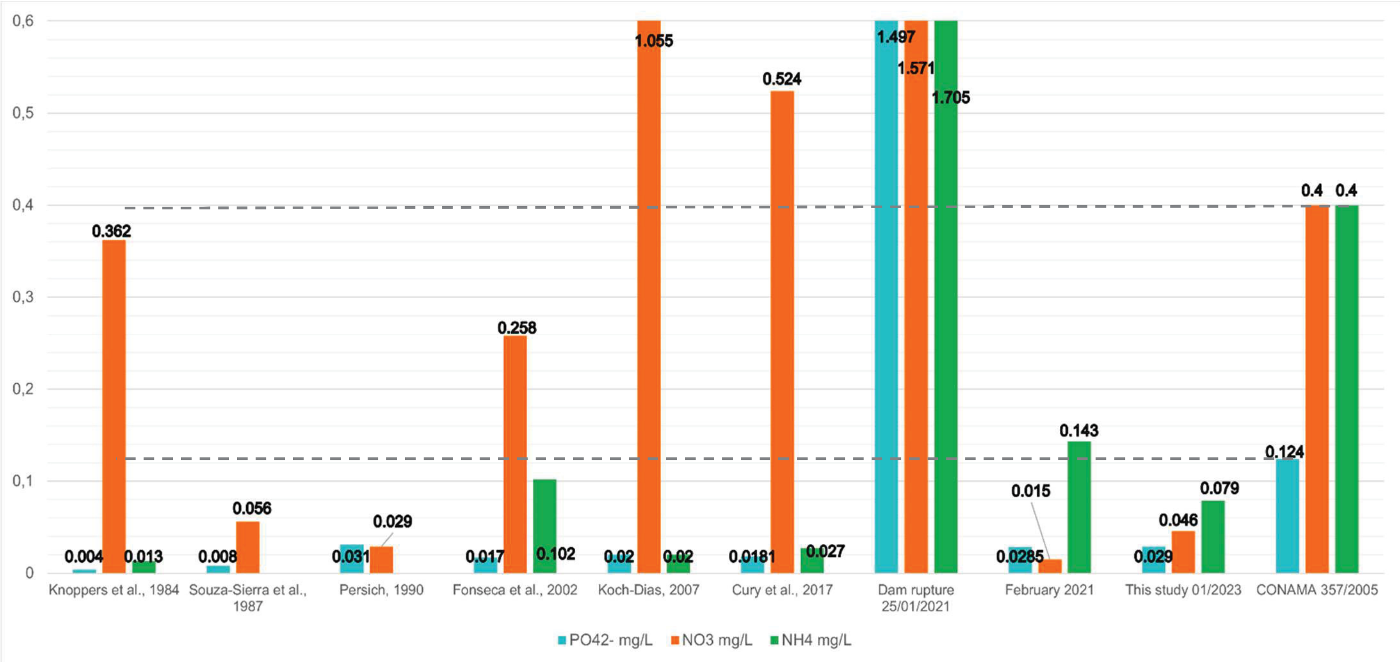


Figure 2. Comparative graph displaying the temporal values for the mean concentrations (in mg.L⁻¹) of orthophosphate ($PO_4^{2-}$), nitrate ($NO_3$), and ammoniacal nitrogen ($NH_4$) across various studies conducted in "Lagoa da Conceição". The values from Resolution CONAMA No. 357/2005 pertain to brackish waters, focusing on total phosphorus, nitrate, and ammoniacal nitrogen parameters. The data for January and February 2021 are sourced from LADOC-UFSC.

### 2.3.2 Heavy Metals in Surface Water and likely causes

The concentrations of heavy metals ranged from 236.91 µg.L$^{-1}$ to 0.3 µg.L$^{-1}$ (Table 2, Figures 4 to 6 Supplementary Material 1). The highest concentrations of Cu (1.39 µg.L$^{-1}$), Pb (0.56 µg.L$^{-1}$), and Hg (0.04 µg.L$^{-1}$) found in the treated effluent from Point 2-LEI, which may serve as a source of these elements in the lagoon. Among the samples collected from "Lagoa da Conceição", the concentrations of heavy metals were ranked in the following order of magnitude: Zn > Fe > Mn > Al > As > Cr > Ni > Cu > Cd > Pb > Hg. Zinc exhibited the highest concentration at Point 9-CAM (236.91 µg.L$^{-1}$, "Rio Vermelho" Campground), followed by Fe at Point 12-CAN (108.13 µg.L$^{-1}$, Mangrove-Channel), Mn at Point 11-POR (107.32 µg.L$^{-1}$, "Porto da Lagoa"), Al at Point 12-CAN (93.28 µg.L$^{-1}$), As at Point 7-ARA (9.74 µg.L$^{-1}$, "Canto dos Araçás"), Cr at Point 12-CAN (7.23 µg.L$^{-1}$), Ni at Point 5-GRA (1.77 µg.L$^{-1}$), Cu at Point 5-GRA (1.22

μg.L⁻¹), Cd at Point 5-GRA (0.3 μg.L⁻¹), Pb at Point 9-CAM (0.25 μg.L⁻¹), and Hg at Point 5-GRA (0.033 μg.L⁻¹, "Gravatá" Trail).

Among the 11 elements analyzed, the highest concentrations were observed at Point 5-GRA in the central sector (Ni, Cu, Cd, and Hg), while three of the highest values were recorded at Point 12-CAN in the Canal sector (Al, Cr, and Fe). Point 5-GRA is located at the beginning of "Rendeiras Avenue", an area that is highly urbanized and characterized by low water circulation, maritime transport, and the presence of an outfall that may discharge domestic effluent. Additionally, urban drainage contributes to significant automobile traffic in this area. Conversely, Point 12-CAN is situated in the middle of the "Barra" Channel, adjacent to a mangrove area, where there is considerable boat activity. According to the Environmental Basic Plan for "Porto da Barra" (Socioambiental, 1997), elements such as Pb, Cd, Zn, and Cu are commonly found in the waters near ports and marinas. This presence can be attributed either directly to anchored boats or indirectly to the corrosion of metal structures. As, Cu, and Zn are frequently found in paint pigments, used as additives in fuels, and may also be present in certain lubricating oils (Costa & Wallner-Kersanach, 2013).

Ribeiro (1998) evaluated the concentration of metals in the mangrove area of "Ratones", located north of "Lagoa da Conceição" (Florianópolis, SC). The study found that the surface water concentrations of Zn, Cd, Mn, and As that were of similar magnitude. In contrast, the present study revealed higher concentrations of Cr, Fe, and Ni, while the levels of Pb were lower. These comparative results are detailed in Table 2, which also presents the classification of the analyzed elements in the List of 275 Priority Pollutants, prioritized by the EPA based on their frequency, toxicity, and potential for human exposure (ATSDR, 2022).

Table 2. Total concentrations of heavy metals (in μg.L⁻¹) in surface water, including the maximum, minimum, average, and standard deviation. The limit values are established by CONAMA Resolution No. 357/2005; SD: standard deviation.

| Heavy Metals | Maximum | Minimum | Mean | SD | CONAMA nº 357/2005 | Ribeiro (1998) | Pollutant Classification* (ATSDR, 2022) |
|---|---|---|---|---|---|---|---|
| **Al** | 93.28 | 38.77 | 65.735 | 18.936 | 100 | - | 188 |
| **Cr** | 7.23 | 1.04 | 3.568 | 1.884 | 50 | 0.66 | 17 (Cr6+)<br>78 (Cr3+) |
| **Mn** | 107.32 | 3.31 | 20.018 | 31.996 | 100 | 11.53 | 143 |
| **Fe** | 108.13 | 33.62 | 76.987 | 26.972 | 300 | ND | - |
| **Ni** | 1.77 | 0.38 | 0.878 | 0.671 | 25 | ND | 57 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Cu** | 1.39 | 0.71 | 1.014 | 0.232 | 5 | - | 120 |
| **Zn** | 236.91 | <0.31 | 57.204 | 69.756 | 90 | 67.9 | 74 |
| **Pb** | 0.56 | <0.02 | 0.127 | 0.189 | 10 | 6.92 | 2 |
| **As** | 9.74 | 0.56 | 6.074 | 3.499 | 0.14 | 11.05 | 1 |
| **Cd** | 0.3 | 0.02 | 0.105 | 0.104 | 5 | 0.2 | 8 |
| **Hg** | 0.039 | <0.003 | 0.0296 | 0.0068 | 0.2 | - | 3 |

According to CONAMA Resolution No. 357/2005, the concentrations of Zn, Mn and As detected in the surface water at various locations in this study exceed permissible limits. These elevated levels pose potential risks to both aquatic organisms and human health. At Point 1-CON (Control), Zn was present in substantial amounts (98.7 μg.L$^{-1}$), further contributing to the geochemical characterization of the lagoon and partially explaining the higher concentrations observed at Point 9-CAM (236.91 μg.L$^{-1}$). The highest concentration of silicates was also recorded at Point 1-CON (see Table 1). As mentioned in Section 2.2, Sampling Point 1-CON represents the geochemical background of the region, characterized by intense rock weathering at a waterfall site with significant turbulence and water flow. This dissolution process, which releases silicates at high rates, is corroborated by the elevated Fe concentrations found in the water samples (96.7 μg.L$^{-1}$), as Fe oxides and hydroxides, common in the area, are deposited under marine influence (Tomazzoli & Pellerin, 2014). It is important to note that As was also detected at Point 1-CON (0.56 μg.L$^{-1}$, Figure 3), with a concentration exceeding the legislative limit. This suggests that As may occur naturally in the environment. Supporting this hypothesis, Ribeiro (1998) reported high concentrations of As in a river near “Lagoa da Conceição” (11.05 μg.L$^{-1}$).

Arsenic was detected at concentrations exceeding the limits established by CONAMA No. 357/2005 in all samples, with the highest concentration of 9.74 μg.L$^{-1}$ recorded at Point 7-ARA. This metal is widely distributed in the biosphere, with concentrations in unpolluted seawater ranging from 2 to 3 mg.L-1, and an average of 2 mg.kg-1 in the Earth's crust (Barra et al., 2000). In marine organisms, As can accumulate easily, with concentrations varying from 1 μg.g-1 to over 30 μg.g-1 (Ochsenkühn-Petropulu et al., 1997). Saline intrusion in “Lagoa da Conceição” may further contribute to the elevated As levels in the lagoon’s surface water. Podgorski & Berg (2020) suggest that As in groundwater—and consequently in surface water—

across various regions globally often originates from geogenic sources, potentially exposing approximately 200 million people to contaminated water. The countries most affected include the USA, Chile, Bolivia, Argentina, Bangladesh, Canada, Mexico, and Japan. Under specific geochemical conditions, particularly in aquifers with recent alluvial sediments, As can leach from rocks and accumulate in groundwater, which may explain the concentrations observed in “Lagoa da Conceição”.

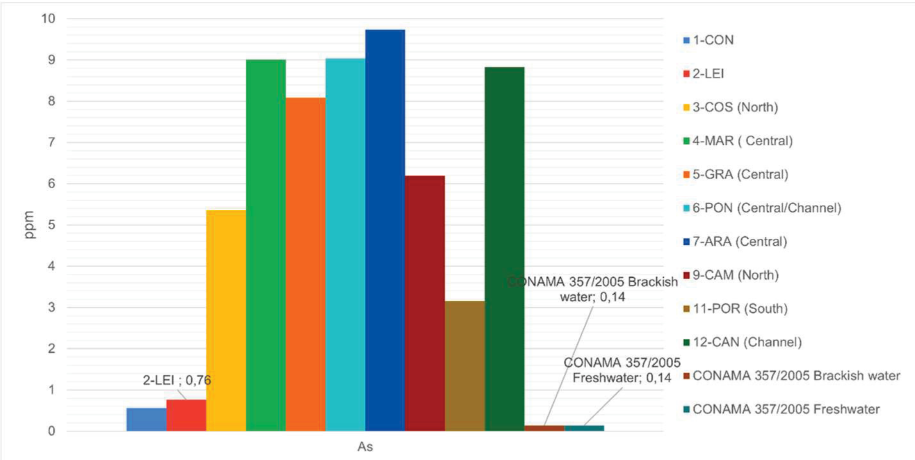


Figure 3. Concentration of As in surface water samples. SD < 10%; N=2.

Manganese was detected at the permissible limit in the southern sector at Point 11-POR (0.107 $mg.L^{-1}$, “Porto da Lagoa”), while Zn exceeded the established limit at Point 9-CAM (0.237 $mg.L^{-1}$, “Rio Vermelho” Campground), in the northern sector. Zinc is commonly used in antifouling paints for vessels, which correlates with the high boat traffic in the lagoon (Costa & Wallner-Kersanach, 2013). Point 9-CAM is located near a maritime terminal and a sewage treatment plant (STP), serving as an area of substance accumulation due to poor water circulation (Figure 1; Figure 3, Supplementary Material 1), resulting in elevated contaminant concentrations. In areas with limited water circulation, anoxic conditions can develop; under low dissolved oxygen levels, metals can react with sulfides, leading to their precipitation in sediments (Rose et al., 1979, apud Ferreira, 2001). Point 9-CAM also recorded the highest Pb concentration in this study (0.25 $\mu g.L^{-1}$). The metals Mg, Pb, Cu, and, to a lesser extent, Zn, appear to be associated with the effluent from LEI (Figures 4, 5, 6 Supplementary Material 1), while other elements may originate from different sources, such as boats, due to the corrosion of metal structures or paints containing heavy metals (Costa & Wallner-Kersanach, 2013).

Few studies in the region have quantified the presence of dissolved heavy metals in water, as these metals typically adhere to suspended particulate matter and settle in aquatic environments. This behavior is influenced by factors such as molecular weight and the elemental characteristics of the metals (Baird, 2002). Free metals can sometimes be insoluble; for instance, they may bind to organic matter, such as humic substances, forming complexes that are not bioavailable (Ferreira, 2001). Some more tolerant plant species can extract substances from the water column, further decreasing the availability of these metals in the dissolved phase (USEPA, 2000). Various biogeochemical processes in estuarine sediments and soils also affect metal-colloid interactions and their bioavailability. Consequently, elements may be released from sediments, leading to increased concentrations of heavy metals in surface water over time (Machado et al., 2016; Gabriel et al., 2021).

Taken together, the Principal Coordinate Analysis indicates that the concentrations of heavy metals in water primarily differ between the Channel sector, which exhibits high levels of As and Cr, and low Mn and Cd, and the South sector, which displays the opposite pattern. The other sectors show variable metal characteristics (Figure 4). These spatial differences necessitate further investigation in long-term studies, particularly given the high hydrological dynamics of coastal waters, as suggested by the low percentage of variance explained by the axes. Furthermore, the elevated concentrations of As in the Channel may be associated with boating activities in this region.

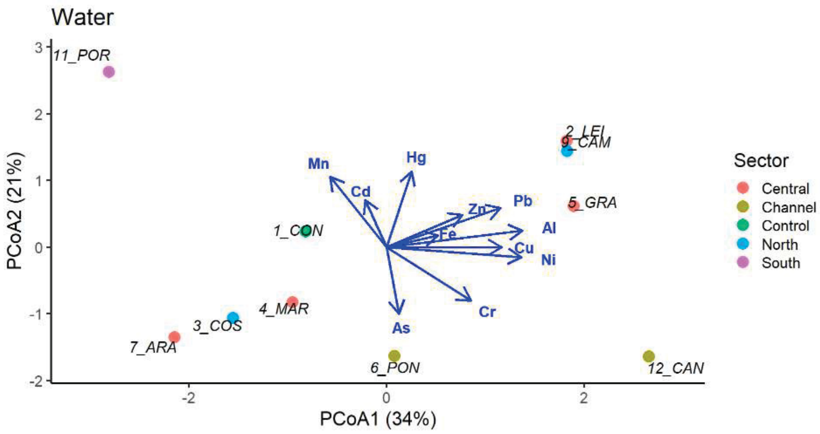


Figure 4. Principal Coordinate Analysis illustrating the spatial variations in heavy metal concentrations in water across sampling points categorized by sectors.

### 2.3.3 Correlation Diagram of Surface Water Parameters

Using a correlation matrix of the evaluated parameters in the water samples, a correlation diagram was constructed (Figure 5). The concentration of As in the water exhibited a strong relationship with both pH and salinity ($r = 0.95$), indicating an association with seawater. Additionally, water alkalinity positively correlated with the concentrations of As ($r=0.76$), Cr ($r=0.79$), and Ni ($r=0.72$), as well as with salinity ($r = 0.75$). This suggests that both alkalinity and salinity contribute to maintaining these metals in a soluble form in the water.

Nutrients ($PO_4^{2-}$, $NH_4^+$ and $NO_3^-$) exhibited strong correlations (> 0.8) with Pb concentration, indicating an anthropogenic source for this metal, specifically domestic sewage, such as effluent from LEI. The concentration of Pb also correlated with other metals, including Ni ($r = 0.72$), Cu ($r = 0.68$), and Al ($r = 0.63$), likely indicating a shared source. Boat traffic, particularly near marinas, may release heavy metals such as Cu and Pb, commonly found in antifouling paints and fuel derivatives. Additionally, activities such as fuel stations and boat maintenance are potential sources of Ni, Cu, and Pb. Moreover, domestic effluents, often rich in nutrients—whether treated or untreated—can introduce Al, Cu, Pb, and Ni into the environment, originating from cleaning products, paints, and other household compounds. The correlation matrix obtained (see Table 7 in Supplementary Material 1) revealed a negative correlation between pH and silicates (r = -0.84), which was anticipated since an acidic environment promotes the dissolution of rocks and shells, thereby increasing silicate concentrations in the water samples. Dissolved oxygen levels were negatively correlated with nutrient concentrations ($PO_4^{2-}$, $NH_4^+$, and $NO_3^-$) (r < -0.61), suggesting oxygen consumption due to the decomposition of organic matter from domestic effluents. Furthermore, a negative correlation was observed between silicates and As concentration (r = -0.74), underscoring an inversely proportional relationship between these elements in this situation.

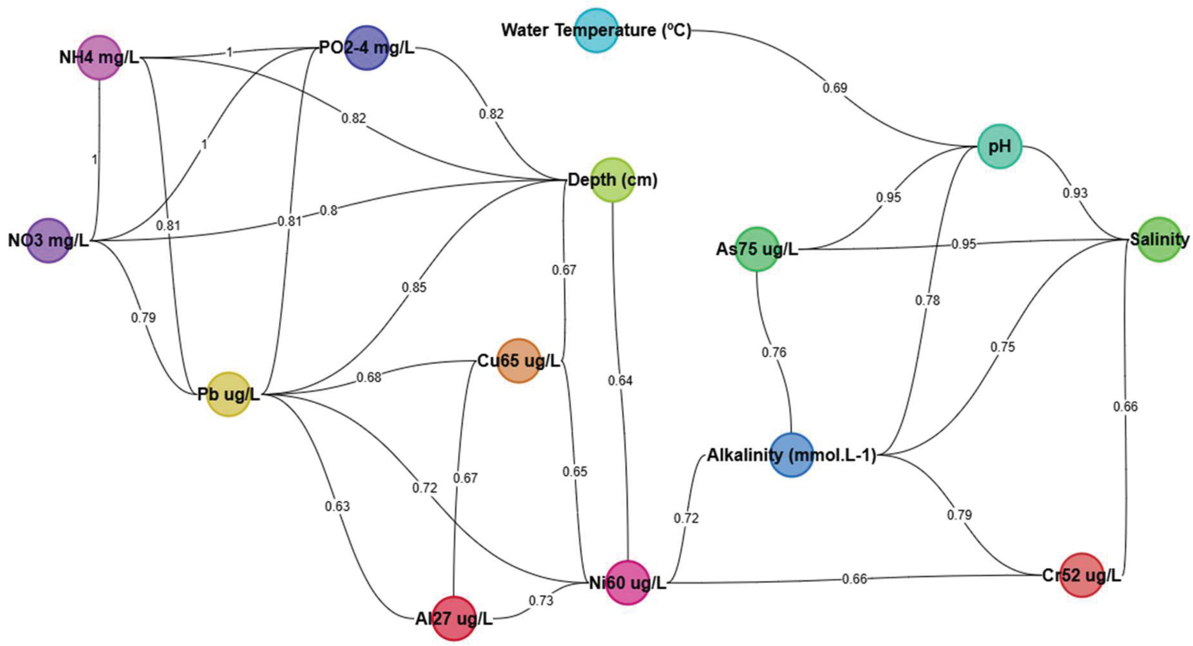


Figure 5. Correlation diagram of Physical and Chemical Parameters with Heavy Metal Concentrations in water.

### 2.3.4 Heavy Metals in Sediment

According to Jia et al. (2021), the distribution of heavy metals in sediments is significantly influenced by various factors, including the presence of (hydr)oxides of Fe and Mn, grain size, total organic carbon content, salinity, and dissolved oxygen levels. Fine clay particles tend to adsorb more elements, resulting in higher concentrations of heavy metals. In contrast, as grain size increases—particularly in the fine sand and silt fractions—trace element concentrations typically decrease (Garcia, 1999).

The sediment samples predominantly exhibited a fine sand grain size, with the exception of the sediment from Point 1-CON, which was classified as granules. In terms of organic matter (OM) content, the sediment from Point 2-LEI displayed a substantial 60.4% OM, attributed to sludge from the sewage treatment plant (STP). The other locations had OM content ranging from 0.33% (Point 1-CON) to 4.62% (Point 5-GRA), resulting in an average of 1.26% ± 1.23. The order of OM concentration was as follows: 5-GRA > 3-COS > 6-PON > 4-MAR > 7-ARA > 11-CAN > 9-CAM > 12-POR > Shoal > 1-CON.

The concentrations of heavy metals in the sediment varied largely, ranging from 0.072 $mg.kg^{-1}$ to 7133.879 $mg.kg^{-1}$ (Table 3, Figures 7 to 9 Supplementary Material 1). Among the 11 elements analyzed, 8 (Al, As, Cd, Cu, Mn, Ni, Pb, Zn) exhibited their highest concentrations at Point 3-COS ("Costa da Lagoa"). The remaining 3 elements analyzed (Cr, Fe, and Hg) reached peak values in the sediment at Point 9-CAM ("Rio Vermelho" Campground). Both locations are situated in the northern region of the lagoon, which is characterized by low water circulation (Figure 3, in Supplementary Material 1), and they consistently receive sediment from the "João Gualberto" and "Vermelho" rivers (see locations in Figure 1), leading to the accumulation of contaminants in the area. There is a prevailing consensus, supported by numerous field studies, that river sediments typically contain higher concentrations of metals compared to marine sediments (Salomons & Förstner, 1984). In this region of the lagoon, low water circulation results in the accumulation of suspended particles, including metals, due to limited mixing and transport. Consequently, metals in the water column are more likely to settle in the sediments, leading to higher concentrations.

Table 3. Maximum, minimum, averages, and standard deviations of total heavy metal concentrations in sediment samples ($mg.kg^{-1}$ dw); values ($mg.kg^{-1}$dw) established by CONAMA 454/12 (the freshwater index applied to Points 1-CON and 2-LEI); SD: standard deviation.

| | | *CONAMA 454/12* | |
|---|---|---|---|
| | | **Freshwater** | **Brackish water** |

| | Maximum | Minimum | Mean | SD | Level 1 (TEL) | Level 2 (PEL) | Level 1 (TEL) | Level 2 (PEL) |
|---|---|---|---|---|---|---|---|---|
| **Al** | 3724.39 | 272.71 | 864.79 | 985.86 | - | - | - | - |
| **As** | 7.10 | 0.71 | 3.36 | 2.21 | 5.9 | 17 | 19 | 70 |
| **Cd** | 0.68 | 0.07 | 0.25 | 0.18 | 0.6 | 3.5 | 1.2 | 7.2 |
| **Cr** | 48.01 | 4.84 | 21.88 | 13.97 | 37.3 | 90 | 81 | 370 |
| **Cu** | 45.00 | 4.41 | 14.34 | 11.72 | 35.7 | 197 | 34 | 270 |
| **Fe** | 7133.88 | 745.35 | 3321.85 | 1989.76 | - | - | - | - |
| **Hg** | 0.06 | 0.02 | 0.03 | 0.01 | 0.17 | 0.486 | 0.3 | 1 |
| **Mn** | 1053.87 | 85.49 | 318.64 | 294.11 | - | - | - | - |
| **Ni** | 10.43 | 1.24 | 3.92 | 2.79 | 18 | 35.9 | 20.9 | 51.6 |
| **Pb** | 5.16 | 0.35 | 1.74 | 1.35 | 35 | 91.3 | 46.7 | 218 |
| **Zn** | 510.96 | 52.42 | 173.72 | 135.45 | 123 | 315 | 150 | 410 |

According to CONAMA 454/12, alarming concentrations of heavy metals have been detected in the sediment of "Lagoa da Conceição", with Cu measured at 45.00 mg.kg-1 and Zn at 510.96 mg.kg-1 at Point 3-COS, exceeding all limits, respectively (Figure 6). This site is characterized by constant tourist activity and is accessible only by boat, featuring a well-established gastronomic route and a large fishing community. Zinc levels also exceed the level 1 limit at Points 4-MAR, 5-GRA, 9-CAM, and 12-CAN. These locations experience intense boat traffic, particularly at the marina (4-MAR) and along the "Barra da Lagoa" Channel (12-CAN). Although these metals are essential for many organisms, the observed concentrations indicate levels at which deleterious effects on aquatic life may occur, and effects are better described below.

The sediment at Point 1-CON exhibited a significant concentration of Zn, indicating a potential geogenic contribution of this element. However, it is improbable that the elevated levels observed at the most impacted sites can be solely attributed to the region's geochemical background, especially given the considerable boat traffic and the proximity of boat maintenance areas. These factors are acknowledged as major sources of Cu and Zn release (Costa & Wallner-Kersanach, 2013).

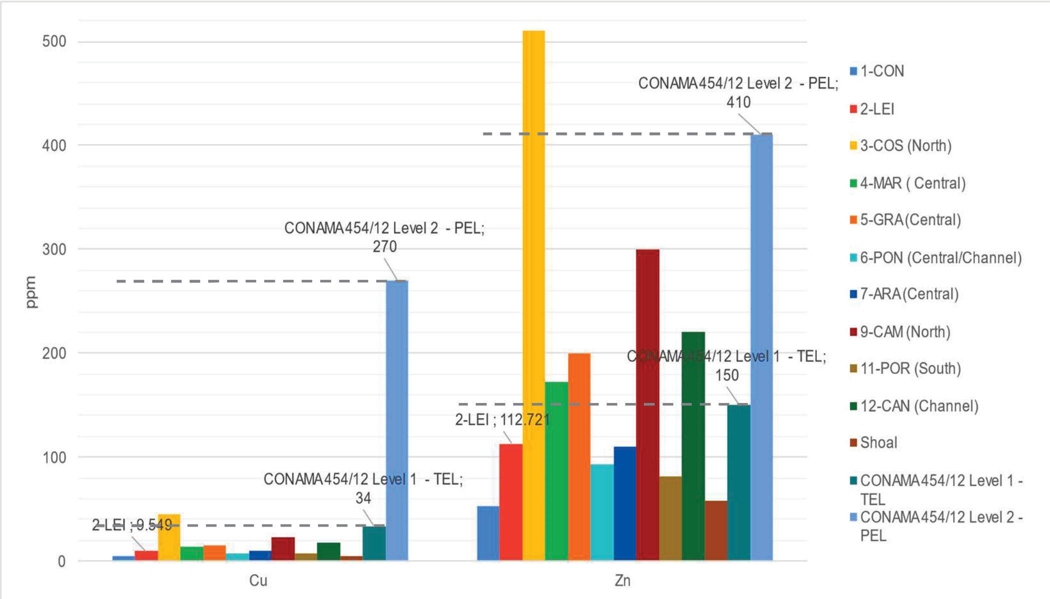


Figure 6. Total concentrations of Cu and Zn in sediment samples (values in $mg.kg^{-1}$ dry weight). SD < 10%; N=2.

The concentrations of heavy metals observed in this study differ significantly from those reported in previous research conducted in the region (Ribeiro, 1998; Garcia, 1999; Koch-Dias, 2007; Mioto, 2013), as detailed in Table 4. Notably, the Cd content in the sediment has dramatically decreased from 411.2 mg/kg to 0.25 mg.kg-1 over the past decade, when comparing current results to those reported by Mioto in 2013. The concentration of Cu (14.34 mg.kg-1) was up to 30 times lower, Ni (3.92 mg.kg-1) was up to 45 times lower, and Pb (1.74 mg.kg-1) was up to 27 times lower in this study compared to findings from other researchers (Ribeiro, 1998; Garcia, 1999; Koch-Dias, 2007; Mioto, 2013). Additionally, significant concentrations of Cr, which were previously undetectable (Ribeiro, 1998), were confirmed in this study (Table 4). The increase in population, the introduction of sewage, and the use of fuels and oils by vessels navigating the lagoon may account for the high concentrations of heavy metals found in the sediment, as highlighted by Koch-Dias (2007). Interestingly, the sludge from Point 2-LEI, along with the “Shoal”, did not exhibit elevated levels of heavy metals in the sediment. These levels remained within the limits established by legislation, effectively ruling out the LEI effluent as the primary source of these elements in “Lagoa da Conceição”.

Studies conducted both in Brazil and globally have found heavy metal concentrations in sediments consistent with those in “Lagoa da Conceição” (Table 4).

The levels of Cr, As, Cu, Mn, Ni, and Pb in the lagoon are below the guidelines proposed by Salomons & Forstner (1984), pioneers in establishing reference values for heavy metals in sediments (Table 3 Supplementary Material 1). However, Cd concentrations were higher than those reported by Rivail (1995) in Florianópolis (SC), Chowdhury et al. (2015) in India, Wang et al. (2016) in some regions of China, and Gabriel et al. (2021) in the “Rio Doce” estuary, four years after the mining tailings dam disaster in “Minas Gerais” State, Southeast Brazil.

