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Research papers

Determining the priority control factor of toxic metals in cascade reservoir sediments via source-oriented ecological risk assessment

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ABSTRACT

Determining the priority control factor is crucial for managing sediment toxic metals (TMs) pollution. Therefore, the vertical profiles of TMs in core sediments from the Nuozhadu (NZD) and Jinghong (JH) cascade reservoirs in the Lancang River were studied to assess the source-oriented ecological risks. The geo-accumulation index (I_{geo}), enrichment factor (EF), potential ecological risk factor (Er), and potential ecological risk index (RI) were employed. Then, combined with principal component analysis (PCA) and the positive matrix factorization (PMF) model, the effects of TMs and contamination sources on ecological risks were revealed. Results showed that the concentrations of As, Cd, Hg, Pb, and Zn in the NZD Reservoir were significantly lower than those in the JH Reservoir, which might be related to the coarser grain size of the NZD Reservoir sediments. While both reservoirs demonstrated elevated contamination levels of Cd and As among all the TMs, the NZD Reservoir also exhibited high levels of Cr, whereas the JH Reservoir showed relatively high levels of Hg. Natural and anthropogenic sources of TMs were quantitatively identified in cascade reservoirs. Cd and Hg exhibited higher ecological risk levels than other TMs in both reservoirs. The JH Reservoir was exposed to significantly higher ecological risks from TMs compared to the NZD Reservoir, and 40.0 % of the sediments in the JH Reservoir were exposed to considerable risk ($300 < RI < 600$). Results of source-oriented ecological risks showed that Cd from anthropogenic sources was identified as the priority control factor in the NZD and JH cascade reservoirs. Our findings give scientific backing for the prevention and control of TM contamination and the planning of sustainable development of water resources in the Lancang-Mekong River.

1. Introduction

Toxic metals (TMs) pollution in aquatic environments has attracted worldwide concern and has become a pressing environmental problem (Gao et al., 2021; Gu et al., 2022; Tang et al., 2022; Varol and Tokatlı, 2022). TMs can give rise to severely harmful effects on human beings and aquatic life because of their extreme toxicity, persistence, and bioaccumulation behavior (Muhammad and Ahmad, 2020; Yang et al., 2022). In the past few decades, large quantities of TM contaminants have been discharged into rivers due to rapid industrialization and urbanization (Chai et al., 2021; Chen et al., 2022; Li and Zhang, 2010; Xu et al., 2020). As a result, reservoir sediments become the primary eventual sink for these TMs owing to the adsorption of sediments and the interception of dams (Canpolat et al., 2022; Cheng et al., 2022; Li et al., 2020; Zhao et al., 2020). However, TMs settled in sediments can be released via physical, chemical, and biological processes, which makes sediment a secondary pollution source and poses tremendous threats to ecosystem security and human health (Gao et al., 2022; Gu et al., 2023; Tang et al., 2016). Besides, sediments in reservoirs also provide valuable records of changes in natural and human-caused processes in watersheds due to their long residence time (Varol, 2020). Therefore, the analysis of reservoir sediments is crucial for revealing the contamination status of TMs in watersheds and providing valuable support for subsequent pollution management.

Multitudinous previous studies have assessed ecological risks based on TM concentrations, but this cannot differentiate ecological risks

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posed by natural and anthropogenic sources (Adimalla, 2020b; Proshad et al., 2022; Tang et al., 2010; Wang et al., 2019; Yang et al., 2020). Because natural sources are uncontrollable, limiting pollution from anthropogenic sources is the key to controlling sediment TM pollution. For this reason, integrating a source-oriented risk assessment methodology is essential for developing ecological risk mitigation strategies. Many researchers are now aware of its importance and are increasingly assessing ecological risks using the source-oriented approach (Li et al., 2023; Men et al., 2020). The first main point of this method is to clarify the source apportionment of TMs (Sun et al., 2022). Because of the inability to quantify the sources of contaminants, several existing approaches (e.g., factor analysis (FA), principal component analysis (PCA), and cluster analysis (CA)) are not capable of source-specific risk assessment (Huang et al., 2021; Zhao et al., 2022a). However, the positive matrix factorization (PMF) model developed by the U.S.EPA (2014) has been demonstrated to address this shortcoming by providing non-negative results, dealing with process data below the level of detection, and allocating source contribution to each element (Song et al., 2021; Yuan et al., 2023). To improve the precision of the source apportionment, the combination of the PCA and the PMF model was employed in the present study.

Identifying the primary contributors (including sources and TMs) to ecological risks is a prerequisite and a highly essential step in preventing and controlling sediment contamination. Due to the diverse substances and toxicity levels of TMs, each specific contamination source can result in significantly different ecological risks (Proshad et al., 2022; Sun et al., 2022). Therefore, a clear understanding of the relationship between ecological risks, TMs, and contamination sources is urgently needed. The systematic exploration of this relationship, however, has received little attention so far. Hence, this study was conducted to reveal the effects of TMs and contamination sources on ecological risks and prioritize the control factors that have the greatest impact on ecological risks.

Stems from the Qinghai-Tibet Plateau, the Lancang River (LCR) cultivates a variety of ecosystems and provides freshwater resources for local economies and communities (Zhang et al., 2020). Human activities in the basin and dam operations in the mainstem have had a significant impact on riverine environmental processes and biogeochemical cycling, particularly on the transport and accumulation of TMs (Zhao et al., 2023). However, sediment TM contamination status and source apportionment in LCR cascade reservoirs are still rarely reported. Only two studies have reported the metal concentrations in the sediment of the Manwan Reservoir which is in the upper of the LCR (Wang et al., 2012; Zhao et al., 2013). In fact, most urban and agricultural activities are concentrated downstream with more population there (Zeng et al., 2022). Therefore, the status of TM contamination in downstream reservoirs should be of greater concern. The Nuozhadu (NZD) Reservoir and Jinghong (JH) Reservoir are core cascade reservoirs in the lower of the LCR.

