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RESEARCH ARTICLE

Heavy metal characteristics in porewater profiles, their benthic fluxes, and toxicity in cascade reservoirs of the Lancang River, China

Zhenjie Zhao[1,2,3] · Shehong Li[2] · Shilu Wang[2] · Jie Liao[2,3] · Weiqi Lu[4] · Di Tan[2,3] · Dan Yang[2]

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Abstract

The construction of cascade reservoirs on the Lancang River (the upper Mekong) has an important influence on the distribution and accumulation of heavy metals. Heavy metal contents in porewater provide vital information about their bioavailability, studies on this aspect are rare until now. In this study, sediment cores were collected from four adjacent cascade reservoirs in the upper Mekong River to study the distribution, potential sources, diffusive fluxes and toxicity of heavy metals in porewater. The findings indicated that the average contents of Mn, Fe, As, Ni, Cu, Zn, Cd, and Pb in the sediment porewater were 6442, 644, 11.50, 2.62, 1.23, 3.95, 0.031, and 0.24 μg/L, respectively; these contents varied as the sediment depth increased. Correlation analysis and principal component analysis showed that Cu, Zn, Cd and Pb were mainly associated with anthropogenic sources, As, Mn and Fe were primarily affected by natural inputs, and Ni was affected by a combination of natural and anthropogenic effects. The diffusive fluxes of Mn, Fe, As, Ni, Cu, Zn, Cd, and Pb in the cascade reservoirs of the Lancang River were 919 – 35,022, 2.12 – 2881, 0.17 – 750, 0.71 – 7.70, 2.30 – 31.18, (-3.35) – 6.40, 0.06 – 0.54, and (-0.52) – 4.08 μg/(m^2 day), respectively. The results of toxic units suggested that the contamination and toxicity of heavy metals in porewater were not serious. Overall, in the cascade reservoirs, the content and toxicity of heavy metals in porewater of the upstream reservoirs were higher than that of the downstream reservoirs. The operation of the cascade reservoirs enabled greater accumulation of contaminants in sediments of the upstream reservoirs. This research gives strong support for the prevention of heavy metal contamination and the sustainability of water resources under the running condition of cascade reservoirs on such a large international river (the Lancang-Mekong River).

Keywords Heavy metals · Porewater · Diffusive fluxes · Cascade dams · Lancang River

Introduction

Heavy metal pollution is a serious threat to aquatic ecology and has become a worldwide concern due to its toxicity, non-biodegradability, and bio-accumulation (Xu et al., 2019; Zeng et al., 2020). Most of the heavy metals discharged into aquatic environment are adsorbed on suspended particulates and eventually deposit in the sediments (Palma et al., 2015). However, when physical or biochemical conditions change, these metals in sediments may be re-dissolved into the porewater from where they can enter the overlying water column through diffusion (Blasco et al., 2000; Sullivan and Taylor, 2003). This subsequent secondary pollution will result in water quality degradation and pose a serious threat to the ecosystem (Wang et al., 2016; Li et al., 2020).

Recently, researchers came to realized that the heavy metal properties of contaminated sediment cannot directly reflect the bioavailability and toxicity characteristics of

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✉ Shehong Li
lishehong@vip.gyig.ac.cn

[1] Key Laboratory of Environmental Pollution Monitoring and Disease Control, Ministry of Education, Guizhou Medical University, Guiyang 550025, China

[2] State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China

[3] University of Chinese Academy of Sciences, Beijing 100049, China

[4] Guizhou University of Finance and Economics, Guiyang 550081, China

sediment (Tang et al., 2015, 2016; Lei et al., 2016), whereas the biogeochemical processes and bioavailabilities of toxic metals at sediment–water interfaces were strongly influenced by metal distributions and mobilities in porewater (Zhu et al., 2016). Moreover, porewater composition may be the most sensitive indicator of the type and extent of the reaction between contaminated sediment and the aqueous phase that contacts it (Wu et al., 2016). Thus, metal concentrations in porewater have been showed to be an effective predictor of toxic effect (Tang et al., 2016; Cleveland et al., 2017).

