Effects of contamination with toxic metals on the environmental quality of Sepetiba Bay (SE Brazil)

The case of Ingá Company

Andreza Portella Ribeiro
Mestrado de Gestão Ambiental e Sustentabilidade, Universidade Nove de Julho, São Paulo, Brazil and Instituto de Pesquisas Energéticas e Nucleares, São Paulo, Brazil
Ana Maria Graciano Figueiredo
Instituto de Pesquisas Energéticas e Nucleares, São Paulo, Brazil
José Osman dos Santos
Instituto Federal de Educação, Ciência e Tecnologia de Sergipe, Lagarto, Brazil
Paulo Alves de Lima Ferreira
Instituto Oceanográfico da Universidade de São Paulo, São Paulo, Brazil
Gustavo Silveira Graudenz and Mauro Silva Ruiz
Mestrado de Gestão Ambiental e Sustentabilidade da Universidade Nove de Julho, São Paulo, Brazil
Michel Michaelovitch de Mahiques and Rubens Cesar Lopes Figueira
Instituto Oceanográfico da Universidade de São Paulo, São Paulo, Brazil, and
Julio Cesar de Faria Alvim Wasserman
Universidade Federal Fluminense, Niterói, Brazil

Abstract

Purpose – The purpose of this paper is to address the case of toxic metal contamination of Sepetiba Bay caused by the Ingá Company. The paper reviews the history of the contamination and discusses the current presence of metals in the bay sediments, demonstrating that the toxic metals are clearly enriched. Sepetiba Bay is prone to significant dredging activities that make metals available in the food chain, affecting human populations, mainly fishermen communities.

Design/methodology/approach – The study presents the case of the Ingá Company based on international literature and data provided by previous studies.

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Findings – Through the analysis and compilation of diverse data from the literature, this study demonstrates that the Ingá Company is a major source of Cd, Pb and Zn due to its calamine processing activities used to obtain high purity Zn.
Originality/value – This study highlights important research to complete the historical scenario of heavy metal contamination of the Sepetiba Bay by Ingá Company. The results indicate that the contaminants from the Ingá Company can indeed be traced in the sediments of Sepetiba Bay. These data have the utmost value for the environmental management of this coastal system, because such high concentrations of toxic metals in marine sediments have serious implications for the environmental quality of the bay and may negatively affect biota and human health. Therefore, this study suggests that it is now necessary to monitor this region for contamination continuously.
Keywords Sediment, Sepetiba, Ingá Company, Toxic metals
Paper type Case study

1. Introduction
In the scope of environmental sciences, toxic metals indicate metals and metalloids that form poisonous soluble compounds and have no biological role. In other words, an element can be considered toxic if it is: not biologically essential, biologically essential but is present in unusually high concentrations or in an oxidation state that is abnormal to organisms. In this context, elements such as As, Cd, Cr, Cu, Hg, Ni, Pb and Zn can be classified as toxic to ecosystems and human health. Although a number of these elements have biological functions (such as Cr and Ni), others are toxic, affecting the central nervous system (As, Hg, Pb), kidneys and liver (Cd, Cu, Hg, Pb) of human beings and marine organisms (Corrill and Huff, 1976; Zevenhoven and Kilpinen, 2001; Järup and Akesson, 2009; Jaric *et al.*, 2011).

Environments such as mangrove forests, bays, tidal flats and estuaries are present throughout the world coasts and play an important role in the life cycles of numerous marine organisms (IBAMA, 2002; Ribeiro, 2006; Pan and Wang, 2012; Majer *et al.*, 2014). The sediments in these systems are considered as substrates for organisms that process organic matter and serve as food for upper trophic levels; however, they are also excellent reservoirs for toxic metals (Christensen and Juracek, 2001; Wildi *et al.*, 2004; Cui *et al.*, 2011; Wetzel *et al.*, 2013).

Therefore, due to their role as reservoirs for metals, sediments are crucial in the evaluation, diagnosis and monitoring of impacted coastal areas. In addition, the analysis of metal contents in this environmental matrix enables the study of the history of pollution in a given area (Salomons and Stigliani, 1995; Mahiques *et al.*, 2009). Such studies are especially important because the coasts are areas of significant conflicts of use, housing large portion of the global population, including many of the world's largest cities (Tibbetts, 2002; Fonseca *et al.*, 2013).

