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Predicting pollutant concentrations in the water column during dredging operations: Implications for sediment quality criteria☆

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ABSTRACT

The development of new dredging techniques that can reduce, or at least predict, the environmental impacts, is in high demand by governments in developing countries. In the present work, a new methodology was developed, to evaluate the level of metals contamination (*i.e.* cadmium, lead and zinc) of the water column, during a dredging operation. This methodology was used to evaluate the impacts of the construction of a new maritime terminal in Sepetiba Bay, Brazil. The methodology quantifies the amount of resuspended sediments and calculates the expected contaminants concentrations in the water column. The results indicated that sediment quality criteria were not compatible with water quality criteria, because the dredging of contaminated sediments does not necessarily yield contaminated water. It is suggested that the use of sediment quality criteria for dredging operations might be abandoned, and the methodology presented in this study applied to assess dredging's environmental impacts, predicting water contamination levels.

1. Introduction

Dredging operations have been shown to be indispensible to the socioeconomic development of nations. According to the International Association of Dredging Companies (2014), dredging operations 1) support trading in ports; 2) respond to increasing demands for robust trade; 3) provide new transportation facilities for responding to population growth and urbanization; 4) support growing tourism and environmental remediation; and 5) protect coastal areas in response to climate change and sea level rise. According to the same source, in 2013 dredging was responsible for €11.68 billion of economic activity worldwide. A rough calculation, based on the average prices per cubic meter (€6.71) of dredged material for the United States (United States Army Corps of Engineers, 2014), indicates a total dredged volume of 1.74 billion m^3 for the year 2013.

In the forthcoming years, these figures tend to increase as the world recovers from the 2009 economic crisis, and as climate change effects in coastal areas become more evident, requiring the construction of coastal protections from rising sea levels and expected higher sedimentation rates in estuaries. Particularly in developing countries, in which economies are heavily based on commodities exports, the increase in dredging operations has been remarkable. For instance, in Brazil, over 120 million m^3 of maintenance and new dredging work have been contracted by the Government since the year 2007 (Brazilian National Secretary of Harbors, 2007). Despite the 2013–2015 Brazilian economic crisis, 44 million m^3 of dredging was contracted in 2014. For this country, dredging is not a matter of choice, because reducing exports of commodities would create an imbalance in the trade budget that would plunge the country deeper into economic crisis.

Regardless the economic importance of the dredging activities throughout the world, it has been shown that dredging causes serious impacts, threatening ecosystems and their biological communities, particularly in areas where dredged sediments are contaminated (Sturve et al., 2005; Vale et al., 1998). This contamination is a serious problem, because harbors are frequently located on urban and industrial coasts, within wave-protected areas, where the conditions for the accumulation of a myriad of contaminants are ideal. The resuspension of even reduced levels of contaminated sediments is a threat, because they can affect the juvenile survival rates of various fish species (Wilber and Clarke, 2001). Dredging operations may also promote the release of contaminants that were trapped in the interstitial water into the water column, promoting contamination of the entire trophic chain (Schultz et al., 1995). More importantly, a wide range of physico-

☆ All the authors contributed to the development and improvement of the presented model.

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chemical modifications to the sediments can be induced by dredging turbulence, which may promote changes in the chemical forms of some metals (Vale et al., 1998), increasing or decreasing bioavailability (Caplat et al., 2005; Piou et al., 2009).

Another impact observed during dredging operations is the modification of oxygen concentrations in the water column. Although the work of Zhang et al. (2010) showed that there was little modification in water-column oxygen, during a dredging operation in a shallow lake in China, Licursi and Gomez (2009) observed a significant increase in the oxygen demand of the water column due to resuspension of organic matter. In very anoxic sediments, where elevated concentrations of hydrogen sulfide and methane are present, dredging may promote intoxication of the organisms or a large oxygen consumption (Graca, 2009). In restricted environments, dredging may engender remineralization of nutrients, resulting in the intensification of eutrophication processes (Licursi and Gomez, 2009).

Because of this range of impacts, the environmental agencies of many countries have issued specific regulations to control dredging operations. In the United States dredging operations are controlled by the Federal Water Pollution Control Act (1972), amended and renamed as the Clean Water Act (1977). Specifically, its sections 303 and 404 established water-quality standards, and regulated dredged material and landfill. In Brazil, the National Council of the Environment issued the Regulation 433 (2004), which regulates permits and defines sediment quality criteria. In both countries, as in many others throughout the world, there is a strong concern over sediment and water-quality criteria during dredging operations, which have been associated with toxicity since the early 1990s (Di Toro et al., 1990). However, setting limiting values for sediment concentrations, based on toxicity results of *in vitro* ecotoxicological assays only, has been questioned by environmental agencies (USEPA, 1993). Simply knowing the total concentrations of contaminants in the sediments alone is not sufficient to assess their risk. Thus, geochemical fractionation and speciation are required, and site-specific values have been developed (Han et al., 2014).