Therefore, taking the NZD and JH cascade reservoirs as a case, this study aimed to (1) explore the contamination characteristics of multiple TMs in core sediments, (2) quantitatively derive the contamination sources via PCA and PMF model, (3) assess the concentration-oriented and source-oriented ecological risks caused by TMs in sediments, and (4) determine the priority control factor.

2. Materials and methods

2.1. Study area

As upstream of the Mekong River, the LCR flows through Qinghai-Tibet Plateau and Yunnan Province in China with a length of 2161 km, ranking as the 5th longest among all rivers in China. The section of the LCR that passes through Yunnan is characterized by urbanized areas with dense populations, agricultural fields, industrial zones, and mining factories while that through Tibet is characterized by sparsely populated areas with limited human activities (Wen et al., 2022). Due to its large descending elevation and huge runoff, the LCR produces abundant hydraulic resources in Yunnan Province. This makes it feasible to develop cascade hydropower stations. (Cheng et al., 2022).

As a major water source for Southeast Asian countries, the LCR holds great significance due to its environmental sensitivity and fragility. A chain of six cascade hydroelectric dams had been constructed on the mainstream of the LCR as of 2016. Given that downstream areas have a higher concentration of urban and agricultural activities, the status of TM contamination in downstream reservoirs, particularly the NZD and the JH Reservoirs, should be of greater concern. These two reservoirs play a core role in the lower reaches of the LCR.

Completed in 2014, the NZD Reservoir has a storage capacity of 2.4 $\times 10^{10}$ m^3 and an install capacity of 5850 MW. The hydraulic residence time of the NZD Reservoir is 1.78 years (Zhao et al., 2022b). The JH dam is located downstream of the NZD dam. Completed in 2009, the JH Reservoir has a storage capacity of 1.1 $\times 10^9$ million m^3 with a normal water level of 899 m. Its install capacity is 1350 MW. The hydraulic residence time of it is 0.40 years (Shi et al., 2020). Both reservoirs are utilized for multiple purposes, including hydroelectric generation, flood control, and fishing.

2.2. Sampling and analysis

In April 2017, sediment cores were collected from the NZD and JH Reservoirs using a gravity corer (Fig. S1). Cores were cut in 1 cm intervals in the field, kept in sealed centrifuge tubes, and refrigerated at 4 °C in the dark during transportation. Sediments were lyophilized before particle size analysis. A fraction of the lyophilized sediments was ground and sieved with a nylon sieve (100-mesh) for chemical analysis.

The sediment grain size was analyzed by Mastersizer 2000 Ltd. (clay: < 4 μm; silt: 4–64 μm; sand: > 64 μm). Total carbon (TC), total sulfur (TS), total nitrogen (TN), and total organic carbon (TOC) in sediments were detected with an element analyzer (Vario MACRO cube). Total phosphorus (TP) was measured by ICP-AES. Metals were determined with ICP-MS (NexlON 1000G) and AFS-9750 after powdered sediments were digested by aqua regia. To verify the accuracy of digestion, method blanks, duplicates, and standard reference materials (GBW07404a, GBW07390, and GBW07981) were used. Recoveries for these elements were 90–110 %, with < 5 % relative differences existing among sediment replicates.

2.3. Evaluation of sediment contamination and ecological risk

To study the contamination status and degree of TMs in core sediments from the NZD and JH Reservoir, the geo-accumulation index (I_{geo}) and enrichment factor (EF) were adopted, with the corresponding details presented in Text S1 and S2, respectively (Adimalla, 2020a; Li et al., 2023; Men et al., 2018; Varol et al., 2020; Wu and Probst, 2021). These indices were chosen due to their widely recognized effectiveness in assessing sediment contamination, offering valuable insights into the sources and levels of metal pollution in aquatic environments. To evaluate the potential impact of metals on ecosystems, the potential ecological risk factor (Er) and potential ecological risk index (RI) were employed, with details presented in Text S3 (Han et al., 2023; Tang et al., 2020; Varol et al., 2022a).

2.4. Sediment quality guidelines

The potential impacts of TMs on benthic species were assessed by comparing their concentrations with threshold effect concentrations (TEC) and probable effect concentrations (PEC) outlined in sediment quality guidelines (SQGs) (Varol et al., 2022b). Adverse effects on benthic species are not expected when TM levels in sediment are below the TEC; however, negative impacts are likely to occur if TM levels surpass the PEC. TM levels falling between the TEC and PEC may or may not result in negative effects (Islam, et al., 2023; Tokatlı, et al., 2023).

2.5. Source apportionment model

To quantitatively identify the contribution of each contamination source to core sediments, the PMF model combined with PCA was used (Han et al., 2021; Men et al., 2021; Wang et al., 2023). Minimizing the objective function Q is the core of the PMF model algorithms, which is determined as follows:

$$x_{ij} = \sum_{k=1}^{p} g_{ik} f_{kj} + e_{ij} \tag{1}$$

$$Q = \sum_{i=1}^{n} \sum_{j=1}^{m} \left[\frac{x_{ij} - \sum_{k=1}^{p} g_{ik} f_{kj}}{u_{ij}} \right]^2 \tag{2}$$

$$\text{For}\, x_{ij} \le MDL,\ u_{ij} = \frac{5}{6} \times MDL \tag{3}$$

$$\text{Else},\ u_{ij} = \sqrt{(Errorfraction \times c)^2 + (0.5 \times MDL)^2} \tag{4}$$

where x_{ij} is the concentrations of the j^{th} TM in i^{th} sediment, g_{ik} is the contribution in k^{th} source i^{th} sediment, f_{kj} is the amount of j^{th} TM from k^{th} source, e_{ij} is the residual, u_{ij} is the uncertainty of j^{th} TM is i^{th} sample, MDL is the method detection limit, and Errorfraction represents the proportion of measurement uncertainty.