On the main stream of the Lancang River (the upper Mekong River), a chain of six cascade hydroelectric dams had been constructed as of 2016 (Fan et al., 2015; Shi et al., 2020), and another 17 dams in the river will be completed over the next few decades (Chen et al., 2019). There is no doubt that the cascade dams on the Lancang River could trap a portion of sediment delivered downstream (Lu and Siew, 2006; Wang et al., 2012). Recent researches estimated that the trapping efficiency of the existed cascade dam reservoirs in the Lancang River might reach to 74–94% (Liu et al., 2015; Binh et al., 2020). Consequently, large amount of sediment has been stored in these dam reservoirs (Fan et al., 2015). In addition, the sediments retained in these reservoirs were finer and rich in clay minerals compared with the downstream sediments (Guo et al., 2020). Therefore, it provides great convenience for heavy metals to accumulate in these reservoirs. Several researches have reported heavy metal contamination in sediments of these reservoirs in the Lancang River (Wang et al., 2012; Zhao et al., 2013; Li et al., 2019). However, until now, few studies have focused on the fluxes of heavy metal released from sediments, and their concentration and toxicity in porewater in the cascade reservoirs. This information is necessary to understand the sources of heavy metals in reservoir water and their toxic risks to the environment and aquatic organisms.

Therefore, in this study, four cascade reservoirs in the Lancang River were selected to (1) investigate heavy metal distribution in porewater profiles, (2) distinguish their potential sources in porewater, (3) examine the diffusive fluxes of metals at the sediment–water interface (SWI), and (4) evaluate the toxicity of heavy metals in the interstitial water.

Materials and methods

Study area

The Lancang River is the upper reach of the Mekong River which is one of the world's famous international rivers. It is a large river in China with a length of 2153 km, ranking the 5th among all rivers in China. Originating from the northern foot of Tanggula Mountain in the south of Qinghai Province, the Lancang River flows through Tibet Plateau and Yunnan Province before flowing to foreign countries (Myanmar, Laos, Thailand, Cambodia and Vietnam) and becoming the Mekong River. The basin in China covers an area of 168,000 km^2 (Guan et al., 1984). The river head is 5244 m above sea level (Fan et al., 2015). With the large descending elevation (1780 m) in Yunnan Province, the Lancang River produces plentiful hydraulic resources there, which is conducive to hydropower cascade development (Liu et al., 2015; Chen et al., 2019). The studied four cascade reservoirs are located in the middle and lower reaches of the Lancang River, which are the Manwan (MW) Reservoir, Dachaoshan (DCS) Reservoir, Nuozhadu (NZD) Reservoir, and Jinghong (JH) Reservoir, respectively (Fig. 1). The detailed information about these reservoirs was displayed in Table S1.

Sampling and analytical methods

Sediment cores were collected using a 100 cm long gravity corer with 6 cm internal diameter in April 2017, and the sampling sites are displayed in Fig. 1. The overlying water was collected near the SWI with a syringe and a silicone tube. Then, cores were sliced at 1-cm interval in the field, stored in sealed sterile centrifuge tubes and kept refrigerated at 4 °C in dark during transport to the laboratory. To obtain porewater, sediments were centrifuged at a speed of 4000 r/min for 30 min (Bufflap and Allen, 1995; Cleveland et al., 2017). The overlying water and porewater were filtered through cellulose membranes (0.45 µm), acidified to 2% HNO_3, and stored at 4 °C until analysis.

The concentrations of Mn, Fe, As, Ni, Cu, Zn, Cd, and Pb were measured by inductively coupled plasma-mass spectrometry (ICP-MS, Agilent, 7700x, USA). Major cations were analyzed by inductively coupled plasma-optical emission spectroscopy (ICP-OES, iCAP6500, Thermo Scientific, Germany) (Zhao et al., 2020).

Diffusive fluxes

The diffusive fluxes of heavy metals across the SWI were estimated using Fick's first law (Eq. (1)) (Berner, 1984).