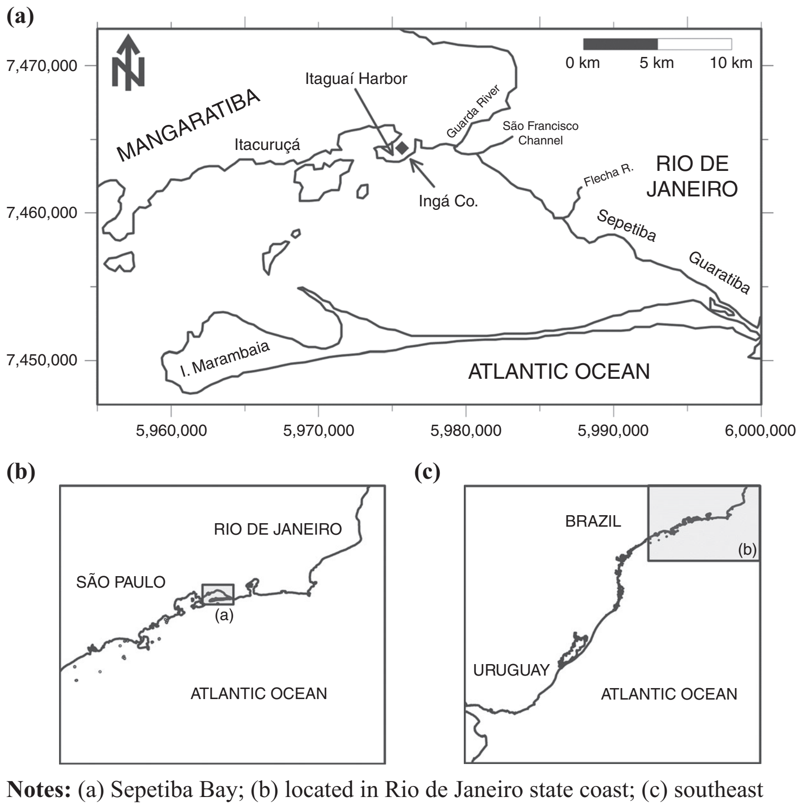
The effects of rapid and uncontrolled industrialization and economic development in coastal regions are a major environmental problem (Zhang *et al.*, 2007). Activities related to ore refinishing and navigation release many metallic contaminants that reach estuarine and coastal systems through riverine discharges, atmospheric transport and soil lixiviation processes (Health, 1987), deteriorating water and sediment quality. In addition, complications regarding the chronic effects, persistency and bioaccumulation of toxic metals in trophic webs (Marins *et al.*, 2004; Wang *et al.*, 2008) can be observed because they participate in numerous biogeochemical cycles (Raj and Jayaprakash, 2008; Duan *et al.*, 2013). The disruption of these biogeochemical cycles with higher concentrations of toxic elements may affect more directly the populations that base their nutrition on seafood.

Toxic metal pollution in coastal environments primarily occurs due to extractive metallurgy activities. Industries that mine, process and refine minerals such as bauxite (for Al), calamine (for Zn), galena (for Pb) and hematite (for Fe), generate ore-processing wastes and sub-products. Without a proper management program, these materials can be a source of toxic metal contaminants and produce additional environmental impacts such as soil and water acidification, visual pollution and chronic effects on the surrounding flora and fauna (BRGM, 2001; Pereira *et al.*, 2008; Wasserman *et al.*, 2013).

This paper discusses the case of toxic metal contamination in Sepetiba Bay (RJ state, Brazil) caused by Ingá Company (producer of Zn), based on the review of data from the literature to provide new and accepted conclusions regarding this situation. Toxic metal wastes from calamine processing were inadequately accumulated at the company's site, and after the company's bankruptcy, society was left with an estimated liability of R$140 million (approximately US$70 million) and a great environmental risk to the bay (Bufoni and Carvalho, 2009).

