
ELSEVIER
Journal of
Environmental
Management

Journal of Environmental Management 121 (2013) 48–56

Contents lists available at SciVerse ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Planning dredging services in contaminated sediments for balanced environmental and investment costs

Julio Cesar Wasserman[a,*], Sérgio Ricardo Barros[b,c,1], Gilson Brito Alves Lima[d,2]

[a] Network of Environment and Sustainable Development (REMADS-UFF), Universidade Federal Fluminense, Niterói, Rua Passo da Pátria, 156, São Domingos, Niterói, RJ, CEP 24210-240, Brazil
[b] Post-Graduation Program in Systems Management (LATEC-UFF), University Federal Fluminense, Rua Passo da Pátria, 156, São Domingos, Niterói, RJ, CEP 24210-240, Brazil
[c] Fundação de Estudos do Mar (FEMAR), Rio de Janeiro, Brazil
[d] Department of Production Engineering, University Federal Fluminense, Rua Passo da Pátria, 156, São Domingos, Niterói, RJ, CEP 24210-240, Brazil

ARTICLE INFO

Article history:
Received 20 June 2011
Received in revised form
23 October 2012
Accepted 5 February 2013
Available online

Keywords:
Heavy metals
Mapping
Dredging
Environmental impact assessment
Sepetiba Bay
Brazil

ABSTRACT

Dredging of contaminated sediments has shown to be a harmful activity for the environment, because a number of contaminants can be resuspended and become available to the organisms. Furthermore, dredged contaminated sediments may cause significant damages in the dumping site. In order to avoid the drawbacks of this activity, better techniques have to be developed and the present article presents a new procedure for the planning of dredging that reduces the environmental impacts by reducing the amount of dredged sediments and, at the same time, reduces costs. The new technique uses screening of contaminant concentrations in the sediments that are normally part of the environmental impact assessment for dredging activity. A detailed mapping of the contamination, layer by layer is carried out and the areas where the action levels are reached are outlined with polygons, establishing limits within which sediments have to be dredged with safe procedures. In the case presented, construction of a harbor in Sepetiba Bay, Rio de Janeiro, Brazil, the safe procedure is cutter/suction dredging and pumping into a sub-aquatic confined disposal facility (CDF). A detailed evaluation of costs showed that if the whole layers of sediment were to be dumped into the CDF, the cost of the activity would be at least 63.82% more expensive than the proposed procedure, constituting an attractive advantage. Furthermore, as the size of the CDF is significantly smaller, less dredging is necessary, causing smaller environmental impact.

1. Introduction

Dredging activities in contaminated sediments has shown to be a significant threat for the environment, being subject to severe restrictions from a number of governmental agencies worldwide. These restrictions are primarily grounded on the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter from 1972 (also known as the London Convention) that "prohibits the dumping of certain hazardous materials in the sea and requires a prior special permit for the dumping of a number of other identified materials and a prior general permit for other wastes or matters" (IMO, 1972).

The awareness of the dredging activities relies on the fact that contaminated sediments resuspension may cause release of otherwise precipitated material in inert chemical forms (Ottmann, 1985; Vale et al., 1998). For example, heavy metals in reducing coastal sediments tend to be associated with sulfides, precipitating as stable compounds (Bertolin et al., 1997) that are harmless to organisms, including bottom feeders (Casas and Crecelius, 1994). However, strong oxidation process of the sediment caused by dredging and dumping can break the sulfide bonds and release metals to the water column (Cornwell and Morse, 1987; Morse, 1994; Regnell et al., 2001). Although the metals release during the dredging procedure itself is harmful, it was demonstrated that the damages in the disposal area are still more significant and long lasting (Sturve et al., 2005), whenever careless procedures are applied. Furthermore, considering that the dumping areas are frequently unpolluted, the impact of the activity is more profound.

In polluted environments, the restrictions for dredging activities engendered the need for planning techniques that can reduce the environmental impacts. For instance, Palermo et al. (2008) have introduced the concept of Sediment Management Units (SMU) that constitute pre-defined portions of the whole dredging area, where different procedures should be applied as a function of the physical

* Corresponding author. Tel.: +55 21 2629 2207; fax: +55 21 2629 2234.
E-mail addresses: geowass@vm.uff.br, julio.wasserman@gmail.com (J.C. Wasserman), sergiobarros@vm.uff.br (S.R. Barros), gilson@latec.uff.br (G.B.A. Lima).
[1] Tel.: +55 21 2629 5619.
[2] Tel.: +55 21 2629 5721.

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http://dx.doi.org/10.1016/j.jenvman.2013.02.024

characteristics of the sediments, depth to be dredged, current or wave regimes, concentrations of different pollutants and hot spots of contamination. These subdivisions were shown to be very useful in large and complex dredging procedures for remediation of contaminated areas.

The effects of hydrodynamics were show to be particularly important in establishing the impacts during dredging and in the sludge disposal site. During dredging, the impacts are mainly associated with the formation of contaminated suspended matter plumes that may have a broad or a restrict dispersion as a function of the equipments used or as a function of the hydrodynamics. Cutroneo et al. (2012) studied the dispersion of a dredging plume in the Port of Genoa and observed that the concentrations of suspended matter were considerably reduced 200 m away from the activity, indicating a restricted impact, because of the reduced hydrodynamics in the area. Furthermore, they observed that a backhoe dredging caused less resuspension at a distance of 50 m than a trailing hopper suction dredge (THSD). In the Sepetiba Bay, PROOCEAN and Fragoso (2010) applied a tridimensional model to the evaluation of a dredging plume and observed that depending on the tide and the wind the reach of the impact vary between 600 and almost 1000 m, much more widespread than in Italy. This difference is attributed to the fact that the Italian Port is more restricted and subject to smaller tidal and wind currents. In the sludge disposal site, the interaction with hydrodynamics is more delicate, because the sediments are supposed to stay in place for geological periods and the presence of currents may constitute a serious environmental threat. In the Bay of Fundy (Canada), Li et al. (2009) studied the stability of a dredging dumpsite and observed that due to wave mobilization and local strong currents, most of the deposited sludge were spread in a region of 1.4 km in diameter. In this case remobilization of the sediments may solubilizes a series of contaminants that in a undisturbed environment would be immobilized in reduced complexes. The use of Confined Disposal Facilities (CDFs) to the discharge of the residues of dredging operations was shown to be environmentally safer, whenever the CDF location is adequately chosen (Laboyrie, 2004).

