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Dam construction reshapes heavy metal pollution in soil/sediment in the three gorges reservoir, China, from 2008 to 2020

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Dam construction interfered with the original environment of the river system and greatly affected the geochemical behaviors of trace metals. Thus, a set of toxic metals of Cr, Ni, Cu, Zn, As, Cd, Pb and Hg in soil/sediment of the Three Gorges Reservoir (TGR) during the period of 2008–2020 were analyzed and summarized. The results showed that levels of trace metals (except Cr) were apparently higher than the soil background in the TGR and China, in which Cu, Zn, As, Cd, Pb and Hg corresponded to the moderately to highly contaminated grade. As expected, most trace metals (except Ni and As) were observed an evident increase after the full impoundment stage of 2008–2014, suggesting the dam construction of the TGR that promoting the sediment adsorption effects for trace metals. For spatial patterns, metal levels largely depended on the sampling sites, that intensive anthropogenic activities might well be the primary contributors. Main stream with higher concentrations of trace metals in comparison with tributaries reflected the larger loads of metal pollution. In the water-level-fluctuating zone, hydrological regime induced by damming played a critical role on the redistribution of trace metals through eroding soil/sediment particles or bedrocks and altering the physiochemical characteristics and vegetation coverage of soil/sediment. Finally, submerged sediment seemed as a major sink of trace metals that had greater concentration than that in the water-level-fluctuating zone.

KEYWORDS

dam construction, heavy metals, soil, sediment, three gorges reservoir

1 Introduction

Dam construction can evidently alter the original environment of riverine systems, such as flow velocity, hydraulic retention time, sediment discharge, primary productivity, nutrient retention and reoxygenation capacity, and ultimately regulate the accumulation, distribution, and transportation of toxic metals (Maavara et al., 2020; Bing et al., 2022). In the aquatic environment, sediment is not only a large pool for heavy metals, but also a habitat and food source for benthic fauna (Miranda et al., 2021). Toxic metals would be bioaccumulated and bioamplified through the food chain and end up in the diet of humans (Gurung et al., 2018; Hajri et al., 2022). Thus, it is of great significance to pay attention to heavy metal pollution in reservoirs.

The Three Gorges Reservoir (TGR) is the world's largest hydroelectric project. Since 2008, the water level has varied from the base level elevation of 145 m in the period of

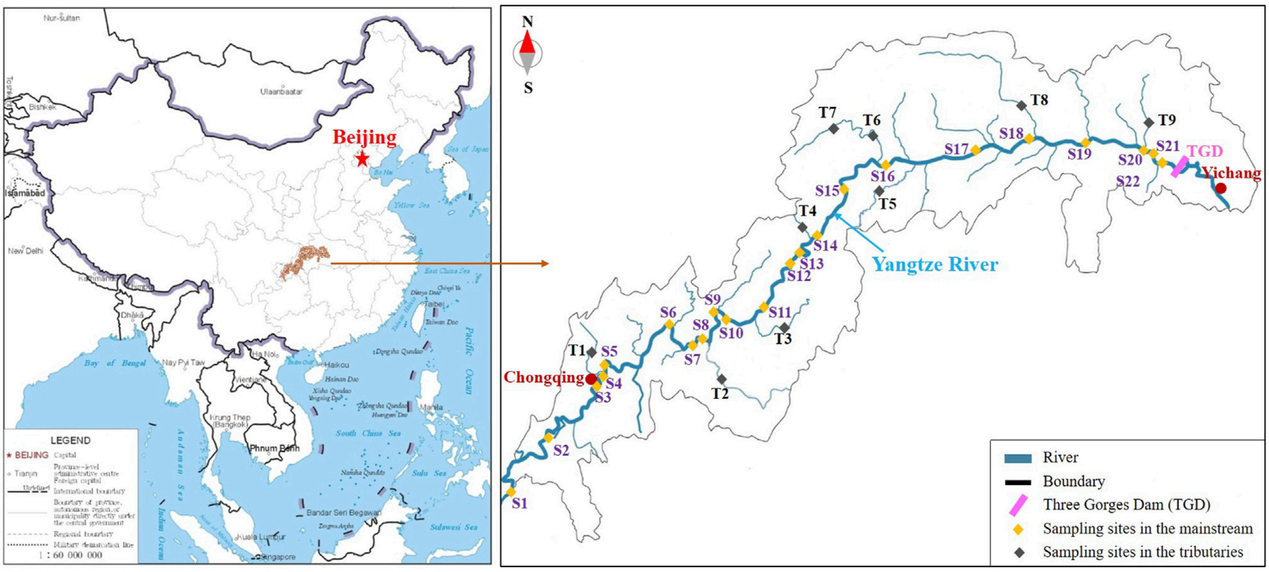

FIGURE 1
Location of the TGR (S1-S22 and T1-T9 represented the sampling sites that had statistical concentrations of trace metals in this study).

