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Geochemical evolution and ecological risk of trace metals in Babitonga Bay sediments (southern Brazil) in response to the closure of the Linguado Channel

Cláudio Rudolfo Tureck
University of the Region of Joinville (UNIVILLE)
Suelen Maria Beeck da Cunha
Federal University of Santa Catarina (UFSC)
Anelise Destefani
Federal Institute of Santa Catarina (IFC)
Celso Voos Vieira
celso.v@univille.br
University of the Region of Joinville (UNIVILLE)
Leticia Haak
University of the Region of Joinville (UNIVILLE)
Tailisi Hoppe Trevizani
University of São Paulo (USP)
Paulo Alves de Lima Ferreira
University of São Paulo (USP)
Rubens Cesar Lopes Figueira
University of São Paulo (USP)

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Geochemical evolution and ecological risk of trace metals in Babitonga Bay sediments (southern Brazil) in response to the closure of the Linguado Channel

Abstract

The obstruction of the Linguado Channel in 1935 represents one of the most profound human interventions in the hydrosedimentary dynamics of Babitonga Bay (southern Brazil), yet its long-term effects on sediment geochemistry remain poorly documented. This study reconstructs the environmental and geochemical evolution of the bay by analyzing the spatial and temporal distribution of metals and metalloids (As, Cd, Cr, Cu, Fe, Ni, Pb, V and Zn) in sediment cores collected along the channel and in adjacent sectors. Concentrations in the non-residual fraction were integrated into a ^{210}Pb-based chronological framework, allowing discrimination between pre- and post-closure periods. The results show a significant increase in concentrations after 1935, especially for Zn, Ni, Pb and As, associated with regional industrialization and reduced hydrodynamic energy. A south-to-north enrichment gradient is observed, with higher metal retention in the landward sector of the dike (cores P7 and P8), whereas areas under strong marine influence display low concentrations and little variation along the profiles. With the exception of Zn and As in the Saguaçu Lagoon, concentrations remain below Level 1 thresholds established by Brazilian dredging guidelines, indicating a low-to-moderate ecological risk scenario, although following an enrichment trend in confined sectors. The results highlight the Linguado Channel as a sedimentary archive of regional environmental history and provide an essential baseline for assessing risks associated with dredging and the potential controlled reopening of the channel, thus offering technical support for integrated coastal management and the conservation of estuarine ecosystems.

Keywords: Linguado Channel; estuarine sediments; trace metals; sediment geochemistry; Babitonga Bay; coastal management.

1 Introduction

Babitonga Bay, located in the northern part of the state of Santa Catarina, is the largest estuary in the state and one of the most relevant coastal systems in southern Brazil, both for its ecological importance and for its socioeconomic and historical

relevance (Gerhardinger et al., 2021; ICMBio, 2010; Vieira et al., 2024). Babitonga Bay encompasses the municipalities of Joinville, Itapoá, Araquari, Balneário Barra do Sul and São Francisco do Sul, totaling an area of approximately 1,400 km² and a population of more than 740,000 inhabitants (IBGE, 2022). Multiproxy paleoenvironmental records indicate that Babitonga Bay functions as a long-term sedimentary archive, with at least 1,500 years of documented history of mangrove dynamics, sea-level variations and climatic changes (Torres et al., 2024; De Azevedo et al., 2021; Galvão et al., 2023). At the regional scale, the Quaternary evolution of the Santa Catarina coastal plain and of transitional systems along the southeastern Brazilian coast is strongly controlled by sea-level oscillations and morphodynamic reorganizations, which shaped the present configuration of estuarine and lagoonal environments, including Babitonga Bay (Kuhn et al., 2023; Moreira et al., 2024).

The bay lies within one of the most dynamic industrial hubs of Santa Catarina, the northeastern region of the state, which includes the municipalities of Joinville, Itapoá, Araquari, São Francisco do Sul, Balneário Barra do Sul and Garuva. This region is characterized by strong metal-mechanical, machinery and equipment, and plastics-manufacturing sectors, accounting for about 36% of the state's industrial output (FIESC, 2021; IBGE, 2022).

However, rapid urban and industrial growth has not been accompanied by proportional sanitation infrastructure, resulting in low rates of collection and treatment of domestic sewage (IBGE, 2022). This deficiency is one of the main sources of anthropogenic pressure on local estuarine and coastal ecosystems, acting synergistically with port expansion and intensified logistics and industrial activities.

Babitonga Bay harbors one of the largest continuous mangrove extensions in South America (Destefani et al., 2019), located within the Atlantic Forest Biome and recognized by Brazilian Ministry of the Environment Ordinance No. 463/2018 (MMA, 2018) as a priority area for conservation and sustainable use (Gerhardinger et al., 2021). Recent studies reinforce the role of mangroves in environmental resilience, provision of ecosystem services and human well-being in Brazilian coastal regions, especially in Babitonga Bay (Bustamante et al., 2024; Gerhardinger et al., 2021). The sensitivity of these ecosystems to hydrological and climatic changes has been documented by Holocene records from the bay itself, which show facies replacement and reorganization

of pollen assemblages in response to sea-level variations and changes in continental inputs (De Azevedo et al., 2021; Torres et al., 2024). Recent projections warn that sea-level rise and land-use change are likely to intensify pressures on these habitats in the coming decades (Filgueras et al., 2024). Similar patterns of adjustment and resilience of mangroves to sea-level oscillations and to changes in channel and delta dynamics have been described in other Brazilian estuaries, such as along the northeastern coast and in the Doce River delta (Cohen et al., 2019; Da Silva et al., 2022), indicating that the responses observed in Babitonga Bay are part of a broader regional context of vulnerability and adaptation of mangrove ecosystems.

In addition to its ecological relevance, the bay is classified as an Important Bird and Biodiversity Area (IBA) by BirdLife International (Bencke et al., 2006) and constitutes an important nursery ground for threatened species such as the green turtle (Chelonia mydas), the Guiana dolphin (Sotalia guianensis), the franciscana dolphin (Pontoporia blainvillei) and the Atlantic goliath grouper (Epinephelus itajara) (MMA, 2014). This combination of high biodiversity, intense human occupation and accelerated landscape transformation makes Babitonga Bay a natural laboratory for understanding anthropogenic impacts on subtropical estuaries.

Despite its ecological and socioeconomic importance, the system has undergone significant changes resulting from multiple anthropogenic pressures, among which the discharge of urban and industrial effluents and port operations stand out (ICMBio, 2010; Martins et al., 2014; Noernberg et al., 2020). These activities have promoted changes in water and sediment quality, affecting the structure and functioning of the subtropical estuarine ecosystem (Angulo et al., 2013; Bradl, 2004; Wang and Mulligan, 2006). Recent reviews highlight that heavy metals in coastal environments originate from multiple sources (industrial, agricultural and domestic) and that their ecological effects depend strongly on mobility and bioavailability conditions in each system, as well as on the management strategies adopted (El-Sharkawy et al., 2025). Studies in tropical deltas and Brazilian estuaries show that partitioning among dissolved, particulate and sediment phases is controlled by local processes of flocculation, organic complexation, sulfide formation and water–sediment interactions (Miranda et al., 2021; Santos et al., 2024), with direct implications for bioaccumulation in benthic and filter-feeding organisms (Santos and Boehs, 2021). In Babitonga Bay, recent studies report increasing concentrations of metals and organic compounds in low-energy areas,

indicating a tendency towards accumulation and potential risk to the biota (Destefani and Resgalla Jr., 2019; Tureck et al., 2024; Vedolin et al., 2020; Kim et al., 2023; Angeli et al., 2016; Melo Júnior et al., 2025).

Historically, one of the most significant interventions in the dynamics of Babitonga Bay was the closure of the Linguado Channel, a former connection with the Atlantic Ocean located in the southern portion of the estuary. The first modifications date back to 1907, with partial infilling of the channel for the construction of a railway branch. In 1935, complete closure was achieved after structural failure of the existing railway bridge (Cremer et al., 2006). The final obstruction profoundly altered the system's hydrodynamics, favoring sediment accumulation, modifying salinity and oxygenation gradients and restricting tidal circulation between the bay and the ocean (Luz, 2015; Silva, 2011; Silveira, 2010). The resulting morphological reconfiguration is consistent with the pattern described for subtropical bays in southern Brazil, in which confinement events caused by natural or anthropogenic barriers promote the accumulation of fine sediments and the reorganization of depositional facies (Galvão et al., 2023; Kuhn et al., 2023; Moreira et al., 2024). Hydrodynamic and sediment-transport modeling studies further indicate that closure of the Linguado Channel led to significant changes in the morphodynamic stability of the system, with the formation of sandbanks and increased siltation at the bay entrance and adjacent sectors (Santos et al., 2019; Souza et al., 2020), reinforcing the interpretation of the channel as a low-energy zone and a sediment trap for fine material and associated contaminants.