Although the hazards of dredging in coastal environments are largely recognized in the scientific literature (e.g. Driscoll et al., 2002; Sturve et al., 2005; Vale et al., 1998), the need for the construction of new harbors and maritime terminals has pulled developing countries like Brazil to significantly increase the activity. In this country, the National Dredging Program established that for 2010, investments of the order of 800 million Dollars (SEP, 2008) should enable some 250 million cubic meters dredging, of which at least 5% (some 12 million cubic meters) may present pollutant loads higher than the sediment quality criteria (*e.g.* 410 mg kg^{-1} for Zn in saline environments) established in local regulations (CONAMA, 2004). The percentage of dredged contaminated sediments may be still greater because authorities systematically choose degraded areas to install new harbors, where sediments have already been largely affected by inputs of heavy metals and other pollutants from various activities. This is the case of Sepetiba Bay, which received large inputs of cadmium and zinc during the years 1970's until the 1990's from a local industry (Pellegatti et al., 2001). It is important to highlight that the environmental impact caused by dredging in contaminated areas directly affects the fishing activity, generating conflict in the coastal zone. The consumption of contaminated fish and oyster tissue by the local populations was targeted as an exposure factor for Cd, Zn and Cr (Penna Franca et al., 1984).

In Brazil, Sepetiba Bay, Guanabara Bay (Rio de Janeiro) and Santos Bay (São Paulo) are some of the most conspicuous examples, where pesticides, hydrocarbons, PCBs, other organics and heavy metals are broadly spread (e.g.: Barrocas and Wasserman, 1998; Hamacher et al., 2000; Hortellani et al., 2008; Marins et al., 1998; Nishigima et al., 2001; Wasserman et al., 2001).

Although in other countries dredging in contaminated areas has been controlled by local and national regulations since the early 1990s, in Brazil an effective law only appeared in 2004 (CONAMA, 2004). The new restrictions drove environmental authorities to demand safer dredging procedures like disposal of sediments in very distant oceanic sites or disposal in upland confined facilities. However, for very large amounts of sediments the sub-aquatic Confined Disposal Facilities (CDF; Laboyrie, 2004) were chosen as the most feasible procedures, considering the environmental impacts and economic costs. The sub-aquatic CDF technique was first applied in Brazil for the dredging of a large maritime terminal in the Sepetiba Bay in 2005, where a 1 m depth layer of contaminated sediment with zinc and cadmium was discarded (Ecologus Eng. Consultiva Ltda, 2005). A large survey of metal concentrations in the different sediment layers of the area was carried out and a simple dredging plan was developed where the whole first meter of sediment in the dredged area (one million cubic meters) was considered contaminated and was destined to the CDF. Although the environmental agency approved this procedure, it is very probable that deeper (>1 m) contaminated layers were destined to unsafe disposal areas, harming the environment, but shallower uncontaminated sediments may had been destined to the neighboring sub-aquatic CDF, increasing costs.

In the present work we established a new planning technique for dredging operations, considering the spatial and vertical distribution of contaminants in the top 200 cm sediment layers. The method is based on the concept of Sediment Management Units (SMU) described by Palermo et al. (2008) and establishes the precise mapping of the pollutants concentrations in the sediment. This precise mapping permitted to outline areas where the contaminated dredged material (above the threshold limits of the Legislation) should be destined to the sub-aquatic CDF, or to unrestricted offshore disposal areas, whenever uncontaminated. Besides a better control of the environmental impacts, the size of the CDF could be more precisely defined, reducing the costs of the operation. Furthermore, we carried out an economic evaluation of the costs of applying the new technique procedure, compared with traditional procedures.

The new planning method was applied to prepare a dredging plan for a new harbor in Sepetiba Bay, Rio de Janeiro, Brazil that was based on 74 sediment cores of 150–200 cm long, layered every 50 cm. Although a large range of metals and organic pollutants were measured in the samples, only Cd and Zn were presented because their concentrations constitute a real threat for the environment.

2. Materials and methods

2.1. Study area

The Sepetiba Bay is located some 50 km West of Rio de Janeiro city (Fig. 1) and is known for its conspicuous metal contamination (Lacerda et al., 1987), associated with a number of continental and coastal sources. Particularly, a zinc products metallurgic plant, installed in the early 1970s accumulated a very large waste pile (some three million tons) contaminated with cadmium and zinc that during heavy rain events leaks to the bay, spreading these pollutants through large areas and exceeding concentrations established by regulations for dredging activities (Barcellos et al., 1997; Pellegatti et al., 2001). In its northern portion, the bay also receives drainages from an industrial region that contaminates the sediments with still mild concentrations of mercury (Marins et al.,

