Release flux of heavy metals from river sediments at different flow rates

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ABSTRACT

This paper simulates sediment motion under different hydrodynamic conditions, aiming to investigate the release flux of heavy metals in river sediments. During the lab experiments, carried out in a circular rectangular flume device, water velocity in the flume was altered by controlling the gate switch, and the flow rate was controlled from 0 to 1 m/s. Sediment from the Le'an River and chlorine-removed tap water were used as experimental sediment and water, respectively. Through analyses of Cu, Zn, Cd, and Pb concentration in water at different flow rates, the relationship between the release flux (y) of Cu, Zn, Cd, and Pb and the flow rate (x) was established with a fitting error of less than 15%. In order to judge the reliability of the conclusions, experimental results were verified outdoors. The results showed when the sediment particle size is between 0 and 250 μm, within 1 hour, a quadratic polynomial correlation between the release flux of Cu, Cd, and Pb from river sediments and water velocity when the water pH is 5–9 and the flow rate is 0–65 cm/s; when the water pH is 5–9, the flow rate is 0–35 cm/s, the release flux of Zn from river sediments was shown to have a quadratic polynomial relationship with water velocity. The error between the calculated and measured values of heavy metals released from sediment in the Le'an River were within 5–30%. Our results can provide a theoretical reference for the control and treatment of heavy metal pollution in rivers and further improve corresponding water quality models.

Key words: flow rate, heavy metals, Le'an River, release flux, sediment

HIGHLIGHTS

• The heavy metal release flux from sediments in river follows a quadratic polynomial relationship with the flow rate.
• The release of heavy metals in the river sediments at different flow rates within 1 h is greater than the adsorption.
• Flow rate and water pH are two important factors affecting the release of heavy metals from sediments.
1. INTRODUCTION

Sediments, which are sources and sinks of pollutants, absorb large amounts of nutrient salts and heavy metals (Zhu et al. 2017). The heavy metal content of sediments generally reflects the level of heavy metal pollution in water. Changes in environmental conditions trigger the release of heavy metals, which will directly or indirectly influence the water quality through biological enrichment (Byrne et al. 2012). Some scholars study the release of heavy metals in constructed wetlands with zeolites as fillers, and found that the upper layer (0–30 cm) of the vertical flow constructed wetlands (VFCWs) was the most effective area for heavy metal removal, showed that significant amounts of Zn and Cu were released from the VFCWs while Pb and Cr rarely escaped, and Zn and Cu existed mainly in the exchangeable state (Zhou et al. 2019). Some scholars study the potential impact of indigenous bacterial processes on the release of heavy metals from sediment. It was found that drastic increases in metal (Zn, Cd) release were observed under acidic conditions (Lors et al. 2004). Several factors affect the release of heavy metals from sediments; for example, the rise of P (Phosphorus) content in the overlying water will inhibit the release of heavy metals from sediments (Chen et al. 2017; Liu et al. 2019). Moreover, high salinity and high nitrogen levels can enhance the bioavailability of heavy metals in sediments (Hong et al. 2011), or the activity of heavy metals in sediments is relatively high in anoxic environments (Acosta et al. 2011). Heavy metal release is also affected by sediment redox potential, sulfide and calcium content (Martin-Torre et al. 2015; Zhou et al. 2020), or the inherent characteristics of the sediment (Xu et al. 2015; Huang et al. 2017).

