Mercury methylation upon coastal sediment resuspension: a worst-case approach under dark conditions

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Abstract Mercury behavior upon resuspension of sediments from two impacted areas of Guanabara Bay was evaluated to assess worst-case methylmercury (MeHg) responses, under dark experimental conditions to prevent demethylation by photolysis. Study areas include the Rio de Janeiro Harbor (RJH) and the chlor-alkali plant–affected Meriti River (MR) estuary. Total mercury (THg) and MeHg concentrations were determined along 24-h experiments of sediment resuspension in the bay water in dark conditions. Fine-grained Meriti River (MR) estuary sediments had 8 times higher MeHg initial concentrations than sandy Rio de Janeiro Harbor (RJH) sediments (3.4 ± 0.29 vs. 0.41 ± 0.1 ng g⁻¹, respectively). Though THg contents were uncorrelated with resuspension time, statistically significant correlations of MeHg ($r_s$=0.78) and %MeHg in relation to THg ($r_s$=0.86) with resuspension time were observed for RJH sediments, indicating net methylation only for this study site. These positive correlation trends correspond to a 2.8 times MeHg concentration increase ($\Delta$MeHg=0.75 ng g⁻¹) and 4.4 times increase in %MeHg ($\Delta$%MeHg=1.0%), after 24 h of resuspension. This suggests that assessments of factors affecting the MeHg spatial–temporal variability and associated toxicity risks can be limited in some sites if concentration changes due to sediment resuspension–redeposition processes are not considered. Therefore, the inclusion of MeHg evaluation before and after sediment resuspension events is recommendable for the improvement of dredging licensing and monitoring activities.

Keywords Estuaries · Harbor · Bioavailability · Chlor-alkali plant · Dredging activities

Introduction

The resuspension of contaminated sediments in the water column constitutes an important secondary source of trace metals in anthropogenically affected estuaries (Angeli et al., 2021; Kalneijars et al., 2010; Roberts,
The resuspension of anoxic sediments increases water turbidity and exposes the sediment particles to oxidizing conditions that can affect metal solubility in the water column (Caetano et al., 2003; Maddock et al., 2007; Monte et al., 2021). Therefore, anthropogenic activities (e.g., sediment dredging) and natural processes (e.g., wind-induced turbulence) that cause sediment resuspension may enhance the bioavailability of trace metal contaminants in the water column and in redeposited sediments (Monte et al., 2015; Fetters et al., 2016), including highly toxic trace elements, such as Hg (Agather et al., 2019; Morse, 1994).

Potential changes in total Hg and methylmercury (MeHg) concentrations due to sediment resuspension events have been previously addressed. Acquavita et al. (2012) observed a negligible release of Hg species to dissolved phase after the resuspension of coastal lagoon sediments, while the percent MeHg values in relation to total mercury Hg increased by 3 to 9 times, indicating enhanced methylation. Kim et al. (2006) evidenced that the sediment resuspension does not appear to directly impact Hg methylation but can lead to changes in the association of Hg to binding phases, which can affect MeHg production. Zhu et al. (2018) interpreted that an increase in net MeHg formation of up to 4 times observed in sediment resuspensions was likely because of a 2 times increase in sulfate concentration, stimulating the Hg(II) methylation activity of sulfate-reducing bacteria (SRB). Due to this complex non-conservative behavior, the predictability of sediment resuspension effects on MeHg concentrations persists a challenge.

Material and methods
Study area and sampling procedures
Guanabara Bay is a ~380 km² coastal system that has received large sewage input during the last decades (Kjerfve et al., 1997; Soares-Gomes et al., 2016), with sediment dredging operations periodically made due to harbor activities and for reducing siltation, which may affect metal pollutant behavior upon sediment resuspension (Machado et al., 2011; Maddock et al., 2007). This bay receives industrial and domestic sewage daily, due to deficient basic sanitation structures in the drainage basin, contributing for metal demethylation (Rodriguez-Gonzalez et al., 2013; Sharif et al., 2014).
contamination of sediments from harbors and estuaries (Cordeiro et al., 2015; Silveira et al., 2011). The main sources of Hg to the bay sediments are a chlor-alkali plant, urban effluents, and harbors (Covelli et al., 2012; Machado et al., 2008; Wasserman et al., 2000).

The Meriti River (station MR; Fig. 1) receives effluents of a chlor-alkali plant, resulting in large Hg contamination in the river water column and sediments since the 1970s (Rego et al., 1993). Consequently, Hg concentrations in Meriti River estuarine sediments reached up to 37,000 ng g\(^{-1}\) (Wasserman et al., 2000). The Rio de Janeiro Harbor (station RJH; Fig. 1) is among the largest harbors in Brazil, showing metal contamination attributed to harbor activities and discharges from a polluted channel (Neto et al., 2006; Cordeiro et al., 2015), as reflected by a moderate Hg pollution in the RJH area (Covelli et al., 2012).