2. Study area

Sepetiba Bay (Figure 1), located 60 km from the Rio de Janeiro metropolitan region (southeast Brazil), has undergone considerable urban and industrial development in the last several decades. Its basin is home to approximately 400 industries, most of which



Notes: (a) Sepetiba Bay; (b) located in Rio de Janeiro state coast; (c) southeast Brazil

Figure 1.
Location of Itaguaí Harbor and Ingá Company

are metallurgic plants that release wastes rich in metals and other potentially toxic substances directly in the bay and its waters (Cunha *et al.*, 2009; Gomes *et al.*, 2009; Paraquetti *et al.*, 2004).

Itaguaí Harbor is located in Sepetiba Bay, occupying an area of over ten million m^2. This harbor can receive large vessels (Pellegatti *et al.*, 2001) and is a major port associated to an industrial complex in the most important geo-economic region in Brazil. These port facilities brought intense economic development to the region but also generated conflicts on the surrounding environment (Pedlowsky *et al.*, 1991; Silva-Filho *et al.*, 1999; Wasserman *et al.*, 2000).

Particularly important in the case of the contamination with heavy metals, the fishermen have been using these environments for many generations in a more or less sustainable way (Begossi, 1993). Because their feeding habits is composed of around 65 percent fish meet (Begossi and Richerson, 1992), they can be considered the main group affected by contamination with heavy metals. They are perfectly conscious of the risk and have struggled against the installation of new harbors and against the further dredging operations in their fishing areas. The Environmental Impact Assessments of dredging operations that have been carried out in Sepetiba Bay devote many pages to the description of the fishing activities and have to determine mitigation techniques to reduce contamination of fishermen.

Atmospheric emissions also constitute significant source of contamination in the bay. Pedlowsky *et al.* (1991) and Silva-Filho *et al.* (1999) identified significant atmospheric deposition of Zn, but variable with time due to air mass dynamics, with levels comparable to those of direct fluvial input.

In addition to the numerous and diffuse sources of chemicals to Sepetiba Bay, Cd and Zn have a critical direct source: the currently deactivated Ingá Company, whose installations still contain toxic wastes generated from calamine processing for the production of Zn. Although the company is now defunct, several episodes of contamination have occurred since its bankruptcy due to dam breaches that released the accumulated wastes to the bay (Pinto, 2005; Ribeiro, 2006).

In 1962, the Ingá Company began its calamine processing activities for the production of high purity Zn. Since then, mountains of residues from this procedure have been accumulated in open air in the company's courtyard. The procedures used by the Ingá Company generated significant amounts of Zn, Cd and other toxic metals, such as As and Pb (Ribeiro, 2006).

Only in 1984 did the firm built a containment dam around the perimeter of the stacks of residues; however, the dam's construction was irregular, and the dam broke down in 1996, releasing high contents of As, Cd, Pb and Zn to the bay. According to Molisani *et al.* (2004), Ingá Company contributed 24,000 kg yr^{-1} of Cd and 3,660,000 kg yr^{-1} of Zn to the bay until 1998, when the company declared bankruptcy.

The interruption of the operation of Ingá Company combined with the intense regional rains increased the risk of bay contamination due to the possibility of dam breaches. For instance, in the summer of 2003, the physical structure of the containment dam began to deteriorate, and the effluents were drained directly to the surrounding mangrove forests (Medeiros and Pinto, 2006).

As a results of the 2003 incident, the Brazilian Federal Court mandated that both the city of Itaguaí (in which the Ingá Company was located) and the Rio de Janeiro state government fund and execute the Ingá Rejeito Zero (Ingá Zero Waste) project. This project reinforced the physical structure of the containment dam and implemented procedures for waste treatment. In 2006, an estimated 800,000 kg of Zn, 2,500 kg of

Cd, 350 kg of Pb and 20 kg of As were removed from the wastes (Medeiros and Pinto, 2006).

Even though there are several anthropic sources of toxic metals to Sepetiba Bay, none causes much contamination as the Ingá Company. Molisani *et al.* (2004) found high concentrations of the toxic metals Cd and Zn in species of mollusks, crustaceans and fish largely consumed by the local population in the Sepetiba Bay.

It is clear that the Ingá Company contributed to the degradation of the environmental quality of Sepetiba Bay as it was a substantial point of As, Cd, Pb and Zn. However, the simple presence of these metals in sediments does not indicate their toxicity, as this also depends on their bioavailabilities and mobilities, an important information to derive toxic metals' biomagnification through the trophic chain and determine risk for humans.