The actions of wind and waves cause an intense exchange of substances between sediments and water bodies (Zhu et al. 2013), and the impact on heavy metal release from sediments cannot be ignored (Wang et al. 2020). The released amount is related to the resuspension and deposition of sediments (Argese et al. 1997). Wind and waves can effectively activate the sediment layer and lead to the adsorption and release of heavy metals in the sediments (Huang et al. 2016; Tang et al. 2020), thereby resulting in the continuous exchange of heavy metals in the sediments at the water-soil interface (Zhu et al. 2017). Many studies have targeted the release of heavy metals from sediments under different hydrodynamic conditions. However, most of them are focused on factors affecting the release of heavy metals from sediments, the different forms and levels of heavy metals in water after release, or the exploration of the migration and transformation rules of the different forms of heavy metals (Zheng et al. 2013; Lu et al. 2019). Few reports exist on the quantitative analysis of heavy metal release from sediments at different flow rates (Wen et al. 2021; Yan et al. 2021), and even fewer studies have been conducted on heavy metal release from river sediments (Liu et al. 2018a; Cai et al. 2021).
The Le'an River is the secondary tributary of Poyang Lake, the largest freshwater lake in China, and the primary tributary of the Raohe River (Liang et al. 2020). The geographical location of Le'an River is shown in Figure 1. The total length of the river is 280 km with a drainage basin of 8,521 km². Studies have shown that the Le'an River is the main source of heavy metals in Poyang Lake (He et al. 1998; Niu et al. 2017; Zhang et al. 2018). The largest open-pit copper mine in Asia (Dexing copper mine) is located near the Dawu River, a tributary of the Le'an River, with serious levels of heavy metal pollution (especially heavy metals such as Cu and Zn, followed by Cd and Pb) (Tao et al. 2014). The total length of the Dawu River is 14.3 km. A large amount of acidic and alkaline wastewater from the Dexing Copper Mine is discharged annually into the Dawu River (He et al. 1998), which carries it into the Le'an River. This results in serious water pollution and the river is becoming almost a wastewater ditch. The acidic wastewater released from the mine has a pH of 2.5–3.5, and the pH of the alkaline wastewater is about 10.5 (Jiang et al. 2018). The acidic space between the ‘ditch’ is about 2–3.5 and the alkaline space between the ‘ditch’ is about 10–11 (Zhang et al. 2018).

This article simulates the sediment movement dynamics by an indoor sink device and analyzes heavy metal levels in the overlying water at different velocities. Through the laws of mass conservation, we also explored the dynamics of heavy metal release from river sediments at different flow rates. A field test was also conducted to verify the findings of indoor experiments and draw conclusions for the Le'an River in order to provide theoretical reference for further studies on the mechanisms of the internal release of heavy metals from sediment in natural bodies of flowing water.

2. TEST MATERIALS AND METHODS

2.1. Indoor test device

The water tank device (produced by Hohai University, China) is shown in Figure 1. It consists of a water tank (4 m³ volume), water pump, flow meter, water level meter and rectangular glass flume (3.8 m × 0.8 m × 1 m). The pump has a maximum flow rate of 100 m³/h. The gate valve is mainly used to control the flow, and the flow meter is installed behind the pump. In the test, the cascade tailgate and pump gate of the flume outlet are adjusted to ensure a stable water level and flow rate in the flume.

We use chlorine-removed tap water as testing water; 10 cm deep sediment columns from the lower reaches of the Le'an River are collected by a column sediment sampler as the test sediments. The collected sediments are laid on the bottom of a sink, lightly flattened and size-controlled to retain 10 cm thickness. After the samples were left to stand for 24 h, the water tank was filled with water and the device started. The water depth was controlled at 80 cm, and the water was set still for 24 h. The water velocity of the Le'an River is between 0 and 1 m/s all year round (Chen et al. 2016), and therefore we set the flow rate to 0, 5, 15, 25, 35, 45, 65, 85 and 100 cm/s by controlling the gate. The velocity was gradually increased from 0 to the highest test value. Each flow rate setting was maintained for 1 h to ensure that water samples in the device were evenly mixed and all water flowed through the flume at least once.

2.2. Outdoor test

In order to enable the indoor test conclusion to be verified outdoors, members of the research team conducted a field test in March, April and May 2019, at the upper reaches of the Le'an River (V1), midstream (V5), downstream (V6), and 1 km,10 km, 20 km after the tributary of the Dawu River converges (V2, V3, V4). During the test period, all the six verification points (V1, V2, V3, V4, V5, and V6) experienced four different wind speed conditions: strong, moderate, light, and calm (without flow velocity). The specific locations of the verification points are shown in Figure 1. Water samples were collected at different stages of the test at water depths typical for the middle of the water body at the sampling site, with the velocity and depth of water recorded at the time of sampling. During the test, water depths corresponding to the six verification points (V1, V2, V3, V4, V5 and V6) were 1.56 m, 1.65 m, 1.79 m, 1.54 m, 2.13 m, and 0.96 m, respectively.