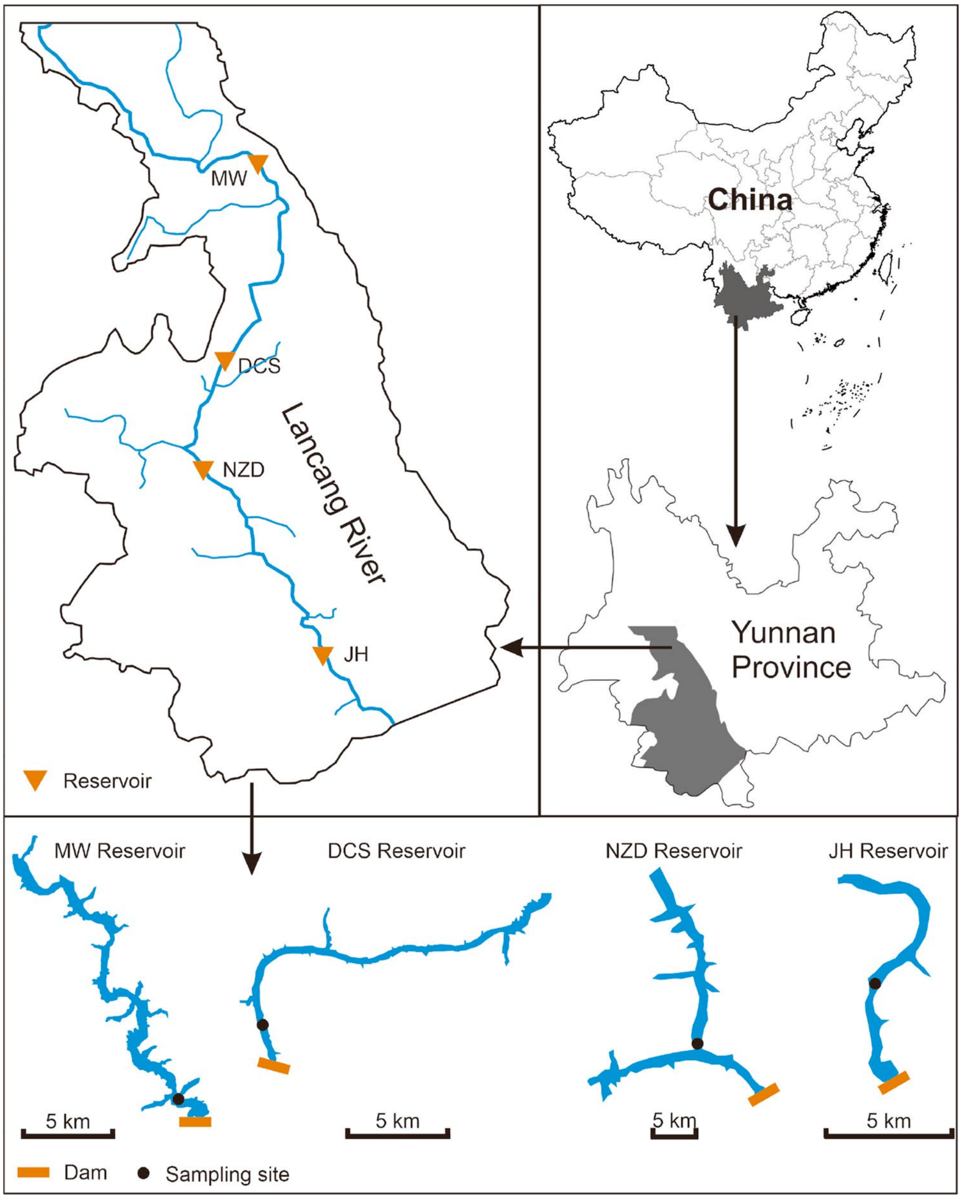
$$J = \varphi \cdot D_s \cdot (dC/dZ)_{z=0} \tag{1}$$

where J is the metal flux and φ is the porosity of surface sediment and can be calculated by the dry weight and the wet weight of the sediment (Tang et al., 2016). $(dC/dZ)_{z=0}$ is the metal concentration gradient at the SWI. D_s is the sediment diffusion coefficient of metals which is calculated as the following equations (Ullman and Sandstrom, 1987):

$$D_s = \varphi D_0 (\varphi \le 0.7) \tag{2}$$

$$D_s = \varphi^2 D_0 (\varphi > 0.7) \tag{3}$$

Fig. 1 Locations of the sampling sites in cascade reservoirs of the Lancang River



where D_0 is metal diffusion coefficient in free solution and values of D_0 for each metal were adopted from Li and Gregory (1974).

Porewater toxicity analysis

To examine the toxicity level of metals in porewater, the interstitial water criteria toxic units (IWCTU) was adopted (Liu et al., 1999; Lourino-Cabana et al., 2011):

$$\mathrm{IWCTU}_{M_e} = \frac{[M_e]_{i,w}}{FCV_{M_e}} \tag{4}$$

$$\mathrm{NI} = \left[\frac{\left(\mathrm{IWCTU}_{\max}\right)^2 - \left(\mathrm{IWCTU}_{\mathrm{mean}}\right)^2}{2}\right]^{1/2} \tag{5}$$

where $[M_e]_{i,w}$ is the heavy metal concentration in porewate, and FCV_{M_e} represents the final chronic value of the metal by hardness. The calculation method for FCV_{M_e} was shown in Table S2. If the IWCTU_{M_e} is greater than 1, it indicates a risk of toxicity to aquatic organisms (Zhu et al., 2016). The NI (Nemeraw index) was calculated to reflect porewater quality. The NI was categorized into five levels: no impact ($\mathrm{NI} < 1$), slight impact ($1 < \mathrm{NI} < 2$), moderate impact ($2 < \mathrm{NI} < 3$), strong impact ($3 < \mathrm{NI} < 5$), and serious impact ($\mathrm{NI} > 5$) (Tang et al., 2016).