Both sites show whole-sediment acute and chronic toxicity to benthic fauna (Campos et al., 2019), while enhanced bioavailability of other metal pollutants has been observed for Guanabara Bay sediments submitted to resuspension experiments (Machado et al., 2011; Maddock et al., 2007).

Fig. 1 Location of Rio de Janeiro Harbor (A), Meriti River estuary (B), and bay water (star) sampling sites within Guanabara Bay (Rio de Janeiro State, Brazil)
In March 2015, three surface sediment samples were collected per study site using a Van Veen grab and stored in the dark, under refrigeration until arriving at the laboratory, whereas nearby bay water was collected in a 6-L decontaminated plastic container (Fig. 1). The presented results are averages and standard deviations derived from separate analyses of subsamples from these triplicates. For each sampling time along the resuspension experiments, each one of these sediment subsamples was agitated in the sampled water and analyzed in duplicate, per sampling site. The sediment to water proportion used in the experiments was based on previous works (Machado et al., 2011; Monte et al., 2015; Monte et al., 2021). Approximately 7.0 g of wet sediments was agitated in 125-mL Erlenmeyer flasks containing unfiltered water from the main channel of Guanabara Bay, under oxidizing condition. During agitation, the flasks were maintained open, in contact with atmosphere, using a mechanical shaker at a speed of 200 rpm. The procedures were based on previous studies simulating dredging conditions in estuarine environments (Machado et al., 2011; Monte et al., 2015, 2019), while the agitation speed used in the experiments is within the range reported in the literature (e.g., Acquavita et al., 2012; Fetters et al., 2016; Xie et al., 2019). This was performed under dark conditions maintained by covering the flasks with aluminum foil. Sediment samplings were carried out in the time intervals of 0.05 h, 0.5 h, 1 h, 3 h, 6 h, 12 h, and 24 h. Resuspended sediments were fully transferred from flasks to be treated for the analyses described below. Blank flasks were included and sampled in duplicate for each resuspension interval, prepared with the same bay water and cleaned glassware used for experimental samples, but without the addition of sediment samples, and submitted to the same analytical procedures as the flasks that contained sediments.

**THg and MeHg determinations in sediments**

The sediment samples were dried at <40 °C and homogenized for pretreatment extractions. Total mercury (THg) determination was performed after the extraction method described in Malm et al. (1989), in which an aliquot of 0.5 g (dry weight) is digested with concentrated aqua regia (1HCl:3HNO₃). THg detection was held in a portable multifunctional atomic absorption spectrometer with Zeeman background correction (Lumex 915 M). The equipment accuracy was tested using certified reference material (PACS 3), resulting in a 92.2% recovery. A detection limit of 4 ng g⁻¹ THg was obtained. MeHg determination was performed according to previous studies (Bastos et al., 2020; Kasper et al., 2018; Taylor et al., 2011). Sediment subsamples of 0.05 g were extracted with 25% KOH methanol (4 mL g⁻¹), heated at 68 °C between 2.5 and 4 h. Derivatization by aqueous ethylation with sodium tetraethyl borate (NaBEt₄) was used, and MeHg determination was performed in an atomic fluorescence spectrometer coupled to a gas chromatograph (Merx-Brooks). These results were recorded in a software MERX-M Guru version 4.01. A certified reference material was analyzed (IAEA 433) for MeHg, with a recovery of 109% and a detection limit of 0.29 ng g⁻¹.

**Grain size and organic matter estimates**

The sediment grain size was determined after 24-h agitation of approximately 1 g of wet samples in 40 mL of a dispersant solution (40 g L⁻¹ sodium hexametaphosphate), using a particle size analyzer by laser diffraction CILAS Shimadzu (model 1064) (e.g., Monte et al., 2015, 2019). The results were calculated using the software GRADSTAT version 1.0. A proxy for organic matter (OM) content was determined using the loss-on-ignition method (e.g., Seelen et al., 2018; Stoichev et al., 2019). This OM proxy corresponds to dry sediment weight loss after calcination of 1.0 g samples at 450 °C for 4 h, for which a precision within ±20% is routinely obtained (Heiri et al., 2001).

**Statistical analysis**

Potential influences of resuspension time on sediment composition were evaluated by non-parametric Spearman rank correlation tests, performed using a Statsoft Statistica® program, version 12. A significance level of 0.05 was accepted for Spearman correlation coefficients (rₛ) interpretation.

**Results and discussion**

The grain size results were very homogeneous in relation to each site and very contrasting between sites. Station MR sediments had a largely dominant silt grain size
(79.4 to 85.8%), with undetectable sand content, while station RJH sediments were essentially sandy (96.5 to 98.7%), with only 1.1 to 3.2% of silt, as determined for sediment samples before resuspension. The OM contents were also different between sites, with higher values in MR sediments (Fig. 2), without significant correlation trends with resuspension time for both sampling stations ($r_s = -0.62$ to $-0.36$; $p > 0.05$). Higher average OM values were observed in MR ($10 \pm 2.6$% to $12.1 \pm 2.3$%) than in RJH ($0.9 \pm 0.3$% to $2.4 \pm 0.6$%) along time, as implied from large grain size contrasts between sites. Maximum and minimum contents of OM, THg, and MeHg are in the supplementary material.