3. Results and discussion

3.1. Vertical profiles of core sediments in cascade reservoirs

3.1.1. Sediment grain size

The grain size of sediment from the NZD Reservoir was coarser than that from the JH Reservoir (Fig. 1). In the NZD Reservoir, most of the sediments consisted mainly of silt, except the depth of 20 cm which consisted of sand. The values of median grain size (D50) for core sediments in the NZD Reservoir were generally below 20 μm, with exceptions at the depths of 19–21 cm and 8 cm. A large variation of grain size existed in the vertical direction, with a coefficient of variation (CV) of 1.01. In the JH Reservoir, the sediments were mostly composed of silt and clay. The values of D50 for core sediments in the JH Reservoir were typically below 10 μm, except for the surface sediment. The variation of sediment grain size in the vertical direction was slight, with a CV of 0.23. In addition, the values of D50 for sediments in the NZD Reservoir were significantly higher than those in the JH Reservoir ($p < 0.001$), with an average value of 13.9 μm and 6.1 μm, respectively.

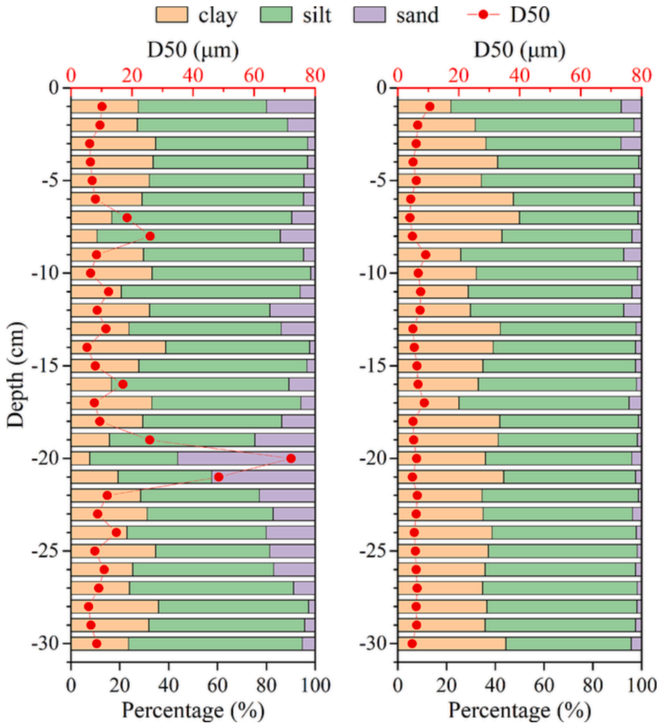

Fig. 1. Median grain size (D50) and texture analysis results of sediments cored from the NZD Reservoir (left) and the JH Reservoir (right). (clay: < 4 μm; silt: 4–64 μm; sand: > 64 μm).

3.1.2. Metals in core sediments

In the NZD Reservoir, the concentrations of As, Cd, Cr, Cu, Hg, Ni, Fe, and Mn exhibited significant vertical variations, with their CV values exceeding 0.25 (Fig. 2 & Table 1). Notably negative correlations were identified between D50 and the concentrations of As, Cd, Cr, Cu, Ni, Pb, Zn, and Fe ($p < 0.05$). Additionally, concentrations of As, Cd, Cr, Cu, Ni, Pb, Zn, and Fe showed troughs at 20 cm depth where sediment grain size was the largest. The above results suggested that metal concentrations in sediments from the NZD Reservoir were highly affected by grain size, with the larger the sediment grain size, the lower the metal concentration. In addition, Cr, Cu, Ni, and Fe exhibited a similar distribution pattern, which was different from other metals such as As and Mn. This reflected the similarity in the origin and geochemical behavior of these metals (Gu, 2021).

In the JH Reservoir, metal concentrations did not exhibit statistically significant relationships with D50 ($p > 0.05$). The concentrations of Cr, Ni, and Fe displayed vertically fewer variations, with the same CV value of 0.06 (Table 1). Moreover, the vertical distribution of Cr, Ni, and Fe followed similar trends (Fig. 3), suggesting the homology of the three elements (Varol et al., 2022a). In contrast, Cd had the largest variation in vertical direction with a CV value of 0.31. The minimum concentration of As, Cd, Cu, Pb, and Zn all occurred at the 20 cm depth.

The concentrations of As, Cd, Hg, Pb, and Zn in the NZD Reservoir were significantly lower than those in the JH Reservoir ($p < 0.001$), which might be a result of the finer grain size of sediments in the JH Reservoir. In the NZD Reservoir, the mean concentrations of TMs (mg/kg) occurred in the following order: Zn (111.5) > Cr (102.0) > Ni (44.0) > Cu (43.5) > Pb (38.9) > As (21.5) > Cd (0.21) > Hg (0.06). While in the JH Reservoir, the mean concentrations of TMs (mg/kg) occurred in the order of Zn (137.7) > Cr (98.0) > Pb (52.8) > Cu (46.7) > Ni (42.8) > As (34.0) > Cd (0.40) > Hg (0.11).

3.2. Pollution status of TMs in core sediments of cascade reservoirs

3.2.1. Geo-accumulation index (I_{geo})

In the NZD Reservoir, the average I_{geo} values of TMs decreased in the order of Cd > As > Cr > Cu > Hg > Zn > Ni > Pb (Fig. 4). The mean I_{geo} value for Cd was 0.66, with 16.7 % of the samples showed “Moderately polluted”, which suggested that Cd occurred at relatively high pollution levels. The mean I_{geo} values for Cu, Hg, Zn, Ni, and Pb were all below 0, denoting unpolluted status.