A high concentration of Zn was observed in the lagoon, consistent with previous studies conducted in the region (Table 4), although these levels are elevated compared to global findings. The concentrations exceed those reported by Zhang et al. (2013) and Jia et al. (2021) in highly urbanized areas of China, Chowdhury et al. (2015) in an Indian estuary, Bowen (1979) in Canada, and Mendes (2018) and Gabriel et al. (2021) in Brazil. The elevated concentrations of Mn and Fe align with findings from other studies, such as those by Chowdhury et al. (2015) in India and Queiroz et al. (1994) in Florianópolis. This phenomenon can be attributed to the natural abundance of these elements, which are essential for metabolic processes in both plants and animals (Morgan & Connoly, 2013). Additionally, Mn oxides contribute to the increased concentrations of heavy metals in the environment through adsorption and co-precipitation, as particles in solution become coated with Fe and Mn oxy-hydroxides, effectively removing heavy metals from the liquid phase (Salomons & Förstner, 1984; Garcia, 1999).

Table 4. Total concentrations of heavy metals in sediment (in $mg.kg^{-1}$ dw) in “Lagoa da Conceição” and other locations worldwide.

| | Al | As | Cd | Cr | Cu | Fe | Hg | Mn | Ni | Pb | Zn | Local |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **This study** | 864.78 | 3.36 | 0.25 | 21.88 | 14.34 | 3321.85 | 7.76 | 318.64 | 3.92 | 1.74 | 173.72 | “Lagoa da Conceição”, Florianópolis, Brazil |
| **Ribeiro, 1998** | - | 2.305 | 0.12 | ND | - | 732.59 | - | 725 | - | 46.68 | 63.59 | “Lagoa da Conceição”, Florianópolis, Brazil |
| **Garcia, 1999** | - | 0.69 | 0.38 | - | 32.85 | - | ND | - | 71.35 | 21.69 | 196.59 | “Lagoa da Conceição”, Florianópolis, Brazil |
| **Koch-Dias, 2007** | - | - | 0.21 | - | 28.26 | - | - | 392.02 | 171.68 | 26.59 | 74.85 | “Lagoa da Conceição”, Florianópolis, Brazil |
| **Mioto, 2013** | - | - | 1.81 | - | 411.2 | - | 0.2 | - | - | 12.8 | 337.2 | “Lagoa da Conceição”, Florianópolis, Brazil |
| **Bowen, 1966** | - | 1.8 | 0.2 | - | 55 | - | 0.08 | - | 75 | 12.5 | 70 | Sudbury, Canada |
| | - | 6 | 0.06 | - | 20 | - | 0.03 | - | 40 | 10 | 50 | Sudbury, Canada |
| **Bowen, 1979** | 7.2 | 7.7 | 0.17 | 72 | 33 | 4.1 | 0.19 | 770 | 52 | 19 | 95 | Sudbury, Canada |
| **Queiroz et al., 1994** | - | 6 | 1.95 | 61 | - | - | - | 863 | 11 | 26 | 98 | “Itacorubi”, Florianópolis, Brazil |
| **Rivail, 1995** | - | 20.76 | 0.09 | - | 25.25 | - | 0.03 | - | 30.03 | 0.58 | 101.05 | Florianópolis, Brazil |
| **Robbe, 1989** | - | - | 0.52 | - | 86 | - | 6.17 | - | - | 58 | 235 | Seine River, France |
| **Chowdhury et al., 2015** | - | 3.82 | 0.21 | 28.3 | 28.39 | 2942 | 0.07 | 647.25 | 34.5 | 15.8 | 34.42 | Sundarban, Índia |
| **Yang et al, 2014** | - | 0.1-243 | 0.001-1.97 | 0.03-23 | 0.10-44.0 | - | - | - | 0.06-25.9 | 0.01-3.34 | - | Changjiang River, China |
| **Wang et al., 2016** | - | 1.4-2.5 | 0.003-0.32 | - | 0.9-6.0 | - | - | - | - | 0.04-8.2 | - | Huanghe River estuary, China |
| **Zhang et al, 2013** | - | 0.2-8.2 | 0.001-0.3 | - | 0.3-3.3 | - | - | - | - | 0.19-4.58 | 3.7-36.0 | Pearl River Estuary, China |
| **Mendes, 2018** | 555156.75 | - | - | 112.06 | 1668.61 | - | - | - | - | - | 130.7 | “Alegria” River, Medianeira, Brazil |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Jia et al., 2021** | - | 0.63-2.6 | 0.03-1.63 | 0.17-2.27 | 1.09-7.40 | - | - | - | 0.62-8.97 | 0.16-20.14 | 6.24-140 | Modaomen, South China |
| **Gabriel et al., 2021** | - | 4 | 0.1 | 14 | 4.9 | - | - | 142.9 | 5.9 | 135.4 | 12.5 | “Doce” River Estuary, Minas Gerais State, Brazil |

Compared to concentrations in water, heavy metals in sediment exhibited much greater predictability in the Principal Coordinate Analysis, as nearly 97% of the variation could be summarized in the first two axes (Figure 7). Additionally, the analysis clearly demonstrates lower concentrations in the control point and higher concentrations at the northern sampling points, with the Channel, Central, and South sectors displaying intermediate values. These results underscore the long-term contamination of the sampling sites and support the discussions presented above.

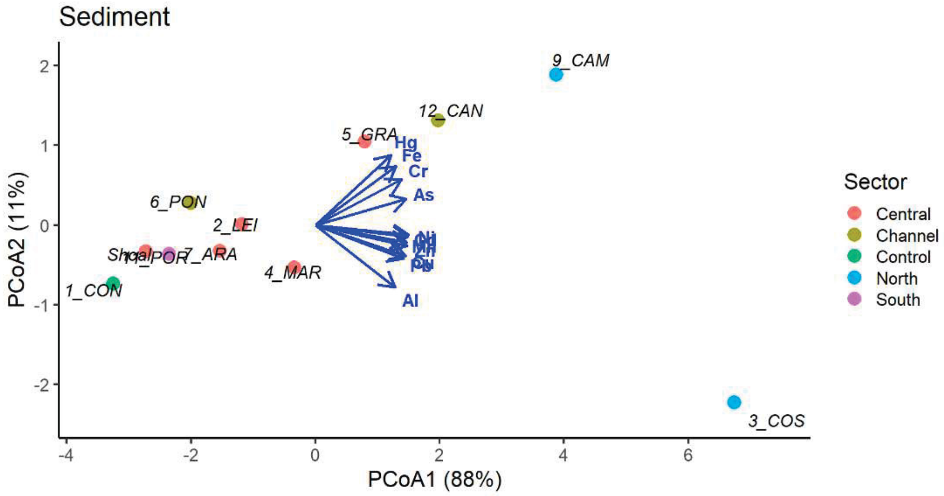


Figure 7. Principal Coordinate Analysis illustrating the spatial variations in heavy metal concentrations in sediment across sampling points categorized by sectors.

2.3.5 Partitioning of Metals Between Solid and Liquid Phases

The partition coefficient (Kd) was calculated to assess the distribution of metals between surface water and sediment (see Table 6 in the Supplementary Material 1). Higher Kd values indicate that metals are more readily retained in the solid phase through adsorption reactions, while lower Kd values suggest that metals are more likely to migrate from the solid phase and remain in solution (Jia et al., 2021). Due to the non-detection of certain metals (Hg, Ni, Pb, and Zn) in water samples, Kd could not be evaluated for these metals at some locations.

Among the major elements (Mn, Fe, and Al), Mn exhibited the highest Kd value (225.19 at Point 3-COS), indicating that it readily transitions from the aqueous phase to the solid phase, primarily through the formation of Fe/Mn (hydr)oxides, which precipitate and accumulate in the sediment. Among the trace elements, Cu recorded the highest Kd value (57.70 at Point 3-COS). The lowest Kd value was observed for As (0.23 at Points 6-PON and 7-ARA).

Point 3-COS, which exhibited the highest concentrations of metals in the sediment, also demonstrated the highest Kd values for the analyzed metals. As indicated in Table 2 (Supplementary Material 1), this location has elevated salinity and smaller grain size, both of which likely contributed to the deposition of metals and metalloids in the sediment. As noted by Jia et al. (2021), the partitioning of metals between solid and liquid phases is influenced by various factors, including water characteristics (such as salinity) and sediment properties (such as grain size, Fe/Mn oxides, and dissolved oxygen), as well as the intrinsic properties of the metals themselves. The behavior of As is consistent with the findings of Jia et al. (2021), which indicate that its Kd decreases as salinity increases, demonstrating a negative correlation between these variables ($r = -0.68$). While several studies have suggested that the Kd of Pb decreases with increasing salinity (Zhao et al., 2013; Feng et al., 2017; Jia et al., 2021), this study observed a positive correlation between salinity and the Kd of Pb ($r = 0.84$). Additionally, other environmental factors, such as dissolved oxygen concentration ($r = 0.67$) and pH ($r = 0.89$), also appear to influence this process.

2.3.6 Threats of heavy metals to the environment and the anthropogenic activities

Heavy metal contamination in coastal lagoons poses significant threats to local biodiversity, adversely affecting various organisms through direct toxic effects. For instance, elevated concentrations of metals such as Mg, Pb, and Cd can lead to bioaccumulation in aquatic organisms, resulting in physiological and reproductive impairments. A study conducted in the Aveiro Lagoon in Portugal observed that increased Mg contamination resulted in a decline in both the total abundance and species richness of the macrobenthic community, with more tolerant taxa becoming increasingly prevalent (Nunes et al., 2008). Similarly, in the Gulf of Palermo, Sicily, heavy metal pollution has been linked to alterations in the spatial distribution of benthic foraminifera, a group of microorganisms essential for sediment stability and nutrient cycling (Valenti et al., 2008). The study found an anticorrelated spatial relationship between certain groups of foraminifera and metal concentrations, indicating that metal pollution can disrupt the composition and function of benthic communities. These examples highlight the critical need for monitoring and mitigating heavy metal pollution in coastal lagoons to preserve biodiversity and maintain the ecological balance of these vital ecosystems.

The presence of As in surface water is concerning, as it is recognized as a significant human health risk, ranking first on the List of Priority Pollutants (see Table 2). Exposure to As levels above legal limits can lead to a variety of health issues, including conjunctivitis, cardiovascular diseases, central nervous system disorders, peripheral vascular disorders, cancer, and limb gangrene (Barra et al., 2000). In plants, substantial evidence indicates that As exposure reduces germination rates (Shri et al., 2009). In juveniles of the Streaked prochilod fish Prochilodus lineatus (Valenciennes, 1837), As exposure resulted in disruptions in blood mineral balance, increased antioxidant enzyme activity in the liver, and neurological damage. In Zebra fish Danio rerio (Hamilton, 1822) liver cells, As also caused significant DNA damage. These adverse effects were observed even at low concentrations and short exposure durations, underscoring the high toxicity of As to aquatic organisms (Modesto, 2021).

Excess Cu can damage the brain and kidneys, cause liver cirrhosis, lead to chronic anemia, and irritate the stomach and intestines in humans (Salem et al., 2000; Wuana & Okieimen, 2011). Copper toxicity in aquatic organisms primarily affects the gills and osmoregulation, interfering with oxygen transport and energy metabolism in fish, which can result in tissue hypoxia and death. In algae, Cu disrupts cellular membranes by increasing permeability, thereby impairing ion regulation. Marine gastropods and bivalve mollusks accumulate Cu, which disrupts their biochemical functions and osmoregulation, negatively impacting their overall health and survival (Eisler, 1998).

High levels of Zn can induce oxidative stress, hinder growth, and compromise immune function, along with other adverse effects. Zinc can accumulate in fish gills, impairing oxygen uptake and causing hypoxia, which may lead to organism mortality (Zaynab et al., 2022). A recent study by Valdiglesias et al. (2023) demonstrated that Zn-containing nanoparticles can adversely affect human glial cells and disrupt the locomotion of zebrafish embryos, indicating potential neurotoxicity.

Relatedly, Zn and Cu, when accumulated through the consumption of contaminated seafood, can negatively impact human health over time (Gu et al., 2017). A technical note published by researchers from the Federal University of Santa Catarina (PES 11, 2021), an estimate of the general health risk (THQ), indicating that

Zn levels exceeded twice the threshold established by USEPA (2010). Elevated metal levels disrupt the ecological balance of the lagoon and highlight the importance of monitoring and controlling pollution to protect both aquatic life and human health. Therefore, public authorities should prioritize the removal of these contaminants from the sediment, employing nature-based solutions such as bioremediation to stabilize the pollutants (Song et al., 2019).

Additionally, areas of restricted metal dispersion (e.g. the northern region of “Lagoa da Conceição” lagoon) allows heavy metals such as Pb, Cu, and Ni to be absorbed by benthic organisms, resulting in bioaccumulation. This process disrupts the food web by exposing higher trophic level organisms to toxic concentrations of these metals. Furthermore, benthic fauna may experience significant adverse effects on growth, reproduction, and survival due to the toxic impacts of metals like Pb and Cu. These disruptions not only threaten the health of organisms but also destabilize the lagoon’s ecological balance by affecting processes such as organic matter decomposition, nutrient cycling, and water clarity, ultimately impacting aquatic plant photosynthesis and overall ecosystem functioning.

Finally, anthropogenic activities, such as boat traffic and effluent discharge, significantly affect the health of coastal lagoons. Boat traffic, for instance, contributes to heavy metal contamination (e.g., Cu and Zn) from antifouling paints and fuel leaks, particularly in areas like Channel, which hosts a dense fleet of vessels and a fuel station, as well as near boat terminals such as points 9-CAM and 3-COS. In the central region, particularly at sampling points 4-MAR and 5-GRA, channels discharge untreated or inadequately treated effluents, introducing excess nutrients and toxic substances that disrupt the ecological balance and degrade water quality (Cardoso et al., 2016; Souza et al., 2020). Our findings underscore the complexity of contamination dynamics, highlighting the impacts of an evaporation-infiltration lagoon rupture that releases domestic effluent, while also revealing the ecosystem's resilience to these disturbances.

## 2.4 CONCLUSION

In this study, we summarized key aspects of pollution in a major coastal lagoon located in a large city in southern Brazil. We identify the primary threats and propose management actions. Our findings suggest that the lagoon is undergoing a self-purification process following accidental contamination, with nutrient concentrations naturally decreasing over time and remaining within Brazilian legal limits. This indicates the ecosystem's resilience, making the threats of eutrophication more likely to be acute. However, As was detected at elevated levels across all sites, exceeding guideline values and posing a long-term risk. While potential sources include boat paints, pigments, and animal farming, geochemical background levels also adds a possible natural contribution. Arsenic speciation is highly recommended to assess the severity of elevated arsenic levels, as different chemical species of arsenic exhibit varying degrees of toxicity. While inorganic arsenic is highly toxic and potentially carcinogenic, organic forms tend to be significantly less harmful. Therefore, speciation enables a more accurate evaluation of the risks to human health and the environment.

Regarding other metals, elevated Zn levels in water samples are likely attributed to boat traffic, illegal sewage discharges, fluvial inputs, and poor water circulation. Critical levels of Zn and Cu in sediment, primarily due to significant fluvial input and low circulation, also pose a threat to biota, particularly as concentrations exceed effect levels. Immediate remediation of the northern region, where circulation is low, is essential to mitigate the harmful effects of these pollutants on local health.

Mitigation strategies should incorporate bioremediation utilizing native plant species, with a focus on those exhibiting high growth rates, biomass productivity, and metal-removal capabilities. Controlled dredging may be necessary to eliminate contaminated sediment, while pollution-reduction education programs can enhance community awareness and encourage sustainable practices. Continuous monitoring is essential to ensure the safety of seafood, including fish, shrimp, and clams. Stricter oversight of sewage systems is required, particularly in areas lacking public infrastructure. Expanding sewage collection and implementing advanced treatment methods, such as activated carbon filtration or ultraviolet treatment, may effectively remove heavy metals, thereby improving water quality and public health. Further research across various climatic periods would complement our findings. Standardized monitoring efforts are vital for comparative analysis, especially before and after contamination events. According to the Brazilian National Water and Basic Sanitation Agency (ANA, 2024), only 55% of Brazilians have access to sewage treatment. The Legal Framework for Sanitation (Law 14.026/2020) aims to achieve universal sanitation services, targeting 90% sewage coverage by 2035. This initiative would enhance Brazil's position in global sanitation indices and aligns with Goal 6 of the UN 2030 Agenda for Sustainable Development, which seeks to ensure water and sanitation for all. Overall, our results reinforce the threat of pollution to biodiversity, ecosystem services, and the livelihoods of fishing communities, as well as the local economy, which relies on tourism and water sports. The challenges are significant, and our study is critical for informing management actions.

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## 2.7 SUPPLEMENTARY MATERIAL 1

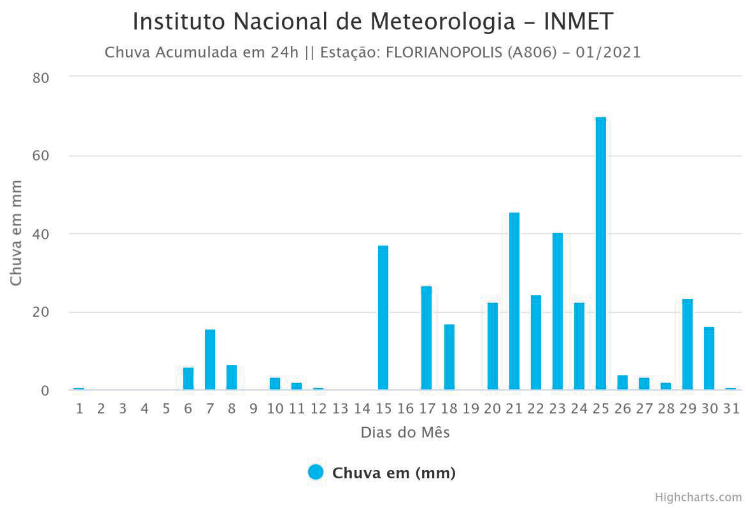


Figure 1. Precipitation chart for January 2021, during which the treated effluent dam of ETE-Lagoa da Conceição broke (Source: INMET, 2024).

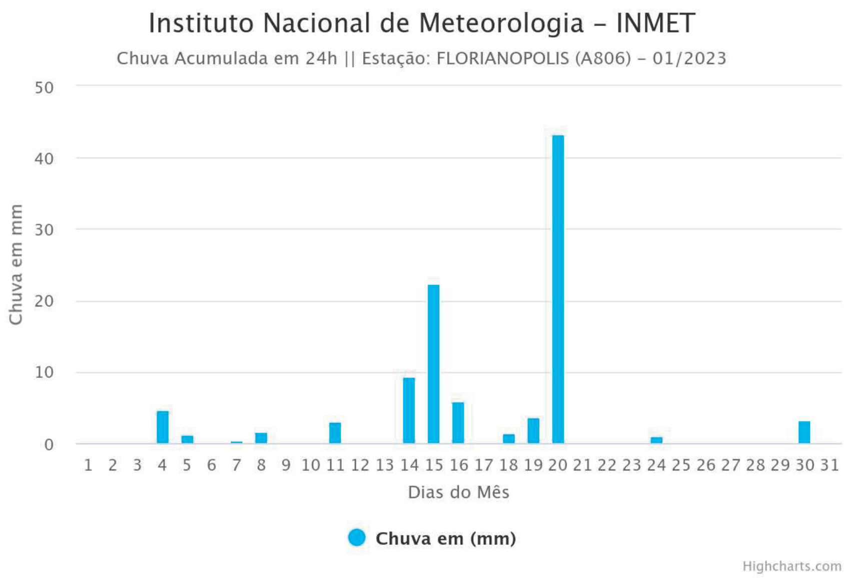


Figure 2. Compared to Figure 1, precipitation chart for January 2023, in which sampling for monitoring was conducted (INMET, 2024).

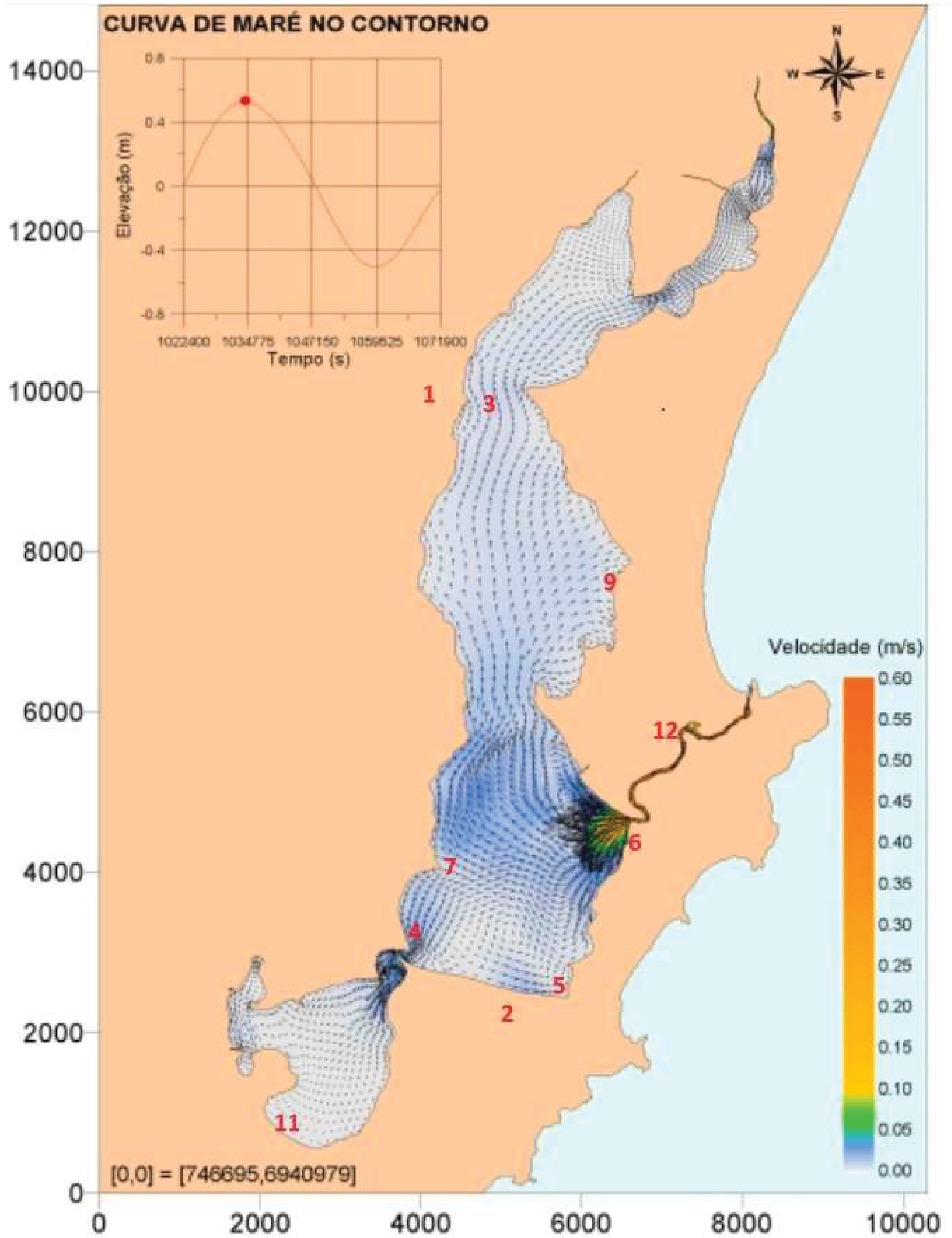


Figure 3. Circulation pattern related to the high tide situation at the channel entrance, considering only the tidal regime (without wind). The vectors correspond to velocities, and the magnitudes are indicated by the color pattern. The sampling points are highlighted in red (Adapted from Andrade and Rosman, 2001).

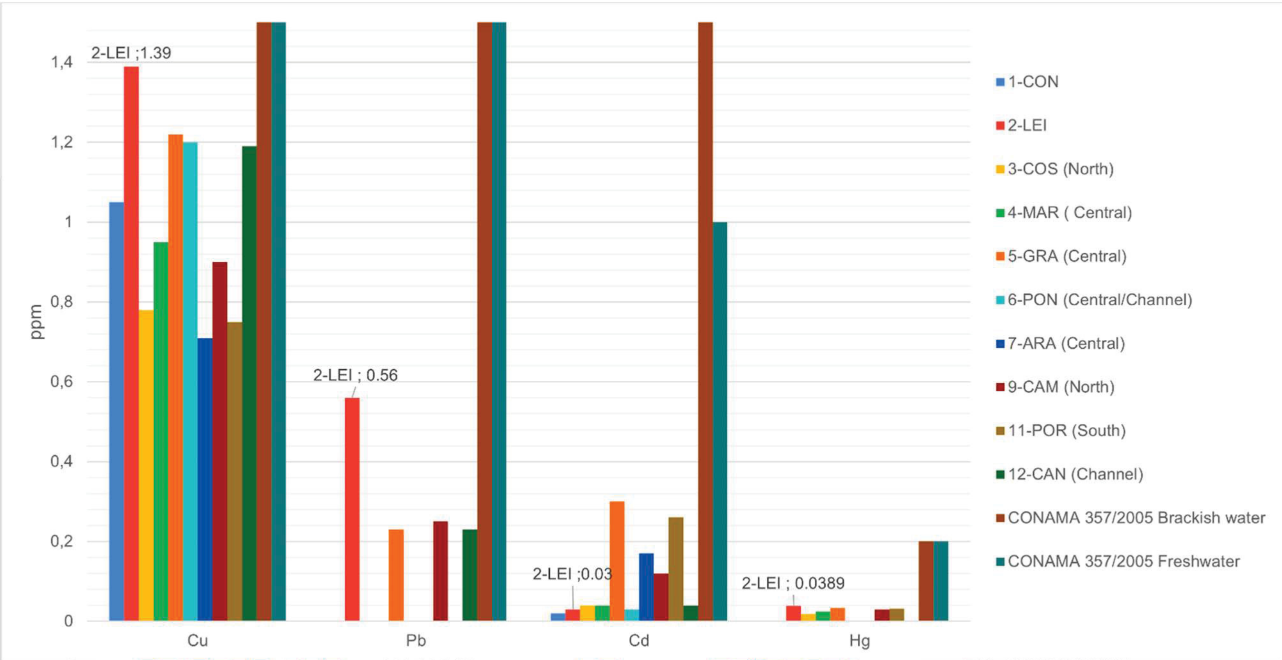


Figure 4. Concentrations of Cu, Pb, Cd, and Hg in surface water samples.

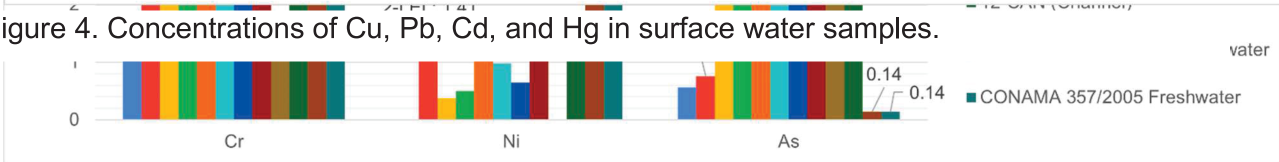


Figure 5. Concentrations of Cr, Ni, and As in surface water samples.

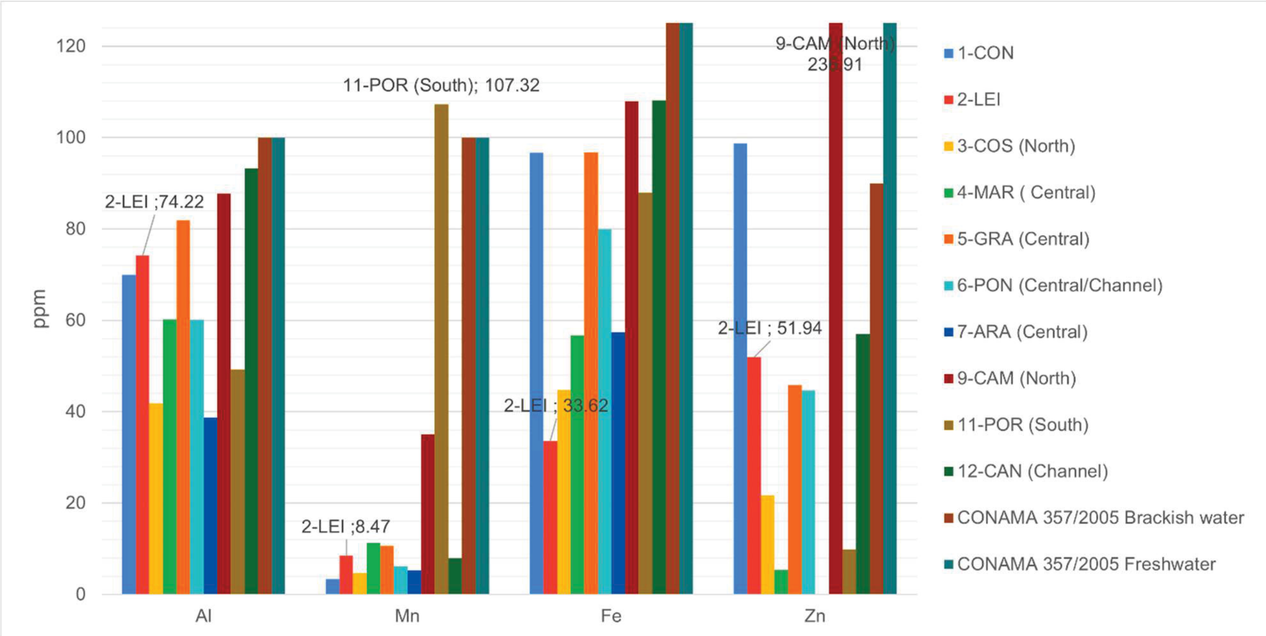

Figure 6. Concentrations of Al, Mn, Fe, and Zn in surface water samples.