The average THg concentrations in MR sediments ranged from $11,250 \pm 4480$ ng g$^{-1}$ to $14,380 \pm 4840$ ng g$^{-1}$ along resuspension time, with unclear temporal trends (Fig. 3). These values were within the THg concentration range reported for contaminated sediments from the same estuary (nearly 2700 to 30,000 ng g$^{-1}$; Wasserman et al., 2000; Machado et al., 2008), within the THg concentration range reported for contaminated sediments from the same estuary (nearly 2700 to 30,000 ng g$^{-1}$; Wasserman et al., 2000; Machado et al., 2008), since mangrove wetlands are known as efficient biogeochemical barriers for Hg (Lacerda et al., 2022), and one to two orders of magnitude below that found in SPM along other Guanabara Bay areas (20 to 205 ng g$^{-1}$; Kehrig et al., 2009), an area that experiences widely variable exposure to metal pollutants input from diffuse and point sources (Soares-Gomes et al., 2016). For RJH sediments, however, the observed low MeHg concentrations enhanced with resuspension time ($r_s = 0.78$; $p < 0.05$), ranging from an initial concentration of $0.40 \pm 0.2$ ng g$^{-1}$ to a final concentration of $1.12 \pm 0.5$ ng g$^{-1}$ (Fig. 4). This average increase of 2.8 times in resuspended RJH sediments corresponds to a $\Delta$MeHg of 0.75 ng g$^{-1}$ for 24 h of resuspension. An apparent daily MeHg production of 0.75 ng g$^{-1}$ is consistent with the range of Hg apparent methylation rates of <0.05 to nearly 1.3 ng g$^{-1}$ day$^{-1}$ reported for sediments from three different estuarine regions of the world by Heyes et al. (2006).

Station RJH presented an initial percentage of methylmercury in relation to total Hg (%MeHg) one
order of magnitude higher than observed for station MR (0.31 ± 0.10% vs. 0.032 ± 0.010%, respectively; Fig. 5). The RJH %MeHg values were also correlated with resuspension time ($r_s = 0.86; p < 0.05$), resulting in a final Δ%MeHg of 1.0%, while MR sediments did not display clear concentration trend along time (Fig. 5). Previous experimental resuspension data under dark conditions, however, observed daily increases of %MeHg up to 0.1% in average for the plume of Adour River estuary (Sharif et al., 2014). These differences may be partly attributed to the intensity of bacterial activity fueled by organic matter and associated to redox conditions. Bacterial activity in suspended particles supports the possibility for water column MeHg production (Seelen et al., 2018), while the interplay between Hg methylation and MeHg degradation determines the net MeHg contents (Kim et al., 2006). Therefore, the methylation capacity differences between sites may be related to variations in the bacterial community growth conditions, such as availability of organic carbon, electron donors, and acceptors (Goñi-Urriza et al., 2015). This is probably impacted by previous dredging events in the RJH site, which is typical of harbor areas (e.g., Birch et al., 2020), while more chronic industrial pollution affected the MRE site, which may lead to contrasting responses from microbial communities.

There were no significant correlations between THg, MeHg, and OM along the resuspension time ($r_s = -0.64$ to 0.54; $p > 0.05$), despite that THg has been correlated with organic matter in some Guanabara Bay sites (e.g., Covelli et al., 2012; Machado et al., 2008), while this did not occur for THg and MeHg in mangrove sediments from this bay (Kehrig et al., 2003). Particularly in MR estuary, there are largely dominant associations of THg with organic matter, as demonstrated by correlation and sequential extraction analyses (Barrocas & Wasserman, 1998; Wasserman et al., 2000).

The MeHg is mainly produced under anoxic conditions in sediments and waters, predominantly by sulfur- and iron-reducing bacteria (Compeau & Bartha, 1985; Mazrui et al., 2016), whereas aerobic conditions during sediment resuspension can oxidize metal sulfides, releasing soluble Hg(II) ions, which are susceptible to be partly associated to metal oxides (e.g., Morse, 1994) and partly assimilated by SRB and methylated (Hines et al., 2013). For example, there is experimental evidence that bioturbation of mangrove sediments favors Hg methylation under oxidizing conditions near the water–sediment interface, since SRB can also be active under oxidized conditions (Correia and Guimarães, 2016). However, increased oxygenation in the resuspension system will be a limiting factor to methylation, if redox conditions became sufficiently oxidizing to
inhibit SRB activity (Kim et al., 2006). Consequently, concurrent MeHg demethylation and Hg(II) methylation processes are frequent, while demethylation can often overwhelm, via biological and/or photochemical pathways (Heyes et al., 2006; Sharif et al., 2014), as may be expected for euphotic surface water conditions.