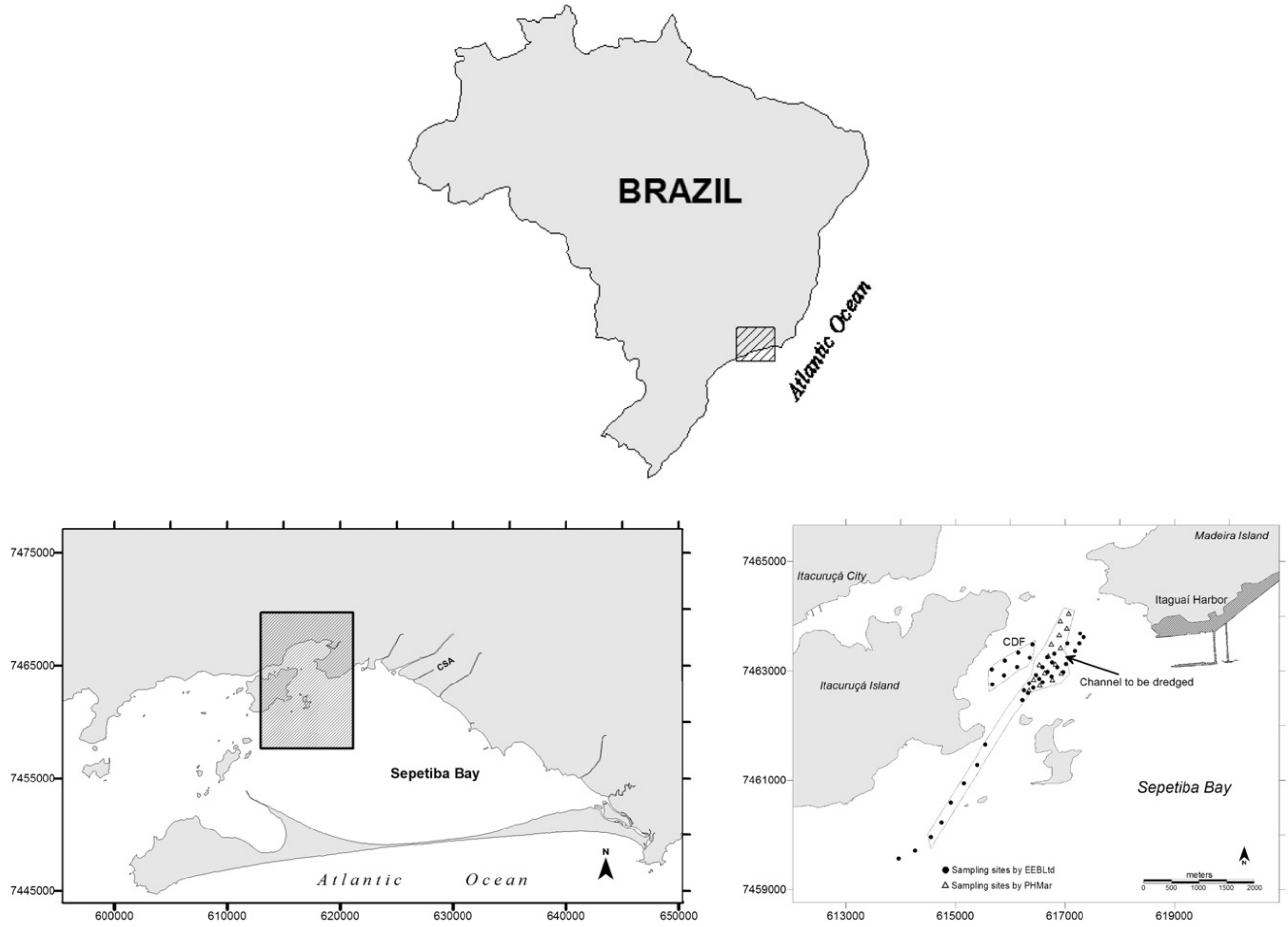

Fig. 1. Location of the study area and position of the sampling sites.

1998; Silva et al., 2003), and other pollutants (Barcellos et al., 1997). Although the bay shows increasing concentrations of many pollutants, only Zn and Cd present concentrations above the Brazilian sediment quality criteria for dredging activities (CONAMA, 2004).

A few studies have evaluated the bioavailability of metals in the sediments of Sepetiba Bay through sequential extraction (three first phases, corresponding to bioavailable metals; Fiszman et al., 1984; Pestana, 1989) and through the AVS/SEM model (6N HCl extraction; Ribeiro, 2006). These works showed that the amount of bioavailable Cd is 70% through sequential extraction or 100% through the AVS-SEM model. For Zn, bioavailable concentrations are 50% through sequential extraction and 53% through the AVS-SEM model. Another approach to establish the harm of heavy metals in Sepetiba Bay was toxicity tests that were carried out by Ecologus Eng. Consultiva Ltda (2005) in sediments. While sediments alone did not show significant toxicity to digging amphipods, elutriates at 100% and 50% concentrations showed to be toxic to sea urchin embryos. Although these results reinforce the hazard of contaminated sediments in Sepetiba Bay, in the present work, total concentrations were preferred because the Brazilian Environmental Legislation limits were established only for total concentrations, and comparisons with bioavailable fractions are not possible.

2.2. Sampling

The sediment concentrations presented in this paper were obtained from the Environmental Impact Assessment of a new harbor in the Sepetiba Bay (Ecology and Environment do Brasil, 2009). The applied methodology is briefly presented: Before the dredging service, 38 core samples were collected and analyzed by Ecology & Environment do Brasil Ltd. (EEBLtd) from 1 to 2 m depth (filled balls in Fig. 1). Sampling was complemented by the collection, carried out by PH Mar Environmental Consulting Ltd. (PHMar), of 15 triplicate 150 cm long cores (three cores per site) from the sites indicated in Fig. 1 (empty triangles). Sampling was carried out with a gravity sampler and layers of 50 cm were sliced. The choice of thicker slices is due to the fact that even smaller dredgers are not able to remove layers of sediment thinner than 50 cm. Slicing was carried out immediately after collection and samples were placed under refrigeration (approximately 4 °C in an ice box) for transportation to the laboratory, where they were deep frozen for later analyzes.

2.3. Analytical methods

The elements Cd and Zn were measured in the sediment samples by commercial laboratories (Bioagri Ambiental, Rio de Janeiro and Labágua, Laboratório e Engenharia Ambiental Ltda., Niterói) using a total extraction procedure as established by APHA (1995), method number 3111. In this method total extraction of dried sediments was done with nitric and perchloric acid solutions (3:1) and the measurements were carried out by flame atomic absorption spectrophotometry (FAAS). The quality of the results was assured by simultaneous measurement of reference materials and blank samples.

2.4. Data treatment and model preparation

First, total metallic concentrations obtained from the different layers of the sediment cores were separately plotted in distribution maps, using the software Surfer®, that outline concentration contours, layer by layer, using the *Kriging* interpolation method. A total of 32 maps were generated for the studied metals and for the evaluated depths (0–50 cm, 50–100 cm, 100–150 cm and 150–200 cm). The contours that represented the threshold values (level 1 or level 2) of the Brazilian regulation for dredging activities (CONAMA, 2004) were highlighted in red.

When dealing with sediment quality criteria for dredging activities, it doesn't matter whether concentrations of various contaminants are low, if there is at least one that exceeds the threshold limit, the sediments as a whole are considered harmful. In the study area, Cd and Zn were the metals that presented values above the action levels concentrations, outlining, for each depth, a map of contaminated patches that can be called a "pollution map". These pollution maps (four per metal) could then be used as a reference for the procedures to be carried out in every contaminated patch. A precise list of vertices (coordinates) limiting the polygon of the contour for each layer could be established and the precise calculation of the volume could be carried out.

2.5. Environmental dredging costs

In order to evaluate the advantages of the new method, a comparison of "business as usual" (BAU) cost scenario with the new method scenario cost was carried out. The concept of "business as usual" was borrowed from climate changes modeling (Hofmann and Schellnhuber, 2009) and applies to the destination of the whole 2 m depth layer into a Confined Disposal Facility (CDF). In order to evaluate the costs of both scenarios, the market cost of the dredged cubic meter was obtained from USACE (2010).[3] The evaluation prepared by the US Army Corps of Engineers indicates a wide variability of dredging costs, ranging from U$ 2.99 to U$ 37.02 per cubic meter, depending on the dredged volume, the used technology (hopper or not-hopper dredging), and whether it is a new work or maintenance work. In the USACE table, no distinction of price is made for different depths or areas with different current velocities. This is probably due to the fact that most dredging services are carried out in harbors, where depth does not exceed 10 or 15 m and this facilities are normally installed in protected areas, where currents are not very fast. An average value for new work dredging was calculated for the year 2010 as U$ 19.97 per cubic meter and values of U$ 14.40 per cubic meter for hopper dredging or U$ 22.39 per cubic meter for non-hopper dredging. The values for hopper dredging are going to be used when sediments are uncontaminated and the values for non-hopper dredging (suction dredging) are going to be used in contaminated sediments, with dumping into the CDF. These costs are not available for the Brazilian dredging industry.

3. Results and discussion

Although the concentrations of various elements were measured, only Cd and Zn exceed the threshold values established by the Brazilian regulations for dredging operations (Table 1). Considering the measured values, the environmental agency officials established that the whole sediment top layer of 2.0 m was harmful for the organisms and special procedures should be deployed that, in this case would be suction dredging and disposal of the material into a CDF. Suction-dredgers can operate in very fine grained sediments with a minimum resuspension that reduce chemical interactions between the sediment and the water column (Rokosch and Berg, 2002). Furthermore, if the sediments are consolidated a cutter-head may be used. Dumping of the sediments in the CDF may also be a problem, because turbulence may promote oxidation and therefore chemical modification of the sediment, so a diffuser should be used to reduce the water pressure. All these equipments will promote a smaller accumulation of pollutants from the sediment to the organisms. In the case of applying these procedures, many environmental advantages are obtained, however financial costs are increased.