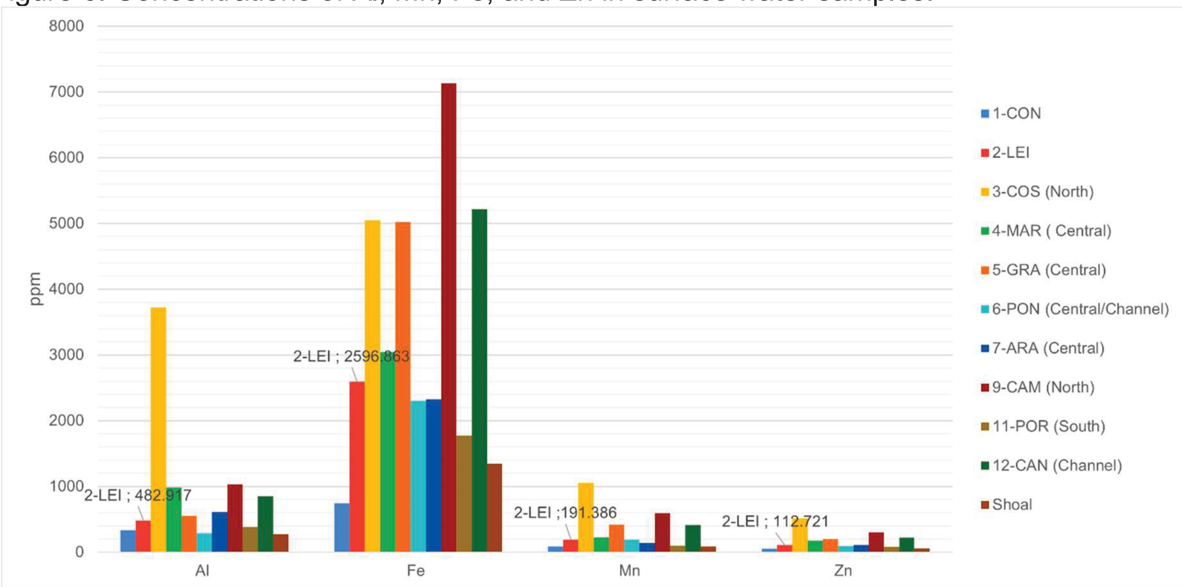

Figure 7. Total concentrations of Al, Fe, Mn, and Zn in sediment samples (values in mg/kg dry

weight).

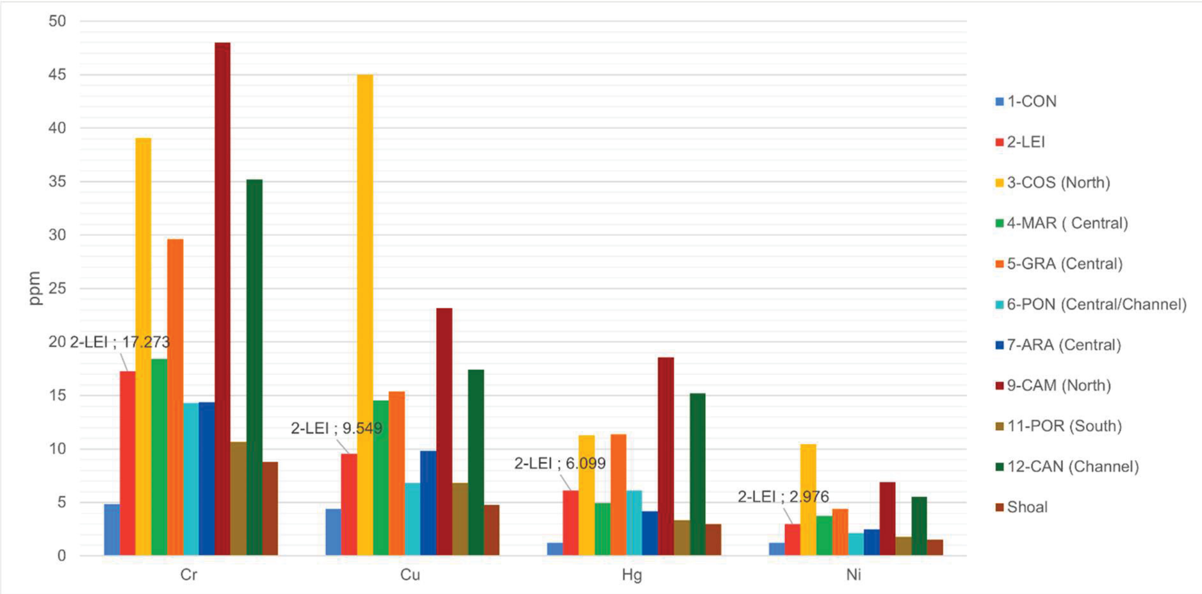


Figure 8. Total concentrations of Cr, Cu, Hg, and Ni in sediment samples (values in mg/kg dry weight).

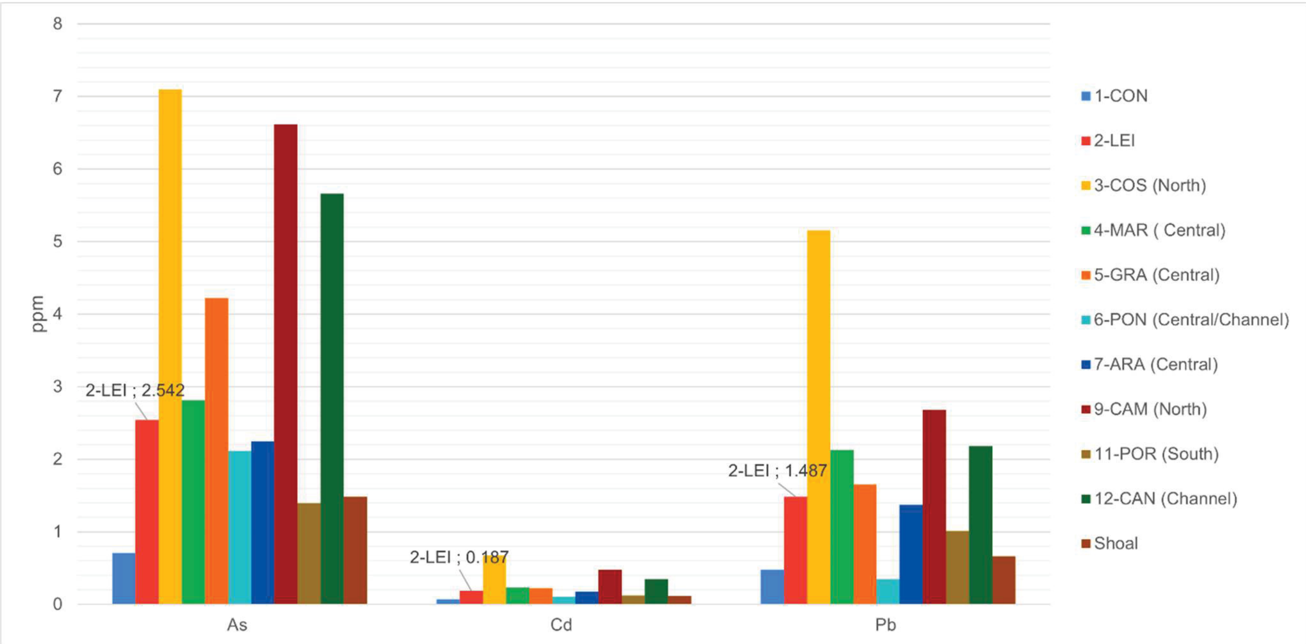


Figure 9. Total concentrations of As, Cd, and Pb in sediment samples (values in mg/kg dry weight).

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Table 2. Sampling points by sector of Lagoa da Conceição. Points 8 and 10 were excluded due to inaccessibility, leaving 10 sampling locations from Points 1 to 12.

| Sector | Sampling point | Coordinates |
|---|---|---|
| **Control** | 1 - Costa da Lagoa Waterfall (1-CON) | -27,543521, -48,463654 |
| **Central** | 2 - LEI (Evapoinfiltration lagoon) (2-LEI) | -27,6123, -48,4518 |
| | 4 - Stormwater Channel between Marina and Ponta das Almas (4-MAR) | -27,6062, -48,4624 |
| | 5 - Stormwater Channel at Praça Renato Antônio de Souza, entrance to Gravatá Trail (5-GRA) | -27,608762, -48,442088 |
| | 7 - Stormwater Channel at Canto dos Araçás (7-ARA) | -27,5949, -48,4596 |
| **South** | 11 - Stormwater Channel at Porto da Lagoa (11-POR) | -27,6261, -48,4678 |
| **Channel** | 6 – Bridge at the entrance to the Barra da Lagoa Channel (presence of marinas and stormwater channels) (6-PON) | -27,5911, -48,4361 |
| | 12 - Barra da Lagoa Channel, near mangrove area (12-CAN) | -27,577377, -48,429604 |
| **North** | 9 - Near Rio Vermelho Camping/STP Barra da Lagoa (9-CAM) | -27,5596, -48,4402 |
| | 3 - Fishing community at Costa da Lagoa (3-COS) | -27,543433, -48,460155 |

Table 3. Physicochemical Parameters of Water Measured in the Field.

| Sampling Point | Location Description | Salinity (PSU) | DO (Mg.L$^{-1}$) | pH | Alkalinity (Mmol.L$^{-1}$) | Water Temperature (ºc) |
|---|---|---|---|---|---|---|
| **1-CON** | Costa da Lagoa Waterfall (Control) | 0.08 | 11.0 | 7.34 | 0.1 | 23.94 |
| **2-LEI** | LEI (Central) | 0.34 | 4.3 | 7.6 | 1.19 | 29.7 |
| **3-COS** | Costa da Lagoa (North) | 16.25 | 5.7 | 8.08 | 1.98 | 25.0 |
| **4-MAR** | Marina (Central) | 16.83 | 6.7 | 8.4 | 2.03 | 31.87 |
| **5-GRA** | Gravatá Trail (Central) | 16.53 | 8.6 | 8.38 | 3.81 | 30.56 |
| **6-PON** | Brigde of Channel (Central/Channel) | 24.18 | 8.3 | 8.47 | 2.36 | 31.66 |
| **7-ARA** | Canto dos Araçás (Central) | 18.13 | 9.0 | 8.4 | 1.89 | 30.38 |
| **9-CAM** | Campground Rio Vermelho (North) | 13.79 | 7.0 | 8.32 | 1.59 | 32.74 |
| **11-POR** | Porto da Lagoa (South) | 5.85 | 8.4 | 8.0 | 0.94 | 30.81 |
| **12-CAN** | Mangrove (Channel) | 18.96 | 7.1 | 8.44 | 3.04 | 30.25 |

| | | | | | |
|---|---|---|---|---|---|
| **MAXIMUM** | 24.18 | 11.0 | 8.47 | 3.81 | 32.74 |
| **MINIMUM** | 0.08 | 4.3 | 7.34 | 0.1 | 23.94 |

Tabl*e 3.* Detection Limits (DL) and Quantification Limits (QL) for the metals and metalloids in the surface water samples

| | **Water** | |
|---|---|---|
| **Metal** | **DL (ug/L)** | **QL (ug/L)** |
| **Al** | 0.1064 | 0.3225 |
| **As** | 0.1041 | 0.3135 |
| **Cd** | 0.0068 | 0.0123 |
| **Cr** | 0.0238 | 0.0459 |
| **Cu** | 0.2699 | 0.6996 |
| **Fe** | 0.4525 | 1.2175 |
| **Hg** | 0.01 | 0.03 |
| **Mn** | 0.1131 | 0.3769 |
| **Ni** | 0.26 | 0.4667 |
| **Pb** | 0.006 | 0.02 |
| **Zn** | 0.125 | 0.3122 |

Table 4. Detection Limits (DL) and Quantification Limits (QL) for the metals and metalloids in the sediment samples

| | **Sediments** | |
|---|---|---|
| **Metal** | **DL (mg/kg)** | **QL (mg/kg)** |
| **Al** | 0.0213 | 0.0645 |
| **As** | 0.0208 | 0.0627 |
| **Cd** | 0.0014 | 0.0025 |
| **Cr** | 0.0048 | 0.0092 |
| **Cu** | 0.054 | 0.1399 |
| **Fe** | 0.0905 | 0.2435 |
| **Hg** | 0.0049 | 0.0162 |
| **Mn** | 0.0226 | 0.0754 |
| **Ni** | 0.052 | 0.0933 |
| **Pb** | 0.0012 | 0.004 |
| **Zn** | 0.025 | 0.0624 |

Table 5. Background values of heavy metals in soils and sediments, according to Salomons and Forstner (1984).

| Metals ($mg.Kg^{-1}$) | Sludges and clays | Recent freshwater sludges and clays | Lake sediments | Soils | Mean of this study |
|---|---|---|---|---|---|
| Fe (%) | 4.72 | - | 4.34 | 3.2 | 70% |
| Mn | 600 | - | 760 | 760 | 318.6 |
| Zn | 95 | - | 118 | 59.8 | 173.7 |
| Cr | 83 | 60 | 62 | 84 | 21.88 |
| Ni | 68 | 32 | 66 | 33.7 | 3.92 |
| Cu | 45 | 31 | 45 | 25.8 | 14.34 |
| Pb | 20 | - | 34 | 29.2 | 1.74 |
| Hg | 0.2 | - | 0.35 | 0.098 | 0.008 |
| Cd | 0.2 | - | 0.4 | 0.62 | 0.25 |

Table 6. Kd values calculated for each metal(loid) at sampling points.

| Sampling point | Kd Al | Kd As | Kd Cd | Kd Cr | Kd Cu | Kd Fe | Kd Hg | Kd Mn | Kd Ni | Kd Pb | Kd Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1-CON (Cachoeira Costa da Lagoa)** | 4.76 | 1.27 | 3.60 | 4.66 | 4.20 | 7.71 | 125400.00 | 25.83 | - | - | 0.53 |
| **2-LEI** | 6.51 | 3.34 | 6.23 | 7.20 | 6.87 | 77.24 | 0.00 | 22.60 | 2.11 | 2.66 | 2.17 |
| **3-COS (Costa da Lagoa)** | 89.06 | 1.32 | 16.90 | 7.40 | 57.70 | 112.94 | 0.04 | 225.19 | 27.46 | - | 23.57 |
| **4-MAR (Marina Central)** | 16.31 | 0.31 | 5.90 | 5.33 | 15.30 | 53.55 | 49420.00 | 20.16 | 7.50 | - | 32.18 |
| **5-GRA (Entrada Trilha do Gravatá)** | 6.76 | 0.52 | 0.74 | 6.25 | 12.59 | 51.88 | 0.00 | 39.54 | 2.49 | 7.18 | 4.36 |
| **6-PON (Ponte entrada do Canal)** | 4.85 | 0.23 | 3.43 | 3.73 | 5.69 | 28.79 | 0.00 | 31.18 | 2.21 | - | 2.08 |
| **7-CAN (Canto dos Araçás)** | 15.69 | 0.23 | 1.04 | 5.83 | 13.85 | 40.49 | 41920.00 | 26.18 | 3.79 | - | - |
| **9-CAM (Camping Rio Vermelho)** | 11.72 | 1.07 | 3.97 | 12.25 | 25.74 | 66.10 | 0.00 | 16.94 | 5.19 | 10.72 | 1.27 |
| **11-POR (Porto da Lagoa - Sul)** | 7.80 | 0.44 | 0.47 | 8.08 | 9.14 | 20.15 | 333200.00 | 0.92 | - | - | 8.21 |
| **12-CAN (Canal da Barra da Lagoa)** | 9.12 | 0.64 | 8.75 | 4.87 | 14.63 | 48.24 | 0.00 | 52.45 | 3.14 | 9.49 | 3.86 |
| **Maximum** | 89.06 | 3.34 | 16.90 | 12.25 | 57.70 | 112.94 | 333200.00 | 225.19 | 27.46 | 10.72 | 32.18 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Minimum** | 4.76 | 0.23 | 0.47 | 3.73 | 4.20 | 7.71 | 0.00 | 0.92 | 2.11 | 2.66 | 0.53 |

Table 7. Correlation matrix of the parameters analyzed in the surface water.

| x | Al27 mg/L | Cr52 mg/L | Mn55 mg/L | Fe57mg /L | Ni60 mg/L | Cu65mg /L | Zn66mg /L | Pbmg/L | As75 mg/L | Hg202 ug/L | Cd114 mg/L | Depht | Salinity | Tempera ture | DO mg/L | pH | Alkalinit y | PO2-4 mg/L | NO3 mg/L | Silicates mg/L | NH4 mg/L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Al | 1.00 | | | | | | | | | | | | | | | | | | | | |
| Cr | 0.41 | 1.00 | | | | | | | | | | | | | | | | | | | |
| Mn | -0.16 | -0.37 | 1.00 | | | | | | | | | | | | | | | | | | |
| Fe | 0.61 | 0.20 | 0.25 | 1.00 | | | | | | | | | | | | | | | | | |
| Ni | 0.73 | 0.66 | -0.35 | 0.23 | 1.00 | | | | | | | | | | | | | | | | |
| Cu | 0.67 | 0.23 | -0.41 | 0.05 | 0.65 | 1.00 | | | | | | | | | | | | | | | |
| Zn | 0.62 | 0.05 | 0.00 | 0.54 | 0.29 | 0.11 | 1.00 | | | | | | | | | | | | | | |
| Pb | 0.63 | 0.17 | -0.14 | -0.11 | 0.72 | 0.68 | 0.33 | 1.00 | | | | | | | | | | | | | |
| As | -0.04 | 0.58 | -0.26 | 0.14 | 0.36 | -0.15 | -0.20 | -0.31 | 1.00 | | | | | | | | | | | | |
| Hg | 0.15 | -0.13 | 0.41 | -0.22 | 0.18 | 0.11 | 0.14 | 0.53 | -0.33 | 1.00 | | | | | | | | | | | |
| Cd | -0.07 | -0.14 | 0.55 | 0.30 | 0.09 | -0.27 | -0.11 | -0.05 | 0.15 | 0.40 | 1.00 | | | | | | | | | | |
| Depht | 0.36 | 0.26 | -0.39 | -0.40 | 0.64 | 0.67 | -0.11 | 0.85 | -0.14 | 0.23 | -0.21 | 1.00 | | | | | | | | | |
| Salinity | -0.08 | 0.66 | -0.28 | 0.12 | 0.33 | -0.12 | -0.15 | -0.35 | 0.95 | -0.37 | 0.04 | -0.20 | 1.00 | | | | | | | | |
| Temperature | 0.25 | 0.16 | 0.29 | 0.18 | 0.47 | 0.09 | 0.13 | 0.22 | 0.55 | 0.29 | 0.33 | 0.06 | 0.44 | 1.00 | | | | | | | |
| DO | -0.09 | -0.37 | 0.08 | 0.57 | -0.38 | -0.24 | 0.02 | -0.60 | 0.05 | -0.55 | 0.30 | -0.62 | -0.02 | -0.22 | 1.00 | | | | | | |
| pH | 0.02 | 0.61 | -0.05 | 0.19 | 0.42 | -0.16 | -0.10 | -0.21 | 0.95 | -0.13 | 0.26 | -0.15 | 0.93 | 0.69 | -0.09 | 1.00 | | | | | |
| Alkalinity | 0.29 | 0.79 | -0.30 | 0.18 | 0.72 | 0.28 | -0.18 | 0.13 | 0.76 | 0.02 | 0.31 | 0.23 | 0.75 | 0.42 | -0.17 | 0.78 | 1.00 | | | | |
| PO2-4 | 0.16 | -0.21 | -0.13 | -0.57 | 0.28 | 0.57 | -0.03 | 0.81 | -0.53 | 0.46 | -0.25 | 0.82 | -0.54 | 0.00 | -0.63 | -0.48 | -0.23 | 1.00 | | | |
| NO3 | 0.14 | -0.25 | -0.09 | -0.56 | 0.25 | 0.55 | -0.03 | 0.79 | -0.56 | 0.47 | -0.24 | 0.80 | -0.58 | -0.01 | -0.61 | -0.51 | -0.27 | 1.00 | 1.00 | | |
| Silicates | 0.02 | -0.62 | 0.08 | 0.22 | -0.54 | 0.01 | 0.16 | -0.16 | -0.74 | -0.21 | -0.16 | -0.24 | -0.75 | -0.67 | 0.57 | -0.84 | -0.73 | 0.01 | 0.04 | 1.00 | |
| NH4 | 0.16 | -0.22 | -0.13 | -0.56 | 0.28 | 0.57 | -0.03 | 0.81 | -0.53 | 0.46 | -0.25 | 0.82 | -0.55 | 0.00 | -0.62 | -0.49 | -0.23 | 1.00 | 1.00 | 0.01 | 1.00 |

# 3 CAPÍTULO 2: “ HEAVY METAL ACCUMULATION BY VEGETATION IN A COASTAL LAGOON OF SOUTHERN BRAZIL: ASSESSING PHYTOREMEDIATION POTENTIAL AFTER A SEWAGE DAM FAILURE”

Este artigo foi submetido para publicação na revista Environmental Research e aguarda revisão.

ABSTRACT

Marine wetlands play a critical role in phytoremediation, as their vegetation is capable of accumulating environmental contaminants such as heavy metals. “Lagoa da Conceição”, a coastal lagoon in southern Brazil known for its tourism, fishing, and seafood cuisine, faces increasing environmental pressures from untreated domestic effluent discharges, intense boat traffic, and the impact of an environmental accident that released approximately 500,000 m³ of effluent containing toxic substances from a sewage treatment station. This study assessed the bioremediation potential of native vegetation around the lagoon, focusing on the accumulation of heavy metals (Al, As, Cd, Cu, Cr, Fe, Hg, Mn, Ni, Pb, and Zn) in plant tissues and their relationship with concentrations in surface water and sediment. We evaluated whether the rupture of the effluent lagoon dam had a localized effect on metal bioaccumulation in plants or whether contamination patterns reflected broader, systemic anthropogenic pressures. Our results showed that *Halodule wrightii* was the most effective metal accumulator, likely due to its ecological plasticity and tolerance to abiotic stress. *Panicum racemosum* also exhibited high accumulation and bioconcentration potential, while *Fimbristylis cymosa* and *Scirpus* sp. demonstrated relevant metal uptake capacities—*Scirpus* sp. notably tolerating high mercury concentrations. *Commelina* sp. displayed the highest bioconcentration factors across several metals, indicating strong phytoremediation potential. Metal accumulation was highly context-dependent, with no clear spatial patterns or consistent clustering based on species or location. Statistical analyses revealed that distance from the accident epicenter, although statistically significant, explained only a small portion of the variation in metal concentrations. Instead, accumulation patterns were more strongly associated with systemic environmental pressures—such as boat traffic, marinas, and limited water circulation—rather than with localized contamination. These findings underscore the importance of a systemic approach to monitoring and remediation policies. Phytoremediation emerges as a viable and sustainable strategy, but its effectiveness depends not only on plant uptake capacity, but also on biomass production, environmental conditions, and practical manageability. Sentinel species such as *H. wrightii* and *Commelina* sp. offer promising pathways for future research.

Keywords: trace metals, aquatic macrophytes, bioconcentration factor, sewage discharge, environmental quality

## 3.1 INTRODUCTION

The coastal zone plays a crucial role as a biogeochemical filter at the land-sea interface, influenced by factors such as water residence time and the coupling between sediment and water (Cabral et al., 2019). In addition to physical and chemical processes, the bioremediation potential of vegetation in marine wetland areas adds an important layer of environmental protection. Given the chronic and acute influx of contaminants from various anthropogenic activities within the watershed, such as inadequately treated domestic effluents, heavy metals deserve particular attention due to their capacity for bioaccumulation and biomagnification within the food chain. This makes the coastal zone a key area for studying the environmental impacts and potential solutions for mitigating the effects of these pollutants.

Despite the essential physiological roles of some metals in biochemical reactions, high concentrations can be toxic, leading to damage to the structures and genetic integrity of various organisms (Moschem and Gonçalves, 2020). Furthermore, some non-essential metals, even at trace concentrations, can produce harmful effects, such as Mercury (Hg) (Barreto, 2011). Arsenic (As), Cadmium (Cd), and Lead (Pb) are examples of pollutants that can cause irreversible damage to animals, resulting in injuries to the central nervous system and impairments in renal, pulmonary, cardiovascular, gastrointestinal, and hepatic functions, as well as increasing the risk of cancer (Balali-Mood et al., 2021). In urban areas with inefficient domestic effluent treatment systems, these metals, along with other pollutants such as excess nutrients and microplastics, can affect the food and ecological security of ecosystems with high water residence times, such as lagoons (Cabral et al., 2019).

Bioremediation is a nature-based solution that can effectively stabilize pollutants in the environment (Song et al., 2019). This technique involves extracting, metabolizing, and/or absorbing contaminants from the environment without compromising physiology of the organisms. From this perspective, aquatic vegetation can facilitate the natural attenuation of polluted environments through phytoremediation (Lacerda et al., 2019). The reduction of organic matter, nitrogen, and phosphorus in effluents is particularly relevant when evaluating the use of aquatic plants in wastewater treatment, representing a low-cost method applicable even in remote areas (Pereira et al., 2012; Turcios et al., 2021).

Some blue carbon plants have demonstrated remarkable resilience in wetlands, exhibiting significant resistance to the toxicity of various heavy metals, such as the Saltmarsh Cordgrass *Spartina alterniflora* (Loisel) and the Sharp angled Spikerush *Eleocharis acutangula* (Roxb.) Schult. (Pio, 2012; Lauriuchi et al., 2021; Xia et al., 2021). Additionally, the biofilm that develops on aquatic plant plays a crucial role in the accumulation of metallic ions, including Cu (copper), Mn (manganese), and Pb by these plants (Araújo, 2014).

“Lagoa da Conceição”, situated on Santa Catarina Island, “Florianópolis”, is one of the primary tourist destinations in southern Brazil, experiencing significant urban concentration. The estuarine region features diverse ecosystems, including mangroves, salt marshes, and submerged meadows, which serve as natural filters by trapping and metabolizing pollutants, thereby effectively removing them from the water column (Lead et al., 2018). Estuarine vegetation forms the vegetative boundary of coastal ecosystems, while their sediments act as sinks for numerous contaminants, including heavy metals. With increasing population density in the surrounding areas and inadequate treatment of urban effluents, “Lagoa da Conceição” has been facing ecological imbalances, negatively impacting the quality of life for both residents and visitors (Roschild et al., 2021). In 2021, an environmental disaster further exacerbated this situation when the collapse of a natural embankment from an Evapo-Infiltration Lagoon (LEI), linked to the “Lagoa da Conceição” Sewage Treatment Plant, released 500,000 m³ of treated domestic effluent into “Lagoa da Conceição” (Roschild et al., 2021; USP, 2021). Notably, this effluent contained elevated levels of nutrients (N-P) and toxic substances that are not adequately removed through conventional treatment methods, such as heavy metals (Cardoso et al., 2025).

It is well established that the accumulation of metals in aquatic plants is influenced by the specific plant species, the physical and chemical conditions of the environment, and the particular metal involved (Moschem and Gonçalves, 2020; Araújo, 2014; Amado-Filho et al., 2004). In this research, the most prevalent plant species around “Lagoa da Conceição” were assessed for their ability to accumulate 11 heavy metals (Al - aluminum -, As, Cd, Cu, Cr, Fe - iron -, Hg, Mn, Ni - nickel -, Pb, Zn), focusing on the long-term impacts resulting from the environmental disaster. Such trace-elements were selected due to their toxicity and previous published data. Additionally, the physical and chemical characteristics of the surface water and surrounding sediment were analyzed to understand their influence on the accumulation of these substances in the plants.

This study aimed to determine whether the epicenter of the accident caused by the rupture of the effluent pond dam (LEI), located near the Sewage Treatment Plant (STP), resulted in a localized impact on metal bioaccumulation in the surrounding vegetation, or whether metal contamination follows a more systemic, diffuse, or regional pattern. Additionally, we sought to clarify whether the distribution of metals in plants is primarily influenced by environmental conditions or by biological traits. The research also focused on identifying sentinel species to assess the environmental health of the system in relation to metal contamination, as well as on identifying promising candidates for phytoremediation. To this end, we evaluated the bioremediation potential of plant species based on their Bioconcentration Factor (BCF), tissue metal concentrations, and total metal accumulation relative to biomass.

## 3.2 MATERIALS AND METHODS

### 3.2.1 Study Area

“Lagoa da Conceição”, located in “Florianópolis” (SC, Brazil) at coordinates 27.60353 S and 48.45355 W, is an urban lagoon spanning 20.3 km² with a maximum depth of 8.89 m (Godoy, 2009). This coastal lagoon is connected to the sea via the “Barra da Lagoa” Channel, and it offers a range of activities, particularly during the summer months, including water sports, fishing, and renowned local cuisine. The lagoon is divided into four distinct sectors—North, South, Central, and Channel—each characterized by unique physical and chemical, sedimentary, biological, and hydrodynamic properties (Figure 1).

The North sector receives significant fluvial inputs from the “João Gualberto” and “Vermelho” Rivers, with sediments primarily composed of fine sand, silt, and clay. This sector faces high organic load contamination due to inadequate sanitation infrastructure (Silva et al., 2017).

The Channel sector serves as the lagoon's connection to the ocean, stretching 2.8 km. It exhibits considerable hydrodynamic activity driven by tidal flows and is characterized by medium to fine sand grain size.

The Central sector comprises fine sand and silt and is affected by saline water intrusion from the Channel. This intrusion creates anoxic zones below 3 m depth, attributed to nutrient overloading from nearby tourist areas and the decomposition of organic matter (Cabral et al., 2019). This sector also houses the Sewage Treatment Plant (STP) within the Municipal Natural Park of the Dunes of "Lagoa da Conceição" (PNMDLC). A notable incident in this area was the rupture of the Evapo-Infiltration Lagoon (LEI), which led to treated effluent spilling into the lagoon (Cardoso et al., 2025).

The South sector experiences low hydrodynamics and is characterized by sediments consisting of fine sand and gravel. This sector has a water residence time of up to 20 days and is heavily impacted by urbanization.

"Lagoa da Conceição" is subject to multiple environmental pressures, including anthropogenic activities such as marina operations, the presence of a fuel station (Central e Channel sectors), and intense boat traffic, all of which may affect water quality (Cardoso et al., 2025).

The Sewage Treatment Plant operates with an average flow rate of 50.00 L/s and utilizes a biological treatment system, consisting of a UASB reactor followed by activated sludge, oxidation ponds, and a secondary clarifier. The treated effluent is directed to the LEIs (2-LEI – Figure 1). A natural slope formed by the sand dunes in the Municipal Natural Park of the Dunes of "Lagoa da Conceição" served as a barrier for one of the LEI, which ruptured during an extreme rainfall event. According to Ciram (Environmental Resources and Hydrometeorology Information Center of Santa Catarina, 2021), January 2021 recorded the highest monthly precipitation in the "Florianópolis" region, reaching 686 mm, marking an absolute monthly record (Figure 1 Supplementary Material 1).