2.3. Sample collection and analysis

2.3.1. Sample collection

During the indoor test, 50 mL of middle water sample was collected from the middle of the tank every ten minutes at each flow rate. During the outdoor test, 500 ml of water samples were collected under different flow rates. All collected water samples were adjusted to pH < 2 by the addition of HNO₃ (Maoming Xiongda Chemical Co., Ltd, China) and stored at –20 °C in the refrigerator (NR-FC50VT, Panasonic, Japan).
2.3.2. Analysis items and methods

The Cu, Zn, Cd and Pb, as representative heavy metals in the Le'an River (Tao et al. 2014), were selected as research objects. The applied analytical methods and detection limits of each element are shown in Table 1 (China 2002 (fourth edition) (in Chinese); Yang et al. 2017; Liu et al. 2018b; Yan et al. 2019; Hu et al. 2020). The concentration measured in this test is the concentration of heavy metals in raw water. In order to reduce the error, each water sample was measured three times in parallel, and the average value was taken as the final result. The water quality in the lab and at each verification point of the Le'an River is shown in Table 2 (Tao et al. 2014; Jiang et al. 2018; Zhang et al. 2018). The sediment characteristics of Le'an River are presented in Table 3.

2.3.3. Calculation method

The present work intends to deduce the release of heavy metals from sediments from the concentration of heavy metals in water according to the law of conservation of mass. The calculation method is as follows (Yiping et al. 2004):

$$r = \{1,000V(C_n - C_0) + \sum_{j=1}^{n} 1,000V_i(C_{j-1} - C_n)\}/(A.t) \tag{1}$$

In the formula, $r$ denotes heavy metal release flux (mg/[m².d]); $V$ indicates the total volume of water used in the test (m³); $C_n$ is heavy metal concentration in water at the nth sampling (mg/L); $C_0$ indicates initial heavy metal concentration in water.

<table>
<thead>
<tr>
<th>Index</th>
<th>Analytical method</th>
<th>Detection limit (mg/L)</th>
<th>Demanded detection limit (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Extraction-flame atomic absorption spectrometry</td>
<td>0.0002</td>
<td>0.05</td>
</tr>
<tr>
<td>Zn</td>
<td>Extraction-flame atomic absorption spectroscopy</td>
<td>0.0005</td>
<td>0.05</td>
</tr>
<tr>
<td>Cd</td>
<td>Flameless atomic absorption spectroscopy</td>
<td>0.00001</td>
<td>0.05</td>
</tr>
<tr>
<td>Pb</td>
<td>Inductively coupled plasma atomic emission spectrometry</td>
<td>0.0002</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Vi is sample volume in every sampling (m³); Cj/C0 denotes heavy metal concentration in water during j – 1 sampling (mg/L); Cn is the heavy metal concentration after raw water addition; t indicates heavy metal release time (d); and A is the surface area of sediment in the flume (m²).

3. RESULTS AND ANALYSIS

3.1. Process of flume test and analysis

3.1.1. Flume test

According to the principles of sediment movement, sediments can be divided into three states: ready to move but still, slightly moving and generally moving (Guo-ren 1999). Heavy metal levels in water vary under different hydrodynamic conditions, and there are some changes in the adsorption and release of the materials in sediments. The characteristics of sediment movement in the flume test in this paper correspond with the sediment movement principles.

Up to a flow rate of about 25 cm/s, the sediment does not move. When the flow velocity of water increases from 0, the shear force on the silt surface gradually rises, and the soil-water interface transforms from the initial relative static state to a thin layer of dilute suspension on the mud surface. At this time, the silt is in a ‘ready to move but still’ state.

With a further increase in the flow rate, the shear force of the sludge continues to rise. The turbulent action of water flow gradually strengthens, and some small pieces of silt in the flume are washed up and suspended on the mud surface. At this stage, also called the ‘slightly moving’ state, the water body becomes turbid and the corresponding water velocity is between 25 and 50 cm/s.

When the flow rate increases to about 60–70 cm/s, the turbulent action of water gets more intense, the bottom silt is lifted in pieces, and water becomes turbid in a short time, especially when a certain part of the silt is lifted; the remaining sludge in this area will move rapidly. The stage is called the ‘generally moving’ state.

Once the flow velocity exceeds 70 cm/s, the state of water flow movement is similar to ‘generally moving’, and a large amount of sediment suspended in water is observed at this time.