Table 1
Summary of the metallic concentrations within the dredging area in the Sepetiba Bay. Threshold levels for metals and semi-metals from CONAMA (2004). Action levels in bold.

	As	Cd	Pb	Cu	Cr	Hg	Ni	Zn
Level 1[b]	8.2	**1.2**[a]	**46.7**[a]	34.0	81.0	**0.15**[a]	20.9	150.0
Level 2[b]	**70.0**[a]	1.2	46.7	**270.0**[a]	**370.0**[a]	0.70	**52.0**[a]	**410.0**[a]
Average (mg kg^{-1})	1.3	1.0	16.4	5.0	18.7	0.05	9.7	138.0
Standard deviation	0.7	1.1	8.6	3.5	9.7	0.03	5.0	151.2
Samples above threshold (n)	0	44	0	0	0	0	0	8
% of samples above threshold[c]	0.0	27.5	0.0	0.0	0.0	0.0	0.0	5.0

[a] Bold values correspond to action levels (CONAMA, 2004).
[b] Threshold values established by the Brazilian National Environmental Council (CONAMA, 2004).
[c] Total number of samples (n) is 190.

It is observed in many sediment cores described in the literature that if the area was not extensively disturbed, higher concentrations should be observed in the uppermost layers (Förstner and Wittmann, 1983; p.136 and 183). This behavior has been observed in the neighboring Guanabara Bay for the concentrations of mercury (Wasserman et al., 2000), where, although sedimentation rates are reported as significantly high, reaching more than 1 cm year^{-1} (Godoy et al., 1998), concentrations bellow the first 40 cm fall to values that are close to the regional background. A sediment core sampled in Enseada das Garças, located in the same Sepetiba Bay, some 10 km East from the study area. Wasserman et al. (2001) also showed the same behavior for zinc, that has its concentrations decreased within the first 30 cm, reaching background values and showing a sedimentation rate of less than 1 cm year^{-1}.

The results of the present work were presented, on a spatial scale, in the contours maps of Figs. 2A–D and 3A–D, indicating that most of the area to be deepened did not show decreasing concentrations with depth. The mixing of the sediment with the sediment column is particularly well registered for the concentrations of Cd that presents elevated concentrations in the lower slices (150–200 cm; Fig. 2D), where values may reach 3 mg kg^{-1}. The expected background concentrations for the Sepetiba Bay that should be observed in the deeper layers would be 0.34 mg kg^{-1} as recently established by Gomes et al. (2009) in a study of Cd concentrations of sediment cores in the same region.

Although from Fig. 3 Zn concentrations seem to be less elevated, it has to be considered that the background values for the region were established by Gomes et al. (2009) and Wasserman et al. (2001) to be around 50 mg kg^{-1}. High unexpected concentrations of up to 300 mg kg^{-1} can be observed in some spots of the deeper 150–200 cm layer (Fig. 3D), indicating that there has been sediment mixing until this layer. Unfortunately, our cores were not long

[3] The worksheet available from http://www.ndc.iwr.usace.army.mil//db/dredging/ddcost/dd10inet.xlsx.

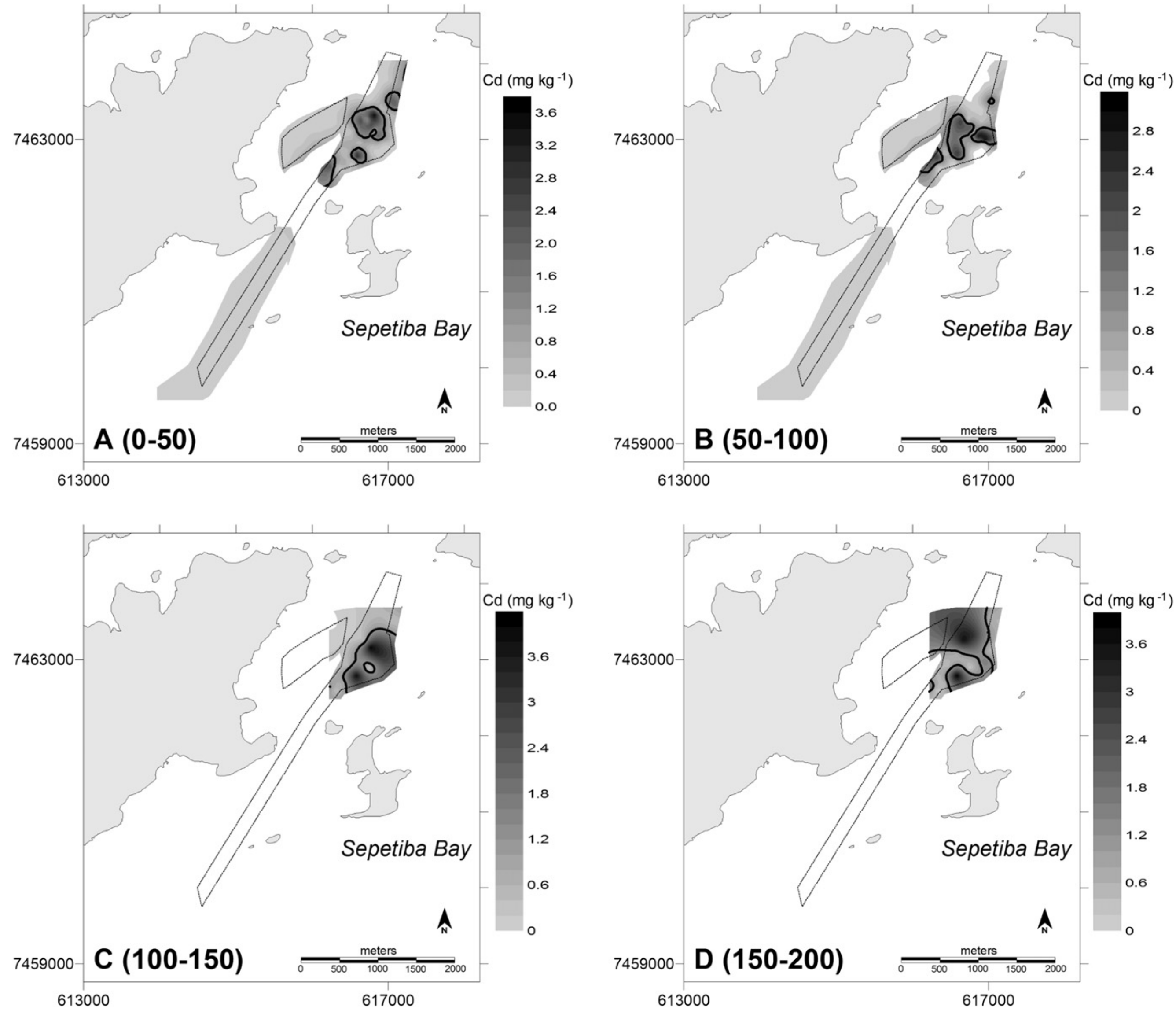

Fig. 2. Cd distribution in four sediment layers: A) 0–50 cm; B) 50–100 cm; C) 100–150 cm; D) 150–200 cm. Areas within the thick black line overcome threshold levels (1.2 mg kg^{-1}, CONAMA, 2004).

enough to determine the depth where this mixing occurs and what depth concentrations reach background level. In the forthcoming dredging preliminary surveys we suggest that longer core samples should be obtained in order to reach these undisturbed background layers.