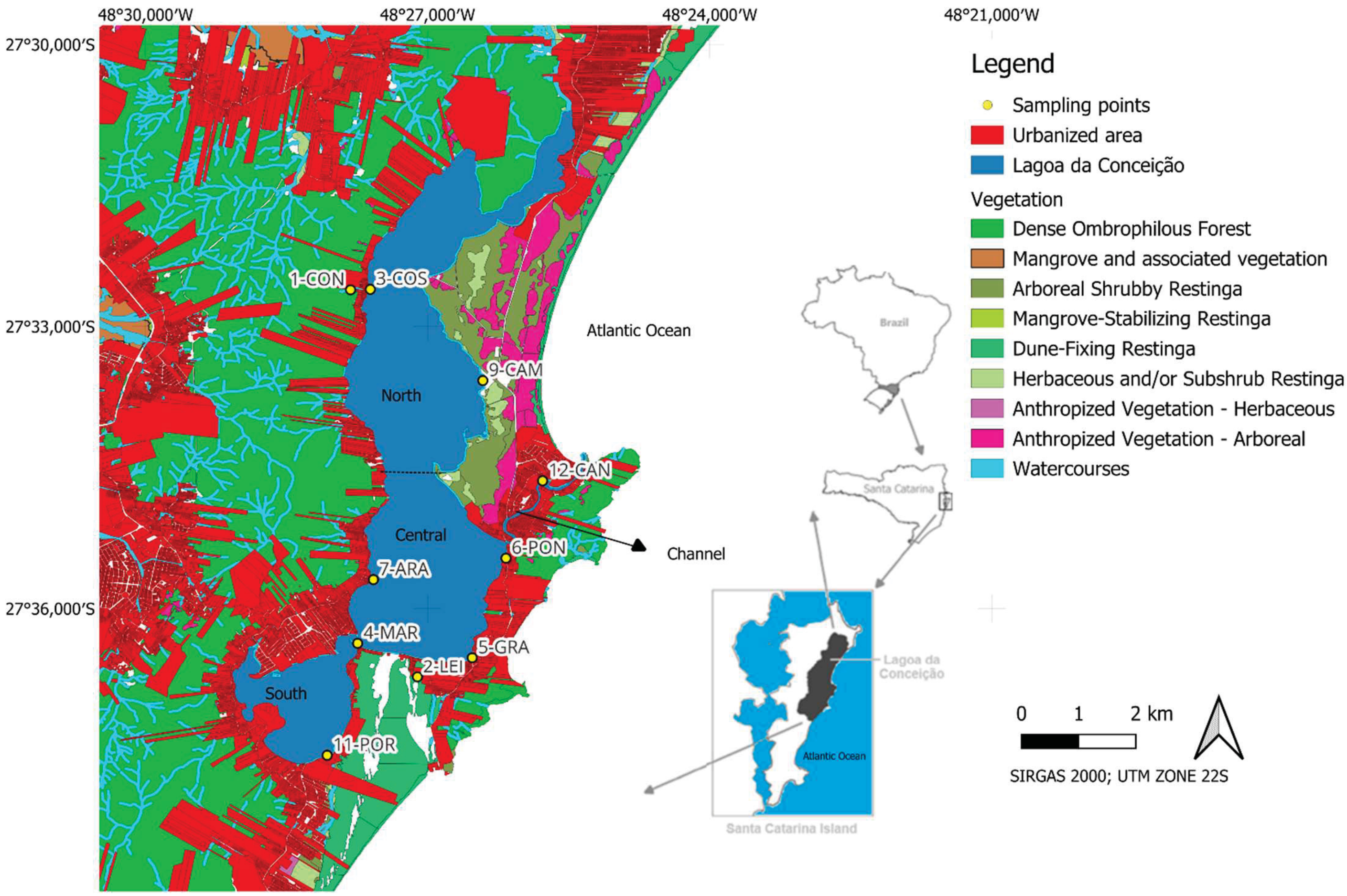


Figure 1. Map of "Lagoa da Conceição", illustrating the four subsystems that divide the area, the vegetation and the urbanization in the region. Sampling points are highlighted.

According to the geological map of “Santa Catarina” Island (Tomazzoli and Pellerin, 2014), the geological matrix of “Lagoa da Conceição” is primarily composed of Ilha Granito, consisting of sienogranites and monzogranites with phenocrysts of potassium feldspar. These minerals are aluminum silicates combined with sodium, potassium, calcium, and occasionally barium. Additionally, there are Marine Beach Deposits, which are fine sandy sediments characterized by a yellow-reddish color due to the presence of iron oxides/hydroxides, deposited under marine influence (Tomazzoli and Pellerin, 2014).

3.2.2 Sampling

Vegetation, water, and sediment samples were collected two years after the accident, on January 26, 2023, following six days of dry weather (Figure 2 Supplementary Material 1), at ten locations in “Lagoa da Conceição” (Table 1, Figure 1). The sampling sites were selected near potential contamination sources in the lagoon, including stormwater channels that discharge runoff from urbanized areas; gas stations and marinas, where contaminating products (such as lubricating oils and fuels) are present; areas directly impacted by treated effluents from wastewater treatment plants; and locations where vessel maintenance occurs, which may involve antifouling paints. Sampling was also conducted in the Evapoinfiltration Lagoon (2-LEI) and in a control area (1-CON) to quantify the natural concentrations of metals in the geological matrix, thereby assessing the region's geochemical background.

Table. 1. Sampling points categorized by sector in “Lagoa da Conceição”. Points 8 and 10 were excluded due to inaccessibility for sampling, leaving a total of 10 sampling locations from Points 1 to 12.

| Sector | Sampling point | Coordinates |
|---|---|---|
| **Control** | 1 – “Costa da Lagoa” Waterfall (1-CON) | -27.543521. -48.463654 |
| **Central** | 2 - LEI (Evapoinfiltration lagoon) (2-LEI) | -27.6123. -48.4518 |
| | 4 - Stormwater Canal between Marina and “Ponta das Almas” (4-MAR) | -27.6062. -48.4624 |
| | 5 - Stormwater Canal at “Praça Renato Antônio de Souza”, entrance to “Gravatá Trail” (5-GRA) | -27.608762. -48.442088 |
| | 7 - Stormwater Canal at “Canto dos Araçás” (7-ARA) | -27.5949. -48.4596 |
| **South** | 11 - Stormwater Canal at “Porto da Lagoa” (11-POR) | -27.6261. -48.4678 |
| **Channel** | 6 – Bridge at the entrance to the “Barra da Lagoa” Channel (presence of marinas and stormwater channels) (6-PON) | -27.5911. -48.4361 |
| | 12 “Barra da Lagoa” Channel, near mangrove area (12-CAN) | -27.577377. -48.429604 |
| **North** | 9 - Near “Rio Vermelho” Camping/STP “Barra da Lagoa” (9-CAM) | -27.5596. -48.4402 |
| | 3 - Fishing community at “Costa da Lagoa” (3-COS) | -27.543433. -48.460155 |

#### 3.2.2.1 Surface water

An analysis of physical and chemical parameters and heavy metals in surface water samples was conducted to assess their relationship with the metal content in vegetation. Surface water samples (duplicates) were collected from “Lagoa da Conceição” using a Van Dorn bottle. In the field, measurements of temperature, pH, salinity, and dissolved oxygen were taken. Immediately after each collection, the samples were preserved and stored until they arrived at the laboratory. The following parameters were determined: total alkalinity was assessed using a titrimetric method, while phosphates ($PO_4^{2-}$), ammonium ($NH_4^+$), and nitrate ($NO_3^-$) were analyzed using a UV-Vis spectrophotometer through colorimetric methods, in accordance with the protocols outlined by Grasshoff et al. (1983), at the Laboratory of Chemical and Biological Oceanography of the Federal University of Santa Catarina (LADOC-UFSC). Blanks underwent the same analytical procedure.

#### 3.2.2.2 Sediment

Analyses of organic matter (OM), grain size, and total heavy metal concentrations were conducted on sediment samples to establish relationships between these results and the metal content observed in the vegetation. Sediment samples were collected using shovels. Squares measuring 50 cm x 50 cm were used to mark the vegetation area, and sediment was collected from within these squares. The samples were stored in plastic bags for heavy metal analysis and frozen until extraction. The organic content was determined by loss-on-ignition, where dry sediment samples were burned in a muffle furnace at 550°C for at least 4 hours (Dean, 1974). Particle size distribution was performed using sieving for sand to granule fractions (>0.063 mm), following the method proposed by Folk and Ward (1965). The Wentworth scale (1922) was used for grain size classification.

#### 3.2.2.3 Vegetation

Botanical material was collected from the vegetation banks at the 10 sampling points, with the three most abundant species sampled at each site. A square measuring 50 cm x 50 cm was used to delineate the collection area for individuals, except at Point 4-MAR, where only one species was present, and Point 11-POR, which had four of the most abundant species. In total, 29 specimens were collected. The floristic composition was based on methods established by Pedralli (1990), which provided recognized protocols for sampling, herbarium preparation, and ecological data evaluation. The taxonomic identification of the material was conducted by comparing the collected specimens with relevant literature, specifically using Souza and Lorenzi (2008) and APG III (2009) for angiosperms. A photographic catalog of the sampling is included in the Supplementary Material (2).

Dry biomass was obtained by thoroughly washing plant samples to eliminate adhering soil or sediment particles, followed by oven-drying at 60–70 °C until a constant weight was achieved (typically between 48 and 72 hours). Subsequently, the dried samples were weighed using an analytical balance.

#### 3.2.2.4 Heavy Metals

The analytes (Al, As, Cd, Cu, Cr, Fe, Hg, Mn, Ni, Pb, and Zn) will be referred to as heavy metals in this article, as this term includes both metals and metalloids (IUPAC, 2002). Heavy metals were analyzed by the Determinations Laboratory II at the Institute of Biological Sciences of the Federal University of Rio Grande (ICB/FURG). The elements were extracted from environmental matrices using microwave-assisted acid digestion, following the EPA 3052S methodology for biota samples, which included the whole plant. For water samples, preparation was conducted according to the methodology outlined in EPA 3015A, while metals from the available fraction of the sediment were extracted based on EPA 3051A. Metal concentrations were determined using ICP-MS (Inductively Coupled Plasma Mass Spectrometry) with the PLASMAQUANT® MS system (Analytik Jena, Jena, Germany), in accordance with the EPA 6020 method.

#### 3.2.2.5 Quality assurance and quality control

The quality assurance and quality control for analyses were based on regular analyses of method blanks, spiked matrices, and, whenever available, reference material and certified reference material processed with the samples (Wade and Cantillo, 1994). The limit of detection (LOD) was three times the standard deviation (SD) of the blank signals (3 × SD; n = 10). The limit of quantification (LOQ) corresponded to ten times the SD of the blank signals (10 × SD; n = 10). Limits of quantification and detection for plants, water and sediment samples are provided in the Supplementary Material 1 (Table 1 and 2) and 2 (Table 1). Analyses of Sediment Reference Material for trace metals (MESS-4) and Freshwater Reference Material for trace metals (SLRS-6) from the National Research Council of Canada (NRC – CNRC) were conducted. For the biota samples, the analytical control was carried out using a certified reference material DORM-5 (National Research Council, Canada). Analytical results of the quality control samples show good agreement with the certified values, with recoveries ranging from 95.3% to 97.5% for metals studied in sediments and from 91.1% to 93.5% in water samples. Procedural analyses were performed in triplicate.

### 3.2.3 Data Analysis

To assess the ability of plants to absorb elements from the sediment, the Bioconcentration Factor (BCF) was calculated. This factor relates the total concentrations of each element (Al, As, Cd, Cu, Cr, Fe, Hg, Mn, Ni, Pb, and Zn) in the plant to their total concentrations in the sediment (Usman et al., 2012; Qiu et al., 2011).

$$\mathrm{BCF} = [\mathrm{Metal\ in\ the\ plant}]/[\mathrm{Metal\ in\ the\ sediment}]$$

The amount of bioaccumulated metal was calculated based on the concentration and biomass of the plant, assessing the total amount it accumulated (Macek et al., 2008):

$$\mathrm{Metal\ content\ (mg)} = \mathrm{Metal\ concentration\ in\ the\ plant}\left(\frac{\mathrm{mg}}{\mathrm{kg}}\right) \times \mathrm{dry\ biomass\ (kg)}$$

Correlation values were calculated for the parameters analyzed both in the field and in the surface water, which included salinity, temperature, dissolved oxygen, pH, alkalinity, nitrate, ammoniacal nitrogen, silicates, phosphates, and heavy metals associated with plants, sediment, and water. Microsoft Excel 2021 was utilized to compute the correlation matrix. The correlation diagrams were created using the EzCorrGraph application (Campos and Licht, 2020), applying a significance level of 99% and a critical correlation index of 0.7.

A dendrogram was created using the total concentrations of heavy metals in each plant specimen, setting a Euclidean similarity threshold of 10%. This analysis aimed to evaluate whether there is a shared accumulation pattern of elements among the plants.

Generalized Additive Models (GAMs) were tested to evaluate the relationship between metal concentrations in plants and the distance from the epicenter. The model was fitted considering metal bioaccumulation as the dependent variable and "Distance from the STP" as the independent variable, using smoothing to capture potential nonlinear relationships.

To investigate the influence of the distance from the epicenter (Point 2-LEI) on environmental composition, a Permutational Multivariate Analysis of Variance (PERMANOVA) was applied, using the Euclidean distance matrix of the parameters analyzed in water and sediment, considering statistical significance at $p < 0.05$.

Principal Component Analysis (PCA) was employed to identify clustering or separation patterns in the data on heavy metal bioaccumulation and sampling points. For that a Euclidian dissimilarity matrix of standardized values of metal concentrations by plants were used.

We used partial distance-based RDA (dbRDAp) to evaluate the correlates of metal bioaccumulation. For that, we used the following matrices as predictors: i) a combined matrix of metal concentrations in water and sediment; ii) a matrix of physical and chemical features of the water; iii) a combined matrix of spatial variables generated by latitude and longitude; iv) a combined matrix of the biological life-forms of macrophytes and their functional traits (leaf length and width, root length, and stem diameter). Spatial variables were generated using the Principal Coordinate of Neighboring Matrices (PCNM). Life-forms were transformed to factors, and all other continuous variables were standardized to avoid over-fitting of variables with high variation. Also to avoid overfitting, variables were previously selected to the dbRDAp model using stepwise selection.

Then the BIOENV (Best Subset of Environmental Variables) analysis was applied to describe which environmental variables best explain the variability in metal concentrations in plants. Heavy metal bioaccumulation was tested considering two approaches: one model in which bioaccumulation is primarily explained by plant physiology (functional group, species, tissue type) and two models based on environmental factors, one focused on water quality (metal concentrations, nutrients—N,P— pH, alkalinity, temperature, dissolved oxygen, silicates) and another on sediment characteristics (organic matter content and metal concentrations).

All statistical analyses mentioned, as well as the graphs presented in this study, were performed using R Statistical Software. The complete results of the statistical analyses are included in the Supplementary Material 2.

## 3.3 RESULTS

### 3.3.1 Surface water and sediment

This results are detailed in Chapter 1 and discussed in the article Cardoso et al. (2025).

In situ analysis of water parameters is provided in the Supplementary Material 1. Salinity data confirm the division of “Lagoa da Conceição” into four subsystems. In “Lagoa da Conceição”, $PO_4$ ranged from 0.024 to 0.035 mg/L, $NO_3$ from 0.003 to 0.155 mg/L, and $NH_4$ from 0.04 to 0.13 mg/L. Two years after the dam rupture, concentrations remained within CONAMA No. 357/2005 limits.

Heavy metal concentrations in surface water ranged from 0.3 to 236.91 µg/L, with notable levels of Cu (1.39 µg/L), Pb (0.56 µg/L), and Hg (0.04 µg/L) in LEI effluent. In “Lagoa da Conceição”, elements with higher crustal abundance were more prevalent (Zn > Fe > Mn > Al > Hg > As > Cr > Ni > Cu > Cd > Pb). Arsenic exceeded CONAMA limits in all samples (0.00056–0.00974 mg/L), but background values at Point 1-CON suggest a natural source. Manganese surpassed the limit in the south (Point 11-POR, 0.107 mg/L), and zinc in the north (Point 9-CAM, 0.237 mg/L).

Sediments were predominantly fine sand, except at Point 1-CON (granules). Organic matter (OM) was highest at Point 2-LEI (60.4%) due to sewage sludge, with other sites ranging from 0.33% to 4.62% (mean 1.26% ± 1.23).

Metal concentrations ranged from 0.072 to 7133.879 mg/kg (Fe > Al > Mn > Zn > Cr > Cu > Hg > Ni > As > Pb > Cd). Site 3-COS had the highest levels of eight elements, and Site 9-CAM had the highest Cr, Fe, and Hg. Both sites, in the poorly circulated northern region, receive input from “João Gualberto” and “Vermelho” Rivers, forming a contaminant accumulation zone. Fluvial sediments typically contain higher metal concentrations than marine sediments (Salomons & Förstner, 1984).

According to CONAMA Resolution 454/12 and NOAA standards, Cu (45.00 mg/kg) and Zn (510.96 mg/kg) at Site 3-COS exceeded TEL - *Threshold Effects Level* (34 mg/kg) and PEL - *Probable Effects Level* (410 mg/kg), respectively. Zinc also surpassed the TEL limit (150 mg/kg) at northern, central, and channel sites (172.5–299.9 mg/kg), associated with heavy boat traffic and antifouling paints. Sediments at Site 2-LEI showed low metal contamination (e.g., Cu 9.55 mg/kg, Zn 112.72 mg/kg).

3.3.2 Vegetation

Taxonomic Survey

A total of 29 plant specimens were collected in the vicinity of “Lagoa da Conceição”, representing 22 different plant species. Among these, members of the Poaceae family were predominant, commonly found in marsh vegetation (Figure 2).

The specimens were collected from the sites listed in Table 2, which shows the ranking of heavy metal accumulation. Specimen 16-*H. wrightii* exhibited the highest total concentration of heavy metals (2251.59 mg/kg), while specimen 28-*P. vaginatum* ranked lowest (33.21 mg/kg). The detailed results are provided in the Table 5 of Supplementary Material (2).

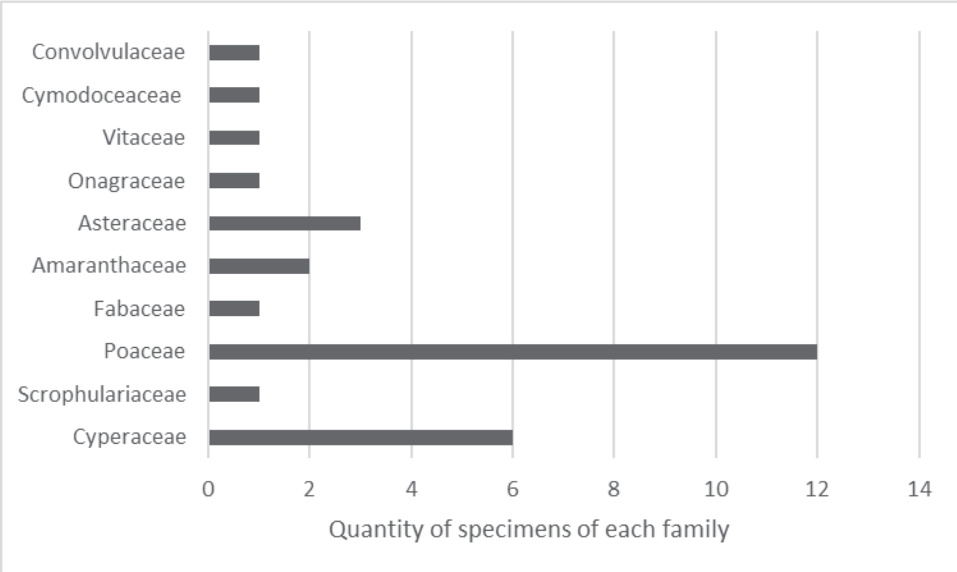


Figure 2. Plant families collected at “Lagoa da Conceição”.

Table 2. Ranking of heavy metal accumulation in the collected specimens - ID, their families, sampling point, and species.

| Ranking | ID | Family | Sampling point | Species |
|---|---|---|---|---|
| 1º | *16-H. wrightii* | Cymodoceaceae | 4-MAR | *Halodule wrightii* Asch. |
| 2º | *17-P. racemosum* | Poaceae | 11-POR | *Panicum racemosum* (P. Beauv.) Spreng |
| 3º | *5-F. cymosa* | Cyperaceae | 12-CAN | *Fimbristylis cymosa* R.Br. |
| 4º | *7-U. arrecta* | Poaceae | 6-PON | *Urochloa arrecta* (Hack. Ex t. Durand and Schinz) |
| 5º | *9-S. alterniflora* | Poaceae | 6-PON | *Spartina alterniflora* Loisel. |
| 6º | *26-Commelina sp.* | Asteraceae | 1-COM | *Commelina sp.* |
| 7º | 6-*S. maritima* | Poaceae | 12-CAN | *Spartina maritima* (Curtis) Fernald |
| 8º | *11-S. trilobata* | Asteraceae | 5-GRA | *Sphagneticola trilobata* (L.) Pruski |
| 9º | *13-L. peruviana* | Onagraceae | 2-LEI | *Ludwigia peruviana* (L.) H.Hara |
| 10º | *2-B. monnieri* | Scrophulariaceae | 9-CAM | *Bacopa monnieri* (L.) Wettstein. |

| | | | | |
|---|---|---|---|---|
| 11º | *10-A. philoxeroides* | Amaranthaceae | 5-GRA | *Alternanthera philoxeroides* (Mart.) Griseb. |
| 12º | *14-U. arrecta* | Poaceae | 2-LEI | *Urochloa arrecta* |
| 13º | *12-P. vaginatum* | Poaceae | 5-GRA | *Paspalum vaginatum* Sw. |
| 14º | *18-S. californicus* | Cyperaceae | 11-POR | *Schoenoplectus californicus* (C.A. Mey.) Soják |
| 15º | *19-P. vaginatum* | Poaceae | 11-POR | *Paspalum vaginatum* |
| 16º | *25-E. bonariensis* | Cyperaceae | 1-CON | *Eleocharis bonariensis* Nees |
| 17º | *1-E. interstincta* | Cyperaceae | 9-CAM | *Eleocharis interstincta* (Vahl) Roem. and Schult. |
| 18º | *27-S. maritima* | Poaceae | 3-COS | *Spartina maritima* |
| 19º | *3-R. corimbosa* | Cyperaceae | 9-CAM | *Rhynchospora corymbosa* (L.) Britton |
| 20º | *8-V. luteola* | Fabaceae | 6-PON | *Vigna luteola* (Jacq.) Benth. |
| 21º | *21-P. vaginatum* | Poaceae | 7-ARA | *Paspalum vaginatum* |
| 22º | *23-S. alterniflora* | Poaceae | 7-ARA | *Spartina alterniflora* |
| 23º | *15-C. verticillata* | Vitaceae | 2-LEI | *Cissus verticillata* (L.) Nicolson and C.E.Jarvis. |
| 24º | *20-Ipomea sp.* | Convolvulaceae | 11-POR | *Ipomea sp.* |
| 25º | *22-A. philoxeroides* | Amaranthaceae | 7-ARA | *Alternanthera philoxeroides* |
| 26º | *4-Scirpus sp.* | Cyperaceae | 12-CAN | *Scirpus sp.* |
| 27º | *24-P. racemosum* | Poaceae | 1-CON | *Panicum racemosum* |
| 28º | *29-E. prostata* | Asteraceae | 3-COS | *Eclipta prostrata* (L.) L. |
| 29º | *28-P. vaginatum* | Poaceae | 3-COS | *Paspalum vaginatum* |

The total concentrations of metals and metalloids in the sampled specimens ranged from ND (not detectable) to 1306.97 mg/kg of dry weight (dw). According to Table 3, the highest value recorded was for the metal Fe. It was observed that the accumulation of elements varied depending on the evaluated plant and the sampling site, following the sequence: Fe > Al > Mn > Zn > Cu > Cr > Hg > Ni > As > Pb > Cd. This order was also confirmed in the assessment of metals in sediment samples, where high concentrations of Fe and Al were detected in the surrounding sediment.

Table 3. Total concentrations of heavy metals in plants from "Lagoa da Conceição". Values in mg/kg dw (ppm).

| | **Maximum** | **Minimum** | **Mean** | **SD** | **Highest accumulating plant** |
|---|---|---|---|---|---|
| **Al** | 586.13 | 8.98 | 152.15 | 169.51 | 16-*H. wrightii* |
| **As** | 1.22 | ND | 0.33 | 0.30 | 17-*P. racemosum* |
| **Cd** | 0.21 | ND | 0.05 | 0.05 | 4-*Scirpus* sp. |
| **Cr** | 12.20 | 0.41 | 2.46 | 2.91 | 16-*H. wrightii* |
| **Cu** | 13.72 | 0.27 | 4.87 | 3.91 | 11-*S. trilobata* |
| **Fe** | 1306.97 | 18.83 | 387.83 | 369.65 | 16-*H. wrightii* |
| **Hg** | 5.49 | ND | 0.43 | 1.05 | 4-*Scirpus* sp. |
| **Mn** | 231.76 | 2.58 | 64.03 | 67.82 | 7-*U. arrecta* |
| **Ni** | 3.23 | 0.06 | 0.999 | 0.91 | 16-*H. wrightii* |
| **Pb** | 1.05 | ND | 0.33 | 0.32 | 16-*H. wrightii* |
| **Zn** | 124.01 | 1.27 | 31.24 | 31.30 | 16-*H. wrightii* |

At the Sewage Treatment Plant (Point 2-LEI), which is directly impacted by effluent discharge, the collected specimens (13-*L. peruviana*, 14-*U. arrecta*, 15-*C. verticillata*) did not exhibit notable heavy metal accumulation, ranking below the top 10 in Table 2. The invasive *U. arrecta* was present due to its tolerance to polluted environments and its ease of propagation. High contaminant levels may have restricted the colonization of other species. Furthermore, the sediment at this site did not show elevated concentrations of these elements; however, the effluent exhibited the highest levels of Cu, Pb, and Hg (see Section 3.1).

At north region, Point 3-COS, which had the highest concentrations of heavy metals in sediment, did not show high levels of these elements in plants. This may suggest that the plants at this site (27-*S. maritima,* 29-*E. prostata,* 28-*P. vaginatum*) lack the capacity to absorb and accumulate these specific metals.

3.3.3 Statistical analysis of bioaccumulation

To assess whether locations closer to the Sewage Treatment Plant exhibit chemical profiles distinct from those farther away, PERMANOVA was used on water and sediment sample data, based on the distance from the epicenter of the accident (Point 2-LEI). The results generated by the model indicated that the distance from the epicenter significantly explains 13.7% of the variation observed in the environmental data (Sum of Squares = 0.3083; $R^2$ = 0.13749; F = 4.3039; p = 0.029; residual $R^2$ = 0.86251). The residual $R^2$ value was 86.3%, suggesting that most of the environmental variation is not explained by the "distance" variable.

Table 4 presents the maximum and minimum values of the Bioconcentration Factor (BCF) for the elements analyzed in this study. The maximum BCF values for heavy metals were observed in three of the collected specimens: specimen 26-*Commelina* sp., located at Point 1-CON, exhibited a high bioconcentration factor for several elements, detailed as follows: Al 1.145; As 0.945; Cd 0.888; Cu 1.936; Fe 0.904; Mn 2.418; Ni 2.195; Pb 1.002; specimen 17-*P. racemosum*, at southern region, also demonstrated significant bioconcentration, presenting the following values for various heavy metals: Al 1.319; As 0.870; Cr 1.068; Cu 1.222; Mn 1.818; Ni 1.560; Zn 1.241; specimen 9-*S. alterniflora*, at central region, a notably high BCF value was recorded for Pb (2.129) and an Al value exceeding 1 (1.138). According to several authors (Pasricha et al., 2021; McGrath and Zhao, 2003), a BCF greater than 1 is one of the key characteristics required for a plant to be classified as a potential hyperaccumulator, demonstrating its ability to accumulate high concentrations of heavy metals without experiencing significant physiological harm.

Table 4. Maximum and minimum values of the Bioconcentration Factor (BCF) for the heavy metals in this study.

| | **BCF** | |
|---|---|---|
| | Maximum | Minimum |
| **Al** | 1.320 | 0.002 |
| **As** | 0.945 | 0.000 |
| **Cd** | 0.889 | 0.000 |
| **Cr** | 1.065 | 0.012 |
| **Cu** | 1.936 | 0.006 |
| **Fe** | 0.904 | 0.004 |
| **Hg** | 0.422 | 0.000 |
| **Mn** | 2.418 | 0.002 |
| **Ni** | 2.195 | 0.006 |
| **Pb** | 2.129 | 0.000 |
| **Zn** | 1.241 | 0.002 |

The total metal content accumulated in plant tissues serves as an indicator of phytoremediation efficiency. Table 5 presents the highest quantities of bioaccumulated metals observed in this study, based on the species exhibiting the greatest biomass. Data on dry biomass are available in the Supplementary Material (2). Specimen 5-*F. cymosa* showed the highest total Fe, Al, As and Pb accumulation, primarily due to its large biomass, and the sample 26-*Commelina* sp. also stood out due to its high biomass, metal content for the metal Ni, and its bioconcentration factor (BCF).

Table 5. Highest metal concentrations found in plant samples from “Lagoa da Conceição.” The “Sample” column refers to the specimen that presented the highest content for each metal.

| | **Highest metal content (mg)** | **Sample** |
|---|---|---|
| **Al** | 0.012 | *5-F. cymosa* |
| **As** | $1.53 \times 10^{-5}$ | *5-F. cymosa* |
| **Cd** | $3.35 \times 10^{-6}$ | *11-S. trilobata* |
| **Cr** | 0.00017 | *15-C. verticillata* |
| **Cu** | 0.00028 | *11-S. trilobata* |
| **Fe** | 0.024 | *5-F. cymosa* |
| **Hg** | $5.98 \times 10^{-5}$ | *4-Scirpus sp.* |
| **Mn** | 0.0047 | *25-E. bonariensis* |

| | | |
|---|---|---|
| **Ni** | $5.06x10^{-5}$ | *26-Commelina sp.* |
| **Pb** | $1.81x10^{-5}$ | *5-F. cymosa* |
| **Zn** | 0.0016 | *15-C. verticillata* |

The correlation diagram among the parameters analyzed in water (pH, alkalinity, salinity, DO, nitrates, phosphates, ammonia, heavy metals), sediment (OM, heavy metals), and the metal concentrations detected in plants is presented in Figure 3. No clear relationship (r>0.7) was found between metals in water and sediment and their accumulation in vegetation, nor with the environmental variables analyzed. This suggests that metal uptake in may be influenced by other factors or mechanisms not investigated in the study.