Statistical analysis

Correlation analysis and principal component analysis were performed to check the significant relationships among heavy metals and identify their potential sources for this study. The independent sample *t* test was applied for two-group comparisons. The above analyses were conducted using SPSS 21.0.

Results and discussion

Distribution of heavy metals in porewater

Heavy metal concentrations in overlying water and porewater exhibited obvious spatial variation (Fig. 2; Table S4). The porewater in the MW Reservoir contained the highest average concentrations of Cu and Cd, and the porewater in the DCS Reservoir contained the highest average concentrations of Ni, Zn and Pb, whereas the mean concentrations of most of the heavy metals in porewater were lowest in the JH Reservoir (the lower reaches). Due to the existence of the cascade reservoirs, particles containing organic matter were preferentially deposited in the upstream reservoirs (Fig. S1). Organic matter usually has a strong affinity for heavy metals, resulting in a stronger capacity of upstream reservoir sediments to retain these metals (Perez-Esteban et al., 2014). In addition, heavy metal concentrations in porewater followed the order of Mn > Fe > As > Zn > Ni > Cu > Pb > Cd at each of the four reservoirs. Due to dilution and settling processes, the lowest concentrations of heavy metals in the overlying water were usually found in the downstream regions (Varol, 2019). However, the highest contents of

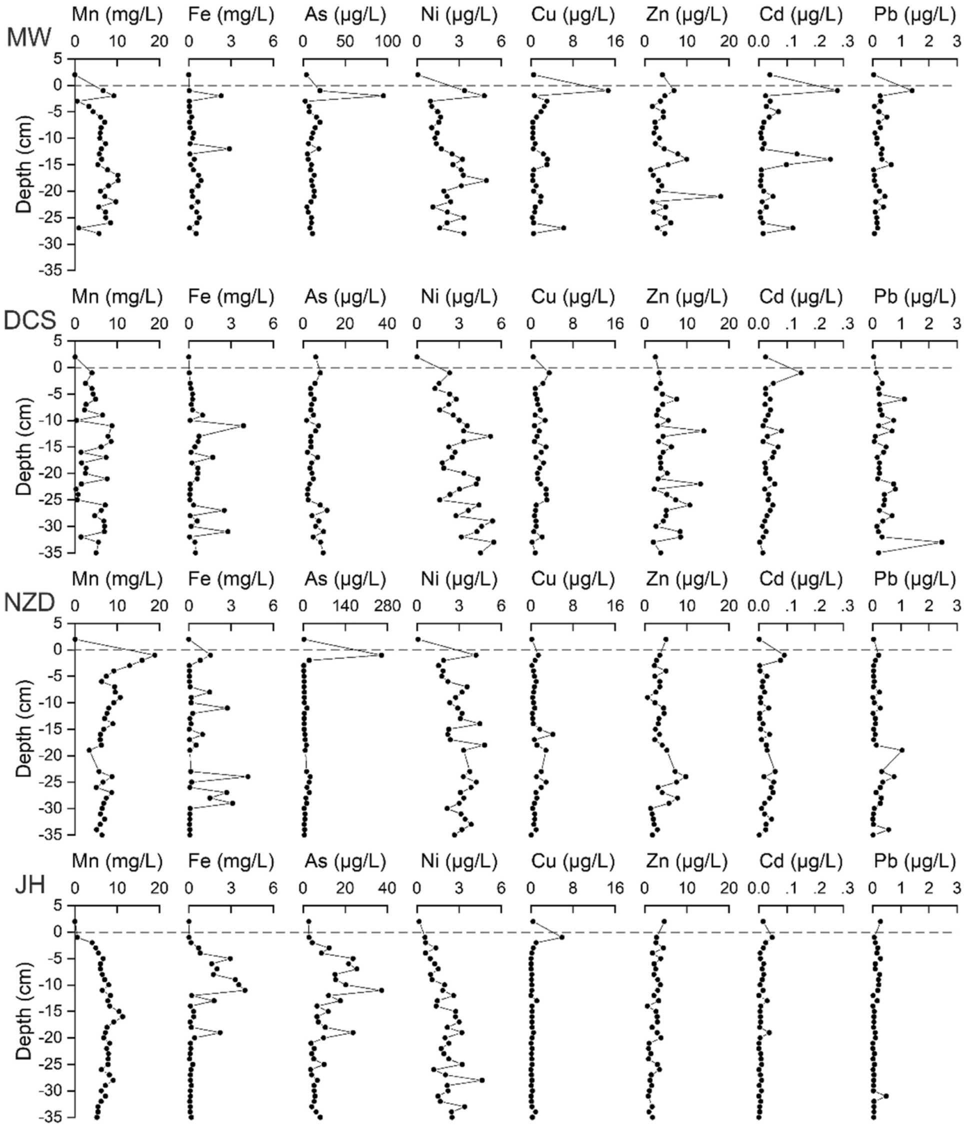


Fig. 2 Heavy metal concentrations in overlying water and porewater from the MW Reservoir, the DCS Reservoir, the NZD Reservoir and the JH reservoir (the dashed lines denote the sediment–water interface)

Ni and Pb in the overlying water were observed in the lower reaches (the JH Reservoir) indicating significant local inputs existed.

The distribution of heavy metals in porewater varied vertically (Fig. 2). The porewater profiles of Fe and As showed a certain degree of similarity at each sampling site. Moreover, significant positive correlations existed between Fe and As in porewater from the MW Reservoir ($r^2 = 0.60$, $p < 0.01$), the DCS Reservoir ($r^2 = 0.56$, $p < 0.01$), the NZD Reservoir ($r^2 = 0.65$, $p < 0.001$), and the JH Reservoir ($r^2 = 0.89$, $p < 0.001$). These results suggested that the solubility and migration of arsenic were highly controlled by Fe oxyhydroxides. Furthermore, the poor relationship between As and Mn in porewater of these reservoirs indicated that Fe oxyhydroxides played a more important role than Mn oxyhydroxides in controlling As solubility which was consistent with results of other researches (Couture et al., 2010a, 2010b; Toevs et al., 2008). Previous studies revealed that Fe could be a good indicator