3.1.2. Changes in the concentration of heavy metals after maintaining different flow rates for one hour

After maintaining each flow rate for one hour, the changes in heavy metal levels at different flow rates in the experimental sink are shown in Figure 2. As seen in the figure, with the flow rate rising from 0 to 65 cm/s, the concentration of Cu, Pb and Cd in water gradually increase, and their levels show little change when the flow rate continues to increase further. When the flow rate is less than 25 cm/s, the concentration of each heavy metal elevates slightly, which is attributed to the fact that the sediment has not yet been suspended in large quantities and is only slightly disturbed. Only heavy metals in interstitial water are released at this time. As the flow rate continues to rise, the sediment changes from ‘ready to move but still’ to ‘slightly moving’, and the concentration of each substance elevates significantly. This is because heavy metals adsorbed between

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Table 2 | The water quality of lab water and each verification point of Le’an River

<table>
<thead>
<tr>
<th>Index</th>
<th>Lab water</th>
<th>V1</th>
<th>V2</th>
<th>V3</th>
<th>V4</th>
<th>V5</th>
<th>V6</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.5–7.5</td>
<td>6–8</td>
<td>2.5–4</td>
<td>3–5</td>
<td>5–7</td>
<td>5–9</td>
<td>6–9</td>
</tr>
<tr>
<td>Zn (μg/L)</td>
<td>2.57</td>
<td>16–24</td>
<td>68–78</td>
<td>58–62</td>
<td>40–46</td>
<td>33–41</td>
<td>24–30</td>
</tr>
<tr>
<td>Cd (μg/L)</td>
<td>0.11</td>
<td>0.67–1.3</td>
<td>1.74–1.88</td>
<td>1.52–1.82</td>
<td>1.21–1.38</td>
<td>0.82–1.05</td>
<td>1–1.15</td>
</tr>
<tr>
<td>Pb (μg/L)</td>
<td>1.86</td>
<td>0.7–1.8</td>
<td>10.1–10.6</td>
<td>8.9–10.6</td>
<td>6.5–8.2</td>
<td>4.3–5.5</td>
<td>1.5–3</td>
</tr>
</tbody>
</table>

Table 3 | Basic parameters of sediment in the Le’an River

<table>
<thead>
<tr>
<th>Index</th>
<th>Heavy metals content/(mg.kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cu</td>
</tr>
<tr>
<td>Le’an River</td>
<td>10.12–764.3</td>
</tr>
</tbody>
</table>

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the sludge particles are gradually suspended into the overlying water as silt on the surface of the sediment is washed up. Also, heavy metals in the interstitial water are released in large quantities at the same time. When the flow rate reaches 60–70 cm/s, the bottom sludge is lifted in pieces and reaches the ‘generally moving’ state, with the concentration of each substance increased to the maximum of its range. At a flow rate of 65 cm/s, the concentrations of Cu, Cd and Pb in water are observed as 195.29 μg/L, 0.3 μg/L, and 6.96 μg/L, respectively, which are 24.85, 2.54, and 3.5 times, respectively, of those in stagnant water. The experiments conducted in this study demonstrate that the characteristics of silt motion observed at 65 cm/s change little with the continued increase of flow rate, and thereby the level of each substance tends to stabilize.

Interestingly, the dynamics of Zn concentration change are not consistent with that of the other three heavy metals. As the flow rate rises from 0 to 35 cm/s, the level of Zn in water gradually increases, but this trend reverses when the flow rate continues to increase to 65 cm/s; we tested different forms of Zn in the water and found that the decrease is primarily caused by the reduced amount of dissolved Zn. The further increase of flow rate does not have a significant effect on Zn concentration.

3.1.3. Changes in the concentration of heavy metals with time at different flow rates
Changes in the concentration of heavy metals with time at different flow rates are shown in Figure 3. The results show that when the flow rate is 65 cm/s, within 1 h, the concentration of Zn in water gradually decreases with time. In other cases, the concentration of heavy metals in water gradually increased with time. Further linear fitting showed that the fitting effect was good, and the R² of the fitting straight line were all above 0.95.