water drawdown to the high level elevation of 175 m in the period of storage (Chen et al., 2013). A water-level-fluctuating zone (WLFZ) 30 m in altitude (accounting for 55% of the total flooded area) is annually subject to shifting wetness and red-ox conditions that plays a vital role on the behaviors of heavy metals (Wang and Zhang, 2013; Eckley et al., 2015). The desiccation of the sediments in summer tends to form Fe/Mn oxides and/or hydroxides to adsorb metals (e.g., Cd, Cu, Pb and Zn), whereas the rewetting of the sediment reduces Fe/Mn oxides and/or hydroxides, thereby releasing the heavy metals adsorbed on them (Zhu et al., 2019). For another, secondary geological disasters and soil erosion generated by periodic flooding, as well as strong human disturbances (e.g., agricultural activities) probably leaded to the migration of accumulated sediments in the WLFZ to increase metals in the overlying water (Bao et al., 2015; Gao et al., 2016; Wang et al., 2017). Thus, heavy metal pollution in the TGR after impoundment has been concerned (Guo et al., 2021; Bing et al., 2022; Dong et al., 2022). From the perspective of previous researches, trace metals such as Cd, Pb, and Zn in the sediments reached a moderate or even high contaminated degree after impoundment of the TGR (Wang et al., 2017; Gao et al., 2019; Zhu et al., 2019; Bing et al., 2022). However, the majority of these studies mainly considered a limited spatial scale (or study unit) or short time scale, so that large-scale and long-term spatial variations are still unclear. To address these problems, concentrations of trace metals in soil/sediment in previous studies during the period from 2008 to 2020 were summarized and analyzed. The primary objectives of this article were to, 1) assess the contamination state of heavy metals in soil/sediment from the TGR; 2) investigate the spatial and temporal distribution for heavy metals in soil/sediment from the TGR; 3) better understand the impact of the hydrological regime on the redistribution of heavy metals.

2 Materials and methods

2.1 Study area

The region of the TGR (28°28′-31°44′N, 105°49′-110°12′E) covers a number of counties and cities in Chongqing and Hubei Province (Figure 1), with a total water surface area of 1,080 km^2 and a storage capacity of 39.3 billion m^3 (Bing et al., 2022). This area experiences a humid subtropical monsoon climate, with rainfall focused on April to October. During the period of 2003–2020, the annual average air temperature and rainfall are 18°C and 1,127 mm, respectively. The information about pollutant discharges (e.g., industrial effluents, urban sewage, fertilizer usage, ship sewage) were shown in Supplementary Figure S1.

2.2 Data sources

Data used in this study were all obtained from previous studies Supplementary Table S1 and Supplementary Table S2.

2.3 Statistical analysis

The calculation method for the geo-accumulation index (I_{geo}) was provided in Supplementary Material. Statistical analysis was performed using SPSS software (version 25) for Windows. Mann-Whitney U test, *t*-test and Kruskal–Wallis test were employed to compare significant difference between paired or unpaired samples. Pearson correlation coefficient were computed for different heavy metals. Significant differences were all declared at $p < 0.05$.