to reflect sediment redox (oxic, sub-oxic, or anoxic conditions) (Campanha et al., 2012; Lei et al., 2016). In the JH Reservoir, the contents of Fe and As in interstitial water generally increased with depth before reaching peaks and then decreased. Their lower contents in the top layers might represent the oxic zone where As was absorbed or co-precipitated with Fe oxyhydroxides (Nikolaidis et al., 2004; Carraro et al., 2015). The peaks of Fe and As in the porewater profile might indicate the sub-oxic zone where partial Fe oxyhydroxides containing As reductively dissolved and released them to porewater causing the elevated concentrations of Fe and As (Keimowitz et al., 2005; Couture et al., 2010a). Similar phenomena have also been discovered by other researchers (Couture et al., 2010a; Deng et al., 2014; Sun et al., 2016). In general, the distribution patterns of most metals (Ni, Cu, Zn, Cd, and Pb) in the interstitial water were not significantly regular, although some enrichment or deficiency existed at certain discrete layers.

Overall, the mean concentrations of Mn, Fe, As, Ni, Cu, Zn, Cd, and Pb in the sediment porewater from the cascade reservoirs of the Lancang River were 6442, 644, 11.50, 2.62, 1.23, 3.95, 0.031, and 0.24 μg/L, respectively. The mean concentrations of Mn, Fe, As, Ni, Cu, Zn, Cd, and Pb in the overlying water from the cascade reservoirs of Lancang River were 19.18, 4.05, 4.10, 0.09, 0.42, 4.10, 0.021, and 0.10 μg/L, respectively. The contents of all the studied metals in overlying water and porewater met the Chinese Surface Water Environmental Quality Standard, except that the concentrations of Mn and Fe in porewater were higher than the standard (100 and 300 μg/L for Mn and Fe, respectively; China EPA, 2002).

Source identification

Correlation analysis and principal component analysis were conducted to explore the potential sources of studied metals in porewater (Chatterjee et al., 2007; Bai et al., 2016).

Correlation analysis

The CA was carried out to identify relationships among the eight metals (Fig. 3). Generally, significantly positive correlations among metals might reflect their similar sources, controlling factors, and transport behavior (Zeng et al., 2020). In this study, a significantly positive correlation was found between Cu and Cd ($R = 0.76$, $p < 0.01$), suggesting that they possibly shared the same source. Positive correlations existed among Mn, Fe, and As ($p < 0.01$), but they were relatively weakly correlated with other metals. Moreover, negative correlations were observed between Cu and Mn, Zn and Mn, Cd and Mn, Pb and Mn, and Cu and Fe, signifying that Mn, Fe, and As might originate from a different source relative to other metals. Cu, Zn, Cd, and Pb exhibited positive correlations among them (Fig. 3).

