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Impact of extreme metal contamination at the supra-individual level in a contaminated bay ecosystem

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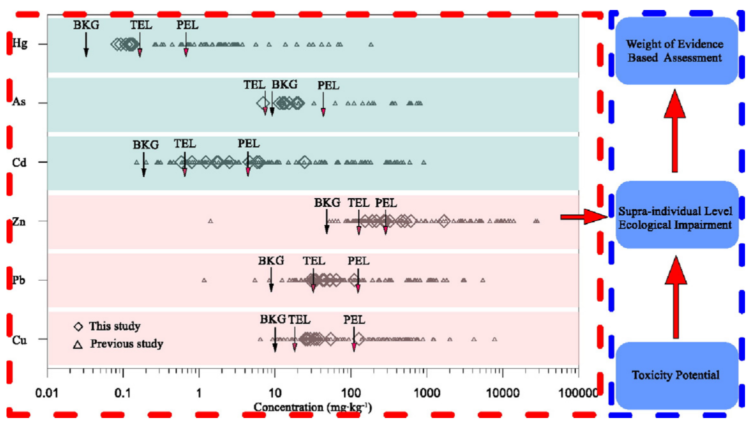
HIGHLIGHTS

- Sediment metals were highly enriched and exhibited considerable toxicity potential.
- Both natural and anthropogenic processes affected geochemical behavior of metals.
- Damaged benthic community coincided with extreme metal contamination.
- Sediments in the entire JZB were moderately to severely impaired.
- A possible linkage between benthic responses and metal contamination was found.

GRAPHICAL ABSTRACT



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ABSTRACT

Anthropogenic stressors impact the global environment and adversely affect the health of organisms and humans. This study was designed as an attempt to evaluate the ecological consequences of severe metal contamination at the supra-individual level based on a field investigation in Jinzhou Bay (JZB), North China in 2010. The chemical results showed high concentrations of metals in the sediment of JZB that were ~129 times greater than the local geochemical background. Furthermore, the measured metals exhibited considerably high toxicity potential indicated by sediment quality guidelines (SQGs). The mean SQGs quotients suggested the overall toxicity incidence was >70% in locations neighboring the Wulihe River mouth. Biomonitoring revealed 116 individuals distributed among a mere 6 species, 4 of which were polychaetes, at 33% of the sampling sites. Thus, few benthic organisms were present in the damaged community structures across the region, which was consistent with the extreme metal contamination. Moreover, the sediment quality assessment, in a weight of evidence framework, demonstrated that the sediment throughout the entire JZB was moderately to severely impaired, especially in the vicinity of the Wulihe River mouth. By synthesizing the present and previous chemical-biological monitoring campaigns, a possible cause-effect relationship between chemical stressors and benthic receptors was established. We also found that the hydrodynamics, sediment sources, and geochemical characteristics of the metals (in addition to the sources of the metals) were responsible for the geochemical distribution of metals in

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JZB. The significance of the overall finding is that the deleterious responses observed at the community level may possibly be linked to the extreme chemical stress in the sediment of JZB.

1. Introduction

The increasing release of contaminants from anthropogenic activities and their accumulation in marine and estuarine sediment threaten local organisms and humans (Long and Chapman, 1985; Chapman et al., 2013). Toxic metals (metals and metalloids) with persistent, toxic and bioaccumulation properties have raised substantial environmental concerns worldwide. Waterborne metals are easily adsorbed by suspended particles because of highly reactive coatings consisting of iron or manganese oxides, carbonate, sulfide, detrital organic matter or microorganisms (Turner and Millward, 2002). In association with suspended particles, metals present at low concentration in water are eventually deposited onto the seafloor and can be detected many times higher in the sediment (Chapman, 1986). At sufficiently high concentrations, toxic metals induce grave ecological consequences and can negatively affect human health (Gao and Chen, 2012; Jiang et al., 2014). Because contaminated sediments are complex matrices under the ever-expanding number of stressors (chemical, physical and biological) and stressor interactions arising from anthropogenic activities and global change (Burton and Johnston, 2010; de Vries et al., 2010; Tlili et al., 2010; Annala et al., 2014), there is growing agreement among marine investigators that biochemical and physiological level responses to contaminants are not sufficient to assess the health of marine ecosystems (Borja et al., 2015). As a global problem, sediment contamination and its harmful effects may be cross multiple ecological scales, from the individual, community, to ecosystem levels (Dang et al., 2013; Botter-Carvalho et al., 2014). Therefore, assessing the ecological consequence of contaminated sediments has been increasingly highlighted but is also exceptionally challenging.

A meaningful sediment quality assessment needs to incorporate multiple lines of evidence and to use appropriate interpretative tools dealing with different types of data (Landis et al., 2013; Chapman and Maher, 2014). Because benthic assemblages receive the most comprehensive exposure to the overall environment involved, they become one of the most effective indicators of environmental degradation in aquatic ecosystems (Chapman and Anderson, 2005; Chapman, 2007a, 2007b; McPherson et al., 2008; Wu et al., 2014a, 2014b). As recent studies have indicated, species diversity is positively correlated with ecosystem stability, recovery, and services, which makes a community-level perspective in ecological risk assessments more instrumental than ever (Clements and Rohr, 2009). In this context, a risk assessment of toxic metals based on the benthic community level (structure, function, and processes) provides the most ecological relevance pertaining to sediment contamination.

Environmental problems in China are associated with rapid economic growth since the 1970s. Although a wide range of measure that have been taken to harmonize economic development and environment protection over the last few decades (Fu et al., 2007), the overall trend is for worsening environmental status (Liu and Diamond, 2005). Therefore, the long-term effectiveness of pollutant reduction and ecological restoration remains to be seen. In coastal ecosystems, increasing metal discharges have led to serious water and sediment contamination (Wang et al., 2014). Elevated levels of toxic metals across the Bohai Sea are mostly from anthropogenic activities (Pan and Wang, 2012). Because coastal ecosystems provide many high-value services that humans depend upon for survival (Wall, 2004; Chapman et al., 2013), it is imperative to evaluate the ecological consequences of metals to better protect coastal environments. In particular, toxic metals in some highly industrialized coastal ecosystems, such as the severely contaminated Jinzhou Bay (JZB), North China, were long regarded as major threats to local organisms and humans (e.g., Wan et al., 2008; Li et al., 2012; Fan et al., 2014). As noted, the environmental crisis in JZB is associated with industrial discharges from mining and smelting facilities (Fan et al., 2002a, 2002b). JZB has clearly been contaminated by metals since approximately 1940 suggested both by core sediment records (Li et al., 1995) and local documents (Wang et al., 2012). In general, the decline of benthic organisms in JZB has been the result of several factors, including overfishing, port-related activities, and exposure to environmental toxicants. Toxic metals at extremely high concentrations have been however increasingly viewed as the predominant factor. Consequently, there is a strong need for an integrated assessment of the extent of adverse effect posed by toxic metals to the local benthic community.

A number of studies on metal distributions in this area were carried out, with emphasis on surface sediment, water, and aquatic organisms (e.g., Wan et al., 2008; Li et al., 2012; Fan et al., 2014). Presently, few studies concerning the effects of toxic metals on benthic assemblages have been conducted in the past 2 decades, leaving the integrated examination of contaminated sediment largely unexplored. Furthermore, there is a growing desire among the public to determine the outcome of the massive efforts on pollution reduction and aquatic ecosystem restoration in the Bohai Sea Economic Rim over recent decades. Therefore, integrating field benthic community structure to characterize the adverse effects of metal contamination in JZB sediment has been the subject of considerable attention. In the present study, we attempt to address these concerns with the following specific objectives: (1) characterizing the distribution of toxic metals to further understand the mechanisms controlling the dispersal, accumulation and fate of metals in JZB; (2) determining the ecological relevance of toxic metals at the supra-individual level to provide possible cause-effect relationships; and (3) evaluating the long-term effects of toxic metals on the benthic community by combining the present investigation with historical field data to provide benchmarks for ecological restoration.

2. Materials and methods

2.1. Study area and background

JZB (Fig. 1) is located on the northeast boundary of Huludao City, North China, and has an average water depth of 3.5 m and an area of 120 km^2. Due to weak self-purification conditions and a heavy load of toxic metals, the shallow, semi-enclosed region presents as one of the most polluted sedimentary environments in the world. The study area is influenced by 5 ephemeral rivers (Wulihe, Cishan, Lianshan, Tashan and Lao) with limited sediment loads and water discharges, resulting in relatively low sedimentation rates (~14 mm/yr) (Chen and Zhou, 1992). Toxic metals are the primary threat in the studied system, mainly because of lead-zinc refining operations, especially the Huludao zinc plant (Wang et al., 2010; Wang et al., 2012). The zinc plant produces one of the highest amounts of Zn across Asia, with Zn, Cu and Pb as the main products and Cd, Hg and As as byproducts (Li et al., 2012). This plant was once listed as one of the largest pollution sources along the Bohai Sea and even across China (Pan and Wang, 2012). Pollutants from smelting activities are dumped into the Wulihe River and finally are delivered to JZB. As mentioned, more than 0.1 million tons of toxic metals (including 300 tons of Hg and over 2300 tons of Cd) from coastal chemical plants were discharged into JZB during 1950–1980 (Wang et al., 1983 and references therein). In addition, more than 1.0 million tons of solid waste from the surrounding metallurgical industry was deposited on the beach of JZB, which acted as a continuing