3. Methodology

Herein, we present a case study of the toxic contamination caused by the deactivated Ingá Company in Sepetiba Bay, Rio de Janeiro State. According to Yin (2001), a case study is an empirical investigation that targets a contemporary phenomenon embedded in some real-life context. In general, this methodology can utilize different sources of evidence to explain the relevant phenomenon. In addition, Alves-Mazzotti and Gewandsznajder (2001) emphasize that case studies provide confidence regarding the generalization of the obtained results.

In this study, data were collected from a literature review focussing on papers published in international journals dealing with toxic contamination, mainly Barcellos (1995), Molisani *et al.* (2004), Medeiros and Pinto (2006), Ribeiro (2006), Gomes *et al.* (2009) and Ribeiro *et al.* (2013). Two of these works were previously published by the first author of the present article as result of a research funded by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

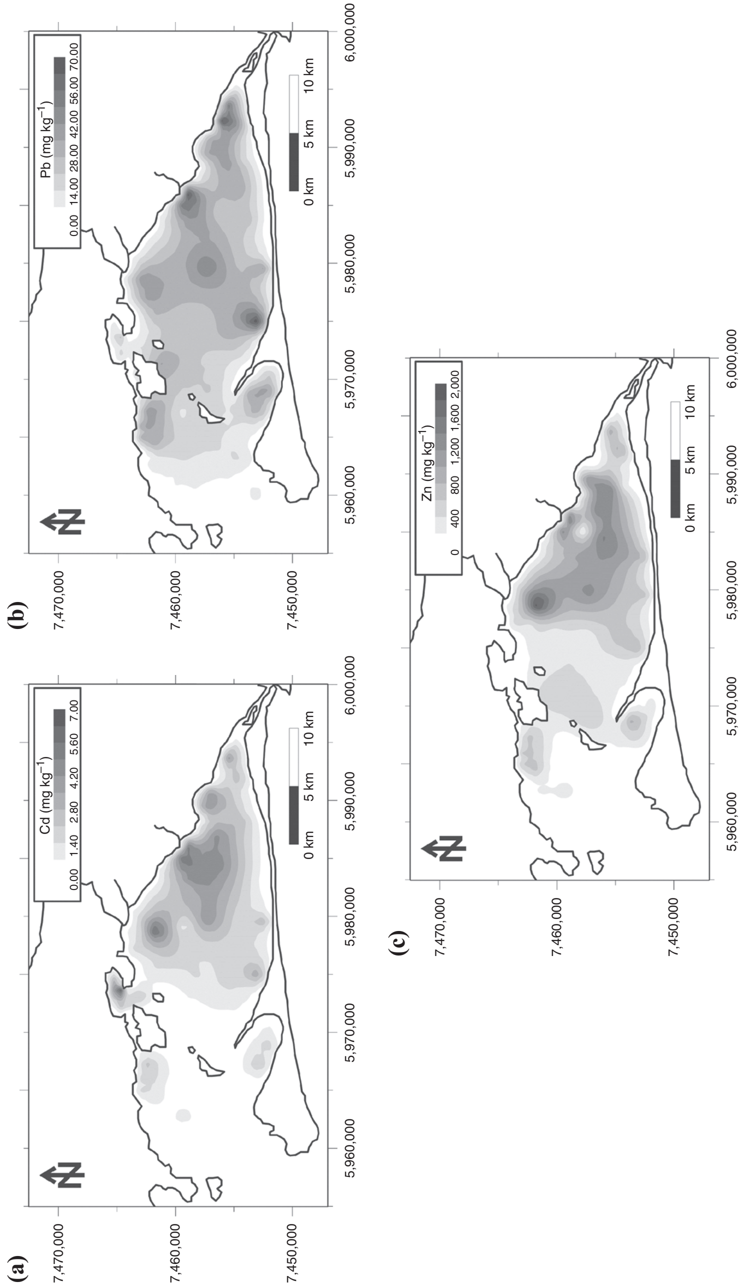
The results of this study are supported by the analyses of toxic contaminants (Cd, Pb and Zn) in the sediments of Sepetiba Bay. The SEM (simultaneously extracted metals)/AVS (acid volatile sulfides) ratio model was also used to check the bioavailability of Cd, Pb and Zn in the bay ecosystem.

