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Review

Metal fate and effects in estuaries: A review and conceptual model for better understanding of toxicity

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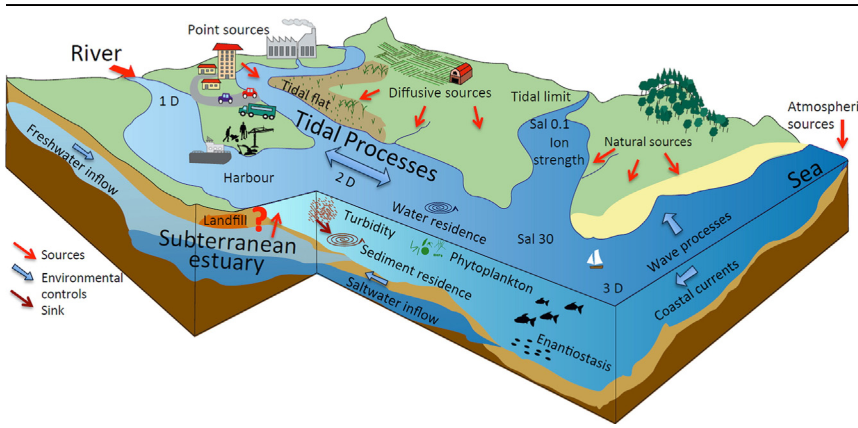
HIGHLIGHTS

- A multidisciplinary overview of metal fate and toxicity in estuaries is provided.
- Physical and biogeochemical gradients cause non-conservative behaviour of metals.
- Water chemistry generally explains metal toxicity in freshwaters.
- Organism physiology generally explains of metal toxicity in saltwater.
- Quantitative interdisciplinary models of metal fate and toxicity are yet required.

GRAPHICAL ABSTRACT



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ABSTRACT

Metal pollution is a global problem in estuaries due to the legacy of historic contamination and currently increasing metal emissions. However, the establishment of water and sediment standards or management actions in brackish systems has been difficult because of the inherent transdisciplinary nature of estuarine processes. According to the European Commission, integrative comprehension of fate and effects of contaminants in different compartments of these transitional environments (estuarine sediment, water, biota) is still required to better establish, assess and monitor the good ecological status targeted by the Water Framework Directive. Thus, the present study proposes a holistic overview and conceptual model for the environmental fate of metals and their toxicity effects on aquatic organisms in estuaries. This includes the analysis and integration of biogeochemical processes and parameters, metal chemistry and organism physiology. Sources of particulate and dissolved metal, hydrodynamics, water chemistry, and mechanisms of toxicity are discussed jointly in a multidisciplinary manner. It is also hypothesized how these different drivers of metal behaviour might interact and affect metal concentrations in diverse media, and the knowledge gaps and remaining research challenges are pointed. Ultimately, estuarine physicochemical gradients, biogeochemical processes, and organism physiology are jointly coordinating the fate and potential effects of metals in estuaries, and both realistic model approaches and attempts

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to postulate site-specific water criteria or water/sediment standards must consider such interdisciplinary interactions.

Contents

1. Introduction

Estuaries are defined as water bodies that connect land and ocean and extend from fully marine conditions to the effective limit of tidal influence, and where seawater is diluted by freshwater inflow (Hobbie, 2000). These environments have traditionally been zones of intense human occupation. They provide a multitude of ecosystem services such as drinking freshwater supply, fisheries, climate regulation, sheltered access to coastal water, coastal protection, water purification and waste treatment (Millennium Ecosystem Assessment, 2005). Estuaries also serve as nursery areas for several species, provide habitat to a high diversity of organisms for the whole or part of their life cycle, and are characterized by a high biological productivity. However, estuaries have also been used for the dilution and disposal of waste worldwide (Kennish, 1991; Spencer et al., 2006b) which contributes to their deterioration.

In this context, trace metals are pollutants of concern (Kinne, 1984; Nemerow, 1991; Fairbrother et al., 2007). Although metals are naturally ubiquitous in aquatic systems (usually within $\mu g \cdot L^{-1}$-range in surface waters), they are increasingly present as a result of anthropogenic activities. Förstner and Wittmann (1979) concluded that the world's six most heavily polluted aquatic environments by trace metals are estuaries. In countries with long historic industrialization, such as United Kingdom, Germany and Netherlands, thousands of tons of metals were systematically deposited in the estuarine and coastal areas (Förstner and Wittmann, 1979). This legacy of contamination is currently aggravated via freshwater input, increasing urbanization and discharges of domestic effluents, industry, fossil fuel burning, mining, groundwater use, surface runoff and soil erosion, and mobilization of historic contaminated sediment (Phillips, 1980; Heath, 1995; Deboudt et al., 2004; Paytan et al., 2009; Bai et al., 2015). Additionally, these contaminants are persistent in the environment, and all metals are potentially bioavailable and toxic to aquatic biota at high concentrations (Kennish et al., 1991; Wood et al., 2012a,b; Machado et al., 2014b).

Integrative models of behaviour and threats of metals are required to better set environmental quality standards and goals. Currently, North American scientists put significant effort into better understanding metal transport, mobilization and toxicity and derive scientifically defensible site-specific water quality criteria for metals in salt water environments – as has already been successfully established in freshwater (Paquin et al., 2003). While in Europe, a lack of knowledge of the ecological status and function of transitional waters is hindering the setting of standard baselines with consequences for the implementation of the Water Framework Directive (European Commission, 2012b). In both cases, it is relevant to ensure that management is based on a better understanding of the main risks and pressures on these systems (Elliotta and McLusky, 2002; Millennium Ecosystem Assessment, 2005; European Commission, 2012b). At best of our knowledge, such an integrated model is still lacking within the literature. Therefore, it is fundamental to discuss metal fate and consequences for their toxicity in a holistic and systematic manner.

The aim of this work is to propose a conceptual model for the distribution, environmental fate, and toxicity of metals in estuaries, including environmental dynamics, metal chemistry and organism physiology. In a first step, the estuarine features important for the environmental dynamics of metal fate are described (Section 3). Secondly, the main biogeochemical processes by which these features affect metal transport, distribution and partitioning concentrations in the different estuarine sub-compartments are introduced (Sections 4, 5 and 6). Finally, the organism physiology and metal toxicity under estuarine conditions are discussed (Section 7), enabling a unique transdisciplinary overview of the threats of these chemical elements in estuarine environments.