From both Figs. 2 and 3, it is clear that the sediments have been largely disturbed, what was explained by local fishermen as a result of the activity of tug boats that operate in the neighboring Itaguaí Harbor (see harbor position in Fig. 1). This explanation is not very reliable because the mobilization of 2 m of sediments would require extremely strong currents that, in its turn, would resuspend huge amounts of particulate matter. A study of the resuspension of bottom sediments in Sepetiba Bay using sediment traps did not either identified such a large turbulence in the bottom sediments (Barcellos et al., 1998). Another hypothesis that can explain the lack of stratification within the sediment is the possible release of dredged materials from previous activities. Before 2004, dredging was barely regulated and wastes were dumped everywhere, yielding homogeneous sediment profiles until deeper layers. Nonetheless, this is a conjectural hypothesis that should be explored with further studies.

An important point that should be raised when analyzing the data of Figs. 2 and 3 is that, although the theoretical behavior of concentrations in sedimentary environments implies reduction with depth, as discussed above, many studies indicated that the ideal behavior is not always observed. The work of Hwang et al. (2009) in the San Francisco Bay shows an increasing concentration with depth profile that is attributed to the recent reduction of anthropogenic sources. Another case in the Sepetiba Bay was reported by Gomes et al. (2009) where from three sediment cores collected in a mangrove area, only one presented a continuously sedimentary behavior.

The next step of the study was to determinate the precise location of the contaminated sediments in each of the layers (whether Cd, Zn or both together are considered). This precise mapping allowed a specific dredging procedure in the limits of the contaminated area, and considerably smaller volumes of the really contaminated sediments will be destined to the CDF, with reduced

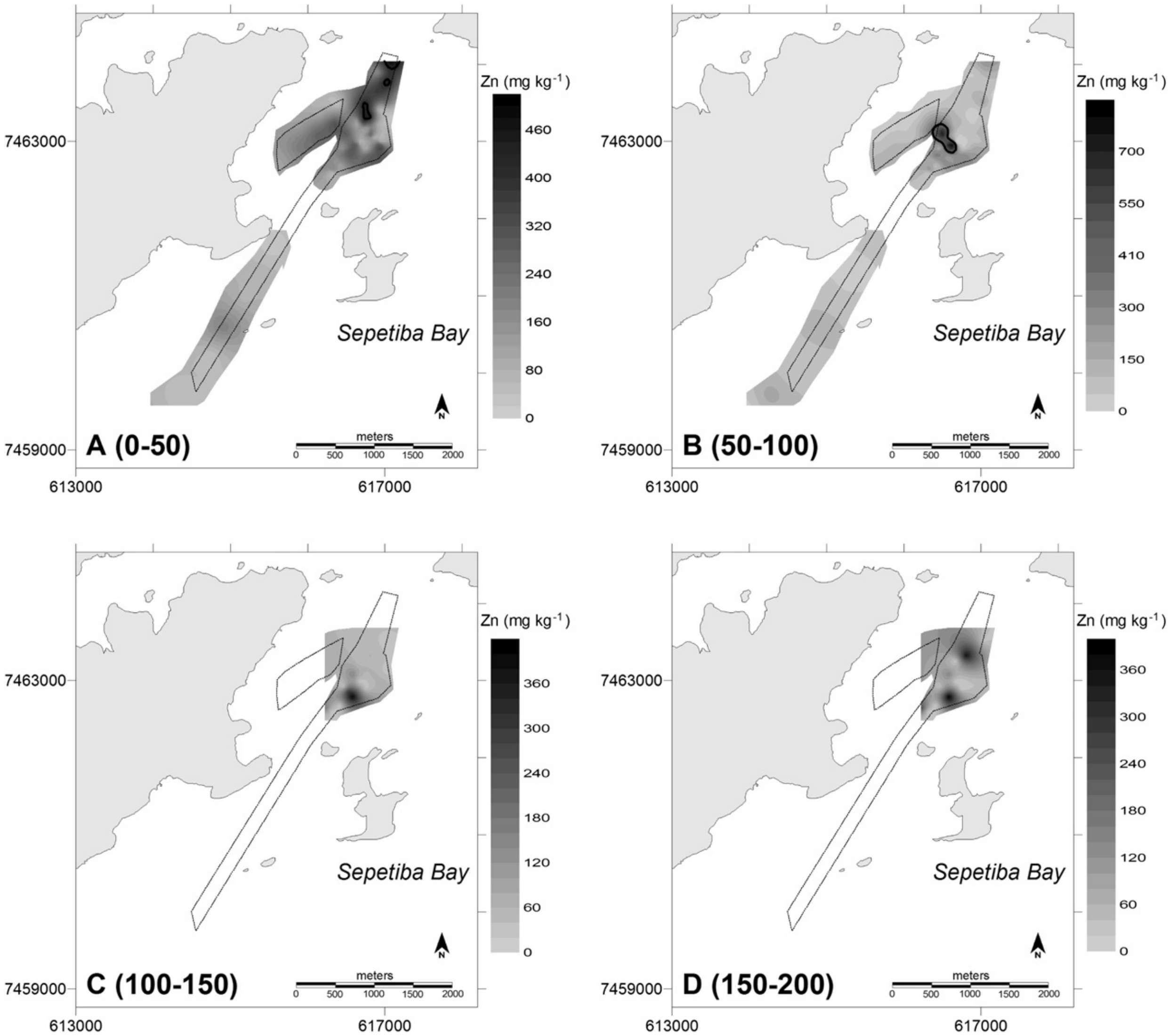

Fig. 3. Zn distribution in four sediment layers: A) 0–50 cm; B) 50–100 cm; C) 100–150 cm; D) 150–200 cm. Areas within the thick black line overcome threshold levels (410 mg kg^{-1}, CONAMA, 2004).

environmental impacts and lower costs. As described in the methodology, overlays of Zn and Cd concentrations for each layer were carried out and the outlines of the contaminated patches were digitalized (Fig. 4). Their areas and volumes were calculated and presented in Table 2.

From Table 2, it can be observed that the volumes presented in the surface layers (0–100 cm) were smaller than the volumes of the deeper layers (100–200 cm). These results are mainly based on the concentrations obtained for cadmium, since zinc in these deeper layers presented concentrations below the Brazilian Regulation limits.

In Sepetiba Bay the large pool of contaminated sediments (Barcellos et al., 1997) should be left untouched for a very long period, letting early and post-early diagenesis bury these materials in safe deposits. However, the Bay is an area protected from oceanic waves and strong currents, with a conspicuous industrial development, and where inhabitants of the drainage basin demand further investments and more logistics equipments, most of them requiring new dredging services. Under such conditions cleaner dredging procedures should be developed and a continuous monitoring of metallic concentrations in organisms should be supported by the harbors authorities and maritime terminals owners. Lacerda and Molisani (2006) showed that, although a continuous increase of Cd and Zn concentrations in the mangrove oyster *Crassostraea rhizophorae* was not observed for the last 30 years, values seem to respond to the short term events of metal contamination in the water column, like during dredging operations. Considering that these oysters are largely consumed by the local population and tourists, the contamination of these organisms constitute a severe human health issue.

3.1. Comparative costs of BAU and new technology

There is a number of sources of potential errors which give rise to uncertainties in the predicted costs of “business as usual” (BAU) and new technology scenarios. In the present evaluation, uncertainty was reduced, as far as possible, through the use of USACE (2010) data sources obtained from registers of a great number of dredging operations in the United States and industry experiences, and through the choice of reasonable modeling assumptions.

The main investment cost of the disposal of the whole 2 m layer of contaminated sediment, covering an area of 72.66 ha (volume of

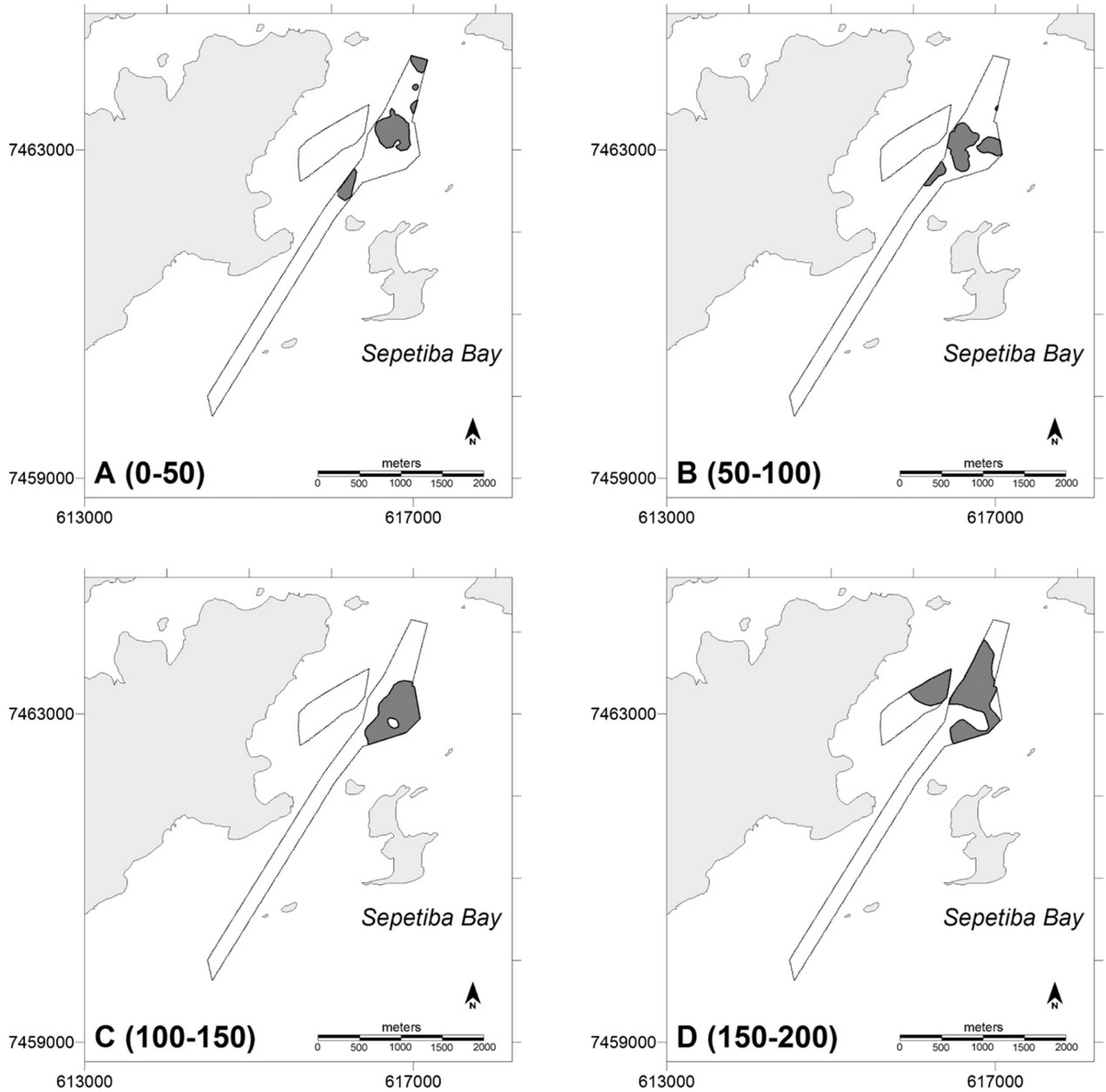

Fig. 4. Hatched areas for each of the layers corresponding to contaminated sediments that have to be disposed in the CDF: A) 0–50 cm; B) 50–100 cm; C) 100–150 cm; D) 150–200 cm.

1,453,200 m^3), is associated with the construction of the CDF. The size of an 11 m depth CDF to receive all these wastes would be 1,598,520 m^3, a little bigger than the volume of the contaminated sediments, because 1 m must be left for an uncontaminated sediment capping. The CDF, plus the deepening of the harbor itself yields a total volume of 3,038,509 m^3. The costs of the BAU scenario are presented in Table 3.

Applying the new planning technique, that is going to be called "chirurgical dredging" the total volume to be dredged from the contaminated area (non-hopper dredger) would be 544,900 m^3. The uncontaminated volume to be dredged from the deepened harbor amounts to 908,300 m^3, that can be carried out with a lower cost hopper dredger. With the new planning technique, the total volume of the CDF was reduced to 599,390 m^3 that also can be dredged with a low cost hopper system and the total volume of the dredging with the "chirurgical dredging" technique is not more than 2,052,590 m^3, corresponding to a volumetric reduction of 985,919 m^3 (32.45%) when compared with BAU. The economy in terms of investment cost was calculated as 38.96% (U$ 21,640,770.00). Table 3 shows the cost comparison between both techniques. A further advantage of the method is that as the service is faster, the beginning of the operations of the harbor may be

Table 2
Volumes to be dredged by layer and to be disposed into the CDF.

Depth	Volume (m^3)
0–50 cm	110,950
50–100 cm	103,500
100–150 cm	146,050
150–200 cm	184,400
CDF capping (1 m thick)	54,490
Total CDF volume	599,390
CDF area for a depth of 11 m	54,490 m^2

Table 3
Costs comparison between BAU and new technology.

Dredging services	BAU			New technology		
	Volume (m^3)	Cost (U$/$m^3$)[a]	Total cost (U$)	Volume (m^3)	Cost (U$/$m^3$)[a]	Total cost (U$)
Deepening for the harbor						
Contaminated (non-hopper)	1,453,200	22.39[b]	32,537,008.00	544,900	22.39[b]	12,200,258.00
Uncontaminated (hopper)	–	–	–	908,300	14.40[c]	13,079,520.00
CDF	1,598,520	14.40[c]	23,012,398.00	599,390	14.40[c]	8,628,857.00
Total	3,038,509		55,549,405.00	2,052,590		33,908,635.00

[a] Values obtained from USACE (2010).
[b] Non-hopper dredging cost.
[c] Hopper dredging cost.

advanced a few weeks constituting significant earnings for the company. In order to evaluate these earnings an estimate of the incomes of the harbor would be necessary, but these data were not provided.

4. Conclusions

Considering that the environmental regulations for dredging activities are becoming more and more restrictive, mainly concerning sediment disposal and sediment resuspension, it is important that more advanced techniques are developed in order to improve environmental safety and reduce costs. In the present work a new method for the planning of dredging activities in contaminated areas was presented. The method called “chirurgical dredging” permitted the volume reduction of the confined containment to 37.7% of its initially projected size, when the method was not applied. Furthermore, the method allows a safer dredging procedure, where the whole contaminated sediments are effectively destined to the CDF.

With the “chirurgical dredging”, long travels of the hopper dredgers or barges to offshore disposal sites to dump contaminated material could be avoided. Another advantage of the described methodology is the increased dredging velocity, because two dredgers can operate simultaneously: a sucker dredger working in the contaminated sediments, dumps the material through a pipeline into the CDF (that can be several kilometers away), where it is dumped with a diffuser; A hopper dredger may be used for the uncontaminated sediment, dredging sediment into their own reservoirs. After filling the reservoirs, it moves to the disposal site (normally offshore) and dumps the dredged material. Sometimes a barge may be used together with the hopper dredge and the sediment is dredged into the reservoir of the barge that, when filled, is pulled by tug boats to the dumping site. In this case two or three barges transporting the sediment make the service quicker, because the dredger doesn’t have to stop the procedure to dump sediments.

A list of vertices (geographical coordinates) establishes the limits of contaminated closed polygons (constituting a volume of 50 cm depth). These coordinates can be delivered to the dredger operators, who will restrict the CDF dredging to these limits. The rest of the area will be dredged by another hopper dredger (for uncontaminated sediments) at a considerably lower cost.

Acknowledgments

The authors are grateful to CNPq for the financial support (grant # 302197/2009-5). The method that is presented in this work was developed to support an environmental impact assessment for the Southeast Harbor in Sepetiba Bay, supported by LLX Logística SA, Brazil.

References

APHA, 1995. Standard Methods for the Examination of Waters and Wastewaters, sixteenth ed. American Public Health Association, Washington, DC.
Barcellos, C., Lacerda, L.D.d., Ceradini, S., 1997. Sediment origin and budget in Sepetiba Bay (Brazil) – an approach based on multielemental analysis. Environ. Geol. 32, 203–209.
Barcellos, C., Lacerda, L.D., Ceradini, S., 1998. Metal scavenging and cycling in a tropical coastal region. In: Wasserman, J.C., Silva-Filho, E.V., Villas-Boas, R. (Eds.), Environmental Geochemistry in the Tropics, first ed. Springer-Verlag, Heidelberg, pp. 157–169.
Barrocas, P.R.G., Wasserman, J.C., 1998. Mercury behaviour in sediments from a subtropical coastal environment in SE Brazil. In: Wasserman, J.C., Silva-Filho, E.V., Villas-Boas, R. (Eds.), Environmental Geochemistry in the Tropics, first ed. Springer-Verlag, Heidelberg, pp. 171–184.
Bertolin, A., Mazzocchin, G.A., Rudello, D., Ugo, P., 1997. Seasonal and depth variability of reduced sulphur species and metal ions in mud-flat pore-waters of the Venice Lagoon. Mar. Chem. 59, 127–140.
Casas, A.M., Crecelius, E.A., 1994. Relationship between acid volatile sulfide and the toxicity of zinc, lead and copper in marine sediments. Environ. Toxicol. Chem. 11, 529–536.
CONAMA, M., 2004. Resolução n° 344, de 25 de março de 2004. Estabelece as diretrizes gerais e os procedimentos mínimos para a avaliação do material a ser dragado em águas jurisdicionais brasileiras, e dá outras providências.
Cornwell, J.C., Morse, J.W., 1987. The characterization of iron sulfide minerals in anoxic marine sediments. Mar. Chem. 22, 193–206.
Cutroneo, L., Castellano, M., Pieracci, A., Povero, P., Tucci, S., Capello, M., 2012. The use of a combined monitoring system for following a turbid plume generated by dredging activities in a port. J. Soils Sediment. 12, 797–809.
Driscoll, S.B.K., Wickwire, W.T., Cura, J.J., Vorhees, D.J., Butler, C.L., Moore, D.W., Bridges, T.S., 2002. A comparative screening-level ecological and human health risk assessment for dredged material management alternatives in New York/New Jersey Harbor. Hum. Ecol. Risk Assess. 8, 603–626.
Ecologus Eng. Consultiva Ltda, 2005. Estudo de Impacto Ambiental do Terminal Marítimo da Companhia Siderúrgica Atlântica. TyssenKrupp, Rio de Janeiro.
Ecology and Environment do Brasil, 2009. Estudo de Impacto Ambiental do Porto do Sudeste, Baía de Sepetiba. RJ. LLX Logística Ltda, Rio de Janeiro. p. 678.
Fiszman, M., Pfeiffer, W.C., De Lacerda, L.D., 1984. Comparison of methods used for extraction and geochemical distribution of heavy metals in bottom sediments from Sepetiba Bay, R.J. Environ. Technol. Lett. 5, 567–575.
Förstner, U., Wittmann, G.T.W., 1983. Metal Pollution in the Aquatic Environment, second ed. Springer-Verlag, Heidelberg.
Godoy, J.M., Moreira, I., Bragança, M.J., Wanderley, C., Mendes, L.B., 1998. A study of Guanabara Bay sedimentation rates. J. Radioanal. Nucl. Chem. 227, 157–160.
Gomes, F.C., Godoy, J.M., Godoy, M.L.D.P., Carvalho, Z.L., Lopes, R.T., Sanchez-Cabeza, J.-A., Lacerda, L.D., Wasserman, J.C., 2009. Metal concentrations, fluxes, inventories and chronologies in sediments from Sepetiba and Ribeira Bays: a comparative study. Mar. Pollut. Bull. 64, 10–20.
Hamacher, C., Brito, A.P.X., Andrade-Brüning, I.M.R., Wagener, A.L.R., Moreira, I., 2000. The determination of PAH by UV-fluorescence spectroscopy in water of Guanabara Bay, Rio de Janeiro. Rev. Brasil. Oceanogr. 48.
Hofmann, M., Schellnhuber, H.J., 2009. Oceanic acidification affects marine carbon pump and triggers extended marine oxygen holes. Proc. Natl. Acad. Sci. U.S.A. 106, 3017–3022.
Hortellani, M.A., Sarkis, J.E.S., Abessa, D.M.S., Sousa, E., 2008. Assessment of metallic element contamination in sediments from the Santos – Sao Vicente Estuarine System. Quim. Nova 31, 10–19.
Hwang, H.M., Green, P.G., Young, T.M., 2009. Historical trends of trace metals in a sediment core from a contaminated tidal salt marsh in San Francisco Bay. Environ. Geochem. Health 31, 421–430.
IMO, 1972. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter. International Maritime Organization, London.
Laboyrie, H.P., 2004. Environmental guidelines for aquatic, nearshore and upland confined disposal facilities for contaminated dredged material, dredging '02: key technologies for global prosperity. In: Proceedings of 3rd Specialty

Conference on Dredging and Dredged Material Disposal. International Navigation Association – PIANC, Brussel, p. 13.

Lacerda, L.D., Molisani, M.M., 2006. Three decades of Cd and Zn contamination in Sepetiba Bay, SE Brazil: evidence from the mangrove oyster Crassostraea rhizophorae. Mar. Pollut. Bull. 52, 974–977.

Lacerda, L.D., Pfeiffer, W.C., Fiszman, M., 1987. Heavy metal distribution, availability and fate in Sepetiba bay, SE Brazil. Sci. Tot. Environ. 65, 163–173.

Li, M.Z., Parrott, D.R., Yang, Z.Y., 2009. Sediment stability and dispersion at the black point offshore disposal site, Saint John Harbour, New Brunswick, Canada. J. Coast. Res. 25, 1025–1040.

Marins, R.V., Lacerda, L.D., Paraquetti, H.H.M., de Paiva, E.C., Boas, R.C.V., 1998. Geochemistry of mercury in sediments of a sub-tropical coastal lagoon, Sepetiba Bay, southeastern Brazil. B. Environ. Contam. Toxicol. 61, 57–64.

Morse, J.W., 1994. Interactions of trace metals with authigenic sulfide minerals: implications for their bioavailability. Mar. Chem. 46, 1–6.

Nishigima, F.N., Weber, R.R., Bícego, M.C., 2001. Aliphatic and aromatic hydrocarbons in sediments of Santos and Cananéia, SP, Brazil. Mar. Pollut. Bull. 42, 1064–1072.

Ottmann, F., 1985. Un problème controversé pour l'environnement marin, les dragages et leurs conséquences. Bull. Soc. Sci. Nat. Ouest Fr. 7 (nouvelle série), 195–206.

Palermo, M.R., Schroeder, P.R., Estes, T.J., Francingues, N.R., 2008. Technical Guidelines for Environmental Dredging of Contaminated Sediments. Environmental Laboratory U.S. Army Engineer Research and Development Center, Vicksburg, MS. p. 304.

Pellegatti, F., Figueiredo, A.M.G., Wasserman, J.C., 2001. Neutron activation analysis applied to the determination of heavy metals and other trace elements in sediments from Sepetiba bay (RJ), Brazil. Geostand. Newslett. 25, 163–171.

Penna Franca, E., Pfeiffer, W.C., Fiszman, M., Lacerda, L.D., 1984. Aplicabilidade da análise pelos parâmetros críticos, usualmente empregada para instalações nucleares no controle da poluição do ambiente marinho por metais pesados. Ci. Cult. J. Braz. Assoc. Adv. Sci. 36, 215–219.

Pestana, M.H.D., 1989. Partição geoquímica de metais pesados em sedimentos estuarinos nas baías de Sepetiba e da Ribeira, Programa de Pós-Graduação em Geociências. Universidade Federal Fluminense, Niterói. p. 211.

Regnell, O., Hammar, T., Helgée, A., Troedssom, B., 2001. Effects of anoxia and sulfide on concentrations of total and methyl mercury in sediment and water in two Hg-polluted lakes. Can. J. Fish. Aquat. Sci. 58, 506–517.

Ribeiro, A.P., 2006. Procedimento de Fracionamento Comparado a Modelo de Atenuação para Avaliação de Mobilidade de Metais Pesados em Sedimentos da Baía de Sepetiba, Rio de Janeiro. Instituto de Pesquisas Energéticas s Nucleares - IPEN, USP, São Paulo. p. 145.

Rokosch, W.D., Berg, N.J., 2002. Dredging Efficiently – Dredging Techniques and Its Effects to the Environment. In: Dredging, Key Technologies for Global Prosperity. pp. 195–203.

SEP, 2008. Programa de Aceleração do Crescimento. Secretaria Especial de Portos, Brasília, DF.

Silva, L.F.F., Machado, W., Lisboa, S.D., Lacerda, L.D., 2003. Mercury accumulation in sediments of a mangrove ecosystem in SE Brazil. Water Air Soil Pollut. 145, 67–77.

Sturve, J., Berglund, A., Balk, L., Broeg, K., Bohmert, B., Massey, S., Savva, D., Parkkonen, J., Stephensen, E., Koehler, A., Forlin, L., 2005. Effects of dredging in Goteborg Harbor, Sweden, assessed by biomarkers in eelpout (Zoarces viviparus). Environ. Toxicol. Chem. 24, 1951–1961.

USACE, 2010. FY 2010 Analysis of Dredging Costs. United States of America Corps of Engineers, Washington, DC (p. electronic worksheet).

Vale, C., Ferreira, A.M., Micaelo, C., Caetano, M., Pereira, M.E., Madureira, M.J., Ramalhosa, E., 1998. Mobility of contaminants in relation to dredging operations in a mesotidal estuary (Tagus estuary, Portugal). Water Sci. Technol. 37, 25–31.

Wasserman, J.C., Freitas-Pinto, A.A.P., Amouroux, D., 2000. Mercury concentrations in sediment profiles of a degraded tropical coastal environment. Environ. Technol. 21, 297–305.

Wasserman, J.C., Figueiredo, A.M.G., Pellegatti, F., Silva, E.V., 2001. Elemental composition of sediment cores from a mangrove environment using neutron activation analysis. J. Geochem. Explor. 72, 129–146.