Several studies conducted since the 1980s have documented ecological impacts resulting from the closure, including deterioration of water and sediment quality, loss of aquatic habitats and reduced fishery productivity (INPH, 1985; Cremer et al., 2006; Franklin da Silva, 2011; Destefani, 2017). The closure also contributed to shoreline siltation, loss of navigability and accumulation of fine material along the BR-280 road embankment (Rocha, 2004; Hoenicke, 2007; Silva, 2011). Despite the consensus regarding the adverse effects of this intervention, uncertainties remain about the consequences of a possible reopening of the channel after almost a century of isolation. The issue has been widely debated but still lacks robust geochemical evidence to support a technically and environmentally sound decision (Duarte, 2023; França, 2015; Tureck et al., 2024).

Given this context, the present study aims to assess the environmental quality of Babitonga Bay sediments through the geochemical characterization of metals and metalloids in sediment cores. We sought to identify temporal variations in the concentrations of these elements in periods before and after closure of the Linguado Channel, relating them to hydrodynamic changes and regional anthropogenic pressures. The results are compared with the limits established by Brazilian Resolution CONAMA No. 454/2012 (Brasil, 2012), in order to support technical decisions regarding dredging, environmental licensing and potential actions for reopening the channel. In addition to filling gaps in the understanding of the geochemical and depositional evolution of Babitonga Bay, the data presented in this work provide direct support for public policies aimed at coastal management, ecological-economic zoning and conservation of estuarine ecosystems in southern Brazil, in line with recent approaches to ecological risk assessment and metal bioavailability in coastal environments (Gabriel et al., 2020; Naik et al., 2023; Rodrigues et al., 2023; Trevizani et al., 2021; El-Sharkawy et al., 2025).

2 Methodology and Data

2.1 Study Area

Babitonga Bay is a complex estuarine system located on the northern coast of Santa Catarina State, comprising approximately 210 km² of water surface, about 80 km² of mangroves (ICMBio, 2010; Gerhardinger et al., 2021) and an insular system composed of 206 islands (Vieira et al., 2024). The system is bounded by the municipalities of Itapoá, São Francisco do Sul, Garuva, Joinville, Araquari and Balneário Barra do Sul, with an estimated population of about 800,000 inhabitants (IBGE, 2022) (Fig. 1).

Historically, Babitonga Bay has undergone several anthropogenic interventions that significantly modified its morphology and hydrodynamics, especially in the southern sector, where the Linguado Channel is located. The closure of the channel, completed in 1935, marked a turning point in the evolution of the estuary, with implications for circulation, sedimentation patterns and associated ecological processes (Silva, 2011; Luz, 2015). From the perspective of regional coastal geodynamics, the Quaternary evolution of the Santa Catarina coastal plain and of transitional systems along the eastern Brazilian margin has been driven by sea-level oscillations and

morphodynamic reorganizations that conditioned the present configuration of estuarine and lagoonal systems, including Babitonga Bay (Galvão et al., 2023; Kuhn et al., 2023; Moreira et al., 2024). Recent multiproxy records obtained in the bay indicate that, over the last 1,500 years, phases of stronger hydrological confinement were associated with the accumulation of fine sediments and the development of mangroves (Torres et al., 2024; De Azevedo et al., 2021), underscoring the importance of a detailed evaluation of current patterns of metal retention in the Linguado Channel.

Table 1 summarizes the main historical milestones and human interventions related to the environmental evolution and sedimentary dynamics of the Linguado Channel and Babitonga Bay. These milestones range from the foundation of Dona Francisca Colony and the onset of artisanal industrialization, through consolidation of the Joinville industrial park and port expansion, to the recent intensification of socio-environmental conflicts associated with multiple uses of the bay (Rocha, 2004; Hoenicke, 2007; Duarte, 2023; Gerhardinger et al., 2021).

Table 1 – Main historical milestones and human interventions in the Linguado Channel and the surrounding Babitonga Bay region.

Period	Historical event	Activity / impact	References
1851–1880	Fundação da Colônia Dona Francisca e início da industrialização artesanal	Economia baseada em agricultura, madeira, erva-mate e manufaturas (serrarias, ferrarias, cerâmicas); primeiras atividades de transformação	Rocha (2004); Hoenicke (2007); Duarte (2023)
1880–1920	Primeira fase da industrialização fabril	Fortalecimento têxtil, metalúrgico e madeireiro; ferrovias, portos, energia elétrica	Rocha (2004); Hoenicke (2007)
1920–1930	Expansão industrial prévia à crise e ao fechamento do canal	Aceleração têxtil, metalmecânico e madeireiro; expansão de infraestrutura urbana	Rocha (2004); Hoenicke (2007)
1935	Fechamento do Canal do Linguado	Evento crítico: altera a hidrodinâmica, reduz troca de maré e favorece acúmulo de sedimentos finos	Este estudo; Luz (2015)
1935–1940	Industrialização sob efeitos do fechamento	Continuidade do crescimento industrial/urbano com impactos mais severos pela baixa circulação hidrodinâmica	Rocha (2004); Hoenicke (2007)
1940–1970	Consolidação do parque industrial	Expansão dos setores metalmecânico, químico, têxtil e plástico; ocupação desordenada; expansão sobre manguezais	Rocha (2004); Hoenicke (2007); Oliveira et al. (2006)
1970–1980	"Milagre econômico"; Distrito Industrial de Joinville (1975); terminal Petrobras/SFS (1977)	Expansão urbana/industrial; ocupação de manguezais; infraestrutura insuficiente	Hoenicke (2007); Rocha (2004); Gerhardinger et al. (2021)
1980–1990	Pesca industrial; reestruturação portuária; início do controle ambiental	SUDEPE fomenta a pesca industrial; infraestrutura portuária modernizada com a construção do terminal graneleiro da CIDASC;	Diegues (1995); Silveira (2010); Hoenicke (2007);

Period	Historical event	Activity / impact	References
		início de políticas de controle; redução parcial dos lançamentos, mas manutenção de passivos	Rocha (2004); Oliveira et al. (2006); Gerhardinger et al. (2021)
1990 –2016	Expansão portuária, consolidação industrial e do turismo; Criação do porto de Itapoá (2011); criação MMA/SEMAM/MMA/CONAMA	Globalização, expansão do setor de plásticos e logística; fortalecimento setor do turismo; Enfraquecimento da pesca artesanal; discussões sobre dragagem e reabertura do canal	MMA, 2014 e 2018; Hostim-Silva et al. (2005); Gerhardinger et al. (2021); Hoenicke (2007); Rocha (2004)
2016 – Presente	Intensificação do uso portuário e conflitos socioambientais	Ampliação e construção de novos terminais portuários; impactos urbanos/ambientais; congestionamentos; pressão sobre comunidades pesqueiras	*Este estudo*; Hoenicke (2007); Rocha (2004); Silveira (2010); Gerhardinger et al. (2021); Luz (2015);

Source: Adapted from Rocha (2004); Hoenicke (2007); Duarte (2023); Luz (2015); Oliveira et al. (2006); Diegues (1995); Borgonha (2005); Silveira (2010); Gerhardinger et al. (2021); Hostim-Silva et al. (2005); Tohy Hadley (1987); CONAMA (Brasil, 2012); MMA (2014).

Babitonga Bay is a shallow estuary, with approximately 75% of its bottom features at depths shallower than 5 m (Vieira and Horn Filho, 2017). Geomorphologically, the system can be subdivided into three main sectors: (i) a main channel oriented NE–SW, with a maximum width of 3.8 km and depths up to 28 m; (ii) the Palmital Channel, to the north; and (iii) the Linguado Channel, to the south, both with average widths up to 1.5 km and depths of approximately 4 m (Vieira et al., 2008; Silva, 2011). The combination of high rainfall, large fluvial sediment input and a history of intensified industrial and port activities makes Babitonga Bay a favorable environment for the accumulation of fine particles and associated metals, especially in low-energy sectors such as the Linguado Channel and Saguaçu Lagoon (Destefani and Resgalla Jr., 2019; Noernberg et al., 2020; Tureck et al., 2024).