The diversity of microorganisms that are Hg methylators (as identified by the gene hgcA-based cloning and sequencing) may be mainly composed of specific prokaryotic groups (e.g., sulfate reducers; Azaroff et al., 2020). However, the Hg methylation gene complex hgcA assures phylogenetically and environmentally diverse Hg methylators between different microbial communities (Podar et al., 2015). These differences may contribute to explain the observed contrasts in MeHg responses to sediment resuspension, in addition to earlier interpretations in the literature on a major role of sulfate reducers.

Besides anthropogenic disturbances (e.g., dredging), the resuspension of sediments by natural processes can result in transport of Hg-bearing particles (e.g., due to tidal and storm-induced shear stress; Chakraborty et al., 2019), which may also occur in aphotic water depths, in closer contact with bottom sediment organisms. As exemplified here, environmental risk assessments related to MeHg production under absence of light may improve predictions on sediment resuspension effects on benthic life. This concern is consistent with an expected increase in the bioavailability of other metal pollutants after sediment resuspension in bottom water layers (e.g., Machado et al., 2011), which may possibly contribute for determining whole-sediment toxicity observed after sediment redeposition (Fetters et al., 2016).

Methylmercury is usually not included in international sediment quality guidelines developed to predict risks of adverse biological effects, which are based on total Hg concentrations, such as the effect range low (ERL) and effect range medium (ERM) (Long et al., 1995), and the threshold effect level (TEL) and probable effect level (PEL) (MacDonald et al., 1996). These guidelines can be used in environmental legislations that regulate dredging activities, as occur in Brazil for the ERL and ERM in relation to several trace metals (CONAMA, 2012). However, MeHg exposure changes after resuspension can be harmful to aquatic life, evidencing that the development of approaches for assessing this risk is recommendable for future improvement of dredging impact assessment.

This worst-case scenario after experimental sediment resuspension under dark conditions may also be relevant for spatial–temporal assessments on MeHg contents in coastal systems. Resuspension-redeposition cycling of Hg-bearing particles occurs naturally (Chang et al., 2019), though human interventions may be more critical. However, usual concerns on spatial–temporal assessments have not accounted the potential effects of MeHg production under dark conditions during the residence time of Hg-polluted sediments in the coastal water column (Sharif et al., 2014). For Guanabara Bay, where (i) heavily polluted river discharges (e.g., Silveira et al., 2011) and algal blooms occur (e.g., Fistarol et al., 2015), (ii) Secchi disk depths are frequently < 75 cm in inner areas (Kjerfve et al., 1997), and (iii) average water depth is ~6 m (Kjerfve et al., 1997), MeHg cycling under conditions without significant photolysis deserves careful attention. As may be expected for many other coastal regions affected by anthropogenic Hg, the observations above suggest that MeHg enrichment or attenuation gradients may be affected by unaccounted sediment resuspension-redeposition cycling influences.

**Conclusions**

The results contributed for elucidating the potential role of Hg-contaminated sediments resuspension-redeposition events on the MeHg behavior in two contrasting coastal areas. Considering that MeHg is much more toxic than inorganic Hg, the performed worst-case estimates (i.e., carried out under photolysis prevention) suggest that toxicity risks associated to sediment resuspension events may be underestimated even for low-THg sandy sediments, if the potential MeHg production is not taken into consideration. Therefore, more caution is requested before assuming that spatial–temporal trends in MeHg distribution along coastal systems behave conservatively, when sediment resuspension-redeposition cycling is involved. Sandy sediments from RJH presented a positive ΔMeHg of 0.75 ng g⁻¹ after 24 h of resuspension, corresponding to a 2.8 times concentration increase. Consideration on these issues can contribute for improving (i) assessments of whole-sediment toxicity risks to benthic organisms along sediment
resuspension-deposition cycles and (ii) spatial–temporal modeling to predict MeHg concentrations in sediments and suspended particulate matter from coastal systems. However, predicting MeHg behavior upon sediment resuspension remains a challenge (e.g., due to effects of sediment heterogeneity on MeHg production in response to light exposure and absence) that deserves further investigation. Future revisions of dredging legislations in Brazil and elsewhere should include MeHg evaluation, considering the possible enhancement of environmental effects associated to MeHg after sediment resuspension events, which can cause the production or degradation of this highly toxic organometallic pollutant.

Author contribution Conceptualization and methodology: CM, APCR, JCW, OM, and WM. Analysis: CM, PMAC, and GCP. Writing—original draft and revised version: CM, APCR, JCW, and WM. All authors discussed results and approved the final manuscript.