In the JH Reservoir, the average I_{geo} values of TMs decreased in the order of Cd > As > Hg > Cr > Cu > Zn > Pb > Ni (Fig. 4). The mean I_{geo} value for Cd was 1.6, with 23.3 % and 66.7 % of the samples showed “Moderately to strongly polluted” and “Moderately polluted”, which suggested that Cd occurred at relatively high pollution levels. Approximately 53.3 % and 6.7 % of the samples were moderately polluted by As and Hg, respectively. The I_{geo} values for Ni were negative in all sediments, indicating unpolluted status, which might be impacted by the comparatively low level of anthropogenic activity (Ma et al., 2020).

3.2.2. Enrichment factor (EF)

In the NZD Reservoir, the average EF values of TMs decreased in the order of Cd > As > Cr > Cu > Hg > Zn > Ni > Pb (Fig. 4). The mean EF

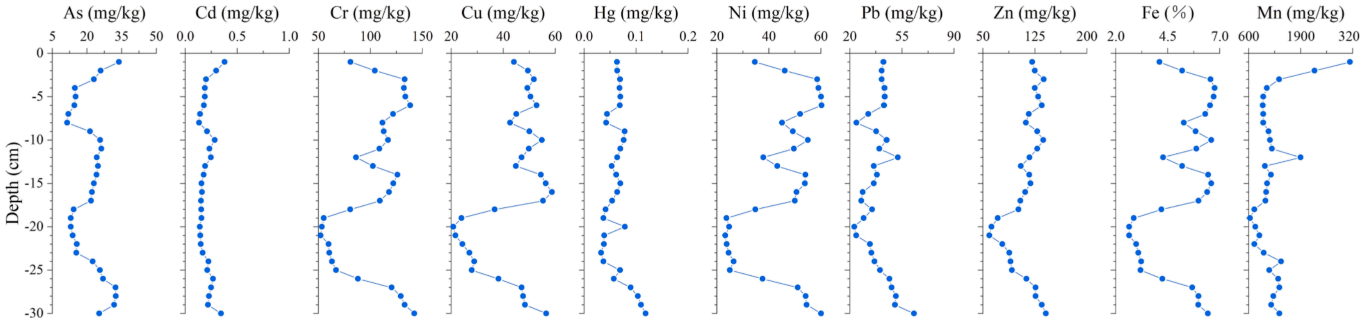

Fig. 2. Vertical distributions of metals in sediments from the NZD Reservoir.

Table 1

Metal concentrations in core sediments from the NZD and the JH Reservoirs. Units: mg/kg, except for Fe which is %.

	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn	Fe	Mn
NZD Reservoir										
Mean ± SD	21.5 ± 6.7	0.21 ± 0.06	102.0 ± 29.2	43.5 ± 11.6	0.06 ± 0.02	44.0 ± 13.0	38.9 ± 9.1	111.5 ± 22.5	5.12 ± 1.44	1196 ± 489
Range	11.4–33.8	0.13–0.38	52.1–142.3	20.8–58.7	0.03–0.12	23.1–60.2	23.0–62.9	59.0–140.9	2.63–6.75	634–3130
CV	0.31	0.30	0.29	0.27	0.33	0.30	0.23	0.20	0.28	0.41
JH Reservoir										
Mean ± SD	34.0 ± 5.9	0.40 ± 0.12	98.0 ± 5.6	46.7 ± 5.4	0.11 ± 0.01	42.8 ± 2.5	52.8 ± 10.0	137.7 ± 18.3	5.47 ± 0.32	1195 ± 184
Range	17.2–47.6	0.20–0.73	87.6–108.7	30.1–55.5	0.08–0.15	38.6–48.9	26.2–71.8	99.6–175.4	4.82–6.28	987–1982
CV	0.17	0.31	0.06	0.11	0.14	0.06	0.19	0.13	0.06	0.15
p[a]	0.000	0.000	0.453	0.174	0.000	0.617	0.000	0.000	0.197	0.992
SQGs										
TEC	9.79	0.99	43.4	31.6	0.18	22.7	35.8	121		
PEC	33	4.98	111	149	1.06	48.6	128	459		
BV	10.9	0.08	58.6	28.7	0.04	36.0	35.7	86.0	5.2	515

Abbreviations: SD, standard deviation; CV, coefficient of variation; SQGs, sediment quality guidelines (MacDonald et al., 2000); TEC, threshold effect concentration; PEC, probable effect concentration; BV, background values for metal concentrations in soils in Yunnan Province.

[a] Independent-sample *t*-test of metals in sediments between the NZD Reservoir and the JH Reservoir.

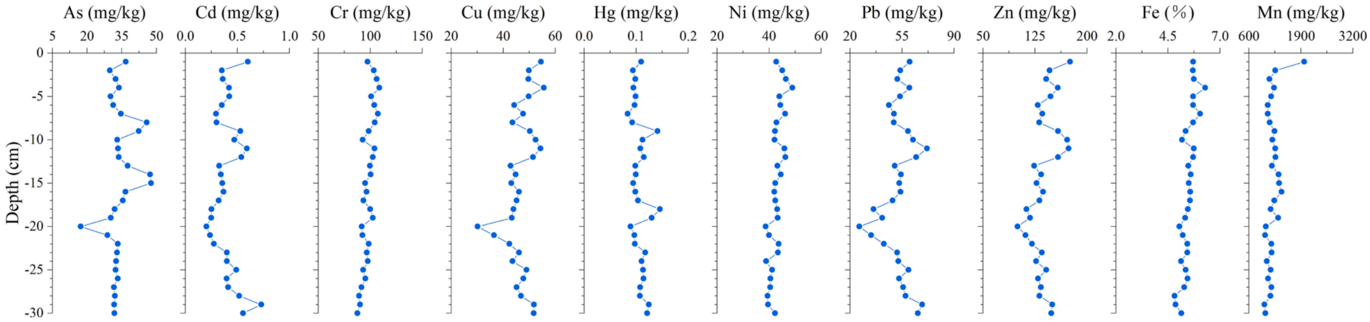

Fig. 3. Vertical distributions of metals in sediments from the JH Reservoir.

values for Cd and As were 2.7 and 2.1, respectively, with 66.7 % of the As and 53.3 % of the Cd exceeding 2, indicating their moderate enrichment level. The mean EF values for the other TMs were between 1 and 2, denoting "minimal enrichment".