In the context of territorial management, Gerhardinger et al. (2021) proposed the concept of the Babitonga Ecosystem, integrating the estuary and the adjacent coastal zone into seven planning units based on ecological and use attributes: Bay Entrance, Palmital Channel, Linguado–Araquari, Joinville Coastal Zone, Central Islands, Linguado–Barra do Sul and Acaraí River. Historically, the bay had two natural connections with the Atlantic Ocean—through Barra do Sul and through the Linguado Channel. The infilling of the Linguado Channel, completed in 1935, substantially modified hydrodynamics, isolating the southern portion of the estuary and converting

the channel into a retention basin for fine sediments and organic matter (Cristofolini et al., 2011; Silva, 2011).

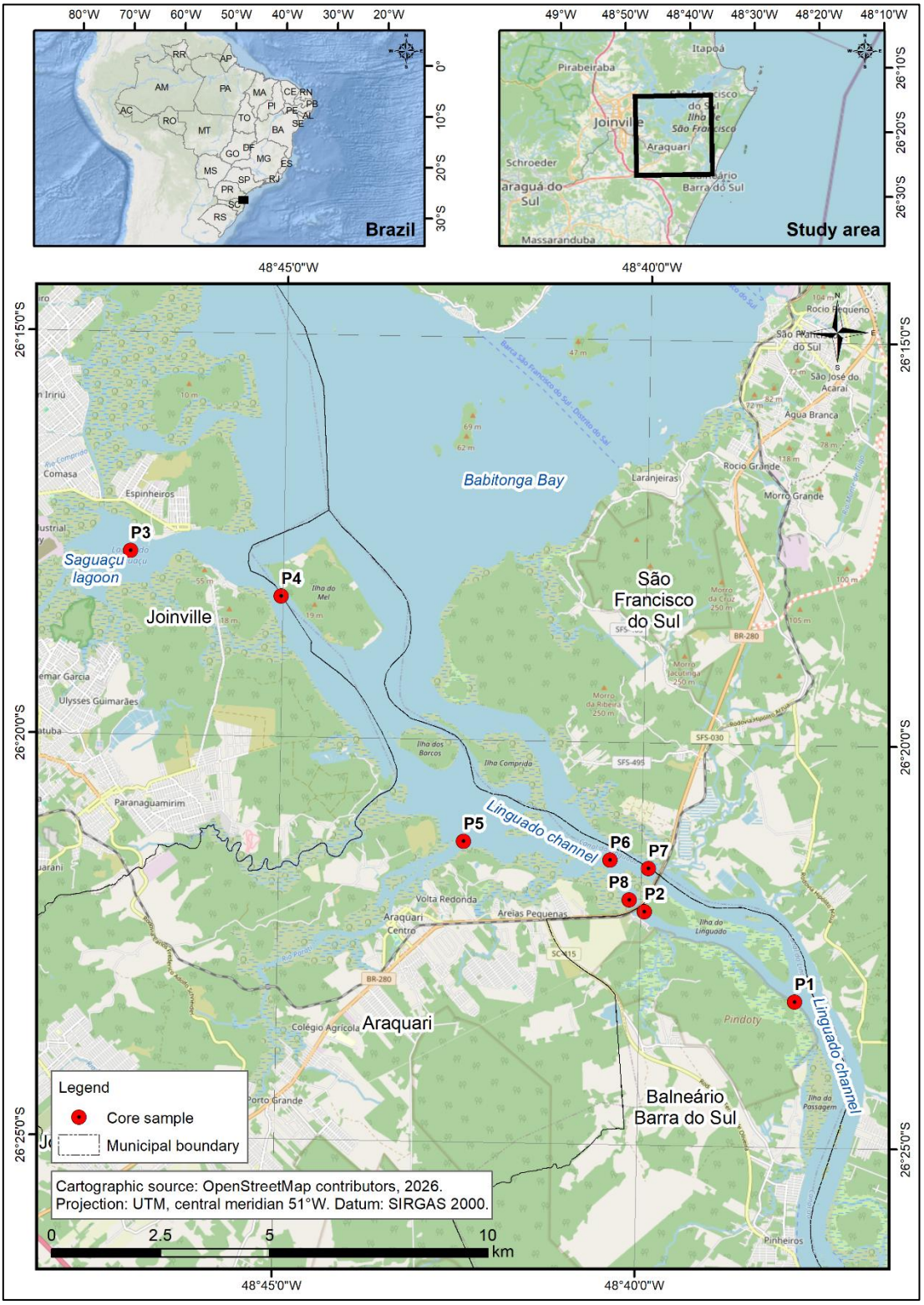


Figure 1. Location of the study area in Babitonga Bay, showing the sediment cores collected in each sector: (i) Linguado Channel (P1, P2 – Balneário Barra do Sul; P5, P6,

P7 and P8 – Linguado - Araquari) and (ii) Babitonga Bay (P3 and P4 – Joinville coastal sector).

In this study, two major sectors of analysis were considered: (i) the Linguado Channel, located south of the BR-280 embankment and corresponding to the Barra do Sul and Acaraí River units; and (ii) Babitonga Bay, comprising the northern system, including the Bay Entrance, Palmital Channel, Linguado–Araquari, Joinville Coastal Zone and Central Islands units. Proximity to the Serra do Mar range conditions a dense hydrographic network, with the Palmital, Cubatão do Norte, Cachoeira and Paraty rivers standing out. This geographical setting favors high rainfall, with mean annual precipitation of 1,908 mm and mean temperature of 20.3 °C (França, 2015), under a humid subtropical climate with hot summers and no defined dry season (Cfa; Köppen–Geiger classification) (França, 2015).

2.2 Sampling

Sediment cores were obtained using a vibracore sampler, allowing the collection of six cores along the Linguado Channel (P1, P2, P5, P6, P7 and P8) and two additional cores in adjacent areas of Babitonga Bay (P3 and P4) (Fig. 1). Core lengths ranged from 2.70 m to 4.22 m.

To avoid contamination, the equipment and liners were cleaned with phosphate-free neutral detergent, rinsed with deionized water and dried in a controlled environment. Before each new core was collected, the sampling system was conditioned with water from the environment to minimize potential cross-contamination. After collection, the liners were removed from the stainless-steel tubes, sealed with PVC caps, wrapped with adhesive tape and properly labeled (location, depth, date and time), ensuring hermetic isolation and traceability. The cores were transported under refrigeration at 4 °C to the Marine Inorganic Chemistry Laboratory of the Oceanographic Institute of the University of São Paulo (LaQIMar–IOUSP).

In the laboratory, the cores were sectioned at 2-cm intervals down to 100 cm depth and, from this point, at 4-cm intervals to the base. Representative samples from the entire length of the eight cores were obtained for geochemical analysis of metals and metalloids, ensuring adequate temporal resolution to detect changes associated with the

closure of the Linguado Channel and the subsequent intensification of anthropogenic activities. Detailed geochronology was determined for cores T2, T5, T7 and T8, totaling 80 layers analyzed for radionuclides.

2.3 Geochronology

Geochronology of the cores was established by determining the activities of ^{210}Pb, ^{226}Ra and ^{137}Cs by high-resolution gamma spectrometry, following procedures described by Figueira (2000), Figueira et al. (2007) and Ferreira (2014). Samples were previously freeze-dried, ground, homogenized and placed into standardized-geometry containers, subjected to minimum counting times of 70,000 s. Water content was used in the calculation of porosity, bulk density and mass depth, essential parameters to normalize the sediment column according to the approach proposed by Ferreira (2014).

Radionuclide activities were determined based on emission lines compiled by the International Atomic Energy Agency (IAEA, 1989). Excess ^{210}Pb (^{210}Pb_{xs}) was calculated as the difference between total ^{210}Pb and ^{226}Ra, allowing the combined application of the CF–CS (Constant Flux–Constant Sedimentation) and CRS (Constant Rate of Supply) models, as established in the literature (Figueira, 2000; Figueira et al., 2007; Ferreira, 2014). Use of these models is justified by the need to simultaneously handle portions of the sediment column with approximately constant sedimentation rates and intervals marked by changes in accumulation rates, resulting from hydrodynamic variations associated with channel closure and intensified human occupation in the drainage basin.

The counting model was validated following the procedures of Neves et al. (2014) and Ferreira et al. (2015), which demonstrated the suitability of the geometry used for simultaneous measurement of natural and artificial radionuclides, especially ^{137}Cs. Counting efficiency of the high-purity germanium (HPGe) detectors followed the approach of Gilmore (2008), and determination of the minimum detectable activity (MDA) was conducted according to IAEA (1989). Analytical precision and accuracy were evaluated according to USEPA (2001), based on certified reference materials.