3.1.4. Relationship between release flux and flow rate
The release flux of each substance is calculated according to Formula (1). Results show that a rising flow rate results in an increasingly greater release flux rate of Cu, Zn, Cd, and Pb from sediment. At a flow rate of 35 cm/s, the release flux of Zn is 17.1 times that in stagnant water. When the flow rate is 65 cm/s, the release flux of Cu, Cd and Pb are 136.9, 14.6, and 14.8 times, respectively, those in stagnant water (Table 4). Among these heavy metals, the release flux of Cu shows the most significant hike, which is attributed to the lower background concentration of Cu in the water used in the experiment (Table 2), and the higher Cu pollution level in sediments (Table 3).

According to the relationship established between the released flux and flow velocity above, quadratic fitting was performed, with results shown in Figure 4. It is concluded that, within a specific flow rate range, the release fluxes of the four heavy metals in sediment all rise with increased flow rate (The flow rate range corresponding to the release flux of Cu, Cd, and Pb is 0–65 cm/s, and the flow rate range corresponding to the release flux of Zn is 0–35 cm/s). When the hydrodynamic strength declines, the suspended sediment sinks again, and will not continue to float or complete the release of heavy metals until the next hydrodynamic strength surge occurs.
3.2. Results of outdoor test

A comparison of the measured and calculated values of heavy metal release flux from sediments within a period of 0.5 h at different water flow rates is shown in Figure 4 (the corresponding flow velocities at each verification point in the outdoor test are selected according to the characteristics of sediment movement. The velocities at each point are 0–25, 25–50, 60–70 cm/s.). In order to determine the heavy metal content in water within this period, calculated values are based on the fitting formula, and the measured values (actual value) are calculated from experimental data, not from fitting formulae.

**Table 4 | Content and release rate of heavy metals at different water flow rates**

<table>
<thead>
<tr>
<th>Index</th>
<th>Flow velocity (cm/s)</th>
<th>Concentration (μg/L)</th>
<th>Ratio</th>
<th>Release flux (mg/(m².d))</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>0</td>
<td>7.86</td>
<td>21.37</td>
<td>13.75</td>
<td>136.9</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>195.26</td>
<td></td>
<td>1,878.08</td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td>0</td>
<td>0.12</td>
<td>2.76</td>
<td>0.13</td>
<td>14.6</td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>0.5</td>
<td></td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>0</td>
<td>1.99</td>
<td>3.82</td>
<td>3.25</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>6.96</td>
<td></td>
<td>48.5</td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>0</td>
<td>2.78</td>
<td>1.93</td>
<td>5.25</td>
<td>17.1</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>8.89</td>
<td></td>
<td>89.75</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3 | Changes in the concentration of heavy metals with time at different flow rates.**

**Figure 4 |**
According to Figure 5, the error between the calculated value and the measured value of each verification point (except V2 and V3) is less than 30%, which indicates that the relationship between the release flux and the flow rate of each heavy metal, as determined in our indoor experiments, can be considered essentially adequate for the prediction of actual heavy metal flux events.

4. DISCUSSION

The absorption and release of heavy metals in the water-sediment interface depend on multiple factors, and there is a close relationship between the absorption and release (Huang et al. 2015). The factors affecting the absorption of heavy metals by sediments include temperature, pH, dissolved oxygen, hydrodynamic conditions, ion concentration, content of organic matter, etc. (Wen & Allen 1999; Soltan et al. 2001; Li et al. 2009). Among them, pH and ion concentration have a greater impact on the absorption capacity (Soltan et al. 2001; He et al. 2009). However, the absorption kinetics of sediments generally reach absorption equilibrium within one or two hours (He et al. 2015). This paper did not carry out a test on the absorption effect of heavy metals in sediments under different flow rates, because the release amount discussed in this paper is the amount released under the combined action of absorption-release. It also shows that the total amount of heavy metals released from sediment under different flow rates is larger than that of absorption in 1 hour.

In this experiment, each hydrodynamic condition was only maintained for one hour. In the field verification experiment, the content of heavy metal in water was measured for only 0.5 hour. In a natural state, there is a dynamic absorption-release equilibrium at the water-sediment interface, and it is reported that it takes at least two days to reach equilibrium under hydrodynamic conditions (He et al. 2015). However, we did not test the time to reach equilibrium in our experiment settings. As heavy metals in water include dissolved state and suspended state (Coyneel et al. 2007; Yu et al. 2019), studies have shown that
Cu, Zn, and Pb are primarily released in dissolved state and Cd is released in suspended state under hydrodynamic conditions (Argese et al. 1997). In this paper, since we measured the total heavy metal concentration in raw water, the migration and transformation characteristics of different forms of heavy metals in water were not analyzed. Therefore, our next step was to study the time required to reach release equilibrium and the morphology migration and transformation of heavy metals.