Total metal concentrations in plants and sediments with anthropogenic tracers (nutrients – $PO_4$, $NO_3$, and $NH_4$) measured in surface water at each sampling site showed no significant association. This finding suggests that metal accumulation in plants is not linked to domestic sewage contributions during the sampling period. The anthropogenic tracers correlated strongly (r=1) with organic matter content in sediment, reflecting the high organic load commonly associated with domestic sewage. Additionally, their correlation with Pb concentrations in water suggests a potential source for this element.

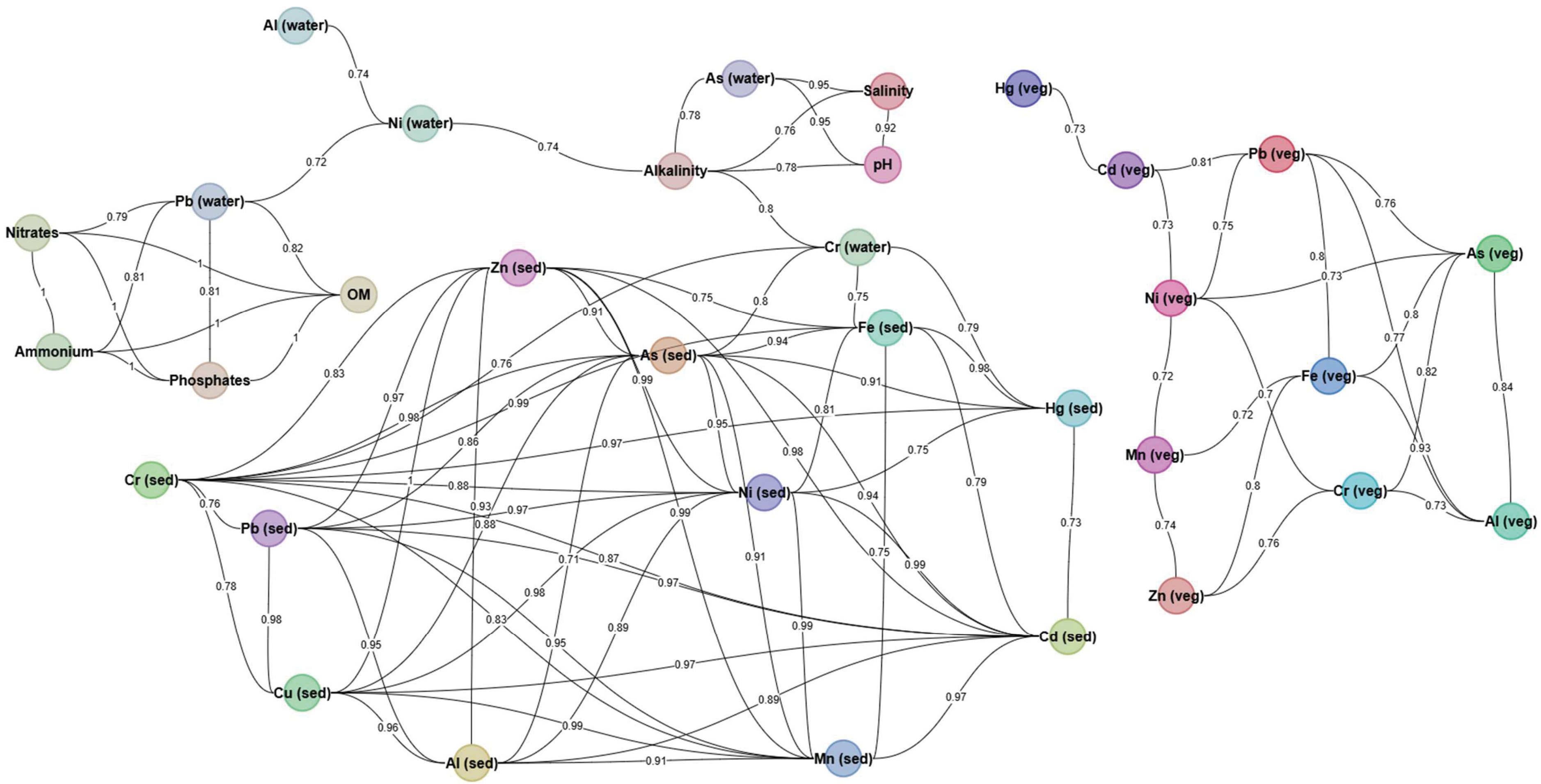


Figure 3. Correlation diagram of all variables. (sed): metals in sediment; (veg): metals in vegetation; (water): metals in water.

Figure 4 illustrates the dendrogram of heavy metal concentration among the analyzed specimens. It is possible to observe the separation into six distinct groups, composed of the following specimens:

- Group 1

7-*U. arrecta* (6-PON), 16-*H. wrightii* (4-MAR), 5-*F. cymosa* (12-CAN), 17-*P. racemosum* (11-POR)

- Group 2

12-*P. vaginatum* (5-GRA), 14-*U. arrecta* (2-LEI)

- Group 3

25-*E. bonariensis* (1-CON)

- Group 4

18-*S. californicus* (11-POR), 19-*P. vaginatum* (11-POR), 1-*E. interstincta* (9-CAM), 27-*S. marítima* (3-COS), 23-*S. alterniflora* (7-ARA), 15-*C. verticillata* (2-LEI), 3-*R. corimbosa* (9-CAM), 8-*V. luteola* (6-PON)

- Group 5

21-*P. vaginatum* (7-ARA), 28-*P. vaginatum* (3-COS), 29-*E. prostata* (3-COS), 4-*Scirpus* sp. (12-CAN), 24-*P. racemosum* (1-CON), 20-*Ipomea* sp. (11-POR), 22-*A. philoxeroides* (7-ARA)

- Group 6

9-*S. alterniflora* (6-PON), 26-*Commelina* sp. (1-CON), 10-*A. philoxeroides* (5-GRA), 6-*S. maritima* (12-CAN), 13-*L. peruviana* (2-LEI), 2-*B. monnieri* (9-CAM), 11-*S. trilobata* (5-GRA)

Group 1, the most distinct from the others in terms of metal concentration, comprised the specimens with the highest heavy metal accumulation (Table 2). Specimens from Group 2 may be clustered due to their tolerance to eutrophic environments and contamination from domestic wastewater effluents. Group 3, 25-*E. bonariensis* (1-CON) formed a unique clade, distinguished by its significant concentration of Mn compared to other heavy metals, despite being located in a control area where metal concentrations in both water and sediment were the lowest recorded in this study.

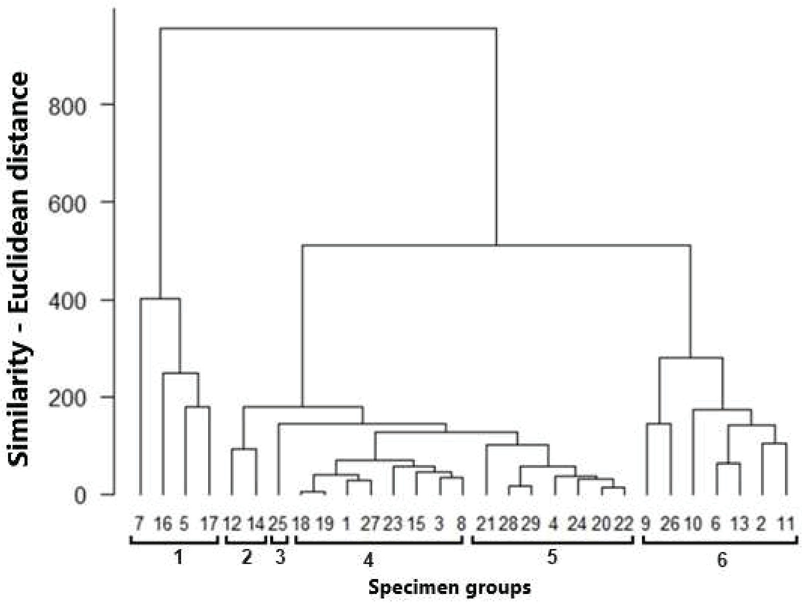


Figure 4. Dendrogram of concentrations of heavy metals in the plants.

Groups 4 and 5 exhibit specimens with similar accumulation patterns for the analyzed heavy metals, consisting of samples that showed lower concentrations in their tissues. These two groups were likely separated due to differences in the accumulation of certain elements, such as iron. Group 4 gathers species from transitional or brackish environments, many of which are estuarine and subject to variable salinity and moderate anthropogenic pressure. This group includes species such as 18-*S. californicus,* 23-*S. alterniflora,* and 27-*S. maritima*, which are known for their adaptability to dynamic environmental conditions and potential for phytoremediation. Group 5 consists of a more diverse assemblage, including 21-*P. vaginatum,* 28-*P. racemosum,* 22-*A. philoxeroides,* and 29-*E. prostata*. These species are generally found in intermediate conditions, either in less impacted locations or in areas subject to diffuse pollution, such as stormwater runoff and scattered boat activity. Group 6, while belonging to the same clade, was positioned further away from Groups 2, 3, 4, and 5, indicating a distinct behavior regarding metal accumulation in these plants. Notably, 9-*S. alterniflora* and 26-*Commelina* sp. (both in Group 6) are two of the three specimens that demonstrated the highest bioconcentration (high BCF) in this study.

According to the PCA plot (Figure 5), some plant samples clustered together, indicating similar metal concentration profiles, with Dimension 1 explaining 61.9% of the sample variance. The variation is primarily due to higher accumulation of heavy metals in individual samples, such as sample 16 (16-*H. wrightii*) and 4 (4-*Scirpus* sp.). Despite this, there is no explicit separation of samples by location. In fact, the three samples from location 2-LEI (in purple) did not show close coordinates on the plot, suggesting that the distance of epicenter of the accident is not a determining factor for the bioaccumulation in plants.

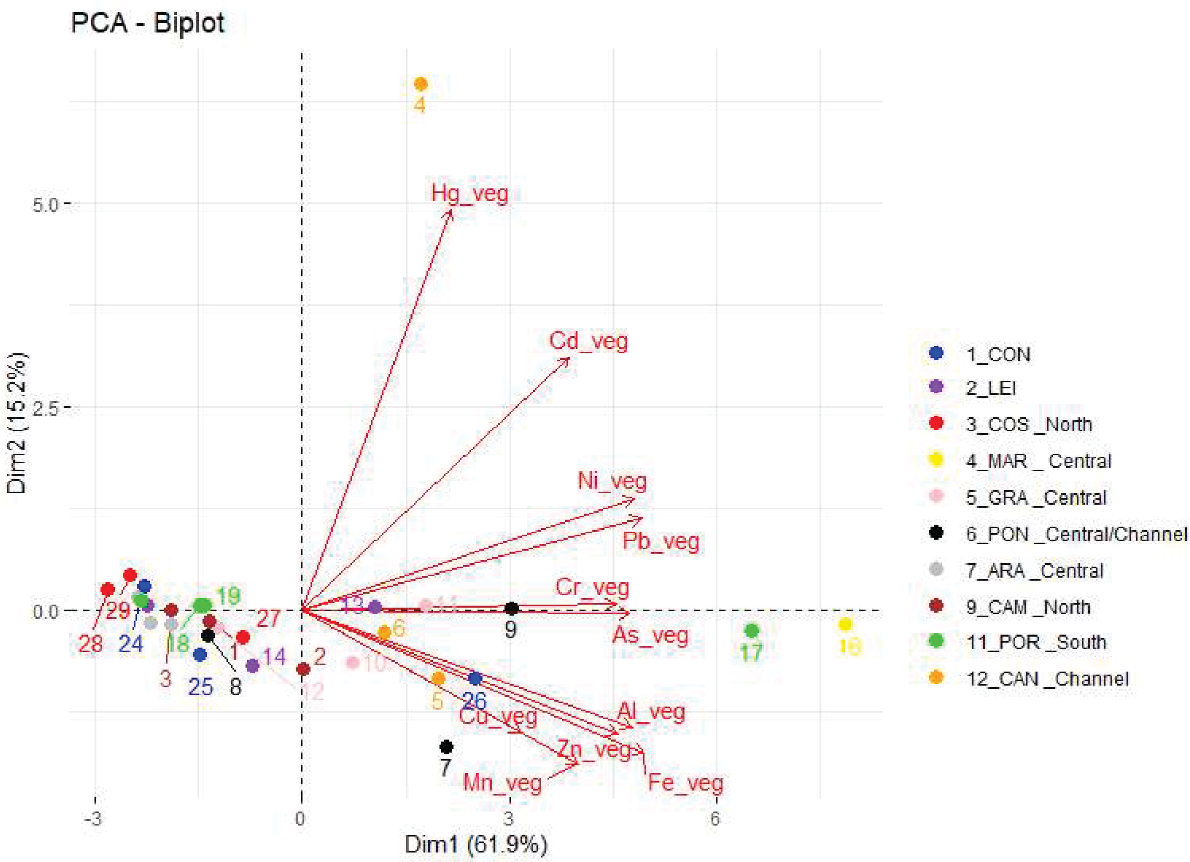


Figure 5. PCA plot showing clusters of metal concentrations in the plant samples (numbers reflect the sample identification—ID—, see Table 2). The colors of the samples indicate the sampling location.

To test whether the concentration of each metal in the plant samples is related to the distance from the contamination epicenter, the GAM (Generalized Additive Models) model was used, and the graphs are shown in Figure 6. According to this model, there is little explanation for the variability in bioaccumulation due to distance. Most of the graphs presented an R-sq.(adj) (adjusted $R^2$) close to zero or negative, indicating little relationship between distance and the variation in the data. The only metal with a considerable fit was Pb, which has a deviance explained = 57.4% and p = 0.0136 for s(Distance) – distance smoothed by the model. The metal Zn shows a slight indication of a relationship with p = 0.0531, but it is still at the threshold of statistical significance.

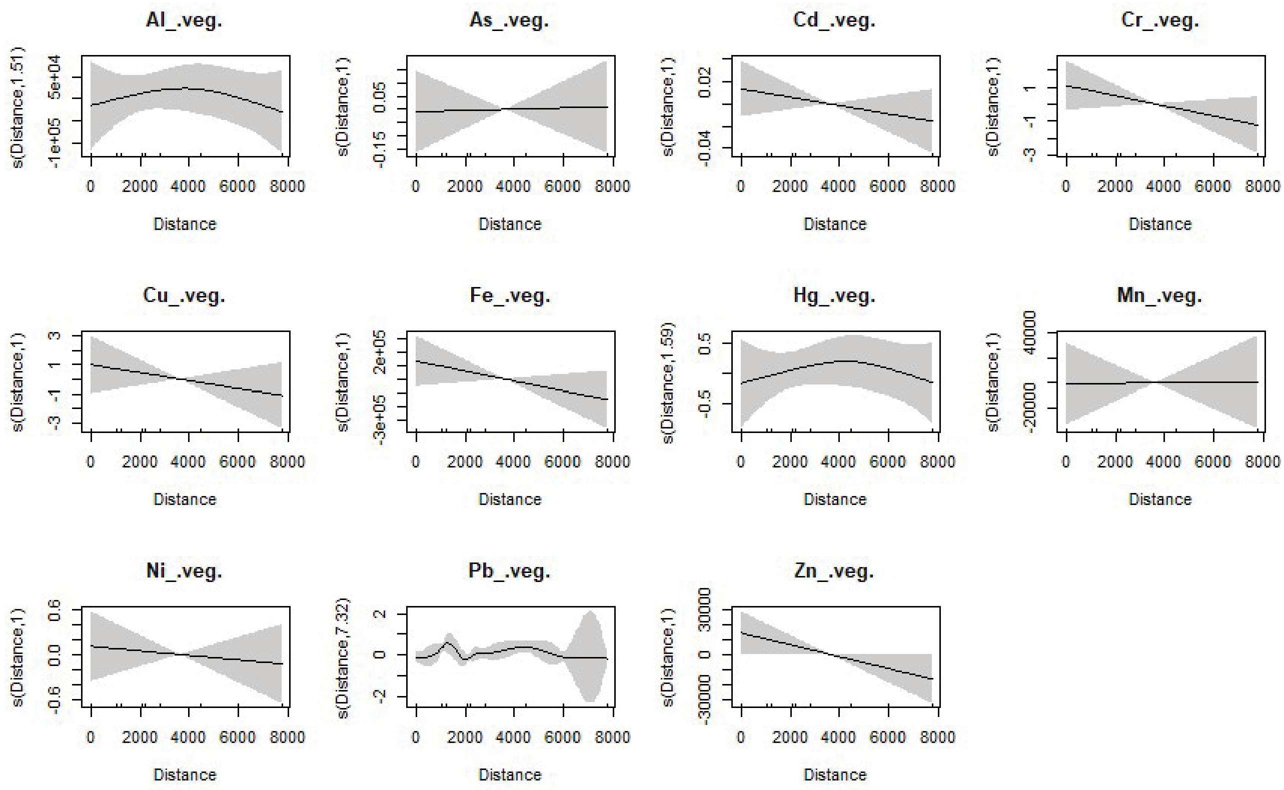


Figure 6. GAM model for the heavy metals accumulated in vegetation in relation to the distance from the epicenter of the LEI accident. Distance: distance from the epicenter to the sample collection point. S(Distance): Distance smoothed by the GAM.

The dbRDAp indicated that only environmental contamination (metal concentrations in water and sediment) and physical and chemical features of the water explained bioaccumulation in vegetation (Figure 7). There was no explanation above zero for any predictor matriz of other interactions between matrices. In line with this, the BIOENV showed that both some metal concentrations in water and sediment, and physical and chemical features mostly influenced bioaccumulation.

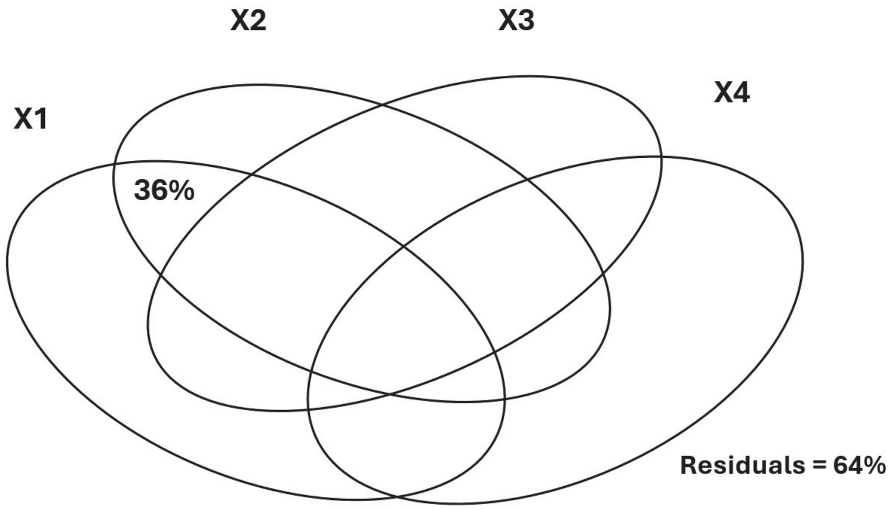


Figure 7. Variation partitioning considering the partial distance-based RDA showing the relative contribution of metal contamination in water and sediment (X1), physical and chemical features of the water (X2), spatial variables (X3), and functional traits of plants (X4). Values not show are 0% of explanation.

Among the water sample variables, temperature, aluminum concentration, and chromium concentration stood out, albeit with a weak correlation (R = 0.197) to biological patterns. In the statistical test involving sediment variables, aluminum and nickel concentrations showed a similarly weak correlation (R = 0.184). Notably, although aluminum is not essential for the physiological processes of plants, it appears to play a role in the bioaccumulation of other elements. This may be due to complex interactions that influence the transport or absorption of metals, a factor not fully explored in this study.

## 3.4 DISCUSSION

### 3.4.1 Concentration of heavy metals and bioaccumulation

The distance to the epicenter had a statistically significant effect but accounted for only a small portion of the water and sediment data variation, suggesting that other environmental or anthropogenic factors play a more dominant role — a pattern commonly observed in coastal and estuarine ecosystems. These environments are influenced by a combination of factors acting simultaneously, including hydrodynamics, land use, riverine inputs, marinas, boat traffic, and natural sedimentation processes. Despite this complexity, the effect of distance was not random, indicating that localized actions can produce spatially constrained impacts. In plant tissues, Pb was the only metal strongly associated with distance, with higher concentrations found farther from the epicenter, possibly due to localized sources and limited water circulation.

Statistical models reveal that physical and chemical variables may play a more decisive role in metal bioaccumulation than biological traits analyzed. This highlights the importance of considering multiple, overlapping sources of contamination beyond dam failure, indicating a scenario of systemic pollution driven by chronic anthropogenic pressures (Cardoso et al., 2025). Activities such as boat traffic and the presence of marinas may contribute to metal inputs through effluent discharges, fuel leaks, and antifouling paint residues, reinforcing the need for integrated environmental monitoring and remediation strategies.

Heavy metal concentrations in water and sediment showed no significant correlation with those in plant tissues (see Figure 3), suggesting that this species may actively contribute to local water purification by absorbing and sequestering contaminants in certain areas. Through bioaccumulation, the plant potentially helps reduce metal levels in its surroundings, thereby exhibiting a natural "cleaning" function.

Overall, the analyzed plant specimens showed a strong capacity for heavy metal accumulation, likely linked to their tolerance to environmental stress. Halophytes and other coastal species are known for thriving in contaminated soils, making them promising for phytoremediation (Turcios et al., 2021). In this study, the seagrass *Halodule wrightii* stood out for its high accumulation potential and adaptability to various abiotic stressors (Rivera-Guzmán et al., 2017; Bercovich et al., 2019; Bertelli et al., 2020). Common in tropical and subtropical coastal zones, this seagrass is recognized for its resistance to heavy metals and has been used as a biomonitor and in phytoremediation studies, especially under adverse conditions (Amado-Filho et al., 1999).

The dune grass specimen 17-*Panicum racemosum* is not a true halophyte, yet it was the second highest metal bioaccumulator in this study, particularly for Cr and As. Its rhizomatous growth, characterized by lateral expansion in multiple directions and the ability to cover large areas, may offer a competitive advantage in contaminated environments (Cordazzo et al., 2006). This growth pattern increases the plant's contact surface with the surrounding substrate, potentially enhancing metal uptake. In combination with other physiological or morphological traits, this strategy may contribute to its high bioaccumulation capacity.

Specimen 5-*F. cymosa*, which ranked third in total heavy metal accumulation, was collected from the "Channel" area, where surface water concentrations of these elements were elevated despite continuous water circulation driven by tidal activity. This observation suggests that the contaminants are not fully dispersed, possibly due to a persistent input of heavy metals in the area. The high accumulation underscores its potential for bioaccumulation in environments with significant pollutant loads. The elevated levels of Al, Fe, and Pb may stem from multiple sources, including effluent discharges from nearby urban areas, navigation-related activities, and the resuspension or erosion of contaminated sediments—phenomena commonly observed in coastal and lagoon systems subject to intense human activity. Notably, the Channel supports a large fleet of boats and hosts a fuel station along the lagoon's margin, both of which impose environmental pressures that may contribute to increased metal concentrations (Cardoso et al., 2025). *Fimbristylis cymosa* is native to Brazil and typically occurs in coastal habitats such as restinga (coastal dune vegetation). Although no studies have specifically documented this species as a heavy metal accumulator, members of the genus *Fimbristylis* have been reported to colonize contaminated environments, indicating a degree of tolerance to such conditions (Messou et al., 2013; Gajic & Pavlovic, 2018). Sample 5-*F. cymosa* also stood out due to its substantial biomass, as discussed below.

Sample 7-*U. arrecta*, a tropical tanner grass collected at the entrance of the Barra da Lagoa Channel, showed the fourth-highest heavy metal accumulation, likely related to its phenotypic plasticity and adaptability to stressful environments (Sato et al., 2021), traits that also contribute to its invasive success in Brazilian freshwater ecosystems. While its ability to tolerate and accumulate metals suggests potential for phytoremediation, its invasive nature demands caution, as it poses ecological risks that must be considered in bioremediation strategies (Argenta, 2011).

Different plant biotypes exhibit varying capacities for bioaccumulation (Figures 4 and 5), highlighting that metal accumulation in plants from “Lagoa da Conceição” is context-dependent, with no consistent grouping pattern based on species or location. For example, specimen 4–*Scirpus* sp. stood out (Figure 5) for concentrating the highest levels of mercury and accumulating significant amounts of nickel compared to nearby plants in the ranking. This genus is common in wetland environments and has been extensively studied for its role in heavy metal bioremediation (Gouder and Mahy, 2002; Carranza-Álvarez et al., 2008; Afrous et al., 2011). Its ability to retain mercury without showing signs of physiological stress—even flowering at the time of sampling—further supports its potential for use in wastewater treatment.

The phytoremediation potential of plant species can be initially assessed through laboratory-based assays under controlled conditions, including tolerance tests and physical and chemical analyses of the growth medium, which allow monitoring plant development under contaminant exposure. In natural environments, bioaccumulation analyses serve as indicators of the most promising species for remediation in contaminated areas. Quantifying pollutants in plant tissues is a key method for evaluating phytoremediation potential, while the Bioconcentration Factor (BCF) offers a complementary approach and is particularly useful for phytotechnology management (Qiu et al., 2011). High BCF values (BCF > 1), defined as the ratio between contaminant concentration in plant tissues and in the surrounding soil or water, suggest strong phytoremediation potential, especially via phytoextraction. Conversely, species with low BCF values (BCF < 1) may still be effective for phytostabilization, provided they are able to tolerate and immobilize heavy metals. In our study, several species exhibited exceptionally high BCFs, notably specimens 26–*Commelina* sp., 17–*P. racemosum*, and 9–*S. alterniflora*, supporting their selection as candidate species for future controlled pilot experiments and applied remediation initiatives.

Although 16–*H. wrightii* showed the highest overall metal accumulation, its low BCF suggests high uptake efficiency even in environments with low metal availability—an advantageous trait for phytoremediation. This may relate to its extensive root system, which could access contaminants from broader areas, including nautical structures near the marina where it was collected. In contrast, *Commelina* sp. —known for its potential in heavy metal phytoremediation, particularly in constructed wetlands (Barreto, 2011; Nathan et al., 2012)—is well-suited for such applications due to its high biomass, well-developed root systems, and tolerance to waterlogged conditions and pollutants. *C. communis*, a species within this genus, has been identified as a potential copper hyperaccumulator (Pan et al., 2021). The species of sample 9-*S. alterniflora* is recognized for its role in phytoremediation, particularly in stabilizing domestic effluents containing metals, oils, and other pollutants (Costa et al., 2012; Valiela et al., 1975).

The genus *Spartina* also includes species reported as hyperaccumulators (Padmavathiamma and Li, 2007).

Plants with lower BCFs may employ a variety of mechanisms to limit metal uptake, including symbiotic associations with mycorrhizal fungi, the release of root exudates (such as diffusates, exudates, and secretions) that bind metals, and alterations in rhizosphere pH that reduce metal bioavailability. These strategies enhance plant tolerance to heavy metals, enabling them to persist in contaminated environments. The specific mechanisms employed often depend on the type of metal and the plant's metabolic requirements, particularly in distinguishing between essential micronutrients like Cu and Zn, and non-essential toxic elements such as Cd (Baker and Walker, 1990; Chowdhury et al., 2015; Pasricha et al., 2021).

In the context of phytoremediation, it is essential to integrate data that reveal how and under what conditions a plant absorbs or stabilizes pollutants. In addition to the Bioconcentration Factor (BCF), which relates metal uptake to environmental availability, the plant's total biomass must also be considered. Species capable of accumulating larger total metal loads due to higher biomass may prove more effective for pollutant removal, even if their BCF values are not particularly high. Thus, the total amount of metal accumulated per unit area provides a more realistic indicator of phytoremediation potential (Ghosh and Singh, 2005). Metal concentration (mg/kg) reflects a plant's ability to accumulate metals per unit of dry mass, whereas the total metal content (mg) incorporates the biomass component, offering a more representative metric for assessing the effective removal of contaminants from the environment (Macek et al., 2008). While the BCF highlights physiological uptake efficiency, the total accumulated metal better reflects the practical efficacy of a species in remediation efforts. Considering these aspects, sample 5-*F. cymosa* emerged as the most promising candidate for environmental metal removal and may be suitable for application in pilot constructed wetland projects in the "Lagoa da Conceição." Likewise, findings for sample 25-*E. bonariensis* support previous studies indicating the phytoremediation potential of the *Eleocharis* genus (Hoang Ha et al., 2009), a conclusion further reinforced by this specimen's high biomass and consequently elevated Mn accumulation.

#### 3.4.1.1 Heavy Metals in Plants and Reported Levels

Considering the essential metals for plants—those that play key physiological roles in plant metabolism—iron showed the highest concentrations among all metals analyzed in this study. This may be associated with Fe precipitation with sulfides in anoxic sediments, as well as with rock weathering and the deposition of marine-influenced Fe oxides and hydroxides. The highest Fe concentration was recorded in the Central sector, where the sampling site is located near a marina heavily influenced by anthropogenic activities, including intense boat traffic and proximity to bridges. Construction materials were visibly buried at the site, which may explain the elevated levels of this metal. This location also presented the highest concentrations of Al, Cr, Ni, Pb, and Zn, likely for similar reasons.

Table 6 provides a comparative overview of heavy metal bioaccumulation data from studies conducted worldwide. Research carried out in India has reported manganese concentrations in plants that exceed those observed in the present study. In contrast, Ribeiro (1998) recorded lower Mn concentrations in the "Ratones" Mangrove, which is located near "Lagoa da Conceição" in "Florianópolis".

Chowdhury et al. (2015) reported higher copper concentrations in plants from urbanized areas compared to those observed in the present study, while researchers in Indonesia found lower Cu levels in plants near mining areas (Table 6). Nickel concentrations in plants from "Lagoa da Conceição" were similar to those reported by Ribeiro (1998) in "Florianópolis" and to values observed in Sundarban, India.

Plants from Lagoa da Conceição exhibited elevated Zn concentrations did not exhibit any apparent developmental impairments. The presence of Zn in surface waters at both the control site and near the effluent indicates contributions from both natural and anthropogenic sources. Antifouling paints—commonly used to protect wooden boats—contain Zn, Cd, Cr, Cu, and strontium chromate, and are considered a significant source of environmental contamination (Garcia, 1999; Costa and Wallner-Kersanach, 2013; Cardoso et al., 2025). Ribeiro (1998) reported significantly lower Zn levels in local plant material, while in India, the maximum Zn concentrations in plants were less than half of those found in "Lagoa da Conceição". In Bangladesh, a highly contaminated region, Zn concentrations were comparable to those observed in this study (Table 6). Zinc is known to exhibit moderate to high toxicity in aquatic environments (Garbarino et al., 1997).

Regarding non-essential metals, which have no known biological function in plants and can be toxic even at low concentrations, aluminum was found at high levels, likely due to its natural abundance, alongside Fe (ATSDR, 2022). In this study, chromium concentrations were notably high, exceeding the levels reported in plants from the “Ratones” Mangrove (Ribeiro, 1998) and in India (Chowdhury et al., 2015). According to Kabata-Pendias and Mukherjee (2007), Cr concentrations reached toxic levels in nearly all plant samples analyzed in this study (Table 6), with potential adverse effects. Only two specimens—25-*E. bonariensis* and 1-*E. interstincta*—showed Cr concentrations below the toxic threshold.

Some plants from “Lagoa da Conceição” exhibited elevated mercury levels compared to other studies (Table 6), despite the absence of concerning concentrations in water and sediment. This suggests that the plants may be bioaccumulating Hg, thereby reducing its levels in the environment. Lead was found at low concentrations, indicating a limited influx, likely from atmospheric sources. Higher Pb levels have been reported in plants in other studies. Cadmium was the metal found at the lowest concentrations in this study and was also not detected in previous plant studies conducted in “Florianópolis” (Ribeiro, 1998). In contrast, higher Cd levels have been observed in other countries, particularly in Bangladesh near gold mining areas.

All collected specimens fell within the normal concentration range for Cu, Zn, Pb, and Cd (Table 6). The zinc level in specimen 16–*H. wrightii* exceeded the phytotoxicity threshold proposed by Padmavathiamma and Li (2007), suggesting that this species, in this context, is tolerant to zinc. Nevertheless, the concentration remains within the normal range defined by Kabata-Pendias and Mukherjee (2007).

Table 6. Comparison of total metal concentrations in plants across studies (values in mg/kg dry weight).

| **Authors** | **Local** | **Fe** | **Al** | **Mn** | **Zn** | **Cu** | **Cr** | **Hg** | **Ni** | **As** | **Pb** | **Cd** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **This study** | "Lagoa da Conceição", Florianópolis-SC | 18.83 – 1306.97 | 8.98 – 586.13 | 2.58 – 231.77 | 1.27 – 124.5 | 0.27 – 13.72 | 0.412 – 12.20 | 0.04 – 5.49 | 0.06 – 3.23 | ND – 1.22 | ND – 1.45 | ND – 0.205 |
| **Ribeiro, 1998** | Ratones Mangrove, Florianópolis-SC | | | 15.11 – 49.46 | 8.75 – 22.55 | | 0.45 – 0.94 | | 2.39 – 2.93 | 0.12 – 0.62 | 1.11 – 2.20 | |
| **Karim et al., 2008** | Bangladesh | | | | 7.0 – 304.0 | | ND – 33.84 | | | 0.1 – 5.33 | | |
| **Chowdhury et al., 2015** | India Sundarban | | | 18.401 –1726 | 7.23 – 52.2 | 6.21 – 31.63 | 0.13 – 6.49 | 0.02–0.13 | 0.11 – 5.41 | 0.01 – 0.31 | 0.04 – 7.09 | 0.04 – 2.97 |
| **Nouri et al, 2016** | Morocco | 204.82 – 2459.66 | | | 33.52–175.35 | 5.33–25.48 | 0.67–4.58 | | | | 0.37–16.40 | 0.68 – 0.99 |
| **Ramlan et al., 2022** | Indonesia | | | | | 0.10 – 1.09 | | 0.12–0.46 | | | | 0.13 – 3.60 |
| **Kabata–Pendias and Mukherjee, 2007** | *Normal range* | | | | 25–150 | 5–30 | 0.1–0.5 | | | | 5–10 | 0.01–0.2 |
| | *Toxic range* | | | | 100–400 | 20–100 | 5–30 | | | | 30–300 | 5–30 |
| **Padmavathiamma and Li, 2007** | *Normal range* | | | | 10–150 | 3–30 | | | | | 0.5–10 | 0.05–2 |
| | *Toxic range* | | | | >100 | 20–100 | | | | | 30–300 | 5–700 |

## 3.5 CONCLUSION

Metal concentrations in surface water at “Lagoa da Conceição” often exceeded legal limits, especially for arsenic, manganese, and zinc, mainly in areas with low water circulation and intense human activity. Sediment analysis also revealed concerning levels of zinc and copper.

Bioaccumulation patterns in plants were more influenced by systemic pressures—such as boat traffic, antifouling paints, and fuel stations—than by the localized effect of the effluent lagoon rupture. While species and locations showed context-dependent variation*, Halodule wrightii, Panicum racemosum,* and *Fimbristylis cymosa* stood out as strong accumulators. *Commelina* sp. and Spartina alterniflora showed high phytoremediation potential. Efforts to implement treatment wetlands should account for both species-specific accumulation capacities and abiotic conditions.

*Halodule wrightii* proved to be a suitable sentinel species, due to its high phenotypic plasticity and resilience, which allow it to persist and accumulate metals even under variable and stressful conditions. In contrast, *Eleocharis bonariensis* showed signs of spatially sensitive responses to contamination, possibly due to its lower generalist tolerance compared to other species. These preliminary observations suggest its potential as a sentinel species, warranting further investigation.

Phytoremediation appears to be a viable, sustainable strategy for reducing contamination in the lagoon. Effective application depends not only on metal uptake efficiency but also on biomass production and manageability. *F. cymosa* showed excellent performance in this regard. Future studies should prioritize evaluating plant growth, biomass productivity, and practical manageability to maximize phytoremediation outcomes. Special attention should be given to the practical implementation of this technique to mitigate risks to both ecosystem integrity and human health—particularly in the northern sector of the lagoon, where seafood consumption is high and contamination represents a direct public health concern.

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## 3.8 SUPPLEMENTARY MATERIAL 2

```
> bioenv_result

Call:
bioenv(comm = dados_biologicos, env = dados_ambientais)

Subset of environmental variables with best correlation to community data.

Correlations:    spearman
Dissimilarities: bray
Metric:          euclidean

Best model has 3 parameters (max. 22 allowed):
Al Cr temperature
with correlation  0.197564
```

Figure 1. Results of BIOENV in the R software interface, considering metal concentrations and water parameters.

```
Call:
bioenv(comm = dados_biologicos, env = dados_ambientais)

Subset of environmental variables with best correlation to community data.

Correlations:    spearman
Dissimilarities: bray
Metric:          euclidean

Best model has 3 parameters (max. 22 allowed):
temperature Al__(sed) Ni_(sed)
with correlation  0.1831193
```

Figure 2. Results of BIOENV in the R software interface, considering metal concentrations and sediment parameters.

Table 1. Limits of Detection (LD) and Quantification (LQ) for metals and metalloids in plant samples.

| | **Plants** | |
|---|---|---|
| **Metal** | **LD (mg/kg)** | **LQ (mg/kg)** |
| **Al** | 0.0227 | 0.068 |
| **As** | 0.0017 | 0.005 |
| **Cd** | 0.0013 | 0.004 |
| **Cr** | 0.0013 | 0.004 |
| **Cu** | 0.0167 | 0.05 |
| **Fe** | 0.0333 | 0.1 |
| **Hg** | 0.001 | 0.003 |

| | | |
|---|---|---|
| **Mn** | 0.0167 | 0.05 |
| **Ni** | 0.0188 | 0.0565 |
| **Pb** | 0.0017 | 0.005 |
| **Zn** | 0.0033 | 0.01 |

Table 2. Principal Component Analysis – Eigenvalues, Percentage of Variance, and Cumulative Variance

| | **Dim.1** | **Dim.2** | **Dim.3** | **Dim.4** | **Dim.5** | **Dim.6** | **Dim.7** | **Dim.8** | **Dim.9** | **Dim.10** | **Dim.11** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variance** | 6.80 | 1.67 | 0.94 | 0.64 | 0.4 | 0.26 | 0.10 | 0.08 | 0.03 | 0.02 | 0.02 |
| **% of var.** | 61.88 | 15.23 | 8.57 | 5.86 | 3.63 | 2.42 | 0.95 | 0.72 | 0.28 | 0.20 | 0.19 |
| **Cumulative % of var.** | 61.88 | 77.12 | 85.7 | 91.5 | 95.1 | 97.6 | 98.5 | 99.3 | 99.59 | 99.80 | 100.0 |

Table 3. PCA - Coordinates, Contributions and CosÂ² of the First 10 Individuals.

| **ID** | **Dist** | **Dim.1** | **Ctr.1** | **Cos2.1** | **Dim.2** | **Ctr.2** | **Cos2.2** | **Dim.3** | **Ctr.3** | **Cos2.3** |
|---|---|---|---|---|---|---|---|---|---|---|
| **1.0** | 2.614 | -2.28 | 2.649 | 0.765 | 0.291 | 0.175 | 0.012 | -0.94 | 3.285 | 0.131 |
| **2.0** | 2.381 | -1.48 | 1.111 | 0.387 | -0.54 | 0.604 | 0.052 | 0.011 | 0.0 | 0.0 |
| **3.0** | 3.735 | 2.511 | 3.194 | 0.452 | -0.84 | 1.471 | 0.051 | 0.0 | 0.0 | 0.0 |
| **4.0** | 1.282 | 1.047 | 0.555 | 0.666 | 0.042 | 0.004 | 0.001 | -0.46 | 0.784 | 0.13 |
| **5.0** | 1.749 | -0.72 | 0.266 | 0.172 | -0.68 | 0.964 | 0.153 | 0.488 | 0.87 | 0.078 |
| **6.0** | 2.331 | -2.24 | 2.549 | 0.926 | 0.059 | 0.007 | 0.001 | -0.54 | 1.082 | 0.054 |
| **7.0** | 1.665 | -0.86 | 0.376 | 0.268 | -0.33 | 0.236 | 0.041 | 0.766 | 2.142 | 0.211 |
| **8.0** | 2.927 | -2.81 | 4.004 | 0.923 | 0.245 | 0.124 | 0.007 | -0.68 | 1.72 | 0.055 |
| **9.0** | 2.642 | -2.48 | 3.136 | 0.887 | 0.423 | 0.368 | 0.026 | -0.63 | 1.471 | 0.058 |
| **10.0** | 7.986 | 7.872 | 31.39 | 0.972 | -0.18 | 0.07 | 0.001 | -0.98 | 3.51 | 0.015 |

Table 4. Principal Component Analysis – Coordinates, Contributions, and Cos² of the First 10 Variables

| **Variable** | **Dim.1** | **Ctr.1** | **Cos2.1** | **Dim.2** | **Ctr.2** | **Cos2.2** | **Dim.3** | **Ctr.3** | **Cos2.3** |
|---|---|---|---|---|---|---|---|---|---|
| **Al_veg** | 0.872 | 11.159 | 0.76 | -0.264 | 4.147 | 0.07 | -0.186 | 3.68 | 0.035 |
| **As_veg** | 0.867 | 11.043 | 0.752 | -0.008 | 0.004 | 0.0 | -0.212 | 4.759 | 0.045 |
| **Cd_veg** | 0.705 | 7.296 | 0.497 | 0.567 | 19.146 | 0.321 | 0.313 | 10.403 | 0.098 |
| **Cr_veg** | 0.83 | 10.108 | 0.688 | 0.013 | 0.011 | 0.0 | -0.377 | 15.092 | 0.142 |
| **Cu_veg** | 0.577 | 4.896 | 0.333 | -0.275 | 4.496 | 0.075 | 0.728 | 56.214 | 0.53 |
| **Fe_veg** | 0.904 | 11.996 | 0.817 | -0.32 | 6.091 | 0.102 | 0.004 | 0.002 | 0.0 |
| **Hg_veg** | 0.392 | 2.26 | 0.154 | 0.898 | 48.139 | 0.807 | -0.092 | 0.892 | 0.008 |
| **Mn_veg** | 0.73 | 7.833 | 0.533 | -0.344 | 7.08 | 0.119 | -0.151 | 2.41 | 0.023 |
| **Ni_veg** | 0.878 | 11.337 | 0.772 | 0.251 | 3.752 | 0.063 | -0.094 | 0.946 | 0.009 |
| **Pb_veg** | 0.898 | 11.847 | 0.807 | 0.205 | 2.517 | 0.042 | 0.224 | 5.337 | 0.05 |

Table 5. Metal concentrations in the plants tissues (dw: dry weight).

| **Sample** | Local | **Species** | Al mg/Kg (dw) | As mg/Kg (dw) | Cd mg/Kg (dw) | Cr mg/Kg (dw) | Cu mg/Kg (dw) | Fe mg/Kg (dw) | Hg mg/Kg (dw) | Mn mg/Kg (dw) | Ni mg/Kg (dw) | Pb mg/Kg (dw) | Zn mg/Kg (dw) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1-E. interstincta* | 9 | *Eleocharis interstincta* | 59.938 | 0.288 | 0.022 | 0.579 | 3.417 | 207.885 | <0.003 | 27.615 | 0.711 | 0.212 | 26.759 |
| *2-B. monnieri* | 9 | *Bacopa monnieri* | 106.004 | 0.515 | 0.017 | 0.841 | 11.303 | 598.79 | <0.003 | 24.361 | 1.052 | 0.301 | 19.751 |
| *3-R. corimbosa* | 9 | *Rhyncosphora corimbosa* | 68.764 | 0.121 | 0.016 | 1.295 | 1.268 | 172.623 | <0.003 | 26.025 | 0.407 | 0.172 | 13.498 |
| *4-Scirpus sp.* | 12 | *Scirpus sp.* | 11.778 | 0.402 | 0.205 | 2.269 | 2.306 | 75.45 | 5.493 | 6.617 | 2.874 | 0.85 | 4.184 |
| *5-F. cymosa* | 12 | *Fimbristylis cymosa* | 572.911 | 0.711 | 0.033 | 1.619 | 4.94 | 1104.894 | 0.233 | 38.457 | 0.808 | 0.846 | 14.379 |
| *6-S. maritima* | 12 | *Spartina maritima* | 246.935 | 0.371 | 0.061 | 4.557 | 4.268 | 577.541 | 0.229 | 90.495 | 1.383 | 0.428 | 45.221 |
| *7-U. arrecta* | 6 | *Urochloa arrecta* | 238.137 | 0.237 | 0.054 | 1.443 | 5.392 | 972.512 | 0.092 | 231.765 | 1.631 | 0.322 | 91.76 |
| *8-V. luteola* | 6 | *Vigna luteola* | 47.461 | 0.058 | 0.029 | 0.985 | 8.511 | 156.067 | 0.04 | 42.106 | 0.747 | 0.112 | 21.176 |
| *9-S. alterniflora* | 6 | *Spartina alterniflora* | 332.245 | 0.485 | 0.088 | 6.479 | 5.789 | 762.232 | 0.677 | 117.829 | 1.921 | 0.741 | 62.574 |
| *10-A. philoxeroides* | 5 | *Alternanthera philoxeroides* | 111.189 | 0.278 | 0.045 | 1.916 | 12.588 | 456.379 | <0.003 | 31.572 | 0.591 | 0.717 | 61.083 |
| *11-S. trilobata* | 5 | *Sphagneticola trilobata* | 185.214 | 0.326 | 0.165 | 1.082 | 13.72 | 645.571 | <0.003 | 57.335 | 0.511 | 0.736 | 56.528 |
| *12-P. vaginatum* | 5 | *Paspalum vaginatum* | 50.596 | 0.112 | 0.033 | 1.15 | 6.817 | 309.978 | <0.003 | 23.101 | 0.552 | 0.288 | 18.544 |
| *13-L. peruviana* | 2 | *Ludwigea peruviana* | 233.296 | 0.343 | 0.055 | 4.606 | 3.931 | 516.749 | 0.538 | 82.104 | 1.335 | 0.435 | 45.02 |
| *14-U. arrecta* | 2 | *Urochloa arrecta* | 50.823 | 0.091 | 0.024 | 1.034 | 6.692 | 258.952 | <0.003 | 97.049 | 1.21 | 0.121 | 44.877 |
| *15-C. verticillata* | 2 | *Cissus verticillata* | 55.395 | 0.097 | 0.014 | 1.133 | 0.905 | 124.009 | 0.141 | 19.589 | 0.303 | 0.088 | 11.012 |
| *16-H. wrightii* | 4 | *Halodule wrightii* | 586.13 | 1.162 | 0.133 | 12.198 | 9.479 | **1306.973** | 1.645 | 205.59 | 3.226 | 1.045 | 124.005 |
| *17-P. racemosum* | 11 | *Panicum racemosum* | 506.553 | 1.215 | 0.096 | 11.363 | 8.378 | 1110.812 | 1.408 | 179.964 | 2.793 | 0.85 | 100.592 |
| *18-S. californicus* | 11 | *Scirpus californicus* | 91.661 | 0.264 | 0.019 | 2.271 | 1.475 | 204.783 | 0.27 | 32.069 | 0.455 | 0.113 | 15.875 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *19-P. vaginatum* | 11 | *Paspalum vaginatum* | 93.913 | 0.286 | 0.016 | 2.664 | 1.53 | 198.932 | 0.232 | 31.525 | 0.468 | 0.131 | 14.641 |
| *20-Ipomea sp.* | 11 | *Ipomea sp.* | 44.891 | 0.169 | 0.007 | 1.582 | 0.659 | 95.167 | 0.133 | 14.678 | 0.197 | 0.051 | 6.547 |
| *21-P. vaginatum* | 7 | *Paspalum vaginatum* | 119.413 | 0.01 | 0.017 | 0.707 | 3.849 | 73.662 | <0.003 | 11.911 | 0.559 | 0.07 | 26.066 |
| *22-A. philoxeroides* | 7 | *Alternanthera philoxeroides* | 39.259 | 0.238 | 0.005 | 1.655 | 0.52 | 81.611 | 0.215 | 11.958 | 0.096 | <0.005 | 5.357 |
| *23-S. alterniflora* | 7 | *Spartina alterniflora* | 16.431 | 0.063 | 0.009 | 0.868 | 1.285 | 134.954 | <0.003 | 55.939 | 0.422 | 0.06 | 12.123 |
| *24-P. racemosum* | 1 | *Panicum racemosum* | 31.375 | 0.346 | 0.005 | 1.829 | 0.396 | 58.637 | 0.315 | 8.378 | 0.115 | <0.005 | 3.502 |
| *25-E. bonariensis* | 1 | *Eleocharis bonariensis* | 54.873 | <0.005 | 0.027 | 0.412 | 3.889 | 115.325 | <0.003 | 146.063 | 0.61 | 0.046 | 20.673 |
| *26-Commelina sp.* | 1 | *Commelina sp.* | 381.319 | 0.671 | 0.064 | 1.728 | 8.543 | 673.954 | <0.003 | 206.677 | 2.724 | 0.481 | 14.88 |
| *27-S. maritima* | 3 | *Spartina maritima* | 56.714 | 0.452 | 0.024 | 1.206 | 8.237 | 197.586 | <0.003 | 26.765 | 0.679 | 0.249 | 20.233 |
| *28-P. vaginatum* | 3 | *Paspalum vaginatum* | 8.979 | 0.158 | <0.004 | 0.808 | 0.272 | 18.826 | 0.225 | 2.581 | 0.061 | 0.027 | 1.269 |
| *29-E. prostata* | 3 | *Eclipta prostrata* | 10.022 | 0.228 | 0.011 | 1.085 | 0.896 | 36.221 | 0.456 | 6.793 | 0.161 | 0.022 | 3.696 |

Table 6. Total metal content in plants, calculated based on biomass. Blank values: ND (below the detection limit).

| **Sample** | Biomass (kg) | Al (mg) total | As (mg) total | Cd (mg) total) | Cr (mg) total | Cu (mg) total | Fe (mg) total | Hg (mg) total | Mn (mg) total | Ni (mg) total | Pb (mg) total | Zn (mg) total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1-E. interstincta* | 2.0E-05 | 1.2E-03 | 5.6E-06 | 4.3E-07 | 1.1E-05 | 6.7E-05 | 4.1E-03 | | 5.4E-04 | 1.4E-05 | 4.1E-06 | 5.2E-04 |
| *2-B. monnieri* | 2.2E-05 | 2.4E-03 | 1.1E-05 | 3.8E-07 | 1.9E-05 | 2.5E-04 | 1.3E-02 | | 5.4E-04 | 2.3E-05 | 6.7E-06 | 4.4E-04 |
| *3-R. corimbosa* | 4.7E-05 | 3.2E-03 | 5.6E-06 | 7.4E-07 | 6.0E-05 | 5.9E-05 | 8.0E-03 | | 1.2E-03 | 1.9E-05 | 8.0E-06 | 6.3E-04 |
| *4-Scirpus sp.* | 1.1E-05 | 1.3E-04 | 4.4E-06 | 2.2E-06 | 2.5E-05 | 2.5E-05 | 8.2E-04 | 6.0E-05 | 7.2E-05 | 3.1E-05 | 9.3E-06 | 4.6E-05 |
| *5-F. cymosa* | 2.2E-05 | 1.2E-02 | 1.5E-05 | 7.1E-07 | 3.5E-05 | 1.1E-04 | 2.4E-02 | 5.0E-06 | 8.3E-04 | 1.7E-05 | 1.8E-05 | 3.1E-04 |
| *6-S. maritima* | 2.4E-05 | 5.9E-03 | 8.8E-06 | 1.5E-06 | 1.1E-04 | 1.0E-04 | 1.4E-02 | 5.5E-06 | 2.2E-03 | 3.3E-05 | 1.0E-05 | 1.1E-03 |
| *7-U. arrecta* | 1.4E-05 | 3.4E-03 | 3.4E-06 | 7.8E-07 | 2.1E-05 | 7.8E-05 | 1.4E-02 | 1.3E-06 | 3.3E-03 | 2.3E-05 | 4.6E-06 | 1.3E-03 |
| *8-V. luteola* | 2.2E-05 | 1.0E-03 | 1.3E-06 | 6.3E-07 | 2.1E-05 | 1.8E-04 | 3.4E-03 | 8.6E-07 | 9.1E-04 | 1.6E-05 | 2.4E-06 | 4.6E-04 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *9-S. alterniflora* | 2.3E-05 | 7.7E-03 | 1.1E-05 | 2.0E-06 | 1.5E-04 | 1.3E-04 | 1.8E-02 | 1.6E-05 | 2.7E-03 | 4.4E-05 | 1.7E-05 | 1.4E-03 |
| *10-A. philoxeroides* | 2.2E-05 | 2.5E-03 | 6.1E-06 | 9.9E-07 | 4.2E-05 | 2.8E-04 | 1.0E-02 | | 7.0E-04 | 1.3E-05 | 1.6E-05 | 1.3E-03 |
| *11-S. trilobata* | 2.0E-05 | 3.8E-03 | 6.6E-06 | 3.3E-06 | 2.2E-05 | 2.8E-04 | 1.3E-02 | | 1.2E-03 | 1.0E-05 | 1.5E-05 | 1.1E-03 |
| *12-P. vaginatum* | 2.0E-05 | 9.9E-04 | 2.2E-06 | 6.5E-07 | 2.3E-05 | 1.3E-04 | 6.1E-03 | | 4.5E-04 | 1.1E-05 | 5.6E-06 | 3.6E-04 |
| *13-L. peruviana* | 3.6E-05 | 8.5E-03 | 1.2E-05 | 2.0E-06 | 1.7E-04 | 1.4E-04 | 1.9E-02 | 2.0E-05 | 3.0E-03 | 4.8E-05 | 1.6E-05 | 1.6E-03 |
| *14-U. arrecta* | 1.2E-05 | 6.0E-04 | 1.1E-06 | 2.8E-07 | 1.2E-05 | 7.9E-05 | 3.1E-03 | | 1.1E-03 | 1.4E-05 | 1.4E-06 | 5.3E-04 |
| *15-C. verticillata* | 1.5E-04 | 8.4E-03 | 1.5E-05 | 2.1E-06 | 1.7E-04 | 1.4E-04 | 1.9E-02 | 2.1E-05 | 3.0E-03 | 4.6E-05 | 1.3E-05 | 1.7E-03 |
| *16-H. wrightii* | 1.3E-05 | 7.7E-03 | 1.5E-05 | 1.7E-06 | 1.6E-04 | 1.2E-04 | 1.7E-02 | 2.2E-05 | 2.7E-03 | 4.2E-05 | 1.4E-05 | 1.6E-03 |
| *17-P. racemosum* | 1.1E-05 | 5.4E-03 | 1.3E-05 | 1.0E-06 | 1.2E-04 | 8.9E-05 | 1.2E-02 | 1.5E-05 | 1.9E-03 | 3.0E-05 | 9.0E-06 | 1.1E-03 |
| *18-S. californicus* | 3.1E-05 | 2.8E-03 | 8.1E-06 | 5.8E-07 | 6.9E-05 | 4.5E-05 | 6.3E-03 | 8.3E-06 | 9.8E-04 | 1.4E-05 | 3.5E-06 | 4.9E-04 |
| *19-P. vaginatum* | 1.7E-05 | 1.6E-03 | 4.9E-06 | 2.7E-07 | 4.5E-05 | 2.6E-05 | 3.4E-03 | 3.9E-06 | 5.4E-04 | 8.0E-06 | 2.2E-06 | 2.5E-04 |
| *20-Ipomea sp.* | 2.1E-05 | 9.6E-04 | 3.6E-06 | 1.5E-07 | 3.4E-05 | 1.4E-05 | 2.0E-03 | 2.8E-06 | 3.1E-04 | 4.2E-06 | 1.1E-06 | 1.4E-04 |
| *21-P. vaginatum* | 1.7E-05 | 2.0E-03 | 1.7E-07 | 2.8E-07 | 1.2E-05 | 6.4E-05 | 1.2E-03 | | 2.0E-04 | 9.3E-06 | 1.2E-06 | 4.4E-04 |
| *22-A. philoxeroides* | 1.7E-05 | 6.5E-04 | 4.0E-06 | 8.3E-08 | 2.7E-05 | 8.6E-06 | 1.4E-03 | 3.6E-06 | 2.0E-04 | 1.6E-06 | | 8.9E-05 |
| *23-S. alterniflora* | 3.3E-05 | 5.5E-04 | 2.1E-06 | 3.0E-07 | 2.9E-05 | 4.3E-05 | 4.5E-03 | | 1.9E-03 | 1.4E-05 | 2.0E-06 | 4.0E-04 |
| *24-P. racemosum* | 1.5E-05 | 4.7E-04 | 5.2E-06 | 7.5E-08 | 2.7E-05 | 5.9E-06 | 8.7E-04 | 4.7E-06 | 1.2E-04 | 1.7E-06 | | 5.2E-05 |
| *25-E. bonariensis* | 3.3E-05 | 1.8E-03 | | 8.8E-07 | 1.3E-05 | 1.3E-04 | 3.8E-03 | | 4.8E-03 | 2.0E-05 | 1.5E-06 | 6.7E-04 |
| *26-Commelina sp.* | 1.9E-05 | 7.1E-03 | 1.2E-05 | 1.2E-06 | 3.2E-05 | 1.6E-04 | 1.3E-02 | | 3.8E-03 | 5.1E-05 | 8.9E-06 | 2.8E-04 |
| *27-S. maritima* | 1.2E-05 | 6.7E-04 | 5.4E-06 | 2.9E-07 | 1.4E-05 | 9.8E-05 | 2.4E-03 | | 3.2E-04 | 8.1E-06 | 3.0E-06 | 2.4E-04 |
| *28-P. vaginatum* | 4.0E-05 | 3.6E-04 | 6.4E-06 | | 3.3E-05 | 1.1E-05 | 7.6E-04 | 9.1E-06 | 1.0E-04 | 2.5E-06 | 1.1E-06 | 5.1E-05 |
| *29-E. prostata* | 4.9E-05 | 5.0E-04 | 1.1E-05 | 5.4E-07 | 5.4E-05 | 4.4E-05 | 1.8E-03 | 2.3E-05 | 3.4E-04 | 8.0E-06 | 1.1E-06 | 1.8E-04 |
| *Maximum* | | 1.2E-02 | 1.5E-05 | 3.3E-06 | 1.7E-04 | 2.8E-04 | 2.4E-02 | 6.0E-05 | 4.8E-03 | 5.1E-05 | 1.8E-05 | 1.7E-03 |

Table 7. Bioconcentration factor for each metal. Zero values reflect the absence of sediment concentration data.