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Availability of data and materials The datasets produced during the current study are available from the corresponding author on reasonable request. All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Acquavita, A., Emili, A., Covelli, S., Faganeli, J., Predonzani, S., Koron, N., & Carrasco, L. (2012). The effects of resuspension on the fate of Hg in contaminated sediments (Marano and Grado Lagoon, Italy): Short-term simulation experiments. Estuarine, Coastal and Shelf Science, 113, 32–40. https://doi.org/10.1016/j.ecss.2012.02.012

Agather, A. M., Bowman, K. L., Lamborg, C. H., & Hammerschmidt, C. R. (2019). Distribution of mercury species in the Western Arctic Ocean (US GEOTRACES GN01). Marine Chemistry, 216, 103686. https://doi.org/10.1016/j.marchem.2019.103686

Angeli, J. L. F., Sartoretto, J. R., Kim, B. S. M., Ferreira, P. A. L., Mahiques, M. M., & Figueira, R. C. L. (2021). Trace element fluxes during the “Anthropocene” in a large South American industrial and port area (Santos and São Vicente estuarine system, SE, Brazil). Environmental Monitoring and Assessment, 193, 594. https://doi.org/10.1007/s10661-021-09378-3

Azaroff, A., Goñi-Urriza, M., Gassie, C., Monperrus, M., & Guyonenaud, R. (2020). Marine mercury-methylating microbial communities from coastal to Capbreton Canyon sediments (North Atlantic Ocean). Environmental Pollution, 262, 114333. https://doi.org/10.1016/j.envpol.2020.114333

Barrocas, P. R. G., & Wasserman, J. C. (1998). Mercury behaviour in sediments from a sub-tropical coastal environment in SE Brazil In: Wasserman, JC, Silva-Filho, EV, Villas-Boas, R (eds), Environmental geochemistry in the tropics, Lecture Notes in Earth Sciences 72, Springer-Verlag, Heidelberg.

Bastos, W. R., Dórea, J. G., Lacerda, L. D., Almeida, R., Costa-Junior, W. A., Baía, C. C., Sousa-Filho, I. F., Sousa, E. A., Oliveira, I. A. S., Cabral, C. S., Manzatto, A. G., Carvalho, D. P., Ribeiro, K. A. N., & Malm, O. (2020). Dynamics of Hg and MeHg in the Madeira River basin (Western Amazon) before and after impoundment of a run-of-river hydroelectric dam. Environmental Research, 189, 109896. https://doi.org/10.1016/j.envres.2020.109896

Birch, G. F., Lee, J.-H., Tanner, E., Fortune, J., Munksgaard, N., Whitehead, J., Coughanowr, C., Agius, J., Chrispijn, J., Taylor, U., Wells, F., Bellas, J., Besada, V., Viñás, L., Soares-Gomes, A., Cordeiro, R. C., Machado, W., Santelli, R. E., Vaughan, M., ... Steinberg, P. (2020). Sediment metal enrichment and ecological risk assessment of ten ports and estuaries in the World Harbours Project. Marine Pollution Bulletin, 155, 111–129. https://doi.org/10.1016/j.marpolbul.2020.111129

Black, F., Poulin, B. A., & Flegal, R. (2012). Factors controlling the abiotic photo-degradation of monomethylmercury in surface waters. Geochimica Et Cosmochimica Acta, 84, 492–507. https://doi.org/10.1016/j.gca.2012.01.019

Caetano, M., Madureira, M. J., & Vale, C. (2003). Metal remobilization during re-suspension of anoxic contaminated sediment: Short term laboratory experiment. Water, Air and Soil Pollut, 143, 23–40.

Campos, B. G., Moreira, L. B., Pauly, G. F. E., Cruz, A. C. F., do Nascimento Monte, C., da Silva, L. I. D., Rodrigues, A. P. C., Machado, W., & Abessa, D. M. S. (2019). Integrating multiple lines of evidence of sediment quality in a tropical bay (Guanabara Bay, Brazil). Marine Pollution Bulletin, 146, 925–934. https://doi.org/10.1016/j.marpolbul.2019.07.051

Chakraborty, P., Jayachandran, S., Lekshmy, J., Padalkar, P., Sitholou, L., Chennuri, K., ShetyeS, Sardar A., & Khandeparker, R. (2019). Seawater intrusion and resuspension-deposition cycles and (ii) spatial–temporal monitoring in SE Brazil In: Wasserman, JC, Silva-Filho, EV, Villas-Boas, R (eds), Environmental geochemistry in the tropics, Lecture Notes in Earth Sciences 72, Springer-Verlag, Heidelberg.

Chang, G., Martin, T., Whitehead, K., Jones, C., & Spada, F. (2019). Optically based quantification of fluxes of
mercury, methyl mercury, and polychlorinated biphenyls (PCBs) at Berry’s Creek tidal estuary, New Jersey. *Limnology and Oceanography, 64*, 93–108. https://doi.org/10.1002/lno11021

Compeau, G. C., & Bartha, R. (1985). Sulfate-reducing bacteria: Principal methylators of mercury in anoxic estuarine sediment. *Applied and Environment Microbiology, 50*, 498–502.

CONAMA. (2012). Procedures for the evaluation of dredging materials in Brazilian jurisdictional waters. Res. No. 454/2012 from the Conselho Nacional do Meio Ambiente. Diário Oficial da República Federativa do Brasil, Brasília (in Portuguese).