Principal component analysis

The PCA was used to further explore the possible sources of the selected metals in porewater. The PCA identified three principal components (PCs) with eigenvalues exceeding 1, explaining 67.2% of the total variance (Table 1). PC1 (Cu, Cd, Pb and Zn), PC2 (As, Fe and Mn), and PC3 (Ni) account for 30.91%, 20.60%, and 15.68% of the total

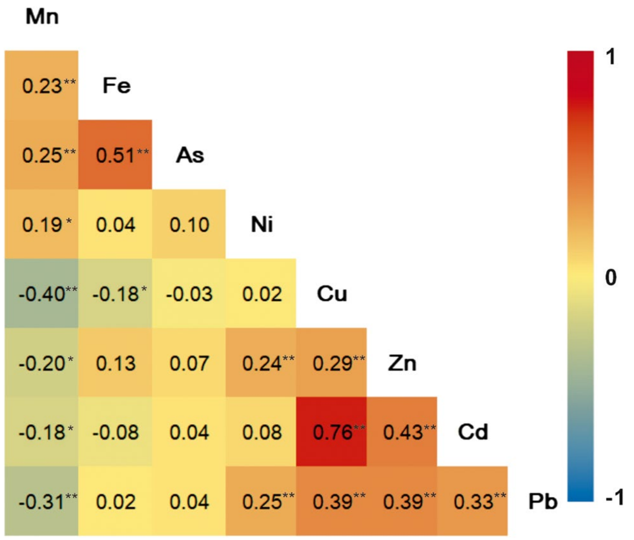


Fig. 3 Correlation coefficients of metals in sediment porewater in cascade reservoirs of the Lancang River. **Significant at the 0.01 level. *Significant at the 0.05 level

Table 1 Factor loadings for varimax rotated PCA of heavy metals

Elements	PC1	PC2	PC3
Mn	−0.546	**0.385**	0.287
Fe	−0.062	**0.850**	0.018
As	0.049	**0.857**	0.025
Ni	0.016	0.017	**0.929**
Cu	**0.829**	−0.115	−0.094
Zn	**0.594**	0.164	0.389
Cd	**0.829**	0.044	0.019
Pb	**0.609**	−0.008	0.384
% of variance	30.91	20.60	15.68
% of cumulative	30.91	51.50	67.18

variance, respectively. Fe and Mn were commonly applied as the geochemical reference elements (Guan et al., 2018; Sun et al., 2018; Varol, 2019) and were strongly correlated with As ($p < 0.01$) (Fig. 3), indicating that PC2 was primarily affected by natural inputs. Cu, Zn, Cd and Pb had high loadings on PC1 and were positively correlated with each other. Combined with the negative correlations between Cu and Mn, Zn and Mn, Cd and Mn, Pb and Mn, and Cu and Fe (Fig. 3), it could be inferred that PC1 is mainly associated with anthropogenic sources. This could also be supported by former researches (Geng et al., 2015; Zhu et al., 2016; Zeng et al., 2020); namely, Cu, Zn, Cd, and Pb were the typical anthropogenic pollutants from agricultural runoff and industrial sewage. Ni was the main component of PC3. Considering the positive correlations of Ni with Mn, Fe, Zn, and Pb (Fig. 3), and the low concentrations of Ni in porewater, thus, PC3 was defined as being affected by a combination of natural and anthropogenic effects.

Diffusive fluxes of metals at the SWI

The diffusive fluxes of the selected metals showed significant variations in the four reservoirs (Table 2). Heavy metal fluxes at the SWI can effectively indicate whether sediment is a source or sink for pollutants in the aquatic systems (Lei et al., 2016; Tang et al., 2016). The diffusive fluxes of Mn, Fe, As, Ni, Cu, Zn, Cd, and Pb in the cascade reservoirs

Table 2 Diffusive fluxes (μg (m^2 day)$^{-1}$) of heavy metals at the sediment–water interface in cascade reservoirs of the Lancang River and other lakes and reservoirs worldwide