Caesium-137 was determined by the 661.7-keV emission line and used as an independent stratigraphic marker, allowing the identification of horizons related to atmospheric deposition during the twentieth century (Neves et al., 2014; Ferreira et al., 2015). Age–depth curves were derived from the relationship between mass depth and

corrected ^{210}Pb_{xs} activity, resulting in the chronological framework employed for temporal interpretation of geochemical parameters. The ages obtained were further compared with known historical milestones in the region (e.g., channel closure in 1935, industrial expansion from the 1950s onwards, implementation of the Joinville industrial district in 1975), enabling association of changes in metal concentrations with specific events of anthropogenic transformation in the basin (Rocha, 2004; Hoenicke, 2007; Duarte, 2023).

2.4 Geochemical Analysis

Metals in the available (non-residual) fraction were determined following US EPA Method 3050B (Acid Digestion of Sediments, Sludges and Soils; USEPA, 1996), based on partial acid digestion. The method promotes the preferential extraction of elements associated with the potentially more labile and ecologically relevant sediment fractions—organic matter, Fe and Mn hydroxides, carbonates and fine-particle surfaces—rather than the crystalline residual fraction. This approach, instead of total digestion, was chosen to focus on the fractions most susceptible to mobilization under dredging, resuspension or channel-reopening scenarios, which constitute the main ecological risk concern in this study (Bradl, 2004; Reimann and De Caritat, 2017).

For each analysis, a 1.0-g aliquot of dry sample was weighed into a 50-mL beaker. The procedure consisted of:

- addition of 5 mL of HNO_3 (1:1) and, after 15 min, 5 mL of concentrated HNO_3;
- gentle heating until reduction of volume, followed by cooling;
- addition of 1 mL of Milli-Q water and H_2O_2 (30%), maintained in reaction for 120 min under controlled heating;
- addition of 2.5 mL of HCl and heating to 90 °C for 15 min;
- filtration of the resulting solution and adjustment of the final volume to 50 mL with Milli-Q water.

After digestion, the elements were quantified by inductively coupled plasma optical emission spectrometry (ICP-OES), using a Varian 710-ES instrument. The elements Al, Cd, Cr, Cu, Fe, Ni, Pb, V and Zn, as well as the metalloid As, were determined, encompassing both lithogenic/granulometric proxies (Al, Fe, V) and trace

metals typical of industrial, urban and port sources that are widely used in contamination assessments in Brazilian estuaries (Angulo et al., 2013; Destefani and Resgalla Jr., 2019; Trevizani et al., 2021; Kim et al., 2023).

Limits of detection (LOD) were defined as the lowest concentration detectable with 99% confidence, and the limit of quantification (LOQ) was calculated assuming 20% imprecision. Analytical quality was evaluated using the certified reference material SS-2 (sediment), for which mean, standard deviation (SD), coefficient of variation (CV) and 95% confidence intervals were calculated (Table 2). Recoveries generally fell within ±20% of the certified values, with coefficients of variation below 15% for most elements, meeting the performance criteria recommended for environmental sediment studies (USEPA, 1996, 2001).

Geochronology was conducted at the Gamma Spectrometry Laboratory (LEG) of the University of São Paulo, using protocols based on Ferreira (2014), Ferreira et al. (2015) and Figueira et al. (2007), ensuring consistency between the chronological framework and the geochemical data.

Table 2. Descriptive statistics (mean, standard deviation – SD, coefficient of variation – CV) and certified values for the reference material SS-2.

Element	Certified value	Certified confidence interval	Mean ± SD	CV (%)	Confidence interval
Al	9,548	9,254–9,842	10,410 ± 1,129	11	9,225–11,595
As	3.36	3.18–3.53	3.3 ± 0.5	13	2.8–4.3
Cd	0.91	0.88–0.94	1.3 ± 0.1	9	1.1–1.4
Cr	92.6	88.4–96.7	101 ± 11	11	87–115
Cu	120	118–122	121 ± 11	9	107–134
Fe	23,083	22,486–23,680	24,085 ± 4,056	17	19,828–28,341
Ni	25.1	24.5–25.6	23.5 ± 1.6	7	21.8–25.2
Pb	244	239–250	214 ± 5	3	208–221
V	30	29.2–30.7	31 ± 2	8	28–34
Zn	281	274–288	282 ± 23	8	254–311

2.4 Data Analysis

Differences in the concentrations of metals (Al, Cr, Cu, Fe, Ni, Pb, V, Zn) and the metalloid As between the periods before and after closure of the Linguado Channel were evaluated using the dated cores T2, T5, T7 and T8. The pre- and post-1935 intervals were defined based on age–depth curves, considering the uncertainties associated with geochronology.

Because of asymmetry and the presence of outliers in the concentration distributions, as well as violation of normality and homoscedasticity assumptions for most series, non-parametric tests were used. Statistical comparisons were performed using Wilcoxon tests (for paired samples along the profiles) and Mann–Whitney tests (for independent comparisons of medians between periods), both with continuity correction, in R (v. 2024). The significance level adopted was $\alpha = 0.05$ for all tests.

Environmental quality of the sediments was assessed by directly comparing the concentrations obtained with the limits established by Resolution CONAMA No. 454/2012 (Brasil, 2012), which provides guidelines for the management of dredged material in waters under Brazilian jurisdiction. Although the samples in this study are not from dredging operations, this comparison allows inference of the likelihood of adverse effects on benthic biota, since the guideline values are based on concentration–effect relationships derived from ecotoxicological tests (Long et al., 1995). Results were organized into spreadsheets, correlating depth, estimated age and position relative to the closure of the channel. Time-series plots were prepared showing temporal variations in concentrations and the reference values from Resolution CONAMA No. 454/2012, considering:

- Level 1, below which there is a low probability of adverse effects on biota; and
- Level 2, above which adverse effects are more likely (Brasil, 2012).

Thus, the results presented here, anchored in Brazilian legislation and based on total concentrations in the non-residual fraction, constitute an essential baseline for spatial and temporal patterns of metals in Babitonga Bay, which may be complemented in future studies by integrated risk metrics and speciation/bioavailability approaches.

3 Results and Discussion

Geochemical analysis of sediment cores from Babitonga Bay and the Linguado Channel reveals a consistent pattern of metal enrichment over the last decades, associated both with hydrosedimentary changes following channel closure in 1935 and with the intensification of industrial, urban and port activities in the Joinville region. This behavior is consistent with that observed in other tropical and subtropical estuaries subjected to hydrodynamic confinement and rapid urbanization (Zhang et al., 2019; Yoda et al., 2021; Angeli et al., 2015; Kim et al., 2023; Vedolin et al., 2020; Trevizani et al., 2021).

3.1 Temporal variation in metal and metalloid concentrations

Median concentrations (Table 3) indicate statistically significant increases in all elements analyzed after closure of the Linguado Channel. The most pronounced increases were observed for Zn (+108%), Ni (+84%), Pb (+81%) and As (+70%), confirming a trend of progressive accumulation in fine, organic-rich fractions. These patterns reflect reduced hydrodynamic energy, consequent increases in particle residence time and more efficient sediment retention (Bradl, 2004; Reimann and De Caritat, 2017).

Water–sediment interactions in low-circulation environments such as the Linguado Channel favor adsorption, co-precipitation with Fe and Mn oxides and organic complexation, which enhance metal retention in silt- and clay-sized fractions and increase the fraction potentially available to biota (Miranda et al., 2021; Santos et al., 2024). Wilcoxon tests yielded $p < 0.001$ for all metals and As, demonstrating substantial geochemical changes in the sedimentary environment between the pre- and post-closure periods (Table 3).

Table 3. Median concentrations (μg g^{-1}), statistical significance of differences between pre- and post-closure periods of the Linguado Channel, and historical–environmental interpretation.

Metal	Before 1935	After 1935	p-value	Historical–environmental interpretation
Al	8,689	12,284	0.0019	Increased input of fine particles and organic matter due to reduced hydrodynamic energy.

As	3.7	6.3	4.2×10^{-7}	Reflects discharge of industrial and urban effluents from the 1950s onwards.
Cr	12.2	17.2	0.0002	Indicates intensification of metallurgical and electroplating activities.
Cu	2.9	4.7	3.1×10^{-6}	Associated with domestic and industrial effluents, especially between 1960 and 1980.
Fe	9,679	13,443	0.0003	Increased accumulation of oxides and organic matter under anoxic conditions.
Ni	4.65	8.55	0.00035	Related to expansion of the metal-mechanical district of Joinville (1970s).
Pb	4.0	7.25	4.6×10^{-6}	Linked to vehicular emissions and port activity (1970–1980).
V	11.8	20.8	0.00013	Mixed natural and industrial sources; retained in reducing environments.
Zn	20.6	42.8	0.00057	Most responsive element; related to galvanization and urban wastes.