In the JH Reservoir, the average EF values of TMs decreased in the order of Cd > As > Hg > Cr > Cu > Zn > Pb > Ni (Fig. 4). With an average EF value of 4.6, approximately 30.0 % and 70.0 % of the sediments showed "significant enrichment" and "moderate enrichment" of Cd, respectively. About 96.7 % and 86.7 % of the sediments showed "moderate enrichment" of As and Hg, respectively. The mean EF values for Cr, Cu, Zn, Pb, and Ni were all between 1 and 2, denoting "minimal enrichment".

3.3. *Assessment of adverse effects on benthic organism*

The concentrations of TMs in core sediments from the two reservoirs were compared with the TEC and PEC (Table 1). For both reservoirs, the concentrations of Cd and Hg in all samples were below the TEC. In the NZD Reservoir, the concentrations of As, Cr, Cu, Ni, Pb, and Zn were observed to fall between the TEC and PEC in 96.7 %, 50 %, 76.7 %, 46.7 %, 66.7 %, and 43.3 % of the sediments, respectively. Similarly, in the JH Reservoir, these concentrations were found to be between the TEC and PEC in 50 %, 100 %, 96.7 %, 96.7 %, 90 %, and 83.3 % of the samples, respectively. Notably, Cr and Ni concentrations in 50 % and 53.3 % of the samples in the NZD Reservoir exceeded the PEC, respectively, while As concentrations in 50 % of the samples in the JH Reservoir surpassed the PEC. These results suggested that Cr and Ni in the NZD Reservoir, as well as As in the JH Reservoir may pose a threat to benthic organisms (Islam, et al., 2023; Tokatlı, et al., 2023; Varol et al., 2022b).

3.4. *Source apportionment*

In the NZD Reservoir, the Kaiser-Meyer-Olkin measure of sampling

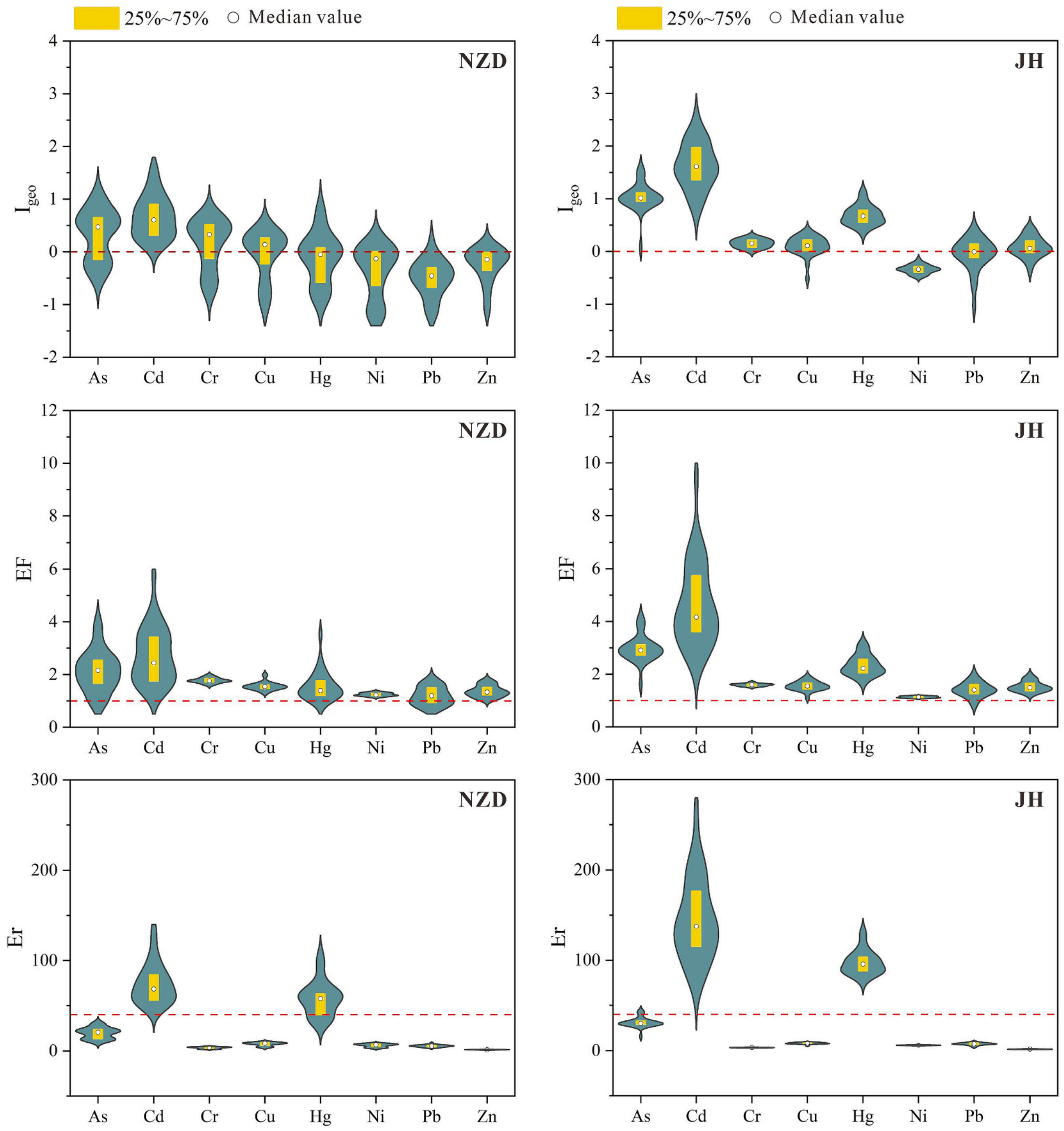

Fig. 4. Violin with box plot of geo-accumulation index (I_{geo}), Enrichment factor (EF), and potential ecological risk factor (Er) for TMs in core sediments from the NZD and JH cascade reservoirs.