4. Results and discussion

The bioavailability of toxic metals to the environment along with their mobilities are essential to verify if a given contaminant can negatively affect the environment (De Jonge *et al.*, 2010; Teuchles *et al.*, 2012). The study of Ribeiro *et al.* (2013) carried on such an evaluation, using a model to estimate Cd, Pb and Zn bioavailability and mobility in the marine sediments of Sepetiba Bay.

Figure 2 shows the spatial distributions of Cd, Pb and Zn in the sediments of Sepetiba Bay. To check their bioavailability, the authors used the SEM/AVS ratio model, which can predict metal toxicity and availability to the ecosystem as AVS are the main metal complexing agents in sediments. If the SEM/AVS ratio is greater than 1, the toxic metals can be liberated to the water, where they are subject to absorption by organisms. Figure 3 shows the results of SEM/AVS model in Sepetiba Bay.

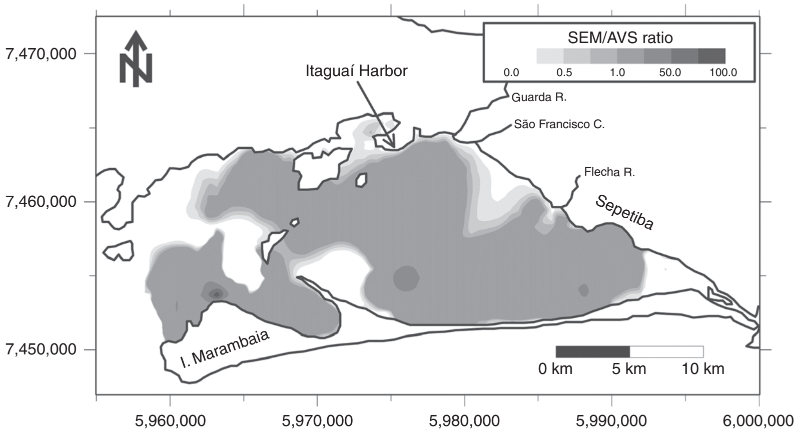
To ascertain metal mobility, the authors also used the geo-statistical model of concentration attenuation, which shows how an element behaves spatially by identifying regions of higher retention as those with higher values of attenuation. Figure 4 represents the model of attenuation of concentrations in Sepetiba Bay.



Notes: (a) Cd; (b) Pb; (c) Zn

Source: Adapted from Ribeiro *et al.* (2013)

Figure 2.
Spatial distribution of toxic metals concentration (in mg kg^{-1}) in sediments of Sepetiba Bay



Source: Adapted from Ribeiro *et al*. (2013)