Cooper, C. J., Zheng, K., Rush, K. W., Jogs, A., Sanders, B. C., Pavlopoulos, G. A., Kyrpides, N. C., Podar, M., Ovchinnikov, S., Ragsdale, S. W., & Parks, J. M. (2020). Structure determination of the HgcAB complex using metagenome sequence data: Insights into microbial mercury methylation. *Communications Biology, 3*, 320. https://doi.org/10.1038/s42003-020-1047-5

Cordeiro, R. C., Machado, W., Santelli, R. E., Figueiredo, A. G., Jr., Seoane, F. C. S., Oliveira, E. P., Freire, A. S., Bidone, E. D., Monteiro, F. F., Silva, F. T., & Meniconi, M. F. G. (2015). Geochemical fractionation of metals and semimetals in surface sediments from tropical impacted estuary (Guanabara Bay, Brazil). *Environment and Earth Science, 74*, 1363–1378. https://doi.org/10.1007/s12665-015-4127-y

Correia, R. R. S., & Guimaraes, J. R. D. (2016). Impacts of crab bioturbation and local pollution on sulfate reduction, Hg distribution and methylation in mangrove sediments, Rio de Janeiro, Brazil. *Marine Pollution Bulletin, 109*, 453–460. https://doi.org/10.1016/j.marpolbul201605028

Covelli, S., Protopsalti, I., Acquavita, A., Sperle, M., Bonardi, M., & Emili, A. (2016). Spatial variation, speciation and sedimentary records of mercury in the Guanabara Bay (Rio de Janeiro, Brazil). *Continental Shelf Research, 35*, 29–42. https://doi.org/10.1016/j.csr.201112003

Fetters, K. J., Costello, D. M., Hammerschmidt, C. R., & Burton, G. A., Jr. (2016). Toxicological effects of short-term resuspension of metal-contaminated freshwater and marine sediments. *Environmental Toxicology and Chemistry, 35(3)*, 670–686. https://doi.org/10.1002/etc.3225

Fistarol, G. O., Coutinho, F. H., Moreira, A. P. B., Venas, T., Canovas, de Paula, S. E. M., Coutinho, R., de Moura, R. L., Valentim, J. J., Tenenbaum, D. R., Paranhos, R., do Valle, R. A. B., Vicente, A. C. P., Amado Filho, G. M., Pereira, R. C., Kruger, R., Rezende, C. E., Thompson, C. C., Salomon, P. S., & Thompson, F. L. (2015). Environmental and sanitary conditions of Guanabara Bay, Rio De Janeiro. *Frontiers in Microbiology, 6*, 1232. https://doi.org/10.3389/fmicb.201501232

Gotti-Urriza, M., corsellis, Y., Lancelou, L., Tessier, E., Gury, J., Monperrus, M., & Guyonneaud, R. (2015). Relationships between bacterial energetic metabolism, mercury methylation potential, and hgcA/hgcB gene expression in Desulfobivrio dechloroacetivorans BerOc1. *Environmental Science and Pollution Research, 22*, 13764–13771. https://doi.org/10.1007/s11356-015-4273-5

Heiri, O., Lotter, A. F., & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *Journal of Paleolimnology, 25*, 101–110.

Heyes, A., Mason, R. P., & Kim, E.-H. (2006). Sunderland E Mercury methylation in estuaries: Insights from using measuring rates using stable mercury isotopes. *Marine Chemistry, 102*, 134–147. https://doi.org/10.1016/j.marchem20050901

Hines, M. E., Poitrans, E. N., Covelli, S., Faganeli, J., Emili, A., Žižek, S., & Horvat, M. (2013). Mercury methylation and demethylation in Hg-contaminated lagoon sediments (Marano and Grado Lagoon, Italy). *Estuarine, Coastal and Shelf Science, 113*, 85–95. https://doi.org/10.1016/j.ecss.201112021

Kasper, D., Forsberg, B. R., Kehrig, H. A., Amaral, J. H. F., Bastos, W. R., & Malm, O. (2018). Mercury in black-waters of the Amazon. In: Myster, R. (Ed.), Igapó (black-water flooded forests) of the Amazon Basin. Springer, Cham 39–56. https://doi.org/10.1007/978-3-319-90122-0_3

Kalnejaia, L. H., Martin, W. R., & Bothner, M. H. (2010). The release of dissolved nutrients and metals from coastal sediments due to resuspension. *Marine Chemistry, 121*, 224–235. https://doi.org/10.1016/j.marchem201005002

Kehrig, H. A., Pinto, F. N., Moreira, I., & Malm, O. (2003). Heavy metals and methylmercury in a tropical coastal estuary and a mangrove in Brazil. *Organic Geochemistry, 34(5)*, 661–669. https://doi.org/10.1016/S0146-6380(03)00021-4

Kehrig, H. A., Palermo, E. F. A., Seixas, T. G., Branco, C. W. C., Moreira, I., & Malm, O. (2009). Trophic transfer of methylmercury and trace elements by tropical estuarine seston and plankton. *Estuarine, Coastal and Shelf Science, 85*, 36–44. https://doi.org/10.1016/j.ecss.200905027

Kim, E.-H., Mason, R. P., Porter, E. T., & Soulen, H. L. (2006). The impact of resuspension on sediment mercury dynamics, and methylmercury production and fate: A mesocosm study. *Marine Chemistry, 102*, 300–315. https://doi.org/10.1016/j.marchem200605006

Kjerfve, B., Ribeiro, C. H. A., Dias, G. T. M., Filippo, A. M., & Quresma, V. S. (1997). Oceanographic characteristics of an impacted coastal bay: Baía de Guanabara, Rio de Janeiro, Brazil. *Continental Shelf Research, 17*, 1609–1643.