Location	Mn	Fe	As	Ni	Cu	Zn	Cd	Pb	Reference
MW Reservoir	14,424	45.68	53.89	7.23	31.18	6.40	0.54	4.08	This study
DCS Reservoir	7437	36.96	6.59	4.37	5.78	1.88	0.25	0.24	This study
NZD Reservoir	35,021	2881	750	7.70	2.30	−2.95	0.17	0.45	This study
JH Reservoir	919	2.12	0.17	0.71	9.62	−3.35	0.06	−0.52	This study
Aha Reservoir (China)	ND	ND	25.48 to 54.71	2.74 to 7.95	−0.27 to 0.27	−36.99 to −32.33	ND	0.27 to 0.55	Xiao et al. (2019)
Shahe Reservoir (China)	ND	ND	108.4	−35.67	−5.11	−20.89	ND		Yuan et al. (2014)
Taihu Lake (China)	ND	ND	ND	−1.74 to 28.9	6.95–54.3	−14.8 to 12.2	ND	2.62 to 19.2	Lei et al. (2016)
Chaohu Lake (China)	3360	ND	80	0.77	ND	ND	−0.02	−0.24	Tang et al. (2015) and Wen et al. (2012)
Lake Hope (USA)[a]	249 to 559	4.47 to 159	ND	−0.24 to 0.04	−0.11 to 0.65	−0.01 to 1.35	ND	0.04 to 0.20	Lopez et al. (2010)
Dianchi Lake (China)	ND	−17.02 to 7.95	−3.09 to 5.11	−19.24 to 1.66	−36.70 to 3.83	−290 to 10.08	−1.22 to −0.13	−50.47 to 2.82	Bao et al. (2008)
Daya Bay (China)	2619	872	ND	2.54	1.64	14.51	0.06	4.79	Ni et al. (2017)

Negative fluxes are directed into sediment from overlying water column

ND no data

[a] Affected by acid mine drainage

of the Lancang River were 919–35,022 μg/(m^2 day), 2.12–2881 μg/(m^2 day), 0.17–750 μg/(m^2 day), 0.71–7.70 μg/(m^2 day), 2.30–31.18 μg/(m^2 day), (-3.35)–6.40 μg/(m^2 day), 0.06–0.54 μg/(m^2 day), and (-0.52)–4.08 μg/(m^2 day), respectively. The fluxes of all metals in the four reservoirs were positive (with the exception of Zn from the ZND and the JH, and Pb from the JH), suggesting export from sediment to overlying water and that sediment was generally the source of heavy metals. Human activities and the weak hydrodynamic conditions after impoundment caused the accumulation of heavy metals in sediment. Among these metals, the diffusive flux of Mn was highest, followed by Fe and As, which might negatively affect the quality of overlying water and pose health risks. The fluxes of Mn, Fe, and As in the NZD Reservoir were considerably higher than those in other reservoirs, which was ascribed to their peak concentrations in the top layer of porewater caused by the anoxic environment at the SWI of the NZD Reservoir. The highest fluxes of Cu, Zn, Cd, and Pb were found in the MW Reservoir signifying the greatest endogenous release of these metals in the upper reaches of the cascade reservoirs, whereas the lowest fluxes of all the studied metals except for Cu were observed in the JH Reservoir which was the last one of the cascade reservoirs. In addition, the negative fluxes of Zn and Pb in the JH Reservoir represented that these two metals diffused from overlying water to sediment. Combining the results of 3.1, it could be inferred that although there was Pb pollution in the JH Reservoir, sediment was able to scavenge some Pb in the overlying water of the JH Reservoir.

The fluxes of metals in this study were comparable with those observed elsewhere (Table 2). The fluxes of Mn in the cascade reservoirs of the Lancang River (except that in the JH Reservoir) were much higher than those reported in other places (such as the Chaohu Lake, the Lake Hope, and the Daya Bay). Fe and As fluxes in this study were similar to other regions (e.g. the Aha Reservoir, the Shahe Reservoir, the Chaohu Lake, the Dianchi Lake, and the Lake Hope), except their extremely high fluxes in the NZD Reservoir. Diffusive fluxes of Ni, Zn, and Pb were compared with all the areas listed. However, the fluxes of Cu and Cd in this study were higher than all of the other regions (except for the Taihu Lake) which were polluted by heavy metals in different degree, suggesting that Cu and Cd from anthropogenic sources should be paid more attention in this region. Actually, the diffusion fluxes might be overestimated because dissolved heavy metals in porewater would be partially absorbed by Fe/Mn oxyhydroxides at the SWI in the process of upward diffusion (Deng et al., 2014; Tang et al., 2016).