adequacy (0.776) and Bartlett's test of sphericity ($p < 0.001$) confirmed the suitability of PCA for analyzing the dataset. Two principal components (PCs) with eigenvalues over 1 were extracted by PCA, explaining 84.2 % of the total variance (Table 2). PC1 (Ni, Fe, Cr, Cu, and Zn) and PC2 (Cd, As, Mn, and Pb) comprised 60.2 % and 24.0 % of the total variance, respectively. The average concentrations of Ni and Fe in

Table 2
Factor loadings for varimax rotated PCA of TMs in sediments.

NZD Reservoir			JH Reservoir			
TMs	Component		TMs	Component		
	1	2		1	2	3
As	0.200	**0.847**	As	0.104	0.125	**0.818**
Cd	0.098	**0.955**	Cd	**0.915**	−0.309	0.058
Cr	**0.985**	0.100	Cr	0.004	**0.916**	0.096
Cu	**0.911**	0.221	Cu	**0.934**	0.235	0.145
Hg	0.552	0.504	Hg	0.250	−0.502	0.024
Ni	**0.990**	0.083	Ni	0.281	**0.898**	0.108
Pb	0.437	**0.738**	Pb	**0.939**	−0.026	0.162
Zn	**0.860**	0.433	Zn	**0.919**	0.168	0.218
Fe	**0.987**	0.028	Fe	0.097	**0.935**	0.237
Mn	−0.048	**0.836**	Mn	0.208	0.099	**0.789**
Eigenvalue	6.020	2.402	Eigenvalue	4.164	2.872	1.047
Variance, %	60.200	24.022	Variance, %	41.637	28.724	10.465
Cumulative,	60.200	84.222	Cumulative,	41.637	70.360	80.826

sediments from the NZD Reservoir were 44.0 mg/kg and 5.1 %, respectively, closely aligning with their respective soil background values of 36.0 mg/kg for Ni and 5.2 % for Fe. Moreover, Fe was often used as the geochemical reference element (Zhao et al., 2021). Therefore, PC1 represented geogenic origin. In contrast, Cd and As showed the highest I_{geo} and EF values among all the TMs (Fig. 4 & Table S1). Therefore, PC2 was associated with anthropogenic origin. Similar to the PCA result, two factors were extracted in the NZD Reservoir based on the PMF model (Fig. 5). Factor 1 was mainly characterized by Ni (62 %), Cr (61 %), and Cu (58 %). As discussed above, this factor represented geogenic origin. Factor 2 was dominated by As (70 %), Cd (67 %) and Pb (61 %). Combined with the result of PCA, factor 2 was allocated to anthropogenic origin. Hg and Zn were nearly evenly distributed between the two components, implying a balanced correlation between the two groups and suggesting that their sources may encompass both natural and anthropogenic origins. As a result, the overall contribution rates to sediment TMs in the NZD Reservoir from natural and anthropogenic sources were 47.6 % and 52.4 %, respectively.

In the JH Reservoir, the Kaiser-Meyer-Olkin measure of sampling adequacy (0.685) and Bartlett's test of sphericity ($p < 0.001$) confirmed the suitability of PCA for analyzing the dataset. Three PCs with eigenvalue over 1 were extracted by PCA, explaining 80.8 % of the total variance (Table 2). PC1 (Pb, Cu, Zn, and Cd), PC2 (Fe, Cr, and Ni), and PC3 (As, Mn) comprised 41.6 %, 28.7 %, and 10.5 % of the total variance, respectively. Parallel to the NZD Reservoir, the JH Reservoir sediments displayed average concentrations of Ni and Fe at 42.8 mg/kg and 5.5 %, respectively, closely resembling the corresponding background levels in the soil. As mentioned above, Fe served as a commonly utilized geochemical reference element. Therefore, PC2 represented geogenic origin. Cadmium was often used as an indicator of human activity (Han et al., 2021; Li et al., 2023). Considering the high contamination status of Cd, PC1 was defined as being affected by human activity. PC3 then could reflect a combined effect of natural input and anthropogenic activity. According to the PMF processing result, two factors were extracted in the JH Reservoir, with 48.5 % and 51.5 % contribution rates, respectively (Fig. 5). Factor 1 was dominated by Cr (58 %) and Ni (57 %). As mentioned above, this factor can be interpreted as natural input. Factor 2 had high loading values for Cd (69 %) and Pb (60 %). Combined with the PCA result, this factor was considered to reflect human activity. As, Cu, Hg, and Zn were nearly evenly distributed between the two components, implying a balanced correlation between the two groups and suggesting that their sources may encompass both natural and anthropogenic origins. As a result, the overall contribution rates to sediment TMs in the JH Reservoir of natural and anthropogenic sources were 48.5 % and 51.5 %, respectively.

3.5. *Ecological risks of TMs in core sediments of cascade reservoirs*

3.5.1. *Concentration-oriented ecological risks*

Cd and Hg exhibited higher ecological risk levels than other TMs in both reservoirs (Fig. 4). For the NZD Reservoir, the average Er values for Cd and Hg were 74.2 and 58.4, denoting moderate ecological risks. For the JH Reservoir, the Er values for Cd and Hg were 145.0 and 97.2, respectively, suggesting considerable ecological risk. In contrast, the average Er values of other TMs in core sediments were lower than 40 in both reservoirs, indicating that the NZD and JH cascade reservoirs had "low potential ecological risk" of these metals.