In general, the release flux of heavy metals from river sediments is closely related to flow turbulence (Zhu et al. 2014), flow turbulence affects the movement of pollutants in the vertical direction (Cheng et al. 2020). In the laboratory test, we collected the surface, middle, and bottom water for detection, the results showing that the concentration of heavy metals in water is different in the vertical direction, the concentration of heavy metals in the bottom water is slightly higher, followed by the middle layer, and the lowest in the surface layer, but the difference is not significant; further analysis showed that the concentration of heavy metals in the middle water was roughly the average of the concentration of heavy metals in the surface and bottom layers. Some scholars take Taihu Lake as the research object (the water depth is 4.8 m), found that the concentration of heavy metals in the vertical direction changes exponentially (Zheng et al. 2013). The reason for the difference may be that both the laboratory test water depth and the outdoor test water depth of this research are relatively shallow (0.7 m and 2.1 m, respectively), and the heavy metals in water are quickly mixed completely in the vertical direction. Therefore, both the laboratory and outdoor experiments of this research collect intermediate water bodies for testing.

According to formula 1, the release flux is proportional to the increased concentration of heavy metals before and after the test (The impact of the small amount of water collected during testing is almost negligible). Figure 3 shows that the concentration of heavy metals in water at different flow rates within 1 hour increases linearly with time (When the flow rate is 65 cm/s, the concentration of Zn in water is excluded), this is consistent with the conclusions of Kyung-Yup Hwang.
(Hwang et al. 2011). We did not analyze the concentration of heavy metals in water after 1 h, because the variation concentration of heavy metals in water after 1 h at different flow rates fluctuates greatly, and $R^2$ is small after linear fitting, indicating that the conclusion of the release flux of heavy metals in this paper is applicable within 1 h.

At present, similar tank experiments in academia are dominated by annular tanks (Huang et al. 2012a, 2012b; Mahdavi et al. 2013; Zheng et al. 2013; Sun et al. 2015; Xu et al. 2015), and pollutant release flux is calculated mainly by calculating the shear stress of the soil and water interface (Wang et al. 2011, 2016). In this paper, a rectangular flume was selected for the experiment, most scholars perform an annular flume simulation of lakes or reservoirs. While the research object in this paper is a river, the hydraulic characteristics of the rectangular flume are closer to reality, and the use of flow velocity to characterize the release flux in this paper is easier to understand and measure. In general, the indoor test should have a similar hydrodynamic condition to the outdoor test. In this paper, the outdoor test mainly affects the water velocity through the wind speed, while it is difficult to simulate different wind speed indoors, so different flow rates are directly set to achieve the purpose of the test. Wind speed determines the degree of wind impact, not only affecting horizontal pollutants transport, but also regulating vertical dynamics (Wang et al. 2020). However, the results of the indoor test in this paper are less error when applied to the outdoor test. We analyzes that this is because the outdoor verification test select the river as research object and the water depth is relatively shallow, so the influence brought by turbulence is less than the flow velocity when the river water depth of is less than 2.1 m (The water depth of the six points in the field verification test in this paper is almost all less than 2.1 m.). Therefore, for the deep water reservoirs and lakes with obvious turbulence phenomenon, the applicability of this conclusion remains to be further studied.