Lacerda, L. D., Ward, R., Borges, R., & Ferreira, A. C. (2022). Mangrove trace-metal biogeochemistry response to global climate change. *Frontiers in Forests and Global Change, 5*, 817992. https://doi.org/10.3389/ffgc.2022.817992

Long, E. R., MacDonald, D. D., Smith, S. L., & Calder, F. D. (1995). Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. *Environmental Management, 19*, 81–97.

Lu, X., Gu, W., Zhao, L., Haque, M. F. U., DiSpirito, A. A., Semrau, J. D., & Gu, B. (2017). Methylmercury uptake and degradation by methanotrophs. *Science Advances, 3*, e1700041. https://doi.org/10.1126/sciadv.1700041

MacDonald, D. D., Carr, R. S., Calder, F. D., Long, E. R., & Ingersoll, C. G. (1996). Development and evaluation of sediment quality guidelines for Florida coastal waters. *Ecotoxicology, 5*, 253–278. https://doi.org/10.1007/BF00118995

Machado, W., Moscatelli, M., Rezende, L. G., & Lacerda, L. D. (2002). Mercury, zinc and copper accumulation in mangrove sediments surrounding a large landfill in southeast Brazil. *Environmental Pollution, 1201*, 455–461.
Machado, W., Santelli, R. E., Loureiro, D. D., Oliveira, E. L., Borges, A. C., Ma, V. K., & Lacerda, L. D. (2008). Mercury accumulation in sediments along an eutrophication gradient in Guanabara Bay, Southeast Brazil. Journal of the Brazilian Chemical Society, 19(3), 569–575.

Machado, W., Rodrigues, A. P. C., Bidone, E. D., Sella, S. M., & Santelli, R. E. (2011). Evaluation of Cu potential bioavailability changes upon coastal sediment resuspension: An example on how to improve the assessment of sediment dredging environmental risks. Environmental Science and Pollution Research, 18, 1033–1036. https://doi.org/10.1007/s11356-011-0517-1

Maddock, J. E. L., Carvalho, M. F., Santelli, R. E., & Machado, W. (2007). Contaminant metal behavior during re-suspension of sulphidic estuarine sediments. Water, Air, and Soil Pollution, 181, 193–200. https://doi.org/10.1007/s11270-006-9290-z

Malm, O., Pfeiffer, C., Bastos, W. R., & Souza, C. M. M. (1989). Utilização do acessório de geração de vapor frio para análise de mercúrio em investigações ambientais por espectrofotometria de absorção atômica. Ciência Cultura, 41(1), 88–92.

Mason, R. P., Choi, A. L., Fitzgerald, W. F., Hammerschmidt, C. R., Lamborg, C. H., Soerensen, A. L., & Sunderland, E. M. (2012). Mercury biogeochemical cycling in the ocean and policy implications. Environmental Research, 119, 101–117. https://doi.org/10.1016/j.envres.2012.03.013

Mazrui, N. M., Johnsson, S., Thota, S., Zhao, J., & Mason, R. P. (2016). Enhanced availability of mercury bound to dissolved organic matter for methylation in marine sediments. Geochimica Et Cosmochimica Acta, 194, 153–162. https://doi.org/10.1016/j.gca.201608019

Monte, C. N., Rodrigues, A. P. C., Cordeiro, R. C., Freire, A. S., Santelli, R. E., & Machado, W. (2015). Changes in Cd and Zn bioavailability upon an experimental resuspension of highly contaminated coastal sediments from a tropical estuary. Sustainable Water Resources Management, 1, 332–335. https://doi.org/10.1007/s40899-015-0034-3

Monte, C. N., Rodrigues, A. P. C., Freire, A. S., Santelli, R. E., Braz, B. F., & Machado, W. (2019). Dredging impact on trace metal behavior in a polluted estuary: A discussion about sampling design. Brazilian Journal of Oceanography, 67, 19227. https://doi.org/10.1590/S1679-8759201902706701

Monte, C. N., Rodrigues, A. P. C., Freitas, A. R., Braz, B. F., Freire, A. S., Cordeiro, R. C., Santelli, R. E., & Machado, W. (2021). Ecological risks associated to trace metals of contaminated sediments from a densely urbanized tropical eutrophic estuary. Environmental Monitoring and Assessment, 193, 767. https://doi.org/10.1007/s10661-021-09552-7

Morse, J. W. (1994). Interactions of trace metals with authigenic sulfide minerals: Implications for their bioavailability. Marine Chemistry, 46, 1–6.