The JH Reservoir was exposed to significantly higher ecological risks from TMs compared to the NZD Reservoir (Fig. 6). The mean RI value for TMs in the NZD Reservoir sediments was 176.2, indicating a moderate risk. Overall, 70.0 % of the sediments were exposed to moderate ecological risk and 30.0 % were at low risk. The mean RI value for TMs in the JH Reservoir sediments was 299.9, indicating a moderate risk. Overall, 40.0 % and 60.0 % of the sediments were exposed to considerable risk and moderate risk, respectively.

3.5.2. *Source-oriented ecological risks*

For the NZD Reservoir, the anthropogenic source made the dominant contribution to RI. The contribution of Factor 1 (natural source) and Factor 2 (anthropogenic source) to RI was 40.0 % and 60.0 %, respectively (Fig. 7). For specific TMs, Hg exhibited the highest contribution rate in factor 1 (38.0 %), while Cd exhibited the highest contribution rate in factor 2 (46.8 %). As a result, cadmium from the anthropogenic source was identified as a major contributor to ecological risks.

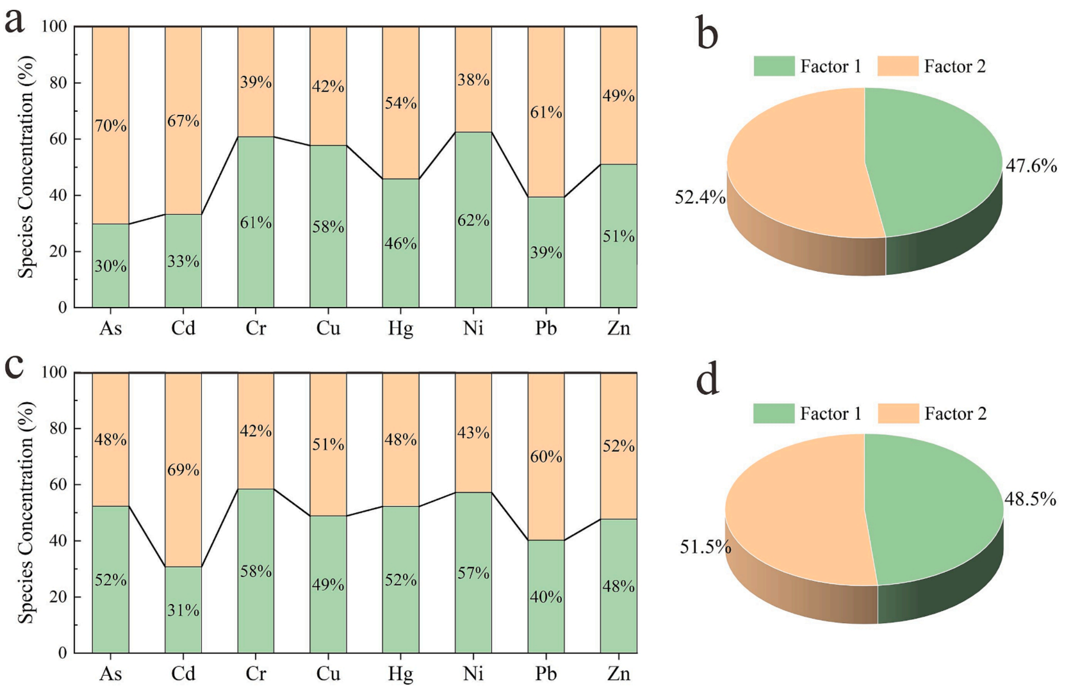

Fig. 5. Source apportionment of TMs in sediments of the MW Reservoir (a, b) and the DCS Reservoir (c, d). (a, c) Species contribution of two pollution sources for TMs. (b, d) The percentage of different pollution sources.

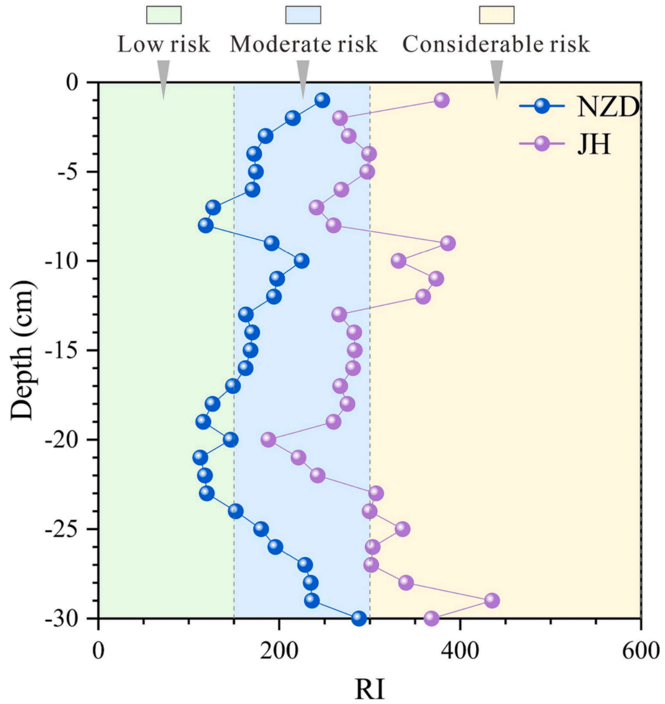

Fig. 6. Vertical distributions of potential ecological risk index (RI) for TMs in core sediments from the NZD and JH cascade reservoirs.

For the JH Reservoir, the anthropogenic source gave the dominant contribution to RI, similar to the NZD Reservoir. The contribution of Factor 1 (natural source) and Factor 2 (anthropogenic source) to RI was 41.6 % and 58.4 %, respectively (Fig. 7). For specific TMs, Hg exhibited the highest contribution rate in factor 1 (40.7 %), while Cd exhibited the highest contribution rate in factor 2 (57.4 %). As a result, cadmium from the anthropogenic source was identified as a major contributor to ecological risks.