Integration of geochemical data with historical milestones of Babitonga Bay occupation indicates a direct correlation between concentration peaks and phases of economic expansion. The interval 1907–1935 corresponds to the phase of gradual obstruction of the Linguado Channel, which led to increasing confinement and intensification of fine sediment deposition. Between 1940 and 1970, a marked increase in Cu, Zn and Ni is observed, consistent with the consolidation of Joinville's metal-mechanical, textile and plastics industries. The period 1970–1980, marked by the "economic miracle", implementation of the industrial district and intensification of port and petroleum traffic, coincides with peaks in Pb and V, elements commonly associated with fossil-fuel combustion and cargo handling (Destefani, 2017; Turoczy et al., 2001; Yoda et al., 2021).

This succession of geochemical signatures in response to historical milestones of industrialization and hydrodynamic changes reinforces the role of the Linguado Channel as a sedimentary archive of regional environmental history, in agreement with long-term paleoenvironmental characterizations obtained from multiproxy records within Babitonga Bay itself (De Azevedo et al., 2021; Torres et al., 2024; Galvão et al., 2023).

3.2 Spatial distribution and vertical profiles of concentrations

Spatial analysis reveals a south-to-north gradient of metal accumulation within the Linguado Channel, with sites upstream of the dike (P7 and P8) showing the highest Fe, Zn, Ni and Pb contents. This trend is directly related to low circulation energy, hydrodynamic confinement and the predominance of silt and clay, which favor metal adsorption and complexation with organic matter (Vieira and Horn Filho, 2017; Noernberg et al., 2020; Reimann and De Caritat, 2017). Similar patterns have been described for tropical and subtropical estuaries where low-energy zones act as metal sinks, such as in Caravelas (Angeli et al., 2014, 2015, 2016) and in confined sectors of the Paranaguá and Santos estuaries (Vedolin et al., 2020; Kim et al., 2023; Trevizani et al., 2021).

Ponto 1 – Balneário Barra do Sul

At P1, located in an area under strong marine influence and high hydrodynamic energy, concentrations of all elements were low and relatively constant along the profile. The predominance of sandy sediments, high water-mass renewal rates and intense bottom reworking hinder the deposition of fine fractions and organic matter, the main carriers of metals. No value exceeded Level 1 limits of Resolution CONAMA No. 454/2012 (Brasil, 2012), indicating a low probability of ecotoxicological effects (Fig. 2).

Figure 2. Vertical profiles of metal and metalloid concentrations at Point 1 (Balneário Barra do Sul). The horizontal line indicates the Level 1 guideline value established by Brazilian Resolution CONAMA No. 454/2012.

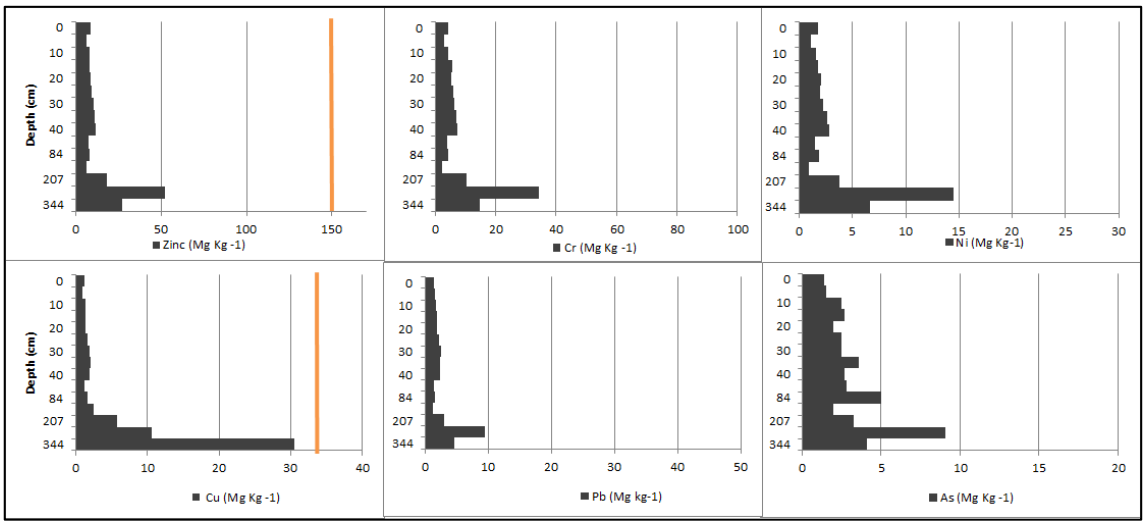


Figure 2. Vertical profiles of metal and metalloid concentrations at Point 1 (Balneário Barra do Sul). The horizontal line indicates the Level 1 guideline value established by Brazilian Resolution CONAMA No. 454/2012.

Point 2 – Downstream of the channel embankment (Balneário Barra do Sul)

At P2, also under strong marine influence, metal contents were low, with a slight increase in As and Zn in layers corresponding to 1965–1970, possibly associated with increased industrial discharges from Joinville during this period (Angeli et al., 2015; Oliveira et al., 2006). After 1980, concentrations return to values close to baseline, suggesting that hydrodynamic dispersion remains efficient and local deposition continues to be limited (Fig. 3).

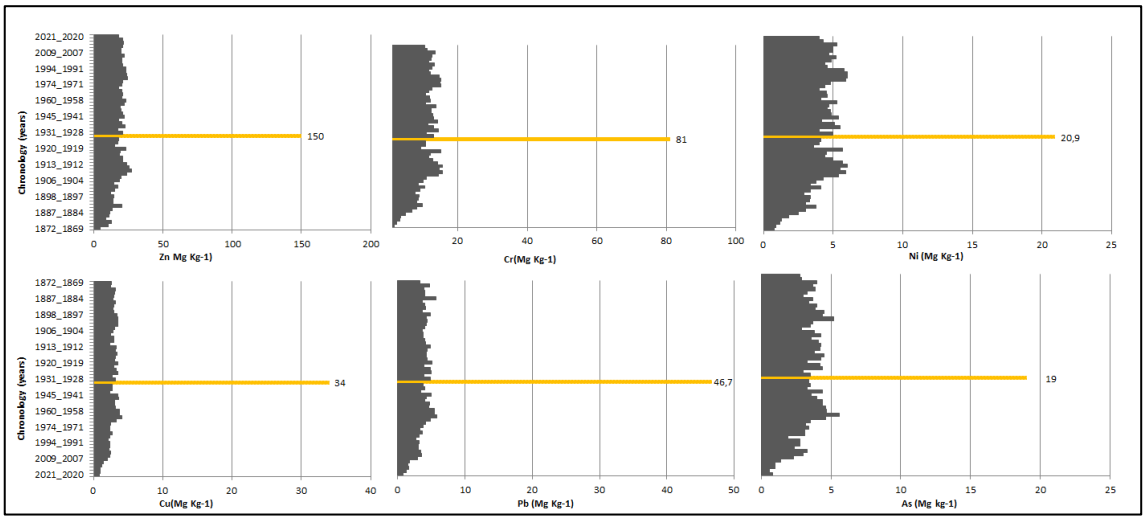


Figure 3. Vertical profiles of metal and metalloid concentrations at Point 2 (Balneário Barra do Sul). The vertical line marks the year 1935 (closure of the Linguado Channel), and the horizontal line indicates the Level 1 guideline value of Resolution CONAMA No. 454/2012.

Point 3 – Saguaçu Lagoon (Joinville)

P3 stands out as the most critical site, with notably elevated Zn and As values exceeding Level 1 limits of Resolution CONAMA No. 454/2012 (Zn = 154.9 mg kg^{-1}; As = 43.9 mg kg^{-1}, approximately twice the guideline value of 19 mg kg^{-1}). This pattern is consistent with the historical discharge of urban and industrial effluents from Joinville into Saguaçu Lagoon, widely documented in regional studies (Martins et al., 2014; Oliveira et al., 2006; Destefani and Resgalla Jr., 2019; Tureck et al., 2024).