Neto, J. A. B., Gingle, F. X., Leipe, T., & Brehme, I. (2006). Spatial distribution of heavy metals in surficial sediments from Guanabara Bay: Rio de Janeiro, Brazil. Environmental Geology, 49, 1051–1063. https://doi.org/10.1007/s00254-005-0149-1

Oremland, R. S., Culbertson, C. W., & Winfrey, M. R. (1991). Methylmercury deposition in sediments and bacterial cultures: Involvement of methanogens and sulfate reducers in oxidative demethylation. Applied and Environment Microbiology, 57, 130–137.

Pacyna, E. G., Pacyna, J. K., Steenhuisen, F., & Wilson, S. (2006). Global anthropogenic mercury emission inventory for 2000. Atmospheric Environment, 40, 4048–4063. https://doi.org/10.1016/j.atmosenv.200603041

Podar, M., Gilmour, C. C., Brandt, C. C., Soren, A., Brown, S. D., Crable, B. R., Palumbo, A. V., Somenahally, A. C., & Elias, D. A. (2015). Global prevalence and distribution of genes and microorganisms involved in mercury methylation. Science Advances, 1(9), e1500675. https://doi.org/10.1126/sciadv.1500675

Rego, V. S., Pfeiffer, W. C., Barcellos, C. C., Malm, O., & Souza, C. M. M. (1993). Heavy metal transport in the Acari-São Joào do Meriti River System, Brazil. Environmental Technology, 14, 167–174.

Roberts, D. A. (2012). Causes and ecological effects of resuspended contaminated sediments (RCS) in marine environments. Environment International, 40, 230–243. https://doi.org/10.1016/j.envint.201111013

Rodriguez-Gonzalez, P., Bouchet, S., Monperrus, M., et al. (2013). In situ experiments for element species-specific environmental reactivity of tin and mercury compounds using isotopic tracers and multiple linear regression. Environmental Science and Pollution Research, 20, 1269–1280. https://doi.org/10.1007/s11356-012-1019-5

Seelen, E. A., Massey, G. M., & Mason, R. P. (2018). Role of sediment resuspension on estuarine suspended particulate mercury dynamics. Environmental Science and Technology, 52, 7736–7744. https://doi.org/10.1021/acs.est.8b01920

Sharif, A., Monperrus, M., Tessier, E., Bouchet, S., Pinaly, H., Rodrigue-Gonzalez, P., Maron, P., & Amouroux., (2014). Fate of mercury species in the coastal plume of the Adour River estuary (Bay of Biscay, SW France). Science of the Total Environment, 447, 701–713. https://doi.org/10.1016/j.scitotenv.2014.06.116

Silveira, R. P., Rodrigues, A. P. C., Santelli, R. E., Cordeiro, R. C., & Bidone, E. D. (2011). Mass balance in the monitoring of pollutants in tidal rivers of the Guanabara Bay, Rio de Janeiro, Brazil. Environmental Monitoring and Assessment, 181, 165–173. https://doi.org/10.1007/s10661-010-1821-9

Soares-Gomes, A., Gama, B. A. P., Baptista-Neto, J. A., Freire, D. G., Cordeiro, R. C., Machado, W., Bernardes, M. C., Coutinho, R., Thompson, F. L., & Pereira, R. C. (2016). An environmental overview of Guanabara Bay, Rio de Janeiro. Regional Studies in Marine Science, 8, 319–330. https://doi.org/10.1016/j.rsma.2016.01.009

Stoilchev, T., Tessier, E., Coelho, J. P., Lobos Valenzuela, M. G., Pereira, M. E., & Amouroux, D. (2019). Multiple regression analysis to assess the spatial distribution and speciation of mercury in surface sediments of a contaminated lagoon. Journal of Hazardous Materials, 367, 715–724. https://doi.org/10.1016/j.jhazmat.201812109

Taylor, V. F., Carter, A., Davies, C., & Jackson, B. P. (2011). Trace-level automated mercury speciation analysis. Analytical Methods, 3(5), 1143–1148.

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

Xie, M., Alsina, M. A., Yuen, J., Packman, A. I., & Gaillard, J. F. (2019). Effects of resuspension on the mobility and
chemical speciation of zinc in contaminated sediments. *Journal of Hazardous Materials*, 15(364), 300–308. https://doi.org/10.1016/j.jhazmat.2018.10.043

Zhu, W., Song, W., Adediran, G. A., JiangT, R. A. T., Pereira, E., Skyllberg, U., & Björn, E. (2018). Mercury transformations in resuspended contaminated sediment controlled by redox conditions, chemical speciation and sources of organic matter. *Geochimica Et Cosmochimica Acta*, 220, 158–179. https://doi.org/10.1016/j.gca201709045

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