In conclusion, the sediment analysis of the NZD and JH cascade reservoirs identified Cd from anthropogenic sources as the primary factor requiring prioritized control. Anthropogenic sources in the study area encompass emissions from vessels in reservoirs, exploitation of tributary rivers, discharges from non-ferrous metal mining and smelting, untreated sewage effluents, and fertilizers or pesticides used in farmland along the riverbank (Wang et al., 2012). Recent research has identified that fuel combustion and exhaust emissions from various transportation sources, including ships within the cascade reservoirs, may contribute to elevated Cd concentrations in the surface water of the LCR. Furthermore, the activities associated with Lancang Lead Mine have also been linked to an increase in Cd levels in the surface water of the basin (Zhao et al., 2023). Therefore, we advocate for the implementation of effective measures to curb anthropogenic Cd input into the Lancang River basin.

4. Conclusion

In this study, the vertical profiles of TMs in core sediments from the NZD and JH cascade reservoirs were studied to assess the source-oriented ecological risks. Results showed that the concentrations of As, Cd, Hg, Pb, and Zn in the NZD Reservoir were significantly lower than those in the JH Reservoir. While both reservoirs demonstrated elevated contamination levels of Cd and As among all the TMs, the NZD Reservoir also exhibited high levels of Cr, whereas the JH Reservoir showed relatively high levels of Hg. Among TMs, Cr and Ni in the NZD Reservoir, as well as As in the JH Reservoir may pose a threat to benthic organisms. In the NZD Reservoir, the contribution rates of natural and anthropogenic sources were 47.6 % and 52.4 %, respectively. In the JH Reservoir, the contribution rates of natural and anthropogenic sources were 48.5 % and 51.5 %, respectively. According to the concentration-oriented ecological risks, Cd and Hg exhibited higher ecological risk levels than other TMs in both reservoirs. The JH Reservoir was exposed to significantly higher ecological risks from TMs compared to the NZD Reservoir, and 40.0 % of the sediments in the JH Reservoir were exposed to considerable risk. According to the source-oriented ecological risks, Cd from anthropogenic sources was identified as the priority control factor in the NZD and JH cascade reservoirs. We recommend

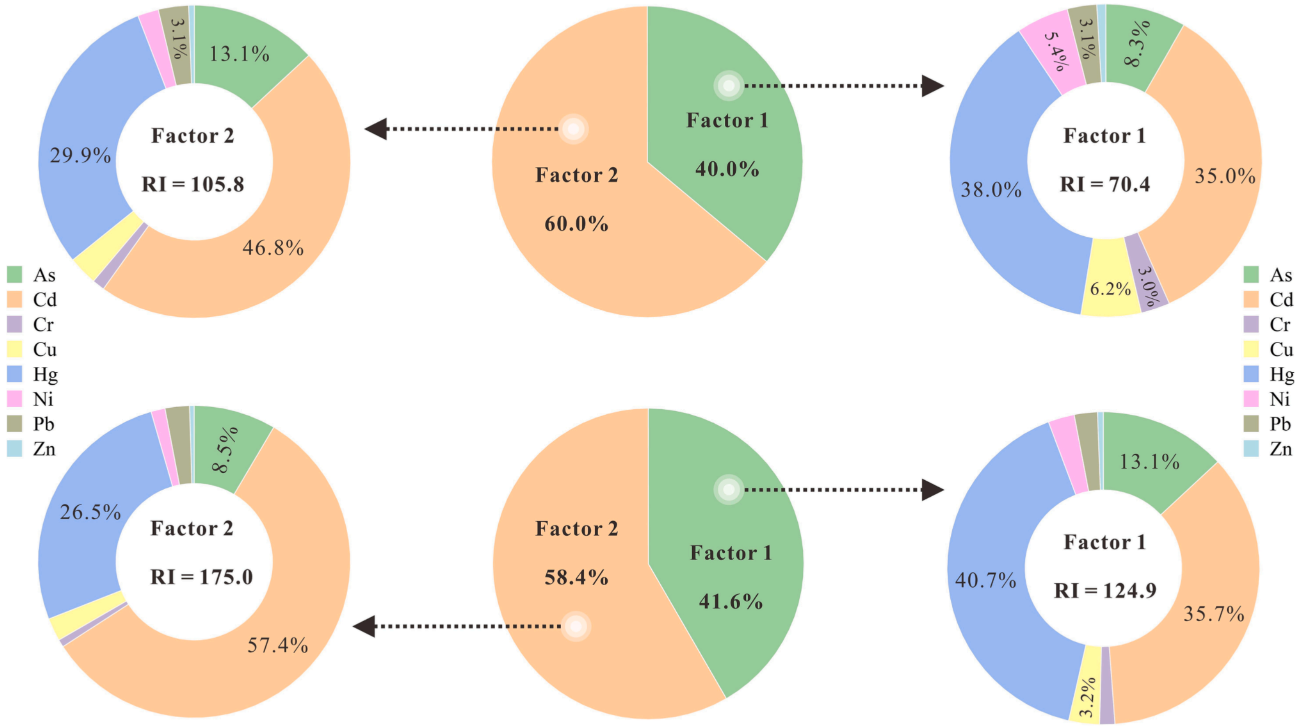

Fig. 7. Contribution percentages of different contamination sources and different TMs to RI in the NZD Reservoir (upper part) and the JH Reservoir (lower part).

implementing effective measures to prevent anthropogenic Cd input into the Lancang River basin.

We acknowledge that the outcomes of our study might be subject to bias given the limited spatial and temporal coverage of our samples. Future research with more extensive and frequent sampling is crucial for a better understanding of the influences of natural processes and anthropogenic activities on TMs in cascade reservoirs. These insights are crucial for effective TM contamination prevention, control, and sustainable water resource planning, especially in the context of rapid urbanization and industrialization.

CRediT authorship contribution statement

Zhenjie Zhao: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition. **Shehong Li:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Yunlong Li:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2024.130755.

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