Toxic units

Heavy metal concentration in sediment porewater can reflect their bioavailability and the changing trend of metals in overlying water (Burgess et al., 2013; Ji et al., 2018). Therefore, it has replaced sediment as an effective predictor of toxic effects (Tang et al., 2016). The IWCTU was applied to analyze the toxicity level of a single metal in porewater, and the NI was used to evaluate the combined effects of metals. Results showed that the IWCTU values of each metal (Ni, Cu, Zn, Cd, and Pb) were less than 1 and the NI values were also low (0.05–0.10) in all the four reservoirs from the Lancang River (Table 3). These results indicated that these metals in porewater showed no toxicity risks for biota in the study areas. However, this method does not include assessments for Mn, Fe, and As. Considering the strong release fluxes and high concentrations of Mn, Fe, and As in porewater, especially in the NZD Reservoir, their potential risks in porewater should be taken seriously. It is interesting to note that the values of $\sum \mathrm{IWCTU}_i$ and NI in porewater from the upstream reservoirs (the MW Reservoir and the DCS Reservoir) were higher than those from the downstream reservoirs (the NZD Reservoir and the JH Reservoir; $p < 0.01$). It suggested that the operation of the cascade reservoirs enabled greater accumulation of contaminants in sediments of upstream reservoirs, which made the porewater of upstream reservoirs exhibit relatively stronger toxicity.

The results of toxic units suggested that the heavy metal contamination and toxicity in porewater were not serious. However, Deng et al. (2017) reported that Cd was moderately polluted in the sediment of the MW Reservoir and the DCS Reservoir, and Wang et al. (2012) indicated that Cd, Cu, Pb, and Zn were slightly enriched in sediment from the MW reservoir and could cause adverse effect. This seeming contradiction revealed that the risks of these metals releasing from the sediment to the water column were pretty low, and high total contents of heavy metals in contaminated sediment might not result in a severe

Table 3 The IWCTU and NI values for heavy metals in porewater from the cascade reservoirs of the Lancang River

Reservoir	IWCTU_i					$\sum \mathrm{IWCTU}_i$	NI
	Ni	Cu	Zn	Cd	Pb		
MW	0.03 ± 0.01	0.10 ± 0.16	0.03 ± 0.02	0.03 ± 0.04	0.06 ± 0.06	0.24 ± 0.25	0.09 ± 0.11
DCS	0.04 ± 0.01	0.09 ± 0.06	0.03 ± 0.02	0.02 ± 0.02	0.10 ± 0.09	0.28 ± 0.15	0.10 ± 0.07
NZD	0.04 ± 0.01	0.06 ± 0.05	0.02 ± 0.01	0.02 ± 0.02	0.04 ± 0.04	0.17 ± 0.10	0.06 ± 0.04
JH	0.03 ± 0.01	0.03 ± 0.08	0.02 ± 0.01	0.01 ± 0.01	0.03 ± 0.03	0.12 ± 0.09	0.05 ± 0.05

consequence. This was further supported by the fact that contents of Ni, Cu, Zn, Cd and Pb in porewater were all below the USEPA chronic water quality criteria of 8.2, 3.1, 81, 8.8, and 8.1 μg/L, respectively (USEPA 2009). Generally, these metals showed relatively low diffusive fluxes from the sediment porewater to overlying water in most sites, suggesting that the release risk of these elements from sediment in the study area was not high. The mobility and transformation processes might be controlled by many factors, such as hydrological conditions, hardness, pH, redox potential, and the mineralization of organic matter (Lourino-Cabana et al., 2011; Lei et al., 2016). Therefore, porewater is very essential to comprehensively evaluate heavy metal pollution in sediments of aquatic ecosystem.

Conclusion

Despite its irreplaceable roles in the cycling of trace metals in aquatic ecosystems, porewater was little studied. Thus, the contents, diffusive fluxes, potential sources, and toxicity of metals in porewater were examined in the cascade reservoirs of the Lancang River. The concentrations of most of the heavy metals in porewater were lowest in the downstream reservoir. With the exception of Mn and Fe in porewater, the contents of heavy metals in overlying water and porewater met the Chinese Surface Water Environmental Quality Standard. Anthropogenic input was the main source of Cu, Zn, Cd, and Pb in sediment porewater, while As, Fe, and Mn were primarily affected by natural processes, and Ni was associated with mixed sources. Almost all the metals had positive diffusive fluxes from the interstitial water to the overlying water column in the four reservoirs suggesting that porewater was a direct source of heavy metals to the overlying water. According to the results of toxic units, the contamination and toxicity of Ni, Cu, Zn, Cd, and Pb in porewater were not serious. Considering the strong release fluxes and high concentrations of Mn, Fe, and As in porewater, their potential risks should be given a concern. This study and subsequent research would contribute to the prevention of heavy metal pollution and provide further powerful support for the sustainable development planning of the Lancang-Mekong water resources.

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Data availability Data and material is available for research purpose and for reference.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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