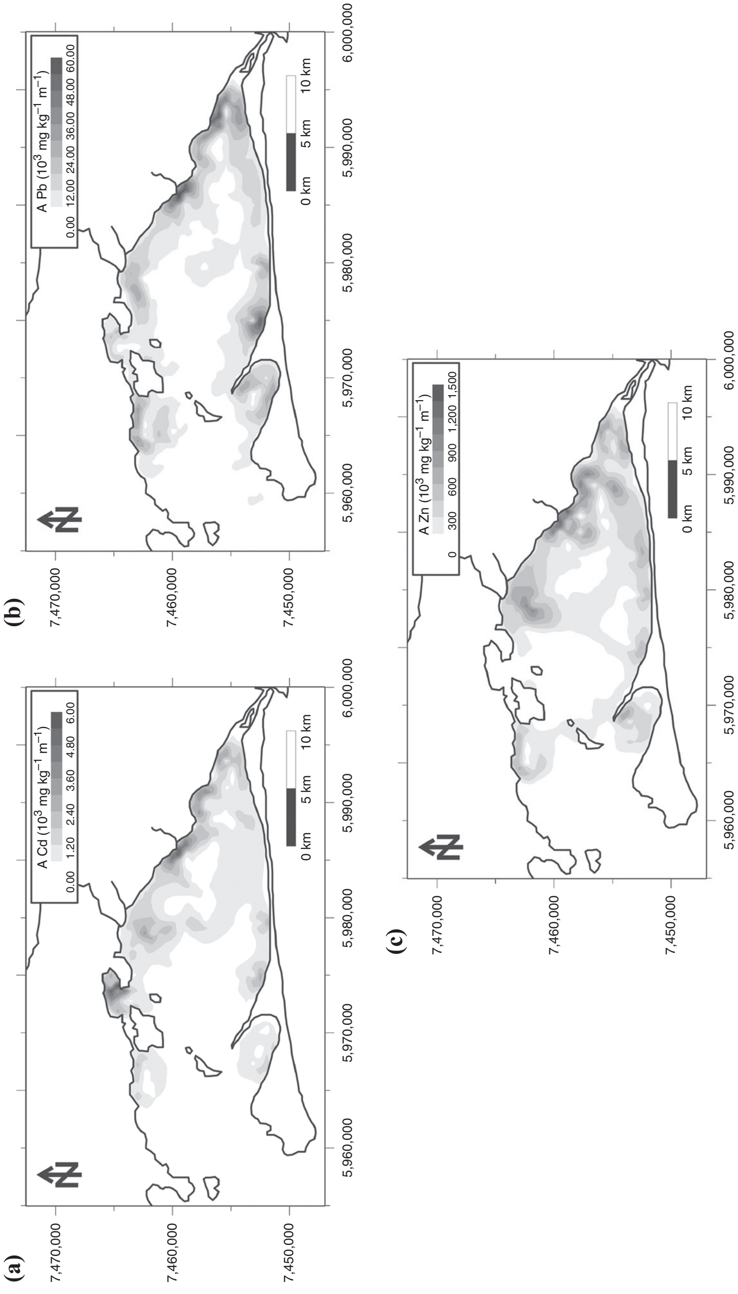
Figure 3.
Spatial distribution of the SEM/AVS ratio in sediments of Sepetiba Bay

The authors' findings indicate that high concentrations of Zn are found mostly near the Ingá Company and Itaguaí Harbor; these values exceed the probable effect level limit of 271 mg kg^{-1} (Canadian Council of Ministers of the Environment (CCME), 1999), the threshold above which there is a significant probability of adverse effects on biota. The findings do not indicate bioavailable toxic metals, as the SEM/AVS ratios imply weak metal retention in the sediments. Stronger metal retentions are observed in the northeast and southeast regions of the bay, likely due to the presence of extensive mangrove forests, in which their retention is a function of organic matter content in the sediments. The fishing of benthic species in this area was studied by Begossi (1993) and constitutes a real risk of human contamination.

The regions with low SEM/AVS ratios presented higher levels of toxic metals because the metals are retained in the form of sulfides, and are unavailable to the biota. This strong retention is also indicated in Figure 4, where the highest values of attenuation indicate low mobilities in the northeast region of the bay near São Francisco Channel, Guarda River, Itaguaí Harbor and the Ingá Company, the sources of these elements to the bay.

Based on the emission factors of contaminants and their deposition levels, Molisani *et al.* (2004) suggested that the main source of Cd and Zn to Sepetiba Bay are effluents from the Ingá Company. The levels of Cd and Zn reached 200 mg kg^{-1} and 4,200 mg kg^{-1}, respectively, during the company activities (Figure 5). These results are corroborated by the study of Barcellos (1995), who identified Cd and Zn concentrations of 396 and 37,300 mg kg^{-1}, respectively, in marine sediments around the Ingá Company. Ribeiro *et al.* (2013) reported maximum values of 7.62 mg kg^{-1} for Cd, 48.83 mg kg^{-1} for Pb and 612.43 mg kg^{-1} for Zn in marine sediments of Sepetiba Bay. The amounts of these contaminants that still reach the bay since the closure of the company are unknown.

Moreover, Gomes *et al.* (2009) showed that Sepetiba Bay is not only contaminated with Cd and Zn (present levels: 5.0 mg kg^{-1} and 600 mg kg^{-1}, respectively), but also shows yearly increases in metal fluxes. The increases in annual Cd flux from 1.6×10^{-3} to 2.2×10^{-2} g m^{-2} y^{-1} and in annual Zn flux from 0.26 to 4.27 g m^{-2} y^{-1} can be associated with the activities of the Ingá Company in this area.