The high As concentrations, however, should be interpreted with caution, since the method applied quantifies total arsenic and only a fraction (inorganic As^{3+}) is ecotoxicologically more aggressive (Acquavita et al., 2021; Wang and Mulligan, 2006). Arsenic bioavailability in tropical estuarine sediments is strongly controlled by redox conditions, pH, sulfide content and the ratio between simultaneously extracted metals and acid-volatile sulfides (ΣSEM/AVS) (Rodrigues et al., 2023). Studies in Brazilian estuaries indicate that moderate concentrations of As and other metals in sediments can result in relevant bioaccumulation in bivalves and other benthic organisms, with implications for food webs and human health (Santos and Boehs, 2021; Angeli et al., 2019). These aspects reinforce the need for future speciation and bioavailability assessments in this sector (Fig. 4).

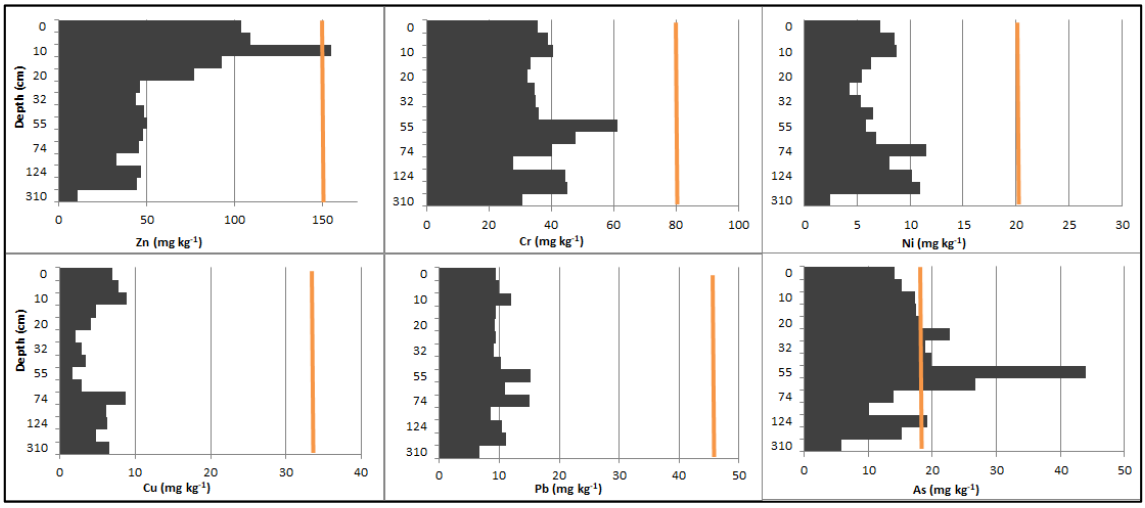


Figure 4. Vertical profiles of metal and metalloid concentrations at Point 3 (Saguaçu Lagoon). The horizontal line indicates the Level 1 guideline value established by Resolution CONAMA No. 454/2012.

Point 4 – Ilha do Mel

At P4, located in an area of higher hydrodynamic energy due to exposure to tidal currents, metal contents were low and relatively homogeneous throughout the sediment column. The high energy regime and the predominance of coarser sediments limit the accumulation of fine fractions and organic matter, resulting in values well below legal limits and no evidence of significant contamination (Demori, 2008; Yoda et al., 2021) (Fig. 5).

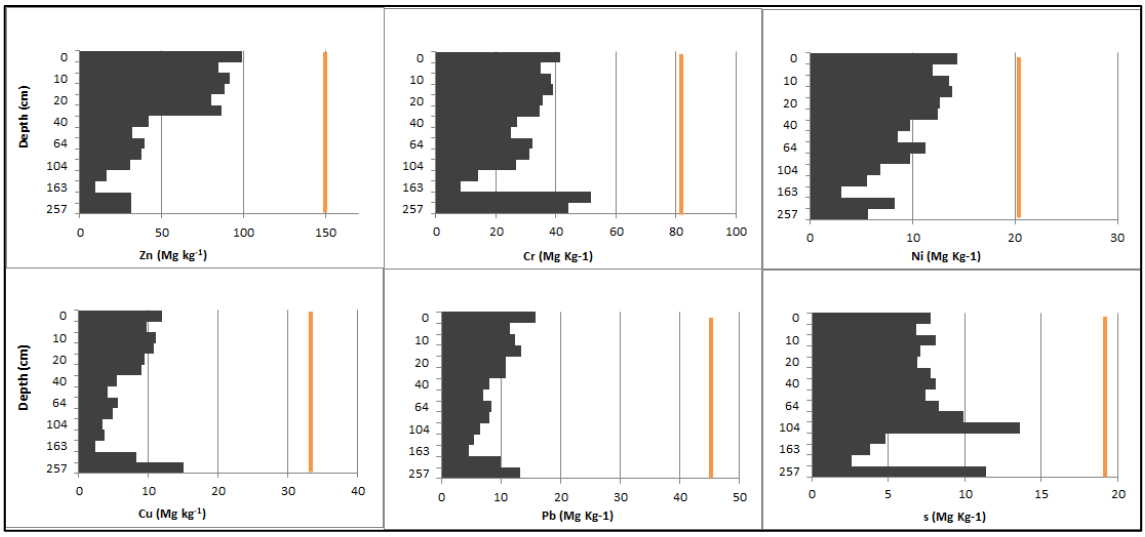


Figure 5. Vertical profiles of metal and metalloid concentrations at Point 4 (Ilha do Mel). The horizontal line indicates the Level 1 guideline value of Resolution CONAMA No. 454/2012.

Point 5 – Paraty River mouth (Araquari)

At P5, a slight increase in Cu, Cr and Zn concentrations was observed between approximately 1960 and 1975. Before channel closure, this sector functioned as a dispersal pathway for sediments from the Paraty River basin. Partial blockage of marine flow and changes in estuarine circulation after 1935 may have altered the export dynamics of fine particles, increasing local deposition of associated metals (Angeli et al., 2014; Reimann and De Caritat, 2017) (Fig. 6).

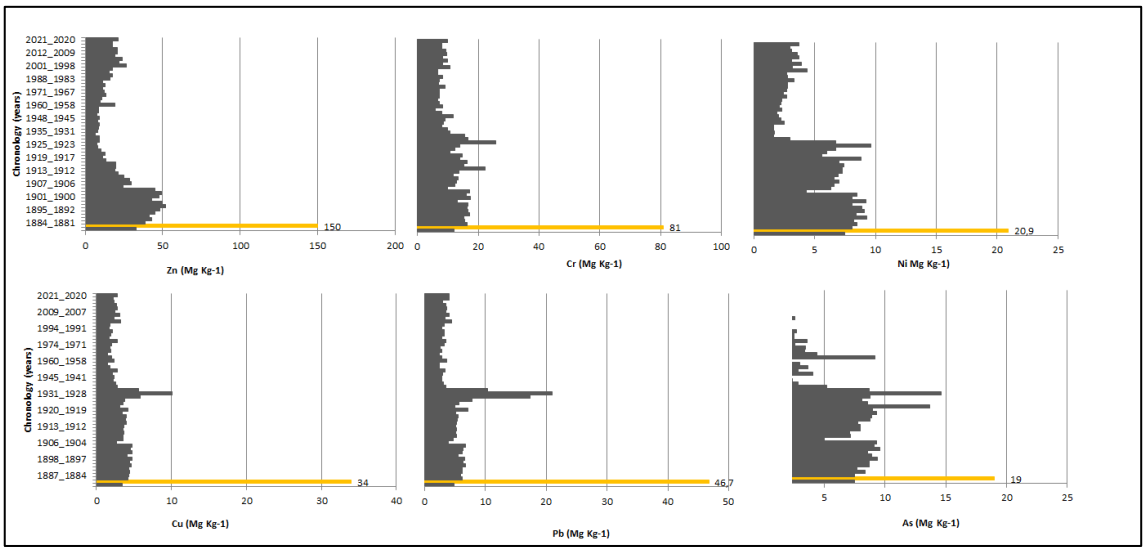


Figure 6. Vertical profiles of metal and metalloid concentrations at Point 5 (Paraty River mouth). The vertical line marks the year 1935 (closure of the Linguado Channel), and

the horizontal line indicates the Level 1 guideline value of Resolution CONAMA No. 454/2012.

Point 6 – João Dias Island

At P6, concentrations generally remained below Level 1 limits of Resolution CONAMA No. 454/2012 (Brasil, 2012), with the exception of Ni, which reached 21.6 mg kg^{-1} at 5 cm depth. Small peaks of Cu and Zn in the surface layers may be associated with recent extreme hydrological events that intensified bank erosion and input of fine sediments and organic matter into the bay (Bustamante et al., 2024; Angeli et al., 2016). This pattern suggests that climatic variability and extreme events may modulate short-term redistribution of metals in this sector (Fig. 7).