| **Sample** | Al | As | Cd | Cr | Cu | Fe | Hg | Mn | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *1-E. interstincta* | 0.058 | 0.044 | 0.046 | 0.012 | 0.148 | 0.029 | 0.000 | 0.047 | 0.103 | 0.079 | 0.089 |
| *2-B. monnieri* | 0.103 | 0.078 | 0.036 | 0.018 | 0.488 | 0.084 | 0.000 | 0.041 | 0.152 | 0.112 | 0.066 |
| *3-R. corimbosa* | 0.067 | 0.018 | 0.034 | 0.027 | 0.055 | 0.024 | 0.000 | 0.044 | 0.059 | 0.064 | 0.045 |
| *4-Scirpus sp.* | 0.014 | 0.071 | 0.586 | 0.064 | 0.132 | 0.014 | 0.362 | 0.016 | 0.520 | 0.390 | 0.019 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *5-F. cymosa* | 0.674 | 0.126 | 0.094 | 0.046 | 0.284 | 0.212 | 0.015 | 0.093 | 0.146 | 0.388 | 0.065 |
| *6-S. maritima* | 0.290 | 0.066 | 0.174 | 0.129 | 0.245 | 0.111 | 0.015 | 0.218 | 0.250 | 0.196 | 0.205 |
| *7-U. arrecta* | 0.816 | 0.112 | 0.524 | 0.101 | 0.789 | 0.423 | 0.015 | 1.201 | 0.755 | 0.925 | 0.987 |
| *8-V. luteola* | 0.163 | 0.027 | 0.282 | 0.069 | 1.246 | 0.068 | 0.007 | 0.218 | 0.346 | 0.322 | 0.228 |
| *9-S. alterniflora* | 1.138 | 0.230 | 0.854 | 0.453 | 0.847 | 0.331 | 0.111 | 0.610 | 0.889 | 2.129 | 0.673 |
| *10-A. philoxeroides* | 0.201 | 0.066 | 0.203 | 0.065 | 0.819 | 0.091 | 0.000 | 0.075 | 0.134 | 0.434 | 0.306 |
| *11-S. trilobata* | 0.334 | 0.077 | 0.743 | 0.036 | 0.893 | 0.129 | 0.000 | 0.137 | 0.116 | 0.446 | 0.283 |
| *12-P. vaginatum* | 0.091 | 0.027 | 0.149 | 0.039 | 0.444 | 0.062 | 0.000 | 0.055 | 0.125 | 0.174 | 0.093 |
| *13-L. peruviana* | 0.483 | 0.135 | 0.294 | 0.267 | 0.412 | 0.199 | 0.088 | 0.429 | 0.449 | 0.293 | 0.399 |
| *14-U. arrecta* | 0.105 | 0.036 | 0.128 | 0.060 | 0.701 | 0.100 | 0.000 | 0.507 | 0.407 | 0.081 | 0.398 |
| *15-C. verticillata* | 0.115 | 0.038 | 0.075 | 0.066 | 0.095 | 0.048 | 0.023 | 0.102 | 0.102 | 0.059 | 0.098 |
| *16-H. wrightii* | 0.596 | 0.413 | 0.564 | 0.661 | 0.652 | 0.430 | 0.333 | 0.902 | 0.860 | 0.491 | 0.719 |
| *17-P. racemosum* | 1.320 | 0.870 | 0.787 | 1.065 | 1.223 | 0.627 | 0.423 | 1.818 | 1.560 | 0.839 | 1.241 |
| *18-S. californicus* | 0.239 | 0.189 | 0.156 | 0.213 | 0.215 | 0.116 | 0.081 | 0.324 | 0.254 | 0.112 | 0.196 |
| *19-P. vaginatum* | 0.245 | 0.205 | 0.131 | 0.250 | 0.223 | 0.112 | 0.070 | 0.319 | 0.261 | 0.129 | 0.181 |
| *20-Ipomea sp.* | 0.117 | 0.121 | 0.057 | 0.148 | 0.096 | 0.054 | 0.040 | 0.148 | 0.110 | 0.050 | 0.081 |
| *21-P. vaginatum* | 0.196 | 0.004 | 0.097 | 0.049 | 0.391 | 0.032 | 0.000 | 0.086 | 0.227 | 0.051 | 0.237 |
| *22-A. philoxeroides* | 0.065 | 0.106 | 0.028 | 0.115 | 0.053 | 0.035 | 0.051 | 0.086 | 0.039 | 0.000 | 0.049 |
| *23-S. alterniflora* | 0.027 | 0.028 | 0.051 | 0.060 | 0.131 | 0.058 | 0.000 | 0.402 | 0.171 | 0.044 | 0.110 |
| *24-P. racemosum* | 0.094 | 0.487 | 0.069 | 0.378 | 0.090 | 0.079 | 0.251 | 0.098 | 0.093 | 0.000 | 0.067 |
| *25-E. bonariensis* | 0.165 | 0.000 | 0.375 | 0.085 | 0.881 | 0.155 | 0.000 | 1.709 | 0.492 | 0.096 | 0.394 |
| *26-Commelina sp.* | 1.145 | 0.945 | 0.889 | 0.357 | 1.936 | 0.904 | 0.000 | 2.418 | 2.195 | 1.002 | 0.284 |
| *27-S. maritima* | 0.015 | 0.064 | 0.036 | 0.031 | 0.183 | 0.039 | 0.000 | 0.025 | 0.065 | 0.048 | 0.040 |
| *28-P. vaginatum* | 0.002 | 0.022 | 0.000 | 0.021 | 0.006 | 0.004 | 0.020 | 0.002 | 0.006 | 0.005 | 0.002 |
| *29-E. prostata* | 0.003 | 0.032 | 0.016 | 0.028 | 0.020 | 0.007 | 0.040 | 0.006 | 0.015 | 0.004 | 0.007 |
| *Maximum* | 1.320 | 0.945 | 0.889 | 1.065 | 1.936 | 0.904 | 0.423 | 2.418 | 2.195 | 2.129 | 1.241 |
| *Minimum* | 0.002 | 0.000 | 0.000 | 0.012 | 0.006 | 0.004 | 0.000 | 0.002 | 0.006 | 0.000 | 0.002 |

Table 8. Correlation matrix of sediment, water and plant parameters.

| | Al (veg) | As (veg) | Cd (veg) | Cr (veg) | Cu (veg) | Fe (veg) | Hg (veg) | Mn (veg) | Ni (veg) | Pb (veg) | Zn (veg) | Al (sed) | As (sed) | Cd (sed) | Cr (sed) | Cu (sed) | Fe (sed) | Hg (sed) | Mn (sed) | Ni (sed) | Pb (sed) | Zn (sed) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Al (veg) | 1,000 | | | | | | | | | | | | | | | | | | | | | |
| As (veg) | 0,836 | 1,000 | | | | | | | | | | | | | | | | | | | | |
| Cd (veg) | 0,421 | 0,494 | 1,000 | | | | | | | | | | | | | | | | | | | |
| Cr (veg) | 0,729 | 0,817 | 0,480 | 1,000 | | | | | | | | | | | | | | | | | | |
| Cu (veg) | 0,414 | 0,409 | 0,447 | 0,241 | 1,000 | | | | | | | | | | | | | | | | | |
| Fe (veg) | 0,931 | 0,797 | 0,473 | 0,684 | 0,576 | 1,000 | | | | | | | | | | | | | | | | |
| Hg (veg) | 0,103 | 0,339 | 0,727 | 0,348 | -0,081 | 0,074 | 1,000 | | | | | | | | | | | | | | | |
| Mn (veg) | 0,666 | 0,513 | 0,361 | 0,555 | 0,380 | 0,719 | 0,022 | 1,000 | | | | | | | | | | | | | | |
| Ni (veg) | 0,674 | 0,734 | 0,726 | 0,704 | 0,401 | 0,674 | 0,599 | 0,715 | 1,000 | | | | | | | | | | | | | |
| Pb (veg) | 0,767 | 0,761 | 0,809 | 0,654 | 0,596 | 0,796 | 0,501 | 0,441 | 0,751 | 1,000 | | | | | | | | | | | | |
| Zn (veg) | 0,673 | 0,600 | 0,497 | 0,758 | 0,570 | 0,799 | 0,094 | 0,741 | 0,631 | 0,652 | 1,000 | | | | | | | | | | | |
| Al (sed) | -0,228 | -0,014 | -0,187 | -0,153 | -0,134 | -0,247 | -0,011 | -0,315 | -0,230 | -0,180 | -0,246 | 1,000 | | | | | | | | | | |
| As (sed) | -0,160 | -0,013 | 0,026 | -0,223 | 0,069 | -0,083 | 0,103 | -0,429 | -0,150 | 0,095 | -0,195 | 0,711 | 1,000 | | | | | | | | | |
| Cd (sed) | -0,216 | -0,006 | -0,119 | -0,205 | -0,069 | -0,189 | 0,047 | -0,420 | -0,205 | -0,071 | -0,262 | 0,890 | 0,939 | 1,000 | | | | | | | | |
| Cr (sed) | -0,150 | -0,012 | 0,039 | -0,221 | 0,125 | -0,047 | 0,077 | -0,422 | -0,140 | 0,123 | -0,159 | 0,573 | 0,978 | 0,872 | 1,000 | | | | | | | |
| Cu (sed) | -0,232 | -0,020 | -0,124 | -0,195 | -0,036 | -0,204 | 0,005 | -0,390 | -0,235 | -0,090 | -0,233 | 0,958 | 0,877 | 0,974 | 0,781 | 1,000 | | | | | | |
| Fe (sed) | -0,121 | -0,006 | 0,093 | -0,200 | 0,198 | 0,003 | 0,075 | -0,408 | -0,121 | 0,186 | -0,102 | 0,456 | 0,940 | 0,791 | 0,987 | 0,691 | 1,000 | | | | | |
| Hg (sed) | -0,087 | -0,008 | 0,126 | -0,216 | 0,167 | 0,029 | 0,129 | -0,376 | -0,068 | 0,215 | -0,125 | 0,369 | 0,913 | 0,734 | 0,967 | 0,611 | 0,980 | 1,000 | | | | |
| Mn (sed) | -0,243 | -0,050 | -0,094 | -0,244 | 0,035 | -0,183 | -0,012 | -0,388 | -0,238 | -0,056 | -0,227 | 0,914 | 0,911 | 0,966 | 0,832 | 0,986 | 0,755 | 0,689 | 1,000 | | | |
| Ni (sed) | -0,206 | -0,012 | -0,068 | -0,208 | 0,004 | -0,159 | 0,046 | -0,407 | -0,199 | -0,019 | -0,223 | 0,891 | 0,950 | 0,991 | 0,880 | 0,982 | 0,806 | 0,747 | 0,987 | 1,000 | | |
| Pb (sed) | -0,212 | 0,013 | -0,128 | -0,149 | -0,088 | -0,211 | 0,039 | -0,410 | -0,221 | -0,090 | -0,239 | 0,947 | 0,859 | 0,971 | 0,763 | 0,984 | 0,672 | 0,586 | 0,949 | 0,966 | 1,000 | |
| Zn (sed) | -0,223 | -0,016 | -0,097 | -0,202 | 0,000 | -0,179 | 0,012 | -0,395 | -0,223 | -0,055 | -0,220 | 0,928 | 0,913 | 0,982 | 0,832 | 0,996 | 0,752 | 0,678 | 0,994 | 0,993 | 0,975 | 1,000 |
| OM | -0,086 | -0,192 | -0,081 | -0,030 | -0,056 | -0,078 | -0,076 | 0,002 | -0,026 | -0,108 | 0,040 | -0,143 | -0,142 | -0,132 | -0,132 | -0,154 | -0,139 | -0,126 | -0,163 | -0,132 | -0,076 | -0,169 |
| Salinity | 0,075 | -0,001 | 0,223 | 0,007 | 0,197 | 0,185 | 0,134 | -0,085 | 0,048 | 0,263 | 0,178 | 0,226 | 0,448 | 0,310 | 0,426 | 0,321 | 0,451 | 0,447 | 0,355 | 0,356 | 0,233 | 0,351 |
| DO | 0,047 | 0,003 | 0,014 | -0,065 | 0,070 | 0,004 | -0,106 | 0,207 | 0,006 | -0,038 | -0,056 | -0,447 | -0,530 | -0,551 | -0,497 | -0,506 | -0,448 | -0,430 | -0,483 | -0,545 | -0,569 | -0,505 |
| pH | 0,110 | 0,061 | 0,254 | 0,092 | 0,211 | 0,229 | 0,164 | -0,157 | 0,053 | 0,330 | 0,227 | 0,074 | 0,442 | 0,259 | 0,473 | 0,225 | 0,534 | 0,521 | 0,252 | 0,289 | 0,177 | 0,268 |
| Alkalinity | 0,066 | -0,028 | 0,397 | -0,035 | 0,406 | 0,212 | 0,163 | -0,198 | 0,005 | 0,450 | 0,200 | 0,120 | 0,503 | 0,268 | 0,506 | 0,286 | 0,578 | 0,562 | 0,353 | 0,361 | 0,234 | 0,331 |
| Phosphate | -0,080 | -0,182 | -0,094 | -0,024 | -0,091 | -0,083 | -0,063 | 0,007 | -0,015 | -0,121 | 0,026 | -0,132 | -0,141 | -0,121 | -0,136 | -0,149 | -0,150 | -0,130 | -0,163 | -0,128 | -0,068 | -0,165 |
| Nitrates | -0,082 | -0,176 | -0,108 | -0,017 | -0,103 | -0,090 | -0,071 | 0,013 | -0,019 | -0,137 | 0,020 | -0,147 | -0,173 | -0,144 | -0,165 | -0,171 | -0,180 | -0,162 | -0,187 | -0,154 | -0,087 | -0,189 |
| Silicates | 0,002 | 0,040 | -0,144 | -0,065 | -0,139 | -0,127 | -0,109 | 0,262 | 0,040 | -0,216 | -0,210 | -0,258 | -0,555 | -0,427 | -0,562 | -0,397 | -0,593 | -0,555 | -0,403 | -0,453 | -0,390 | -0,425 |
| Ammoniun | -0,079 | -0,183 | -0,095 | -0,024 | -0,091 | -0,082 | -0,065 | 0,011 | -0,014 | -0,123 | 0,027 | -0,144 | -0,152 | -0,133 | -0,145 | -0,162 | -0,157 | -0,138 | -0,175 | -0,140 | -0,080 | -0,178 |
| Al (water) | 0,157 | 0,079 | 0,351 | -0,082 | 0,314 | 0,247 | 0,188 | 0,007 | 0,212 | 0,415 | 0,047 | -0,313 | 0,316 | 0,045 | 0,429 | -0,093 | 0,500 | 0,604 | 0,025 | 0,080 | -0,104 | -0,016 |
| Cr (water) | 0,071 | 0,058 | 0,335 | -0,088 | 0,180 | 0,147 | 0,312 | -0,246 | 0,073 | 0,392 | -0,013 | 0,445 | 0,802 | 0,633 | 0,756 | 0,597 | 0,752 | 0,787 | 0,651 | 0,690 | 0,558 | 0,638 |
| Mn (water) | 0,057 | 0,210 | -0,100 | 0,256 | -0,155 | 0,027 | 0,009 | -0,044 | -0,015 | -0,045 | 0,040 | -0,215 | -0,259 | -0,202 | -0,195 | -0,230 | -0,175 | -0,186 | -0,264 | -0,252 | -0,184 | -0,233 |
| Fe (water) | 0,153 | 0,165 | 0,248 | -0,048 | 0,209 | 0,200 | 0,138 | 0,023 | 0,139 | 0,303 | -0,037 | -0,381 | 0,079 | -0,130 | 0,193 | -0,226 | 0,269 | 0,358 | -0,127 | -0,118 | -0,287 | -0,159 |
| Ni (water) | 0,017 | -0,134 | 0,318 | -0,162 | 0,330 | 0,162 | 0,135 | -0,195 | 0,036 | 0,367 | 0,095 | -0,131 | 0,488 | 0,196 | 0,562 | 0,102 | 0,640 | 0,692 | 0,199 | 0,255 | 0,088 | 0,168 |
| Cu (water) | 0,152 | -0,075 | 0,340 | -0,026 | 0,331 | 0,252 | 0,095 | 0,211 | 0,226 | 0,338 | 0,222 | -0,356 | -0,052 | -0,253 | -0,015 | -0,272 | 0,035 | 0,130 | -0,172 | -0,174 | -0,301 | -0,236 |
| Zn (water) | -0,120 | -0,055 | -0,112 | -0,264 | 0,098 | -0,036 | -0,122 | -0,082 | -0,033 | -0,063 | -0,168 | -0,062 | 0,389 | 0,279 | 0,522 | 0,122 | 0,540 | 0,591 | 0,214 | 0,244 | 0,086 | 0,187 |
| Pb (water) | -0,069 | -0,157 | 0,080 | -0,134 | 0,107 | 0,000 | 0,024 | -0,161 | -0,016 | 0,104 | -0,009 | -0,171 | 0,232 | 0,082 | 0,306 | -0,022 | 0,343 | 0,384 | 0,028 | 0,095 | 0,041 | 0,013 |
| As (water) | 0,123 | 0,028 | 0,271 | 0,056 | 0,206 | 0,212 | 0,165 | -0,093 | 0,072 | 0,315 | 0,205 | 0,054 | 0,350 | 0,180 | 0,355 | 0,168 | 0,411 | 0,398 | 0,187 | 0,215 | 0,115 | 0,201 |
| Cd (water) | -0,111 | -0,038 | 0,004 | 0,009 | 0,187 | -0,045 | -0,152 | -0,250 | -0,255 | 0,038 | 0,053 | -0,253 | -0,128 | -0,204 | -0,042 | -0,175 | 0,056 | -0,033 | -0,169 | -0,186 | -0,160 | -0,160 |
| Hg (water) | -0,096 | 0,045 | -0,059 | 0,109 | 0,182 | -0,001 | -0,158 | -0,173 | -0,138 | 0,017 | 0,149 | 0,060 | 0,159 | 0,163 | 0,238 | 0,151 | 0,271 | 0,181 | 0,157 | 0,169 | 0,213 | 0,165 |

| | OM | Salinity | DO | pH | Alkalinity | Phosphates | Nitrates | Silicates | Ammonium | Al (water) | Cr (water) | Mn (water) | Fe (water) | Ni (water) | Cu (water) | Zn (water) | Pb (water) | As (water) | Cd (water) | Hg (water) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OM | 1,000 | | | | | | | | | | | | | | | | | | | |
| Salinity | -0,507 | 1,000 | | | | | | | | | | | | | | | | | | |
| DO | -0,645 | -0,011 | 1,000 | | | | | | | | | | | | | | | | | |
| pH | -0,455 | 0,924 | -0,071 | 1,000 | | | | | | | | | | | | | | | | |
| Alkalinity | -0,173 | 0,761 | -0,174 | 0,783 | 1,000 | | | | | | | | | | | | | | | |
| Phosphate | 0,998 | -0,520 | -0,655 | -0,472 | -0,213 | 1,000 | | | | | | | | | | | | | | |
| Nitrates | 0,996 | -0,558 | -0,634 | -0,504 | -0,253 | 0,999 | 1,000 | | | | | | | | | | | | | |
| Silicates | -0,028 | -0,745 | 0,563 | -0,841 | -0,735 | -0,012 | 0,023 | 1,000 | | | | | | | | | | | | |
| Ammoniun | 0,998 | -0,524 | -0,645 | -0,475 | -0,218 | 1,000 | 0,999 | -0,005 | 1,000 | | | | | | | | | | | |
| Al (water) | 0,169 | -0,037 | -0,116 | 0,050 | 0,318 | 0,158 | 0,141 | -0,001 | 0,160 | 1,000 | | | | | | | | | | |
| Cr (water) | -0,183 | 0,682 | -0,386 | 0,625 | 0,799 | -0,190 | -0,234 | -0,625 | -0,200 | 0,433 | 1,000 | | | | | | | | | |
| Mn (water) | -0,159 | -0,316 | 0,099 | -0,060 | -0,337 | -0,149 | -0,110 | 0,100 | -0,149 | -0,223 | -0,428 | 1,000 | | | | | | | | |
| Fe (water) | -0,600 | 0,142 | 0,559 | 0,236 | 0,173 | -0,605 | -0,601 | 0,198 | -0,601 | 0,583 | 0,186 | 0,245 | 1,000 | | | | | | | |
| Ni (water) | 0,305 | 0,387 | -0,411 | 0,467 | 0,744 | 0,278 | 0,239 | -0,579 | 0,276 | 0,737 | 0,681 | -0,430 | 0,180 | 1,000 | | | | | | |
| Cu (water) | 0,585 | -0,078 | -0,265 | -0,135 | 0,308 | 0,565 | 0,542 | -0,019 | 0,566 | 0,678 | 0,265 | -0,466 | 0,020 | 0,670 | 1,000 | | | | | |
| Zn (water) | -0,049 | -0,103 | -0,017 | -0,054 | -0,147 | -0,040 | -0,043 | 0,124 | -0,037 | 0,632 | 0,079 | -0,076 | 0,503 | 0,290 | 0,122 | 1,000 | | | | |
| Pb (water) | 0,819 | -0,302 | -0,644 | -0,167 | 0,161 | 0,807 | 0,793 | -0,205 | 0,806 | 0,638 | 0,195 | -0,203 | -0,159 | 0,715 | 0,692 | 0,318 | 1,000 | | | |
| As (water) | -0,494 | 0,951 | 0,073 | 0,950 | 0,778 | -0,512 | -0,547 | -0,733 | -0,513 | 0,004 | 0,612 | -0,287 | 0,188 | 0,432 | -0,103 | -0,134 | -0,253 | 1,000 | | |
| Cd (water) | -0,244 | 0,016 | 0,288 | 0,276 | 0,258 | -0,282 | -0,263 | -0,164 | -0,281 | -0,128 | -0,195 | 0,595 | 0,277 | -0,007 | -0,333 | -0,181 | -0,116 | 0,154 | 1,000 | |
| Hg (water) | 0,485 | -0,405 | -0,519 | -0,162 | -0,017 | 0,463 | 0,478 | -0,178 | 0,459 | 0,132 | -0,164 | 0,451 | -0,189 | 0,152 | 0,081 | 0,140 | 0,528 | -0,390 | 0,453 | 1 |

3.9 PHOTOGRAPHIC CATALOG

All photos were taken by the author, except for the figures whose sources are indicated in the respective captions.

**Sample point 1-CON**

Figure 1. Costa da Lagoa Waterfall (Google, 2023)


Figure 2. Plant *24-P. racemosum (1)*


Figure 3. Plant *24-P. racemosum (2)*


Figure 4. Plant *24-P. racemosum (3)*


Figure 5. Plant *25-E. bonariensis (1)*


Figure 6. Plant *25-E. bonariensis (2)*


Figure 7. Plant *26-Commelina sp. (1)*


Figure 8. Plant *26-Commelina sp. (2)*

**Sampling point 2-LEI**

Figure 9. Plants *13-L. peruviana* and *14-U. arrecta*


Figure 10. Plant *13-L. peruviana (1)*

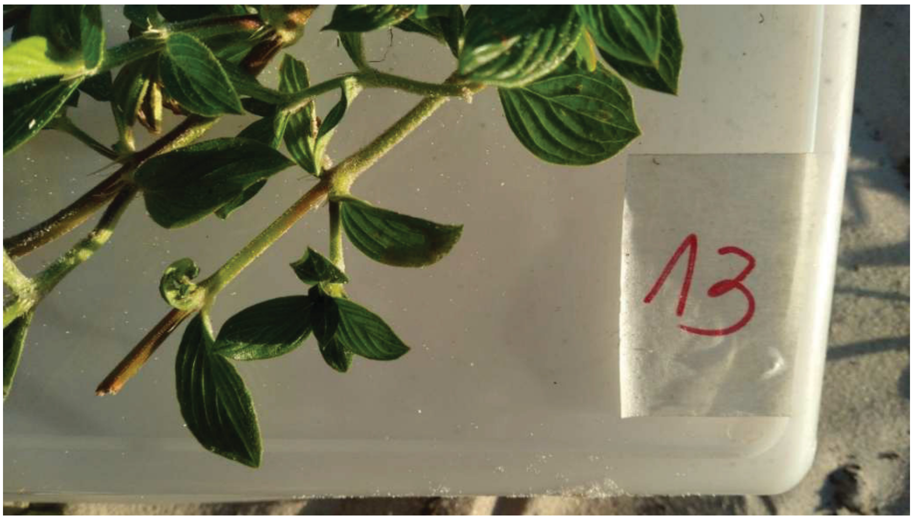


Figure 11. Plant *13-L. Peruviana (2)*


Figure 12. Plant *14-U. Arrecta (1)*


Figure 13. Plant *14-U. arrecta* (2)


Figure 14. Plant *15-C. Verticillata (1)*


Figure 15. Plant *15-C. Verticillata (2)*

**Sampling point 3-COS**

Figure 16. “Costa da Lagoa”

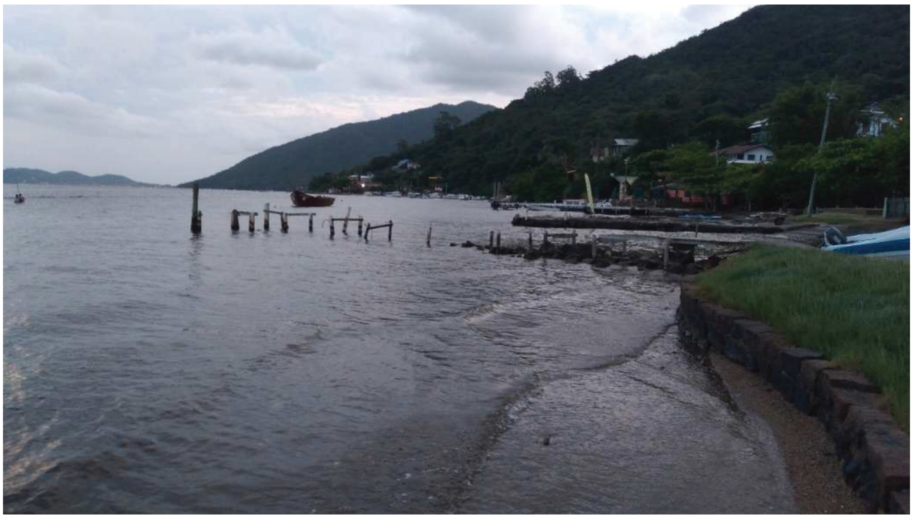

Figure 17. “Costa da Lagoa” sampling location


Figure 18. Plant *27-S. Maritima (1)*


Figure 19. Plant *27-S. Maritima (2)*

Figure 20. Plant *28-P. Vaginatum (1)*

Figure 21. Plant *28-P. Vaginatum (2)*


Figure 22. Plant *29-E. Prostata (1)*


Figure 23. Plant *29-E. Prostata (2)*

## Sampling point 4-MAR

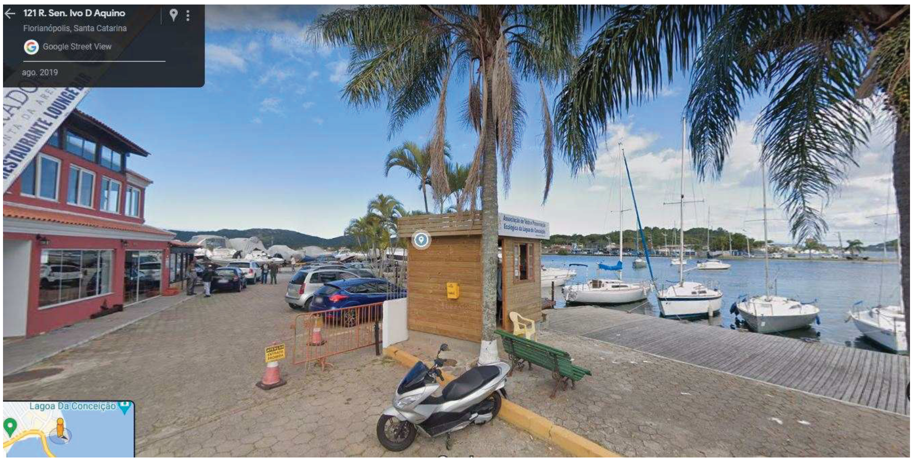


Figure 24. Marina Osni Ortiga (Google Maps, 2023)

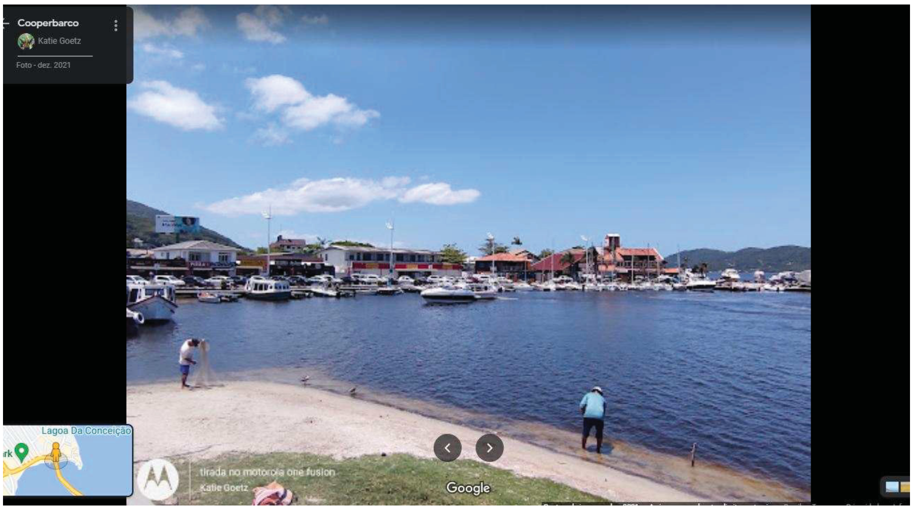


Figure 25. Marina (Google Maps, 2023)

Figure 26. Plant 16-*H. wrightii* (Photo by: South Florida Water Management District, 2021)

## Sampling point 5-GRA


Figure 27. Corner of Av. das Rendeiras, entrance to the Gravatá Trail (Google Maps, 2023)


Figure 28. Stormwater Channel at Sampling point 5-GRA (Google Maps, 2023)


Figure 29. Plant *10-A. Philoxeroides (1)*


Figure 30. Plant *10-A. Philoxeroides (2)*


Figure 31. Plant *11-S. Trilobata (1)*

Figure 32. Plant *11-S. Trilobata (2)*


Figure 33. Plant *12-P. Vaginatum (1)*


Figure 34. Plant *12-P. Vaginatum (2)*


Figure 35. Plant *12-P. Vaginatum (3)*


Figure 36. Plant *12-P. Vaginatum (4)*

**Sampling point 6-PON**

Figure 37. Entrance of Canal da Barra (1)

Figure 38. Entrance of Canal da Barra (2)


Figure 39. Plant *7-U. Arrecta (1)*

Figure 40. Plant *7-U. Arrecta (2)*


Figure 41. Plant *7-U. Arrecta (3)*


Figure 42. Plant *8-V. Luteola (1)*


Figure 43. Plant *8-V. Luteola (2)*


Figure 44. Plant *8-V. Luteola (3)*


Figure 45. Plant *9-S. Alterniflora (1)*


Figure 46. Plant *9-S. Alterniflora (2)*


Figure 47. Plant *9-S. Alterniflora (3)*

Figure 48. Plants 8-*V.luteola* and 9-*S. alterniflora*

## Sampling point 7-ARA

Figure 49. “Canto dos Araçás” (1)

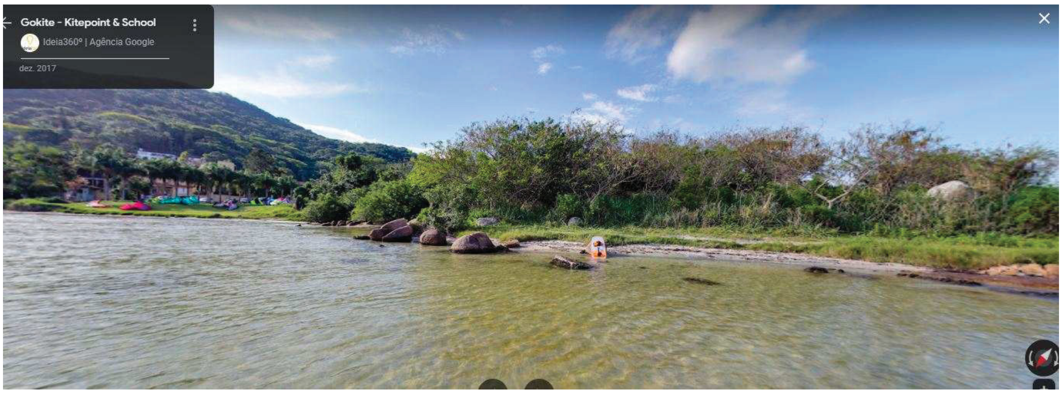


Figure 50. “Canto dos Araçás” (2) (Google Maps, 2023)


Figure 51. Plant *21-P. Vaginatum (1)*


Figure 52. Plant *21-P. Vaginatum (2)*


Figure 53. Plant *22-A. Philoxeroides (1)*


Figure 54. Plant *22-A. Philoxeroides (2)*


Figure 55. Plant *23-S. Alterniflora (1)*


Figure 56. Plant *23-S. Alterniflora (2)*

**Sampling point 9-CAM**

Figure 57. North of “Lagoa da Conceição”

Figure 58. North of “Lagoa da Conceição” (Point 9-CAM)

Figure 59. Plant *1-E. Interstincta (1)*

Figure 60. Plant *1-E. Interstincta (2)*


Figure 61. Plant *2-B. monnieri*


Figure 62. Plant *3-R. Corimbosa (1)*

Figure 63. Plant *3-R. Corimbosa (2)*

## Sampling point 11-POR


Figure 64. “Porto da Lagoa” (South) (Google Maps, 2023)


Figure 65. “Porto da Lagoa” (point 11-POR) (Google Maps, 2023)


Figure 66. Plant *17-P. Racemosum (1)*


Figure 67. Plant *17-P. Racemosum (2)*

Figure 68. Plant *18-S. Californicus (1)*

Figure 69. Plant *18-S. Californicus (2)*

Figure 70. Plant *19-P. Vaginatum (1)*

Figure 71. Plant *19-P. Vaginatum (2)*

Figure 72. Plant *20-Ipomea sp.*

**Sampling point 12-CAN**

Figure 73. “Barra da Lagoa” Channel (Mangrove)

Figure 74. “Barra da Lagoa” Channel

Figure 75. Barra da Lagoa Channel


Figure 76. Plant *4-Scirpus sp.*

Figure 77. Plant *5-F. cymosa.*

Figure 78. Plant *6-S. Maritima (1)*


Figure 79. Plant *6-S. Maritima (2)*


Figure 80. Plant *6-S. Maritima (3)*

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## 4 CAPÍTULO 3: " PLANTAS AQUÁTICAS VS. METAIS PESADOS: GUARDIÃS DA LAGOA DA CONCEIÇÃO (FLORIANÓPOLIS-SC)"

Este capítulo está configurado como um artigo de divulgação científica, elaborado de acordo com as diretrizes editoriais da Revista Bioika, e está formatado para submissão.