Notes: (a) Cd; (b) Pb; (c) Zn

Source: Adapted from Ribeiro *et al.* (2013)

Figure 4.
Model of attenuation ((a), in 10^3 mg kg^{-1} m^{-1}) of toxic metals concentrations (in mg kg^{-1}) in sediments of Sepetiba Bay

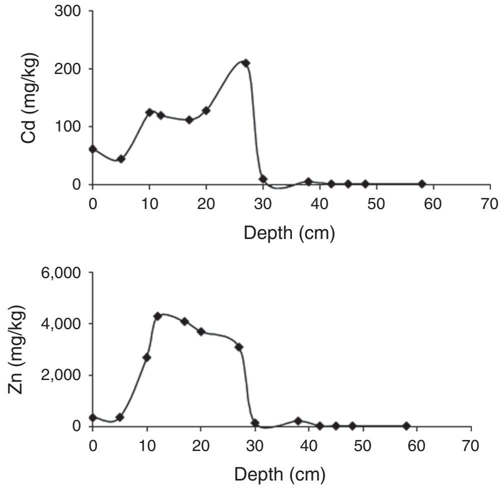


Figure 5.
Vertical profiles of Cd and Zn (in mg kg^{-1}) in a contaminated site that receives effluents from Ingá Company

Source: Adapted from Molisani *et al.* (2004)

Although there are high concentrations of toxic metals in the Sepetiba Bay primarily due to the irregular activities of the Ingá Company (in the case of As, Cd, Pb and Zn), these metals are not bioavailable and are immobile in the sediments. Notwithstanding, the possible release of these toxic metals into the water column due to, for instance, dredging activities, must be taken into consideration. These dredging activities are not frequent, but are necessary for the economic and social development of Sepetiba Bay.

The historical review presented herein shows that the Ingá Company was an irregular ore processing facility that released large amounts of toxic metals in the ecosystem of Sepetiba Bay. Moreover, the sediments of Sepetiba Bay present high levels of metals that can cause serious negative effects on biota and human health. Based on the review of internationally published papers in this study, the contamination situation in the Sepetiba Bay cannot be attributed to natural sources.

The levels of inorganic contaminants due to the history of the Ingá Company in Sepetiba Bay suggests that this irregular company is the source of these contaminants. The company released large amounts of toxic residues to the environment, and no other activity, natural or human, released such levels of metals into the bay.

5. Conclusions

Based on the data taken from the literature regarding inorganic contamination in Sepetiba Bay, the maximum reported levels of Cd, Pb and Zn in sediments are 396, 48.83 and 37,300 mg kg^{-1}, respectively, which imply contamination by these elements. Because such high concentrations in the surroundings of the Ingá Company site and in the marine sediments can be harmful to human health, particularly fishermen communities, and the environment, a continuous monitoring of the region from now on is necessary.

Because a higher metallic retention was observed in the northeast and southeast regions of the bay and there has been a yearly metal influx in this environment, monitoring should be undertaken as part of the local environmental policy supported by public authorities. A particular focus should be set on the fishermen communities who have never been survey for contamination level in hairs, blood or urine. Even considering the reduction of leakages from the Ingá Company wastes due to the implementation of project Ingá Rejeito Zero, risks of accidents and increased environmental damage still exist. In this regard, the government should first take action and decide what to do about the environmental liability left behind by the Ingá Company.

Furthermore, another important issue that was not emphasized in our study, but deserves to be focussed in future research regarding environmental socioeconomic management, is related to some communities along the coast of Sepetiba, whose livelihoods depend on artisanal fishing.

Based on the results of this study, three major considerations regarding potential impacts to society can be highlighted:

(1) Based on the use of chemical methodologies for metal analysis and specialized software for determining the spatial distributions of the obtained data in Sepetiba Bay maps, it was possible to visualize the patterns of Cd, Zn and Pb contamination in the region. In addition, by using a geo-statistical model, it was possible to simulate Cd, Zn and Pb bioavailability and mobility in the environment. This modeling is important because it attempts to connect theory to practice by building a possible bioavailability and mobility scenario that can be helpful to anticipate what might happen in the study region in the coming years. This approach also opens a window for future research on contaminated marine environments (similar to Sepetiba Bay) to provide data for judges and decision makers.