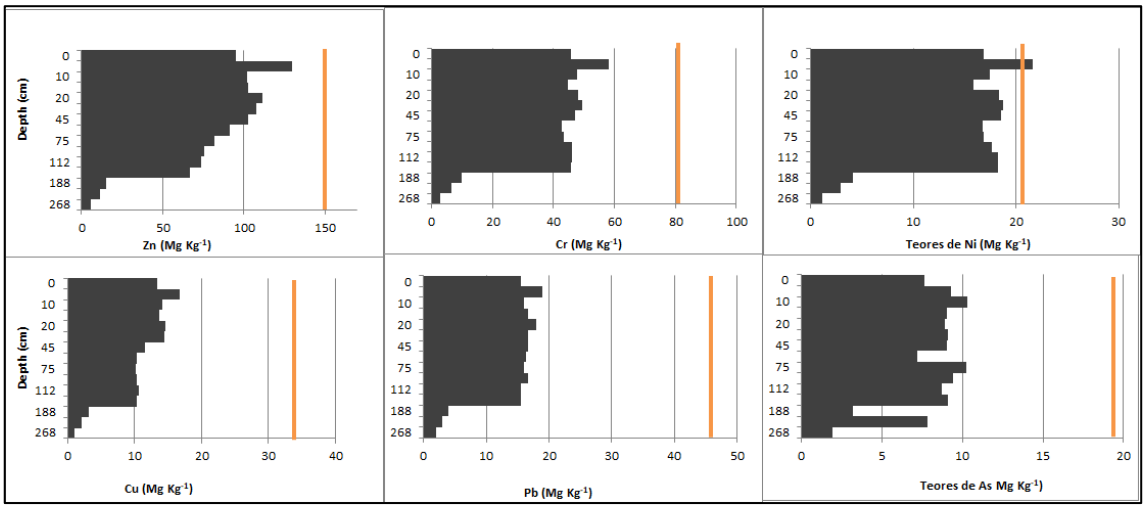


Figure 7. Vertical profiles of metal and metalloid concentrations at Point 6 (João Dias Island). The horizontal line indicates the Level 1 guideline value of Resolution CONAMA No. 454/2012.

Points 7 and 8 – Southern and northern sectors of the Linguado Channel (inner Babitonga Bay)

Cores P7 and P8 showed the highest metal contents of the entire dataset, reflecting strong accumulation after closure of the Linguado Channel. Hydraulic confinement and low circulation favored deposition of fine, organic-rich sediments that retain metals by adsorption and complexation (Reimann and De Caritat, 2017; Angeli et al., 2015; Tureck et al., 2024). This pattern is consistent with that described by Miranda et al. (2021) for low-energy environments, in which water–sediment partitioning is

dominated by organic ligands and Fe/Mn oxides, resulting in high concentrations in non-residual fractions.

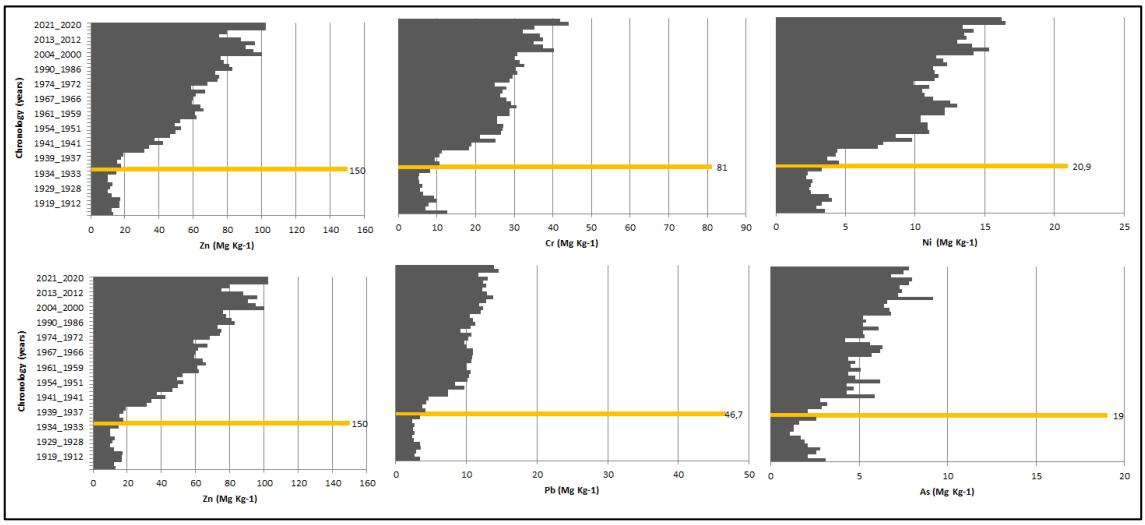


Figure 8. Vertical profiles of metal and metalloid concentrations at Point 7 (southern sector of the Linguado Channel). The vertical line marks the year 1935 (closure of the channel), and the horizontal line indicates the Level 1 guideline value of Resolution CONAMA No. 454/2012.

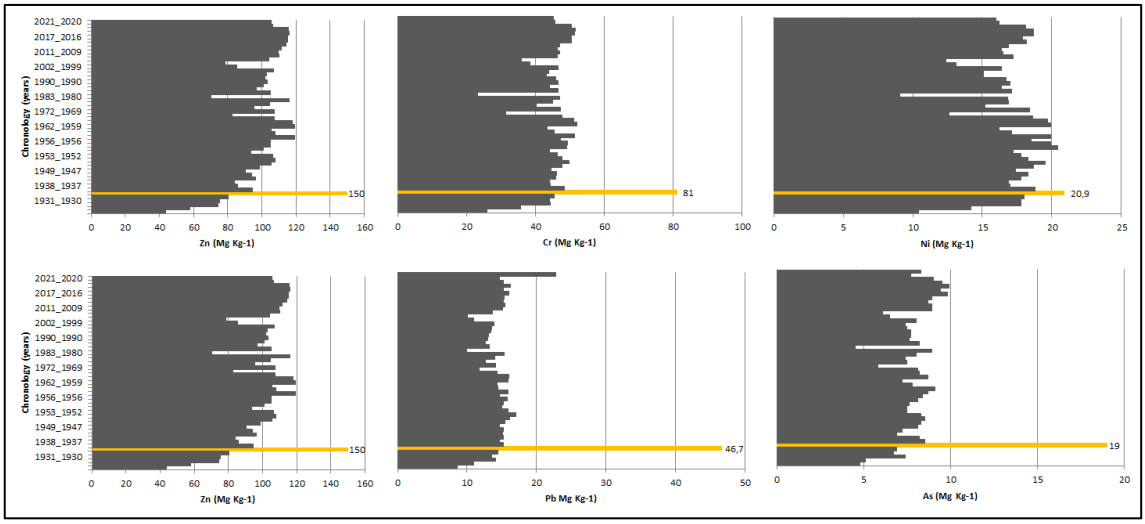


Figure 9. Vertical profiles of metal and metalloid concentrations at Point 8 (northern sector of the Linguado Channel). The vertical line marks the year 1935 (closure of the channel), and the horizontal line indicates the Level 1 guideline value of Resolution CONAMA No. 454/2012.

The upward increase in concentrations from core base to top at both sites indicates continuous, cumulative input over the decades following closure. This behavior is especially marked for Fe, Ni and Zn, elements often associated with

industrial and urban effluents (Angeli et al., 2015; Destefani and Resgalla Jr., 2019; Tureck et al., 2024). Even so, no value exceeded Level 1 limits of Resolution CONAMA No. 454/2012 (Brasil, 2012), indicating no critical contamination according to this criterion (Figs. 8 and 9). This pattern of progressive enrichment without surpassing ecotoxicological thresholds is consistent with the scenario described for other subtropical and tropical estuaries under moderate anthropogenic impact, where integrated indices such as Igeo, CF, mCd and RI point to low-to-moderate but chronic contamination (Trevizani et al., 2021; Naik et al., 2023).

3.3 Comparison with legal thresholds and environmental implications

Mean concentrations of all metals and As in samples from the Linguado Channel and Babitonga Bay remained, with the exception of Zn and As at P3, below Level 1 limits defined by Resolution CONAMA No. 454/2012 (Brasil, 2012). This indicates, in principle, a low probability of adverse ecotoxicological effects on benthic biota, according to the concentration–effect framework derived from Long et al. (1995).

When compared with other Brazilian and international estuaries, values obtained for Babitonga Bay fall in an intermediate contamination range. In the Paranaguá and Santos–São Vicente estuaries, for example, studies report Cu, Zn and Pb levels up to three times higher than those detected in Babitonga, frequently exceeding quality guidelines and accompanied by evidence of biological effects (Vedolin et al., 2020; Kim et al., 2023; Trevizani et al., 2021). In tropical bays under severe industrial impacts, such as the Doce River estuary, integrated indices such as Potential Ecological Risk Index (RI), Contamination Factor (CF) and Pollution Load Index (PLI) indicate critical contamination by metals and significant risk for fisheries and human health (Gabriel et al., 2020). In the Bay of Bengal, Naik et al. (2023) also identified moderate-to-high ecological risk levels for several metals. In Babitonga Bay itself, biomonitoring approaches using filter-feeding organisms and mangrove vegetation show that even under scenarios classified as moderately contaminated, measurable metal accumulation occurs in biota with implications for environmental health (Melo Júnior et al., 2025). Collectively, these studies indicate that metal levels in Babitonga Bay correspond to a relatively low contamination scenario, albeit characterized by gradual enrichment in confined sectors.

On the other hand, the local pattern of progressive enrichment, without exceeding ecotoxicological limits, resembles the situations reported by Zhang et al.

(2019) and Yoda et al. (2021), which characterize environments of moderate and persistent contamination. In these contexts, concern shifts from acute toxicity episodes to long-term cumulative effects, particularly under resuspension conditions and climate-change influence.

Assessments based solely on total concentrations should be complemented by speciation and bioavailability considerations. For arsenic in particular, recent reviews stress that non-residual fractions, especially inorganic As^{3+}, may pose ecotoxicological risks even at moderate total concentrations (Acquavita et al., 2021; Wang and Mulligan, 2006; Sauvé et al., 2000). Angeli et al. (2019) reported bioaccumulation of As and Pb in catfish from tropical estuaries, associated with enriched fine sediments. In this perspective, bioavailability assessments based on ΣSEM/AVS ratios and apparent effects indicators (AEI) have been widely recommended for tropical estuaries (Rodrigues et al., 2023; Santos et al., 2024), allowing discrimination between truly toxic fractions and those bound to geochemically stable phases. In parallel, biomonitoring studies in Brazilian mangroves indicate that key species such as oysters and mangrove vegetation respond to chronic metal contamination even in scenarios of moderate sedimentary concentrations, functioning as sensitive indicators of anthropogenic pressure (Melo Júnior et al., 2025).

In this study, sediment quality was primarily evaluated by comparing measured concentrations with the guideline values of Resolution CONAMA No. 454/2012 (Brasil, 2012), which are based on concentration–effect relationships developed for regulatory purposes. In light of this framework, and considering the absolute concentration levels, enrichment trends and comparisons with other estuaries, Babitonga Bay currently fits a low-to-moderate ecological risk scenario, with potential for intensification in response to hydrosedimentary interventions and climate change (Gabriel et al., 2020; Trevizani et al., 2021; Naik et al., 2023; El-Sharkawy et al., 2025).

3.4 Synthesis and implications for the reopening of the Linguado Channel

Integrated analysis of vertical profiles, spatial distribution and depositional chronologies indicates that closure of the Linguado Channel has been the main driver of hydrosedimentary reorganization in Babitonga Bay, converting the southern sector into a retention basin for fine sediments, organic matter and metals. Sites upstream of the dike (P7 and P8) act as geochemical retention areas, reflecting both hydrodynamic confinement and the history of anthropogenic inputs over recent decades. In contrast,

sectors under stronger marine influence (P1, P2 and P4) maintain low metal contents and relative stability along the cores, confirming the importance of tidal dynamics for dilution and export of particulate material. Saguaçu Lagoon (P3) is the most critical site, with exceedance of Level 1 limits for Zn and As, reflecting the direct influence of Joinville's urban-industrial core.

From a coastal management perspective, the predominance of metals in potentially labile fractions, combined with hydrodynamic confinement, indicates that dredging operations or channel reopening must adopt specific mitigation strategies (Luz, 2015; Gerhardinger et al., 2021). Experimental and field studies demonstrate that resuspension of fine sediments can release reactive metals into the water column, temporarily increasing bioavailability and risk for benthic and filter-feeding organisms (Wang and Mulligan, 2006; Angeli et al., 2015; Miranda et al., 2021). In southern Brazilian mangroves, metal accumulation in oysters and mangrove vegetation has been used to indicate biotic responses to chronic contamination and intensification of anthropogenic pressures (Melo Júnior et al., 2025), reinforcing the need to consider potential impacts on filter feeders and primary producers in Babitonga Bay in the context of dredging or channel reopening.

Recent reviews of metal pollution in coastal environments emphasize that operations in accumulation areas should be accompanied by integrated mitigation strategies combining real-time monitoring, bioavailability assessment, plume-dispersion modeling and safe disposal of dredged material (El-Sharkawy et al., 2025). In this regard, measures such as plume control, continuous monitoring of water and sediment quality, periodic ecotoxicological tests and careful definition of disposal areas are consistent with internationally recommended best practices and with the guidelines of Resolution CONAMA No. 454/2012 (Brasil, 2012).

Management of Babitonga Bay should also incorporate the long-term perspective provided by paleoenvironmental records. Recent multiproxy studies show that Holocene sea-level changes and hydrological reorganizations produced significant facies shifts and changes in the extent and position of mangroves within the bay (De Azevedo et al., 2021; Torres et al., 2024; Galvão et al., 2023). Work in other Brazilian estuaries, such as along the northeastern coast and in the Doce River delta, indicates that mangrove resilience to sea-level oscillations depends strongly on sediment availability, hydrological connectivity and channel dynamics (Cohen et al., 2019; Da Silva et al.,

2022). In Babitonga Bay, projections suggest that sea-level rise, combined with land-use change, may intensify pressures on tidal flats and mangroves in the coming decades (Filgueras et al., 2024). Thus, reopening of the Linguado Channel is likely to trigger complex ecological responses, involving both redistribution of contaminants and reorganization of coastal habitats, and therefore requires integrated planning and long-term monitoring.

In summary, the results indicate a state of moderate but still manageable metal enrichment, provided that proposed interventions are planned based on robust scientific evidence and integrated risk-assessment frameworks. In future studies, the adoption of composite contamination indices (Igeo, EF, CF, mCd, PLI, SQG-Q), as well as bioavailability assessments based on ΣSEM/AVS and AEI, will allow a more refined understanding of the potential effects of channel reopening on biota and on ecosystem services provided by mangroves and associated habitats (Gabriel et al., 2020; Trevizani et al., 2021; Rodrigues et al., 2023; Santos et al., 2024; Naik et al., 2023). Overall, the evidence reinforces the role of the Linguado Channel as a sedimentary archive of regional environmental history and as a central element in any integrated coastal-management strategy for Babitonga Bay.

5 Conclusion

Integrated analysis of vertical profiles and spatial distribution of metals and metalloids in sediment cores shows that closure of the Linguado Channel promoted significant changes in the depositional and geochemical dynamics of Babitonga Bay. Formation of a partially confined system favored sedimentation of fine particles and progressive accumulation of metals, especially in sectors upstream of the dike (P7 and P8), which function as geochemical retention areas. In contrast, sectors under stronger marine influence (P1, P2 and P4) maintain low metal contents and relative stability along the cores, whereas Saguaçu Lagoon (P3) stands out as the most critical site, exceeding Level 1 limits of Resolution CONAMA No. 454/2012 (Brasil, 2012) for Zn and As.

The results indicate a hydrosedimentary gradient controlled by circulation energy and grain size, with Fe, Zn and Ni as the most sensitive tracers of post-closure

environmental changes. Despite the relative increase in concentrations, values remain mostly below ecotoxicological guideline limits, suggesting a current scenario of low-to-moderate ecological risk, but following an enrichment trajectory, particularly in confined sectors. This situation underscores the need for continuous monitoring and careful planning of potential dredging and channel-reopening actions, with emphasis on controlling resuspension of fine sediments and evaluating impacts on biota.

Overall, the Linguado Channel emerges as a sedimentary archive of the environmental history of Babitonga Bay, clearly recording the combined impacts of hydrodynamic interventions and intensified human occupation. The data presented provide an indispensable baseline for integrated coastal-management decisions, offering technical support to evaluate risks and benefits associated with future interventions in the estuarine system.

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Statements and Declarations

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Competing Interests

The authors declare that they have no financial or non-financial competing interests that could have influenced the work reported in this paper.

Ethical Approval

This article does not contain any studies with human participants or vertebrate animals performed by any of the authors. Therefore, formal ethical approval was not required.

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