Associations between toxicity of sediments and the fractionation and speciation of metals have yielded good results, when the Acid Volatile Sulfide/Simultaneously Extractable Metals (AVS/SEM) model was developed (Ankley et al., 1996; Casas and Crecelius, 1994). However, environmental agencies hesitated to adopt the model as a reference for sediment quality criteria, because there was an ongoing and extensive discussion of the roles played by interstitial water concentrations (Lee et al., 2000) and organic matter (Besser et al., 2003) that were not taken into account by the AVS/SEM model. The concept of equilibrium partitioning was developed by Vanderkooij et al. (1991) and extended to consider geochemical partitioning of the sediment, applying sequential extractions (Han et al., 2014; Vangheluwe et al., 2013); of particular significance was the one developed by the European Bureau of References (Ure et al., 1993). It became clear from this debate that even if these methods were used for the definition of sediment quality criteria, neither regional nor worldwide limit values could be determined (Wang et al., 1999) and site-specific values had to be developed. Nevertheless, environmental agencies in developing countries started including sediment quality limits in their country's dredging regulations (*e.g.*: CONAMA/MMA, 2012).

Although the evaluation of the physical-chemical state of metals in sediments has significantly evolved, it is still difficult to predict their concentrations in the water column during dredging operations. Finite elements hydrodynamic transport modeling has been applied, allowing the construction of dispersion plumes of suspended sediment (Nellis et al., 2007), but these simulations give only a general idea of the concentrations in the water column, showing that such concentrations can vary significantly in response to dredging operations. Local characteristics, such as turnover time and local currents, have an important role. The dispersion of the resuspended material will determine the metals concentrations: the more the material is spread, the lower the concentrations in the water column, and the limits of acceptable concentrations in the sediments can be higher in environments with low turnover time.

In the present work a new methodology is presented for predicting concentrations of pollutants in the water column during dredging operations. Based on worst-case scenarios, the methodology calculates the amount of contaminants released to the water column at every dredging point, constructing a map of expected concentrations in the dredged area. The methodology was applied to assess expected cadmium, lead and zinc concentrations during a dredging operation in a new harbor in Sepetiba Bay, Brazil. Our ultimate goal was to investigate whether the Brazilian sediment quality criteria (CONAMA/MMA, 2012) is consistent with the Brazilian water quality criteria (CONAMA, 2005).

2. Materials and methods

2.1. Study area

Sepetiba Bay is a 447-km^2 coastal system (Fig. 1) that has been suffering considerable impacts from human activities both in the drainage basin and along its margins. Although the catchment basin (2617 km^2) has a population of over 1.56 million (Instituto Brasileiro de Geografia e Estatística, 2010), the main pollution loads originate in a broad industrial complex of over 600 plants (FIRJAN, 2015). Among the industries installed in the drainage basin, the most significant sources of pollutants are steel metallurgic units, chemical plants, textile mills, breweries and other beverage-production facilities, production of both non-metallic and metallic minerals, and a large printing complex. Sepetiba Bay is directly affected by Itaguaí and Mangaratiba ports, which have heavy ship traffic with constant loading and unloads of large ships carrying iron ore and coal cargos. In addition, a myriad of small shipyards and other activities located at the bay margins may contaminate its waters with many pollutants.

Despite the number of diffuse sources of trace metals, the major contamination of the sediments with zinc and cadmium is attributed to one plant, the trade company Ingá Metallics, which produced zinc. It went bankrupt in the late 1990s, but left a large refuse pile, located in a contention reservoir that floods and leaks contaminated sediments into Sepetiba Bay when strong rain events occur. These periodic leaks have seriously contaminated the sediments of the bay, which has reported concentrations of up to 37,300 mg kg^{-1} and 396 mg kg^{-1} of zinc and cadmium, respectively (Barcellos, 1995). More recently, Ribeiro et al. (2013) evaluated the mobility of these metals throughout the bay, while Gomes et al. (2009), using dated sediment cores, estimated a historical enrichment of zinc and cadmium in the bay that began back in the 1950s.

Although freshwater inputs have been shown to be very variable, Rodrigues (1990) estimated the mean value to be 242 m^3 s^{-1}. This freshwater inflow into Sepetiba Bay is associated with significant loads of suspended matter, varying from 0.3 to 0.6 $\times$ 10^6 t year^{-1}, representing an average concentration of 40 mg L^{-1} (Lacerda et al., 1988; Molisani et al., 2006). Barcellos et al. (1998) observed that these river inputs are responsible for only 30–60% of the suspended matter in the waters of the Bay. The resuspension of the bottom sediments, caused by friction of deep-water currents against the bottom sediments, seems to be responsible for the remainder. Yet, during extreme storm situations, suspended matter concentrations may attain 300 mg L^{-1} (Barcellos et al., 1998).

The study area is the location of a new maritime terminal to be installed in Sepetiba Bay, located west of the currently operating harbor of Itaguaí (Fig. 1). The area to be dredged is shown in Fig. 1 and was described by Wasserman et al. (2013). Briefly, it is a 1.5 million m^3 dredging operation, in which the authors identified about half a million m^3 of contaminated sediments, planned to be disposed off in a sub-aquatic confined disposal facility a few hundred meters west of the dredging operations.