Região norte da Lagoa da Conceição, destacando uma pequena porção exuberante floresta ao seu redor (Foto: F. D. Cardoso, Lagoa da Conceição, Florianópolis, 2023).

### 4.1 INTRODUÇÃO

O desenvolvimento tecnológico e industrial atingiu patamares impressionantes nos dois últimos séculos. As indústrias produzem os mais variados materiais do nosso dia a dia, como concreto, aço, componentes elétricos e eletrônicos, automóveis, tintas, produtos farmacêuticos, cosméticos, têxtil, mobiliário, pesticidas e fertilizantes usados na produção de alimentos, papel e papelão, entre muitos outros. A maioria desses produtos é fabricada com metais extraídos de rochas. Além de estarem presentes em produtos industriais, alguns metais também são essenciais para o nosso corpo, em pequenas quantidades — como o Ferro, por exemplo, que transporta o oxigênio no sangue, garantindo o bom funcionamento das células.

A produção industrial desenvolve, diariamente, materiais avançados que frequentemente utilizam metais pesados em sua composição. Esses metais, assim chamados por sua alta densidade, ocorrem naturalmente em pequenas quantidades no ambiente. No entanto, quando são amplamente empregados em processos industriais e liberados na natureza pelas atividades humanas, tornam-se biodisponíveis e podem causar efeitos nocivos aos organismos vivos.

Metais como arsênio, cádmio, mercúrio e cromo são exemplos de poluentes tóxicos que, ao se acumularem no corpo de animais (inclusive humanos), podem provocar danos graves e muitas vezes irreversíveis. Entre os efeitos associados estão lesões no sistema nervoso central, prejuízos às funções renais, pulmonares, cardiovasculares, gastrointestinais e hepáticas, além do aumento do risco de câncer.

Os efluentes gerados pelas indústrias, assim como os esgotos domésticos, carregam muitas destas substâncias. Além disso, o tratamento convencional em Estações de Tratamento de Esgotos (ETEs) não é suficiente para remover metais pesados. Desta forma, esses metais acabam atingindo ambientes aquáticos, se tornando um risco para saúde humana e à vida aquática. Por não serem facilmente degradados, os metais pesados se acumulam em fundos de rios e lagos, ou são absorvidos pelos organismos.

A Lagoa da Conceição, em Florianópolis (SC), é um cartão postal de uma das cidades litorâneas mais procuradas do Brasil em épocas de veraneio (Figura 1). A maneira correta de nomeá-la é como laguna, uma vez que é ligada ao mar por meio do Canal da Barra da Lagoa. Turistas são atraídos pela linda paisagem, gastronomia local, pelos esportes náuticos, passeios de barco e pesca.

Figura 1. Lagoa da Conceição. É possível ver as Dunas da Lagoa da Conceição e a ponte que separa os setores Central e Sul da laguna. Ao fundo, o Oceano Atlântico. É nas Dunas que se encontra a Lagoa de Evapoinfiltração de Esgotos (Foto: Charles Guerra/Arquivo Agência RBS, NSCtotal, 2024[1])

Embora seja a capital de Santa Catarina, Florianópolis ainda enfrenta problemas relacionados à disposição e ao tratamento de esgotos. A população local cresce a cada ano, mas o sistema de esgotamento continua insuficiente, o que gera desequilíbrios no ecossistema e reduz a qualidade de vida de quem vive e frequenta a região. O esgoto coletado é encaminhado à ETE Lagoa da Conceição, com capacidade para atender até 30.000 habitantes — número que dobra no verão. O efluente tratado é direcionado para uma Lagoa de Evapoinfiltração, situada nas dunas da Lagoa da Conceição (Figura 2), onde ocorre sua evaporação e infiltração no solo. Como a região abriga amplas áreas de proteção ambiental e não possui rios com fluxo suficiente para lançamento direto, a alternativa adotada para dispor o esgoto tratado foi a Lagoa de Evapoinfiltração.

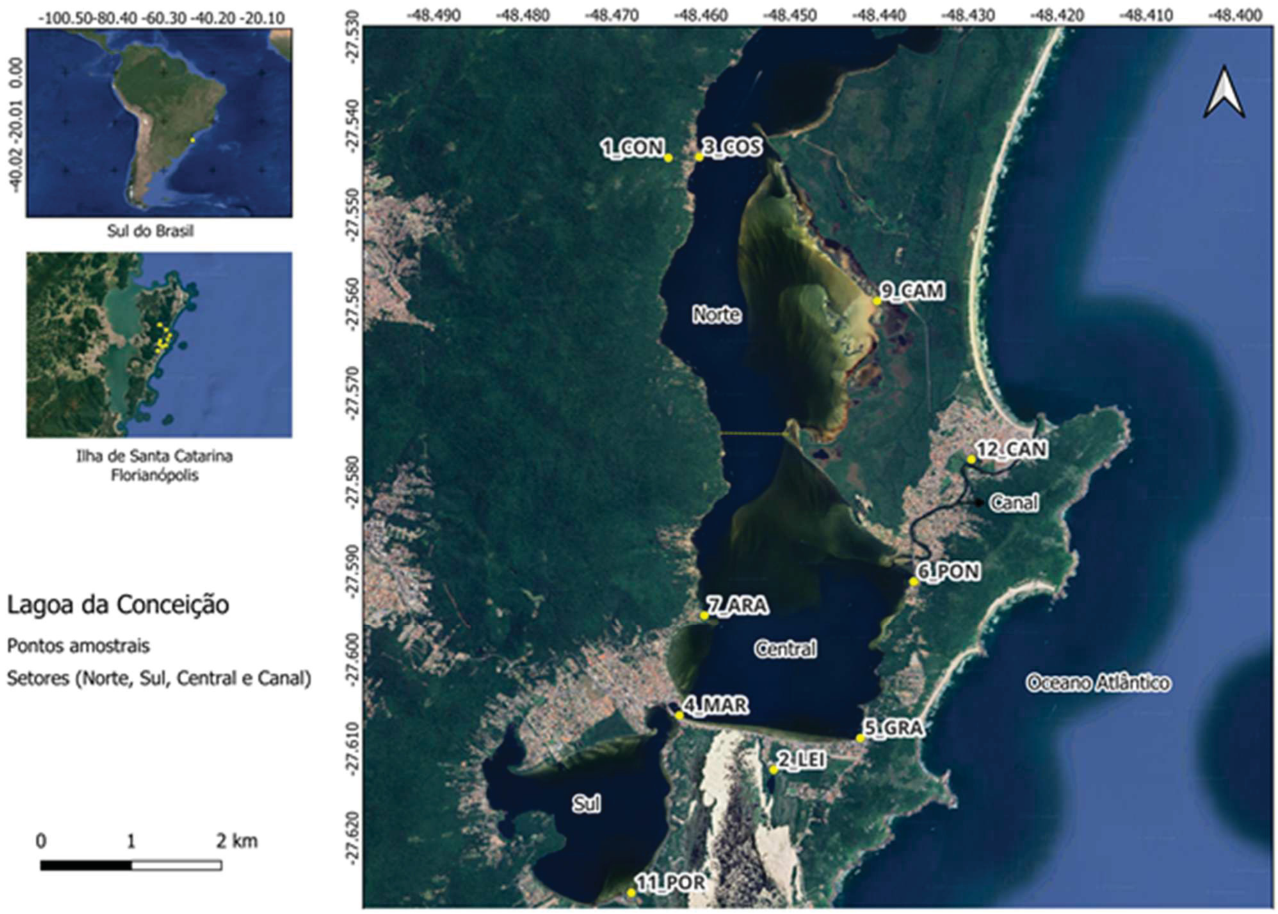


Figura 2. Mapa da bacia hidrográfica da Lagoa da Conceição, onde estão indicados os 4 setores que a dividem – Norte (North), Sul (South), Central e Canal (Channel). Os números indicam os pontos de coleta de amostras.

Em janeiro de 2021, uma chuva extrema rompeu a barragem da Lagoa de Evapoinfiltração. Cerca de 500 mil m³ de esgoto tratado foram extravasados em direção à Lagoa da Conceição, atingindo diversas residências e veículos, mas sem causar perdas humanas diretas (Figura 3). Naquele mês, o Ciram[3] (Centro de Informações de Recursos Ambientais e de Hidrometeorologia de Santa Catarina, 2021) registrou 686 mm de chuva em Florianópolis — recorde histórico mensal. O efluente transportou grandes quantidades de nutrientes, como nitrogênio e fósforo, além de substâncias tóxicas, já que o tratamento convencional da estação não remove completamente poluentes como os metais pesados. Porém, a natureza tem algumas defesas. As plantas aquáticas e ripárias que ocorrem na região têm potencial de absorção desses elementos, e podem ter acumulado grande parte dos metais pesados.

Figura 3. Momento de ruptura do efluente da LEI para a Lagoa da Conceição, em 25/01/2021 (Foto: Ndmais, 2024[4]).

A biorremediação é uma solução baseada na natureza que pode ser eficiente na estabilização de poluentes no ambiente. Nesta técnica, organismos consomem e absorvem contaminantes, sem danos na sua estrutura. A vegetação aquática pode reduzir a presença de contaminantes no ambiente, por meio da **biorremediação**, que em plantas é denominada **fitorremediação**. As plantas aquáticas, ou macrófitas aquáticas, reduzem a quantidade de matéria orgânica, nutrientes e alguns elementos tóxicos, quando utilizadas em *wetlands* (nome atualmente usado para se referir a uma estrutura com plantas aquáticas em tratamentos de água), sendo um método de baixo custo e aplicável até em zonas remotas.

Algumas espécies vegetais, como o **capim marinho** (*Spartina alterniflora*), formam pradarias (Figura 4), comuns em áreas costeiras, como na Lagoa da Conceição. Em diversos locais do mundo esta espécie tem sido utilizada para tratar esgotos domésticos (contendo metais pesados, óleos, fármacos, e outros contaminantes) utilizando fósforo e nitrogênio da água e do sedimento para a sua nutrição, e estocando carbono por meio da fotossíntese. A espécie apresenta um complexo sistema de raízes que atua no aprisionamento de poluentes.

Neste texto, apresentamos um estudo sobre a contaminação e as possibilidades de recuperação da Lagoa da Conceição, em Florianópolis (SC), após o grave acidente ambiental que resultou no despejo de grande volume de esgoto na laguna. Para avaliar a acumulação de metais pesados na vegetação, foram realizadas coletas de plantas, água e sedimento dois anos após a ruptura da barragem da Lagoa de Evapoinfiltração (LEI).

A Figura 2 mostra os pontos de amostragem distribuídos ao longo da Lagoa da Conceição, organizados em quatro regiões — Norte, Sul, Central e Canal —, definidas com base em características distintas, como a dinâmica da água e o grau de influência urbana.

Foram analisados os elementos Alumínio (Al), Arsênio (As), Cádmio (Cd), Cobre (Cu), Cromo (Cr), Ferro (Fe), Mercúrio (Hg), Manganês (Mn), Níquel (Ni), Chumbo (Pb) e Zinco (Zn), todos reconhecidos por sua toxicidade e potencial impacto à saúde humana e ao meio ambiente.

Neste estudo, as concentrações de metais encontradas na Lagoa da Conceição foram comparadas com a nossa atual legislação definida pelo CONAMA, a fim de constatar se o local está contaminado. A Resolução CONAMA 357 de 2005 é uma normativa do Conselho Nacional do Meio Ambiente (CONAMA[6]), que estabelece padrões de qualidade da água para os corpos hídricos no Brasil, visando proteger esses recursos hídricos da poluição e garantir sua qualidade, seja para o abastecimento público, como para recreação, navegação e/ou preservação dos animais e vegetais aquáticos. A Resolução CONAMA Nº 454/20127 orienta sobre as concentrações de elementos para os sedimentos de fundo dos rios, lagos e lagoas.

Os limites do CONAMA para muitas substâncias foram baseados em estudos de laboratório, analisando os efeitos dessas substâncias em organismos aquáticos e na saúde humana, determinando concentrações máximas seguras.


Figura 4. O capim-marinho (*Spartina alterniflora)* é habitat de várias espécies, sendo um pântano salino, altamente produtivo pois recicla nutrientes. A espécie também estabiliza o solo e o protege contra erosão e tempestades. O capim marinho também é um excelente filtro de poluentes como pesticidas e metais pesados, e seu sedimento age como esponja para absorver e reduzir os impactos tóxicos. Adaptado de South Carolina Sea Grant Consortium [11] (2024).

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CONAMA Nº 454/20127 orienta sobre as concentrações de elementos para os sedimentos de fundo dos rios, lagos e lagoas.

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Figura 5. Entrada do Canal da Barra da Lagoa, um dos pontos onde foram coletadas amostras para análise. O Canal da Barra da Lagoa apresenta grande fluxo de embarcações, que podem influenciar na concentração de metais pesados no ambiente (Foto: F. D. Cardoso, Lagoa da Conceição, Florianópolis, 2023).

## 4.2 RESULTADOS DAS ANÁLISES DE METAIS PESADOS:

### 4.2.1 Na água superficial:

Os resultados de análises com tecnologia de ponta indicaram que as águas superficiais da Lagoa da Conceição apresentam um possível teor natural do metal Arsênio. Verificado acima do limite legal em todas as amostras da Lagoa da Conceição, o Arsênio é um elemento amplamente distribuído na biosfera, sendo facilmente acumulado em organismos marinhos. A entrada de água marinha na Lagoa da Conceição pode colaborar com o alto nível de Arsênio na água superficial, já que o Canal da Barra da Lagoa faz a conexão com o mar. As águas subterrâneas também podem contribuir com este teor de Arsênio, já que também foi achado em uma área determinada como “controle”, em um local sem indícios de contaminação – a chamada Cachoeira da Costa da Lagoa, no setor norte da Lagoa da Conceição. O Arsênio ocupa o 1º lugar na lista dos 275 piores poluentes da Agência de Proteção Ambiental Americana[8] (2022), visto que ele ocorre frequentemente, tem alta toxicidade e grande potencial de exposição humana.


Figura 2. Locais onde a concentração de alguns metais pesados na água ultrapassou os níveis considerados seguros.

Joel Podgorski and Michael Berg[9] (2020), num estudo da Revista *Science*, sugerem que em diversos locais do mundo o Arsênio é de origem natural, o que expõe aproximadamente 200 milhões de pessoas à água contaminada, sendo os países EUA, Chile, Bolívia, Argentina, Bangladesh, Canadá, México e Japão os mais afetados. Sob determinadas condições, em aquíferos subterrâneos, este elemento pode se dissolver das rochas e se acumular nas águas subterrâneas, vertendo em águas superficiais através das nascentes.

No setor Sul da Lagoa da Conceição, onde a circulação da água é limitada, os níveis de manganês ficaram acima do limite permitido pelo CONAMA. Já na região Norte, marcada por intensa urbanização e baixa cobertura de esgotamento sanitário, foi o zinco que ultrapassou os padrões estabelecidos.

Níquel, Cobre, Cádmio e Mercúrio tiveram os maiores teores, mas dentro dos limites, na região central, no início da Avenida das Rendeiras, área de maior fluxo de automóveis, transporte marítimo, aporte de esgotos ilegais na lagoa, e baixa circulação de água.

No Canal da Barra da Lagoa, os maiores valores de Alumínio, Cromo e Ferro foram registrados na água, dentro da faixa da normalidade, ainda que haja intensa movimentação de embarcações e posto de gasolina na margem da Lagoa da Conceição.

Elementos como Chumbo, Cádmio, Zinco e Cobre são comuns em áreas de marinas e barcos, principalmente devido à presença destes elementos em tintas anti-incrustantes, combustíveis e óleos lubrificantes. Apesar da análise do efluente da Estação de Tratamento de Esgotos ter apresentado os maiores níveis de Chumbo, Mercúrio e Cobre, os valores estavam abaixo do limite e sem relação aparente com os teores elevados na água superficial.

4.2.2 No sedimento:


Figura 7. Locais onde a concentração de alguns metais pesados no sedimento ultrapassou os níveis considerados seguros.

As maiores concentrações no sedimento foram encontradas na região norte da Lagoa da Conceição, especialmente em áreas com pouca circulação de água, o que favorece o depósito de contaminantes. Neste local, as concentrações de Cobre já ultrapassam o limite em que podem causar efeitos negativos nos organismos, e os teores de Zinco estão ainda mais críticos, com valores  que indicam que é bem provável que existam efeitos negativos na biota. A região norte da Lagoa da Conceição, que inclui o bairro da “Costa da Lagoa”, recebe muitos turistas, principalmente devido à importante rota gastronômica, além da presença de uma comunidade pesqueira no local. Por isso, a remoção destas substâncias do sedimento deve ser prioridade do poder público, sendo a fitorremediação uma alternativa promissora, de pouco custo e fácil manutenção, estabilizando os poluentes, reduzindo a exposição aos mesmos aos seres humanos e animais.

Curiosamente, o teor de metais no lodo da Lagoa de Evapoinfiltração da Estação de Tratamento de Esgotos esteve dentro dos limites estabelecidos pela legislação, descartando a hipótese do efluente da LEI como a principal fonte destes elementos na Lagoa da Conceição. As análises químicas e estatísticas indicaram que é provável que o intenso fluxo de embarcações possa ter maior influência na concentração destes metais pesados na região.

**E as plantas?**

Foram analisados metais pesados em 29 plantas coletadas no entorno da Lagoa da Conceição, nos mesmos locais onde foram analisados água e sedimento. Não foram encontradas relações entre a distância do local do acidente e as concentrações dos metais nos vegetais, indicando que a contaminação é sistêmica, ou seja, devido à várias fontes, como barcos e postos de gasolina.

Uma espécie de **grama-marinha** (*Halodule wrightii*) (Figura 8), encontrada no fundo da Lagoa da Conceição, na região central, foi a que mais concentrou os elementos, principalmente devido à sua grande capacidade de adaptação e tolerância à condições de stress. Por este motivo, tem sido estudada para seu uso em fitorremediação. Ela pode ter sido uma grande aliada na purificação da água da Lagoa da Conceição, pois as amostras do seu entorno não apresentaram concentrações consideráveis de metais pesado.

Figura 8. A grama-marinha (*Halodule wrightii*) (Foto: South Florida Water Management District[10], 2021).

O **capim-das-dunas** (*Panicum racemosum*) (Figura 9), encontrado no sul da Lagoa da Conceição, ficou em segundo lugar no ranking de acumulação de metais, e se destacou pelo teor de ferro, alumínio, zinco, cromo e arsênio. Esta planta é comum em regiões de restinga, a vegetação que se estabelece próximo às praias. Ela tem a habilidade de colonizar facilmente solos arenosos, devido às suas longas raízes, sendo importante em projetos de restauração ecológica em áreas costeiras, como fixadora de dunas. Este é o primeiro estudo que mostrou acumulação destes metais nesta espécie, sem aparente perda à planta.

Figura 9. Capim-das-dunas *(Panicum racemosum)* (Foto: F. D. Cardoso, Lagoa da Conceição, Florianópolis, 2023).

O terceiro lugar no ranking de acumulação de metais pesados foi ocupado pelo **capim-junco** (*Fimbristylis cymosa*), identificado na Figura 10 com flores ovaladas nas pontas. A planta apresesentou altos valores de alumínio, ferro e chumbo, no Canal da Barra da Lagoa. Este tipo de capim (gênero *Fimbristylis*) já é conhecido como colonizador de locais contaminados, indicando tolerância a elementos tóxicos. Assim como esta, várias espécies de vegetação costeira e de zonas úmidas têm a habilidade de crescer em solos contaminados, demonstrando capacidade de sobreviver em ambientes adversos. Além disso, seu destaque representa uma novidade científica para o ramo da fitorremediação, especialmente por combinar alta tolerância com grande produção de biomassa – fator importante para a eficiência da descontaminação.

 

Figura 10. Capim-junco (*Fimbristylis cymosa*) (Foto: F. D. Cardoso, Lagoa da Conceição, Florianópolis, 2023).

O **capim-cipó** (*Urochloa arrecta),* que pode ser visualizado abaixo (Figura 11), ocupou o 4º lugar no ranking de acumulação de metais pesados, exibindo a maior concentração de Manganês deste estudo, na entrada do Canal da Barra da Lagoa, onde há grande tráfego de embarcações. Esta espécie é uma planta aquática exótica invasora, que tem se espalhado pelos ambientes aquáticos brasileiros, pois se adapta muito bem às condições locais. Embora sua capacidade de reter metais possa ser útil para limpar águas poluídas, seu crescimento descontrolado pode causar problemas, como redução de espécies nativas, exigindo manejo adequado para evitar que tome conta da área.

 

Figura 11. Capim-cipó (*Urochloa arrecta)* (Foto: F. D. Cardoso, Lagoa da Conceição, Florianópolis, 2023).

O **junco-verdadeiro** (*Scirpus* sp.; Figura 12), encontrada no Canal da Barra, mostrou ser resistente ao mercúrio, já que estava saudável e florescendo no momento da coleta. Ela apresentou a maior quantidade desse metal no estudo, além de também acumular cádmio, níquel e chumbo, mesmo não estando entre as principais plantas que retêm metais pesados. Além deste vegetal, os resultados indicam que as outras plantas coletadas na Lagoa da Conceição possuem mercúrio em níveis altos. No entanto, a água e o sedimento da lagoa não mostraram grandes quantidades desse metal. Isso sugere que as plantas podem estar absorvendo e armazenando o mercúrio, ajudando a reduzir sua presença na água e no solo. Ainda bem! O Mercúrio é um metal pesado cuja exposição pode afetar o cérebro e o sistema nervoso, além de levar a danos nos rins e aumentar o risco de doenças cardíacas.

Figura 12. Junco-verdadeiro (*Scirpus* sp.)  (Foto: F. D. Cardoso, Lagoa da Conceição, Florianópolis, 2023).

Por fim, a plantinha da Figura 13, conhecida na região como **trapoeraba,** mostrou o maior potencial para tratamento de locais contaminados com metais pesados entre todas as espécies analisadas. E por que esta, e não as outras? A trapoeraba Esta planta apresentou os maiores fatores de bioconcentração para 7 dos 11 metais analisados, indicando uma excelente capacidade de extrair estes elementos do ambiente. Já a grama-marinha, que ocupou o 1º lugar no ranking, não se destacou para este fator, que considera a quantidade do elemento no ambiente em relação ao acumulado na planta.

Figura 13. Trapoeraba (*Commelina* sp.) (Foto: F. D. Cardoso, Lagoa da Conceição, Florianópolis, 2023).

Curiosamente, no local onde houve a ruptura da barragem de esgotos, na região central da Lagoa da Conceição, as plantas coletadas não apresentaram uma grande acumulação de metais pesados. É possível que o nível de contaminantes estivesse tão alto que outros compostos presentes no esgoto possam ter influenciado a absorção dos metais pelas plantas.

## 4.3 CONCLUSÃO

Nosso estudo revelou o quão complexo e dinâmico é entender os processos de contaminação em ambientes aquáticos. Também destacou o papel importante das plantas na limpeza da água e do solo em áreas contaminadas, ajudando a remover os poluentes e impedindo que fiquem disponíveis para os animais e pessoas que usufruem da região. Além disso, esta pesquisa reforçou que a conservação das bordas de vegetação naturais é fundamental, uma vez que ajudam a filtrar a poluição e a proteger os ecossistemas aquáticos. Isso contribui para a recuperação dos ambientes e pode ser uma boa estratégia para lidar com a poluição em espaços aquáticos.

O próximo passo, para potencializar os resultados de fitorremediação, seria aplicar um tratamento sistematizado utilizando algumas destas espécies promissoras em bancos vegetais flutuantes principalmente em locais que estão com concentrações elevadas de metais pesados, como é o caso da turística Costa da Lagoa. Para este sistema, o orgão responsável deve considerar que as plantas utilizadas: 1) precisam ter crescimento rápido, sem risco de invasão, com elevada produção de biomassa; 2) possuem sistemas de raizes longos; 3) são de fácil manejo/poda; 4) toleram e acumulam metais em partes que possam ser colhidas.

## 4.4 REFERÊNCIAS


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## 5 CONSIDERAÇÕES FINAIS

Este estudo foi pioneiro na compreensão da bioacumulação de metais pesados pela vegetação aquática e ripária na Lagoa da Conceição (Florianópolis-SC). Apesar de se limitar a uma avaliação pontual no tempo, preenche uma lacuna importante sobre esse tema na região, ao oferecer dados inéditos que podem embasar futuros monitoramentos.

A hipótese de que as concentrações de metais pesados seriam maiores nas proximidades do epicentro do acidente foi refutada, uma vez que diversos outros fatores se mostraram mais significativos do que a distância em relação ao local do evento. Entre eles, destacam-se o tempo de residência da água no sistema, a profundidade, a hidrodinâmica, o regime de ventos, a salinidade, entre outros aspectos que contribuem para o deslocamento dos poluentes a partir do ponto de entrada no sistema. Os resultados indicaram que as fontes dos metais pesados encontrados na Lagoa da Conceição, em janeiro de 2023, estão mais associadas a focos difusos, como embarcações e emissários de esgoto, do que ao acidente de extravasamento de efluentes da lagoa de evapoinfiltração.

Os resultados ressaltam a importância desta vegetação na restauração ambiental, uma vez que contribui para a remoção dos metais pesados da água e do sedimento, diminuindo a biodisponibilidade dos contaminantes. Observa-se um indicativo de sucesso na implantação de sistemas de fitorremediação (*wetlands*) em grande escala no local, à luz das espécies vegetais envolvidas e das condições abióticas atuantes. Estes sistemas têm o potencial de melhorar a qualidade da água e do sedimento da Lagoa da Conceição a longo prazo, com baixo custo, impulsionados por energia solar, sem uso de fertilizantes, e com impacto ambiental reduzido. Embora seja uma alternativa mais sustentável, é necessário um planejamento para o manejo periódico, com a coleta e remoção da biomassa contaminada e o devido encaminhamento a aterros industriais, evitando a reinserção dos contaminantes no ecossistema.

Estudos subsequentes devem se basear em coletas sistematizadas, com foco nos mesmos pontos amostrais e elementos analisados, levando em conta as variações sazonais e pluviométricas. A quantificação de elementos presentes na água subterrânea é um passo essencial para verificar o background geoquímico das águas, identificando quais e em que proporção estão os metais de origem natural neste ambiente. Realizar análises química para a especiação dos elementos, como o arsênio, indicará em que formas eles ocorrem no local, sendo possível avaliar seu impacto na saúde humana. Recomenda-se também a investigação do potencial de outras espécies nativas para a fitorremediação.

Deixo também uma reflexão, ao levar em consideração que a restauração dos ambientes costeiros exige mais do que o conhecimento técnico. O cerne da questão é bem mais profundo: requer uma educação ética e moral, carente na sociedade atual e amplamente ignorada. Se “respeito” fosse um valor cultivado e incorporado pela pessoas, não por ser “bonito”, mas por ser necessário e fundamental por um bem maior, atitudes simples como jogar o lixo no lixo, ou reduzir o consumo excessivo de materiais, seriam naturais (e não são!). Ética não deve ser uma imposição, e sim uma convicção interna que guie as ações humanas. É a partir dessa consciência individual, do reconhecimento da importância do respeito a todas as formas de vida, nos reconectando com a natureza, que a evolução acontece e a sociedade avança.

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