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Fluctuations in Cd release from surface-deposited sediment in a river-connected lake following dredging

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ABSTRACT

Lakes connected to rivers have highly fluctuating hydrological conditions and therefore processes involving the retention and release of heavy metals are complex. Jinshan Lake is a typical river-connected lake in China, was selected to estimate Cd distribution in the surface-deposited sediment after dredging. Sediment samples with low, medium and high Cd contents were collected for annular flume experiments. The shear stress-induced Cd releases from these sediments were explored and incorporated into a numerical model using the finite volume method (FVM). The process of Cd release was studied for different temporal scales by numerical simulation. We observed that, because of the adequate water exchange between Jinshan Lake and the Yangtze River, the high-water year featured the largest annual release of Cd at 8777 kg, which was 2722 kg and 2033 kg higher than that of normal and low-water years, respectively. A balance between the upstream runoff and downstream tide resulted in the lowest Cd release in a normal-water year. The Cd release during a tidal cycle fell from 48 kg during the flood season to 11 kg during the dry period, whereas the variation coefficient increased from 0.59 to 0.67 during this period. Dredging project generally reduced the release of Cd from sediment in Jinshan Lake and this impact became more prominent in the presence of sufficient water exchange and strong bed shear stress.

1. Introduction

Cadmium is characterized by its strong bioaccumulation and persistent toxicity. One of the most serious consequences of accelerated industrialization and urbanization on freshwater quality is Cd pollution, and it has become a serious environmental and public health concern, especially in urban lakes and rivers (Alves et al., 2014; Islam et al., 2015; Suthar et al., 2009). The increased Cd load in the aquatic environment can be attributed to both exogenous input, such as industrial point sources and urban non-point sources (Ioannides et al., 2014; Kim et al., 2015; Wang et al., 2014a), and internal release from deposited sediment (Arora et al., 2015; Mutia et al., 2012; Wang et al., 2013; Wang et al., 2014b). In general, exogenous input is the major cause of Cd pollution, but in the case of strong flow disturbance, internal Cd release from sediment also plays a promoting role in Cd pollution. In fact, a series of factors such as the pH, dissolved oxygen, salinity and current velocity are involved in metal release processes from deposited sediment, but physical disturbance has been recognized as the dominant factor (Atkinson et al., 2007; Zheng et al., 2015; Guan et al., 2016). When the deposited sediment is intensely disturbed, sediment suspension will enable a strong interaction with the overlying water, which promotes the transfer of the deposited heavy metals into the dissolved or particulate form (Sun et al., 2015; Cheng et al., 2013).

Recently, a lot of research on Cd release from deposited sediments has been performed. For example, Paulson and Cox (2007) examined Cd release from the sediments in Lake Roosevelt (WA, USA), which displayed varying degrees of physical mixing and time scales and indicated the potential toxicity of aqueous Cd concentrations that were induced by the supernatants of aggressively tumbled slurries. Bi et al. (2011) used a particle entrainment simulator (PES) to study Cd release from sediment in the Yangtze River estuary and showed that the intensity of the physical disturbance was the dominant factor that influenced the variation in particulate Cd concentrations. Wang et al. (2012) used hydrodynamic flumes to investigate the mobility of Cd among sediment, pore water and overlying water at velocities of 4.01 cm/s, 12.7 cm/s and 20.23 cm/s, and they found that the increased flow velocity could promote Cd release; the suspended sediment evidently contributed to Cd in the overlying water. These results have shed light into the sediment Cd release mechanisms, but most of them were

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focused on establishing the relations between the release intensity and flow velocity or the flume rotation speed. Little attention has been paid to exploring the transport mechanism under varied shear stress (Wang et al., 2012; Huang et al., 2012).

Under field conditions, a key driver of the heavy metal release from lake sediment shall be the shear stress that acts on the sediment-water interface (Atkinson et al., 2007; Yu and Li, 2010), which is not only related to the water current but also to wind and wind-induced waves. Even with the same depth-averaged velocity, differences in the water depth will lead to different shear stresses and different metal release intensities, and therefore the shear stress should be better than the velocity for indicating the physical turbulence involved in heavy metal release. Moreover, current investigations on Cd release have mostly focused on isolated lakes or rivers, but rarely on river-connected lakes. Compared with an isolated lake, lakes opening to nearby large rivers are always characterized by more complicated environmental characteristics because of their frequent water and material exchanges with the external river, such as high frequency flow, large range of water level fluctuation, low water residence time and abundance of suspended sediment. Dongting Lake, Poyang Lake, Chao Lake, and Jinshan Lake, which are located in the middle-lower reaches of the Yangtze River, are some typical examples. As a result of water exchange with external rivers, the hydrodynamic conditions of these lakes change frequently, and the metal release processes are more complicated.

