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Interplay between flow and bioturbation enhances metal efflux from low-permeability sediments

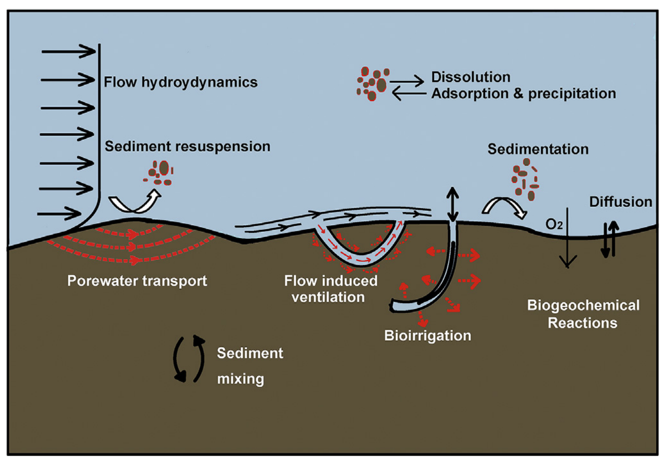
Minwei Xie[a,b,*], Ning Wang[a,c], Jean-François Gaillard[a], Aaron I. Packman[a]

[a] Department of Civil and Environmental Engineering, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208-3109, USA
[b] Marine Envrionmental Laboratory, HKUST Shenzhen Research Institute, Shenzhen 518000, China
[c] Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, Chengdu, Sichuan, 610031, China

HIGHLIGHTS

- Hydrodynamic force enhances efflux of dissolved Cu from low-permeability sediments.
- Interplay between flow and bioturbation further increases efflux of dissolved Cu.
- Bioturbation produces substantial physical and chemical heterogeneity in sediments.
- Bioturbation destabilizes sediments and facilitates sediment resuspension.

GRAPHICAL ABSTRACT



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ABSTRACT

Understanding the interplay effects between processes such as hydrodynamic forcing, sediment resuspension, and bioturbation is key to assessment of contaminated sediments. In the current study, effects of hydrodynamic forcing, sediment resuspension, and bioturbation by the marine polychaete *Nereis virens* were evaluated both independently and together in a six-month flume experiment. The results show that hydrodynamic forcing without resuspension or worm action slightly enhanced efflux of dissolved Cu to the water column, sediment resuspension released considerable amounts of dissolved Cu, and interactions between hydrodynamics and worm burrowing further enhanced Cu efflux. In non-bioturbated sediments, fine particles were only resuspended to the overlying water under the highest imposed shear stress, 0.58 Pa. However, bioturbated sediments were resuspended under all shear stresses tested (0.11–0.58 Pa), indicating that bioturbation destabilized the sediment bed. Further, increases in fluid shear following bioturbation caused rapid releases of dissolved Cu to the overlying water within a few hours. Cu efflux under fluid shears of 0.47 Pa and 0.58 Pa were 360× and 15× greater after the introduction of worms compared with the same flow conditions without their presence. Overall, our results

* Corresponding author at: Marine Environmental Laboratory, Shenzhen Research Institute, Hong Kong University of Science and Technology, Shenzhen 518000, China.
E-mail addresses: minwei.xie@gmail.com, minwei.xie@qq.com (M. Xie).

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indicate that the release of metals from low-permeability sediments is greatly enhanced by interactions between flow and bioturbation.

1. Introduction

Metal contaminants in water bodies can accumulate and reside in sediments for a very long time. These metals are not permanently sequestered, but instead are dynamically partitioned between sediment particles, porewaters, and the overlying water column [1]. The fate of metals in sedimentary environments is regulated by a wide range of physical, chemical and biological processes [2]. Since the early 1980s, when environmental problems caused by contaminated sediments were widely recognized, considerable efforts have been made to remediate contaminated sites [3]. A comprehensive assessment of site contamination status and associated environmental risks is generally needed before remedial decisions are made. Development of a site-specific conceptual site model (CSM) is the first step to understand the fate and transport of contaminants while identifying the governing processes that control the mobility and bioavailability of contaminants is critical in constructing a CSM [3–5].

It is now recognized that sediments represent a highly complex system and that the fate of contaminants is highly dependent on an interrelated suite of sedimentary processes. Biogeochemical processes involving a series of electron acceptors (O_2, NO_3^-, MnO_x, $Fe\text{-}O(OH)_x$, SO_4^{2-}, *etc.*) redistribute metals between sediment particles and porewaters [6,7]. In low-permeability sediments ($k < 10^{-12}\,m^2$), porewater transport is dominated by slow diffusive processes, leading to stratified biogeochemical zonation within the sediments [8,9]. The diffusion of metals across the sediment water interface (SWI) has been considered as the predominant pathway for release of metal ions to the water column in such low permeability sediments [10]. Interfacial advective fluxes of solutes are also known to be important in permeable sediments [11,12]. However, the effects of hydrodynamic forcing on efflux of metals from low-permeability sediments are frequently neglected in site assessments [2,13]. In estuarine environments, natural processes such as tidal cycles and wind induced waves generate variable hydrodynamic forcing over sediment bed across the whole estuary, with reported bottom shear stresses ranged from 0.05 to 1 Pa [14,15]. In our previous work, we also observed that increasing flow shear and sediment resuspension both enhanced the efflux of Cu from low-permeability sediments [13]. Bioturbation, including particle reworking and burrow ventilation, further complicates the system by introducing significant physical, chemical and biological heterogeneities [16–20]. Sediment reworking activities, such as construction and maintenance of burrows, greatly increase the area of the SWI [21]. But this burrow surface area should not be considered simply as an extension of the sediment surface as it contains strong chemical gradients and shows high temporal variabilities [21,22]. Ventilation of oxygenated water into burrows modifies redox and pH distributions in porewater surrounding the burrows, and enhances metal fluxes in sediments [23–25]. Because burrow formation induces such a wide change in sediment properties, we define bioturbation here as all activities of macrofauna that alter sediment pore structure and enhance motion and fluid motion through the sediments.

While the effects of hydrodynamic forcing and bioturbation on the fate and mobilization of metals have been individually studied, the interactions between these two processes have not been evaluated in detail. Therefore, to improve understanding of how the interplay of hydrodynamic forcing and bioturbation controls the mobility and efflux of Cu in low-permeability sediments, we conducted a long-term flume study to evaluate the release of Cu to porewater and overlying water under a range of hydrodynamic conditions with and without bioturbating organisms.

2. Material and methods

2.1. Experimental materials

Metal-contaminated sediments were obtained from Portsmouth Naval Shipyard (PNS). PNS is located on an island at the mouth of the Piscataqua River, Portsmouth Harbor, which is a tidal estuary located at the boundary of Maine and New Hampshire [26]. The water in vicinity of PNS has a salinity of 30 ∼ 32‰. The site has a water depth of ∼6 m and is subject to strong tidal influences, with a tidal range of 3 m [26]. The coastal sediments also provide habitat for a variety of organisms, including benthic fauna communities such as crustaceans, polychaete worms (Fig. 1b), clams, *etc.* [26]. It has been reported that *Nereis virens* [27], a typical marine polychaete, is an important local benthic species in Portsmouth Harbor, with a density of 117 individuals/m^2 [28]. Offshore sediments at this site have received substantial contamination from onshore construction and submarine repair activities. The sediments composed primarily of silt- and sand-sized particles and had a very low permeability. Cu and Zn were identified as the primary metal contaminants (Table S2). Approximately 100 L of contaminated sediments were collected in August 2013, transported in sealed buckets, and stored at 4 °C until experiments were performed.

To evaluate the interplay effects between flow and bioturbation on metals efflux, *N. virens* was introduced to the sediments as a model bioturbating organism. *N. virens* is classified in the functional group of gallery diffusers based on its feeding type, life habit and mobility, and reworks sediments primarily by excavating burrows [9,29]. *N. virens* was collected by Aquatic Research Organisms Inc. (ARO, NH) from Damariscotta River, Boothbay Harbor, which is a tidal estuary located close to the Portsmouth Harbor (∼100 miles).

2.2. Flume setup and experimental procedures

Laboratory flumes have been widely used to study sediment transport and hyporheic exchange processes because they provide precise control of flow conditions [30,31]. The flume has a test section of 2.5 m long (x) × 0.2 m wide (y) × 1 m deep (z) (Fig. 1a). The sidewall of the flume is made of transparent acrylic, which allows direct visualization of the interior of the flume. An impermeable acrylic ramp was placed at the upstream end of the flume channel ($x = 0$ m) to ensure steady and uniform water flow over the sediment bed. A porous polyethylene sheet with 90–130 μm pores (Small Parts International) was emplaced vertically at the downstream end of the test section ($x = 2.5$ m) to retain the sediment bed without restricting porewater flow.

Before the experiments, the flume was cleaned with weakly acidified reverse osmosis (RO) purified water (pH = 2), run for 24 h, and then rinsed with purified RO water twice. 50 L of homogenized sediments were emplaced into the flume to form a 10-cm deep sed-