(2) In-depth research monitoring of the contamination over time is advised not only to provide evidence for lawsuits but also to generate reliable information to increase public awareness of the risks posed by the existing contaminants. This information could also be important to support public policies on environmental liabilities at the federal and state levels.

(3) Because there is strong evidence that the region of Sepetiba Bay is contaminated (Wasserman *et al.*, 2000; Fonseca *et al.*, 2013; Ribeiro *et al.*, 2014), the assessment of the concentration levels of Cd, Zn and Pb in the bodies of the local inhabitants is recommended considering that there is a lack of studies concerning toxicity and/or intake of these metals by the local population (Pereira *et al.*, 2008; Ferreira, 2009; Horta *et al.*, 2011).

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About the authors

Dr Andreza Portella Ribeiro, Graduated in Chemistry at the State University of Ponta Grossa, has PhD title in Nuclear Technology with emphasis in environmental chemical analysis from the University of São Paulo. She develops works in the area of environmental chemistry, working on the following topics: ICP-OES, soils, marine sediments, organic materials, metals, Antarctica. Dr Andreza Portella Ribeiro is the corresponding author and can be contacted at: andrezp@uninove.br

Professor Ana Maria Graciano Figueiredo, Graduated in Chemistry, has PhD title in Nuclear Technology from the University of São Paulo. She is a Researcher at the Institute of Nuclear and Energy Research (IPEN), has experience in the area of environmental chemistry, acting on the following subjects: analysis by neutron activation, heavy metals, rare earths, biomonitors.

Dr José Osman dos Santos, Graduated in Physics at the Federal University of Sergipe and has a PhD title in Nuclear Technology from the University of São Paulo. He is a Professor at the Federal Institute of Sergipe, has experience in the area of Physics, with emphasis on optical and spectroscopic properties of condensed matter and interaction of matter with particles and radiation.

Paulo Alves de Lima Ferreira, an Oceanographer Graduated at the University of São Paulo, is a Collaborator of Laboratory of Marine Inorganic Chemistry and Gamma Spectrometry of the Oceanographic Institute (USP). Paulo Alves de Lima Ferreira operates in the areas of natural and artificial radioactivity in environmental matrices, mathematical modeling radionuclide geochronology applied statistics and the assessment of metals in sediments.

Professor Gustavo Silveira Graudenz, Graduated in Medicine from the Federal University of Rio Grande do Sul and has a PhD from the University of São Paulo. He is a Professor of the Medicine Program in Business Administration at the University Nove de Julho. He has experience in the area of human health and environmental health, with an emphasis on allergology and clinical immunology.

Dr Mauro Silva Ruiz, Graduated in Geology from the Universidade Estadual Paulista Júlio de Mesquita Filho – UNESP, PhD in Geography from the University of Southern Illinois at Carbondale, USA. He is currently a Professor in the Professional Master's Program in Environmental Sustainability Management from the Universidade Nove de Julho (UNINOVE). He has experience in the areas of environment, technological forecasting, technology parks, local production, technology and economics of mineral economics.

Professor Michel Michaelovitch de Mahiques, Graduated in Geology at the University of São Paulo and has a PhD title in Oceanography. He is currently a Professor at the University of São Paulo. He has experience in oceanography, with an emphasis on marine sedimentology, mainly in the following areas: sedimentation, stratigraphy and coastal region, the continental shelf and continental margin.

Professor Rubens Cesar Lopes Figueira, Graduated in Chemistry, has PhD Degree in the Geological Oceanography Oceanographic Institute (USP). He is a Professor at the Institute of Oceanographic (USP). He has experience in the area of nuclear chemistry and radiochemistry, acting on the following themes: marine sedimentation, natural and artificial radionuclide, radiochemical analysis and geochronology.

Professor Julio Cesar de Faria Alvim Wasserman, an Oceanographer from the University of the State of Rio de Janeiro, earned a PhD title in Chemical Oceanography at the Université de Bordeaux (France). It is an Associate Professor at the Fluminense Federal University (UFF) and a Coordinator of the UFF Network for Environment and Sustainable Development.