In this paper, indoor rectangular flume experiments were carried out to reveal the dynamics of heavy metal release from river sediments under different flow rates. The relationship between heavy metal release flux and water velocity proved quadratic polynomial, indicating that the flow rates play an essential role in the circulation of heavy metals in rivers. It also shows that attempting to reduce heavy metal pollution in a river, the internal release of heavy metals from sediments should also be controlled in addition to addressing external pollution. These findings are similar to the conclusions of Reddy (Reddy et al. 1996) on Lake Apopka or those of Sondergaard (Sondergaard et al. 1992) on Lake Arreso. In our experiment, when the flow rate increases in the range of 35–65 cm/s, the concentration of Zn in water decreases. We speculate that certain hydrodynamic conditions (such as at different flow velocities (Huang et al. 2015) and wind speeds (Yuan et al. 2020)) can promote the adsorption of dissolved Zn by the sediment. Apart from the quadratic fitting error of 15% for Cu, the fitting errors of the release fluxes of the other three elements are less than 10%. However, as we verified the above patterns in outdoor tests, it was found that the heavy metal release fluxes of two points (V2 and V3) do not meet those patterns, and the errors between the measured and theoretical values at the other four verification points are within 30%. We assume that the mismatch at V2 and V3 is due to the large fluctuation of water quality and strong acidity (Table 2). It indicates that pH (2.5–5, Table 2) has a significant influence on the release of heavy metals from sediments, which is consistent with previous research conclusions (Atkinson et al. 2007; Wen et al. 2021). The verification errors for both points V1 and V6 are within 20%. This is because the pollution levels of heavy metals at these two points are low, especially at point V1. V1 is near the source of the Le’an River and it is not polluted by any heavy metals. The verification error at point V4 is within 30%, as this point is in the buffer zone after where the wastewater is discharged from the Dexing Copper Mine into the Le’an River. Since the impact of water pH remains at this point, the conclusions of this article are applicable only when the pH is between 5 and 9. The accuracy of the outdoor verification of the equation, however, is not as high as that of the indoor test (the water used for indoor testing was chlorine-removed tap water), indicating that there are further factors affecting the release of heavy metals from sediment.

We could not determine the acceptable margin of error; however, we can refer to the overview of the water quality model that currently considers simulation results acceptable within a 30% margin of error from the water quality model (Li et al. 2011; Wu et al. 2019; Chen et al. 2020). Though we can identify various factors (such as pH, dissolved oxygen (Atkinson et al. 2007), temperature (Huang et al. 2017), the inherent characteristics of the sediment (Xu et al. 2015), high salinity and high nitrogen levels (Hong et al. 2011), the content of P in the overlying water (Chen et al. 2017), sediment redox potential (Martin-Torre et al. 2015), sulfide and calcium content (Zhou et al. 2020)) that affect the heavy metal release from sediments, many issues are yet to be studied: the extent that each factor (especially hydrodynamic conditions and pH) influences heavy metal release from sediments, the release characteristics of dissolved and suspended heavy metals in sediments under different hydrodynamic conditions, the release time to reach a relative equilibrium, the total amount of heavy metals released from sediments under different environmental conditions. Here we analyzed the particle size of sediments in the Le’an River particularly (0–250 μm), since particle size also has a certain impact on nutrient release from sediments (Zhu
Since both indoor and outdoor test sediment samples are obtained from the Le’an River, the effect of sediment particle size on the results of this paper can be neglected. Whether the principles established herein are applicable to other flowing water bodies with different particle size needs further evaluation.

In this paper, the mechanism of heavy metal release from sediments under different fluid flow conditions is discussed and validated through a field test, thereby providing a theoretical reference for further understanding of the endogenous release mechanism of sediments.

5. CONCLUSIONS

In the present work, eight groups of hydrodynamic experiments with velocities ranging 0–1 m/s are set up in a rectangular flume to simulate the principle of river sediment movement dynamics under different flow rates, and the concentration of heavy metals in water is measured at different flow rates. The relationship between the release flux of heavy metals from sediments and the flow velocity are subsequently determined. Results demonstrated that: (1) when the sediment particle size is between 0 and 250 μm, the water depth is below 2.1 m, within 1 hour, the heavy metal release flux from sediments in river follows a quadratic polynomial relationship with the flow rate; (2) the release of heavy metals in the river sediments at different flow rates within 1 h is greater than the adsorption; (3) for rivers with a water depth of less than 2.1 m, the flow velocity has a greater impact on the release flux of heavy metals from sediments than flow turbulence; (4) flow rate and water pH are two important factors affecting the release of heavy metals from sediments; (5) within a certain flow rate and pH range, the error between the measured and calculated values of heavy metal concentrations in a field test on the Le’an River was within 30%, indicating that the relationship established by the present work between the release flux of heavy metals from sediment and the water velocity is basically adequate, and the experimental device can be operated in a feasible manner.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES


