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Focus

Screening-level risk assessment applied to dredging of polluted sediments from Guanabara Bay, Rio de Janeiro, Brazil

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ABSTRACT

Guanabara Bay is characterized by predominant eutrophication and anoxic sediments with a mixture of pollutants. The risk prognosis associated with the dumping of its dredged sediments into the open ocean was addressed by our algorithm. Our algorithm could prioritize areas, characterize major processes related to dredging, measure the potential risk of sediments, and predict the effects of sediment mixing. The estimated risk of dredged sediment was >10-fold than that of ocean sediments. Among metals, mercury represented 50–90% of the total risk. The transfer of dredged material into the ocean or internal dumping in the bay requires a 1:10 dilution to mitigate the risk and bring the risk levels close to that in the EPA criteria, below which there is less likelihood of adverse effects to the biota, and a 1:100 dilution to maintain the original characteristics of the ocean disposal control area. Our algorithm indicator can be used in the design of both aquatic and continental disposal of dredged materials and their management.

1. Introduction

The demand for dredging has increased worldwide because of the physical changes needed in ports and harbors to accommodate post-Panamax vessels; however, the sustainability of dredging is a conflictual issue that includes environmental, socioeconomic, and political aspects on a local and a global scale (Schexnayder, 2010; Manap and Voulvoulis, 2015). Dredging ensures not only the operability of the ports and navigation but also the circulation and renewal of coastal waters, macrodrainage for the disposal of surface waters, operating conditions of hydraulic works, and control of critical hydrological events, resulting in benefits. Different approaches have been integrated to manage the chemical, physical, and biological impacts of dredging and achieve a balanced and sustainable decision, even in developing countries (Abriak et al., 2006; Wang and Feng, 2007; Agius and Porebski, 2008). In Brazil, the notion of sustainable development is a constitutional principle to be followed in the implementation of public policies and the activities it covers.

The primary regulatory reference for the deposition of dredged materials in open sea water is the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention, 1972; LC 72), adopted by approximately 90 countries. This convention stipulates that "*the capacity of the sea to assimilate wastes and render them harmless, and its ability to regenerate natural resources, is not unlimited*." Deposition of such materials in soils and inland waters is regulated by national instruments. Brazil is a signatory to LC 72, but its predominant *modus operandi* is to release the dredged material from coastal areas silted by sediments with some degree of contamination to open sea disposal sites; a process that violates protocol 2006 (article 3 §3): "*In Implementing the Provisions of this Protocol, Contracting Parties shall act so as not to transfer, directly or indirectly, damage or likelihood of damage from one part of the environment to another or transform one type of pollution into another*." However, release at sea is conditionally permitted (London Protocol, 1996) (annex 2 §4):"*... the goal of waste management should be to identify and control the sources of contaminations... Until this objective is met, the problems of contaminated dredged material may be addressed by using disposal management techniques at sea or on land*." In terms of controlling the source, in most Brazilian cases, the cause of contaminated sediments is the lack of sanitation and high industrial pollutant loadings, representing a long-standing (over many decades) socioeconomic environmental liability.

The sustainable management of dredge material is a priority in the context of such stringent legislative and policy frameworks in the European Union and in the United States of America. According to Sheehan and Harrington (2012), the Environmental Impact Assessment Directive (97/11/EEC) and the Habitats and Species Directive (92/43/EEC) have been followed by the Water Framework Directive (2000/60/EC), the Priority Substances Directive (Directive 2008/105/EC) on Environmental Quality Standards, and the EU Marine Strategy Framework Directive (2008/56/EC), all of which may involve potential constraints on dredging projects, including disposal, in the European

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Union. The United States prohibits ocean dumping unless a permit is issued under the Marine Protection, Research, and Sanctuaries Act (MPRSA) of 1988 (16 USC § 1431 et seq. and 33 USC §1401 et seq.), also referred to as the Ocean Dumping Act. The decision to issue a permit is made by the US Army Corps of Engineers, with the agreement of Environmental Protection Agency (EPA), using EPA's criteria (EPA, 1988). However, developing countries may have different approaches toward their environmental management of dredging because of lack of scientific evidence to make an informed decision (Manap and Voulvoulis, 2014, 2015). In Brazil and possibly in other developing countries, there is a deficiency in the conception and planning of dredging interventions, which are generally performed without a master plan that considers the feasibility of alternative disposal, recycling, innovative reuse, and so on and encompasses all activities and stakeholders affected by dredging through collective decision-making, with individual permits being given separately to each venture by the responsible environmental agency. The absence or weakness of relevant management committees in Brazil exacerbates the problem. Conflicts during the licensing process cause major delays in dredging activities, generating economic and social losses (Bidone et al., 2009).

In the absence of a masterplan, and considering only the "dredge and dump" hegemonic system, environmental licensing assumes a key role in dredging in Brazil. Licensing follows the general guidelines; reference procedures; and physical, chemical, and ecotoxicological criteria for the management of the dredged sediments, Resolution no. 454/2012 of the National Council of Environment, Brazil (CONAMA, 2012). There has been some criticism regarding the reference contaminant concentrations (FDEP, 1994; Long et al., 1995; Canadian Council, 1999; MDEPQ, 2007; Röper and Netzband, 2011); these reference concentrations were originally intended to study pollutant behavior and its effects on biota in temperate and cold ecosystems. Two reference levels have been defined: level 1 (L1; threshold below which there is less likelihood of adverse effects to biota) and level 2 (L2; threshold above which there is a greater likelihood of adverse effects to biota).

One aspect missing from the current critical analyses is that these quality criteria are individualistic, i.e., they only represent each specific contaminant, although many contaminants simultaneously pollute the sediments, which results in multiple exposures (van Gestel et al., 2010). Rarely are antagonisms and synergies among the pollutants identified. Although bioassays on susceptible organisms and bioaccumulation can evaluate the bioavailability of contaminants in dredged sediments, their effects on the biota (e.g., mortality) and the food chain, and the risks to human health (US-EPA/US-COE, 1991), there is considerable variability between lab results and field measures (Long et al., 2001).

Several environmental factors such as chemical, physicochemical, biological, and ecotoxicological parameters must be considered together to assess the ecological risk of pollutant exposure in aquatic ecosystems. All these variables must be integrated and some indices should be applied to achieve it, e.g., the Sediment Quality Triad (Long and Chapman, 1985) and the Potential Ecological Risk Index (Håkanson, 1980), which has been applied for risk assessment in dredging studies (e.g., Anderson et al., 2001; Sorensen et al., 2007; Guo et al., 2010; Kapsimalis et al., 2013; Zhang and Liu, 2014).

Burton (2002) asserted that sediment quality guidelines should be used only in a "screening" manner or in a "weight-of-evidence" approach. An alternative approach is to analyze the dredgings and apply an algorithm that relates the concentrations of its contaminants to their total risk (Ragas et al., 2010). This concept of "screening-level risk assessment" allows a simple, fast, efficient, and technically justified approach to provide the information necessary to comply with requirements and facilitate the planning and management of dredging (US ACE 2003). The effectiveness of using an algorithm to assess the potential risks of dredging activities depends on its ability to reflect the main natural processes responsible for the form of contaminants in the sediments to be dredged (i.e., adsorbed on particles, coprecipitated, dissolved, complexed) and to reflect the possible changes due to their transfer to disposal areas. Furthermore, the algorithm should serve as an indicator for the presence/distribution of other contaminants not covered by the mathematical formula, i.e., it serves as an indicator of the overall level of contamination and the risk of a dredged mixture in a given area.

Because disposal areas for dredged materials are typically unpolluted, with contrasting characteristics to those of the dredging area, sulfide oxidation releases dredging-associated metals that, on reaction with binders present in seawater (e.g., chlorides), may remain in the free form or as complexed ions or be adsorbed onto particles coprecipitated with newly formed iron hydroxides (e.g., grain coatings). Dumping causes dispersal of nutrients and contaminants in the water column (free and complex ions in pore water, colloids, adsorbed on fine particles, etc.) within hours and in the long term and, after settling over disposal site sediments, into the surrounding environment or wider areas (Drever, 1982; Salomons and Förstner, 1984; Manap and Voulvoulis, 2015). Release of contaminants into the surrounding medium in their most bioavailable forms (free or complexed ions, exchangeable on particulate matter, etc.) may occur, with toxic and specific risks, as long as the dredgings remain, although dispersion and chronic release of contaminants characterizes a reduction in their localized concentrations (Long et al., 1995; Long et al., 2001). As a result, sedimentation forms as a layer covering the uncontaminated pre-existing sediment, the persistence of which depends on the frequency and quantity of deposited material and on different environmental conditions (resuspension, bottom scattering, tidal currents, and wave action).

We discuss the performance of our approach with an example of sediments dredged from the most polluted sector of Guanabara Bay (GB) and then dumped at two contrasting sites: an internal area near the dredging area (representing a eutrophic and anoxic environment) and an external area situated approximately 15 km out to sea (an oligotrophic-oxic environment). In this study, we use an algorithmic indicator to characterize the main natural processes acting on dredged sediments in GB and measure the relative potential risk when these sediments are transferred and mixed in disposal areas. Currently, and in the future, GB faces a problem of how to dispose over 12 million m^3 of sediments—from ports and their access channels, land reclamation projects, and revitalization of silted and polluted areas that need to be dredged to avoid compromising the development of the region—in an environmentally appropriate manner, especially considering that the disposal areas (predominantly located in the ocean beyond the bay) cannot support these volumes of dredging. Our aim is to produce sufficient information to improve dredging management from the early planning and licensing stages of dredging to operation and monitoring, thereby promoting more sustainable decisions (environmental, social, economic, technical, and institutional).

1.1. Guanabara Bay – a case study

Guanabara Bay (Fig. 1) is a semi-enclosed, low-energy microtidal estuarine environment and one of Brazil's largest bays. The bay is surrounded by the metropolitan region of Rio de Janeiro. The annual average rainfall is 1170 mm, and the mean annual temperature is 23.7 °C, with rainy summers (December to April) and dry winters (June to August), representative of a tropical climate with a strong marine influence. The GB hydrographic basin extends over 4080 km^2 (385 km^2 of water surface, 135 km of coastline, 28 km from east to west, and 30 km from north to south). The entrance to the bay is narrow (1.6 km wide) and approximately 55 rivers empty into it, six of which are responsible for 85% of the runoff (Amador, 1997). The central channel (30–40 m deep) is delimited by 10-m isobathymetry (bay depth: 84% < 10 m; 46% < 5 m), resulting in a decrease in the tidal current velocity, with spring tide velocity declining from 1.6 $m.s^{-1}$ in the main central channel to 0.5 $m.s^{-1}$ inside the bay. The average water temperature is 24.2 ± 2.6 °C and salinity is 29.5 ± 4.8. At the narrow entrance

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