In the present work, Jinshan Lake, which is a typical river-connected lake located in the middle-lower reaches of the Yangtze River in the north of Zhenjiang city, China, was selected as the study area. The water level, volume and flow currents in Jinshan Lake fluctuate frequently with changes in hydrological conditions in the Yangtze River, which in turn leads to variations in sediment Cd release into the lake. The Cd distribution in the surface-deposited sediment after dredging was estimated using field investigation and sediment samples with low, medium and high Cd contents; these samples were collected for laboratory study. Shear stress-induced Cd release mechanisms from deposited sediments were explored by annular flume experiment, which was then incorporated into the numerical metal transportation model that was established in the FVM framework and validated against the field data. Because the external Yangtze River is affected by the downstream estuary tide, high and low tides occur twice a day in Jinshan Lake and cause the Cd release to fluctuate frequently. We selected three typical years to represent high, normal, and low-water years and two typical tidal cycles during the dry and flood seasons to reveal the release characteristics quantitatively under different temporal scales. The impact of dredging on Cd release was also estimated. This study places particular emphasis on the metal release mechanisms under varied bed shear stresses. It provides valuable insight into heavy metal transportation mechanisms under complicated disturbances and provide references for policy makers who try to prevent heavy metal pollution in the research area.

2. Methods and materials

2.1. Study area

Jinshan Lake is located in the middle-lower reach of the Yangtze River in the north of Zhenjiang city, Jiangsu Province, China. It is 4 km in length and 2 km in width, and connected to the Yangtze River by the Leading Channel (which is 3000 m long and 300 m wide) and the Jiaonan Gate (300 m wide) (Fig. 1). This lake is influenced by the irregular semidiurnal tides, with high and low tides occurring twice a day. The average rising tides and ebb tides last for 3.42 h and 9 h, respectively. The low tides usually occur at 6:00 and 18:00, with the high tides occurring at 21:00 and 9:00. The mean water levels during the flood and dry seasons are 3.87 m and 1.97 m, respectively, whereas the tidal gap was higher during the dry season than that during flood season, with the mean values of 1.55 m and 1.16 m, respectively. The surface area and regulation storage of the lake fluctuate frequently owing to the tidal impacts, the averages of which are 6.8 km^2 and 1.6×10^7 m^3, respectively.

The combination of upstream runoff and downstream tide results in an uneven water volume exchange between Jinshan Lake and the Yangtze River. After water with high sediment content enters the lake, the expansion in the flow section leads to a reduced sediment carrying capacity of the current and promotes obvious suspended sediment deposition. The annual deposited sediment in Jinshan Lake is approximately 5.15×10^5 tons, and it contributes to a rising lake bottom elevation. Jinshan Lake was adversely influenced by industrialization and urbanization in the late 20th century because of its location in the urban area. A large amount of industrial effluents, together with domestic sewage and non-point sources, enter Jinshan Lake *via* some city rivers, which helps increase the heavy metal concentration of the lake. These inputs directly led to a-higher metal load in the overlying water. In addition, part of is attached onto the sediment, which might be released and cause secondary contamination and hazards to the overlying water under certain conditions. From September 15th, 2009 to July 30th, 2010, the local government launched a dredging project to remove 9.144×10^6 m^3 of sediment. This project was an effort to enlarge the lake surface and storage and improve its water quality. A great deal of highly polluted surface sediments were dredged out of the lake, but, in view of the persistence and accumulation of heavy metals, the actual influence of this dredging on the lake has not been analyzed. For example, there are questions pertaining whether the release of heavy metals from the remaining sediment post-dredging is lower than it was prior to dredging. There are also questions about the potential ecological risk level of the heavy metals in the lake. Therefore, it is important to perform a quantitative evaluation on the sediment metal release that occurs during the post-dredging period.

2.2. Field investigation

A field investigation was conducted in Jinshan Lake on June 18, 2014 to study the Cd distribution in the sediment after dredging. To find representative investigated sites, Jinshan Lake was divided into five zones according to the water depth, that is, Area I: Leading Channel, Area II: Mainstream, Area III: North Bottomland, Area IV: South Bottomland, and Area V: Jiaonan Gate. Ten sites were set up along the lake according to the environmental geographic characteristics (Fig. 2). At each site, a 50-cm vertical sediment sample was collected by Columnar Sampler, and the top 10-cm surface sediment was taken for tests. According to the requirements in the "Environmental Monitoring and Analysis Method" by the Ministry of Environmental Protection of the People's Republic of China, the samples were kept at a low temperature (4 °C) after impurities such as plant residues and miscellaneous stone blocks were removed. After being dried, the samples were ground into tiny pieces and passed through the sieve of −0.149 mm aperture. They were kept in sealed polyethylene bags for determination. Sediment samples (0.2 g) were placed in MARS-X microwave digestion vessels, and concentrated acids (3 mL HF, 2 mL HCL and 5 mL HNO_3) were added to each sample. The contents of the sealed vessels were then digested by microwave for 50 min. After digestion and cooling, the solutions were placed in Teflon crucibles, evaporated with 0.5 mL $HClO_4$ to near dryness and then diluted to 25 mL with 5% HNO_3. After pretreatment, the digestion solutions were measured by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The instrumental detection limit of the heavy metal in this work was Cd > 0.005 μg/L. For quality control, all the sampling equipment was rinsed with ultrapure water and all the reagents were of analytical grade, except the nitric acid (guaranteed grade). To ensure the precision of the analytical work, the samples were analyzed in three duplicates over the whole process. At each site, the overlying water samples were also collected to obtain the concentrations of suspended sediment (SS), dissolved Cd and particulate Cd. The SS concentration was determined by Gravimetric Method. Vacuum