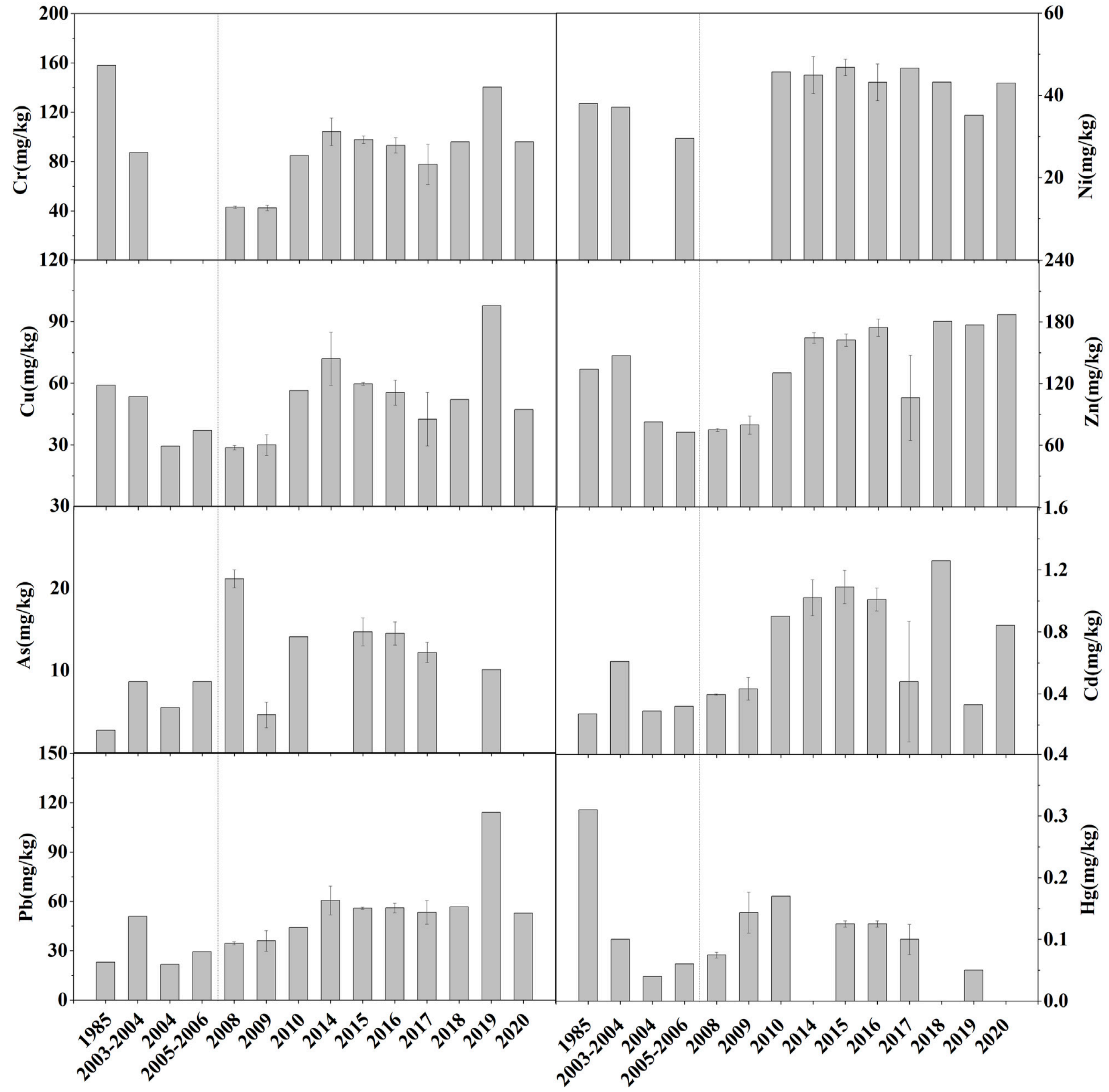

FIGURE 2
The temporal distribution patterns of heavy metals in soil/sediment from the TGR.

3 Results and discussion

3.1 Levels of trace metals

The average concentrations of trace metals in the TGR from 2008 to 2020 were 74.8 mg/kg (Cr), 42.2 mg/kg (Ni), 51.2 mg/kg (Cu), 126 mg/kg (Zn), 12.1 mg/kg (As), 0.77 mg/kg (Cd), 44.1 mg/kg (Pb) and 0.13 mg/kg (Hg), respectively (Supplementary Table S3). The levels of most heavy metals (apart from Cd and Hg) exceeded the threshold effect concentration (TEC) indicating risks of adverse effects, whereas all trace metals were below the probable effect concentration (PEC) (Macdonald et al., 2000). The mean value of Cr (74.8 mg/kg) was basically consistent with the soil background in the TGR, which mainly came from the crust and rocks (Chen et al., 2011). Levels of Ni, Cu, Zn, As, Pb and Hg were 2-3 times higher than the soil background values in the TGR and China, and Cd was 6-7 times higher (Wei et al., 1991; Tang et al., 2008). Based on the average I_{geo} values (Supplementary Figure S2), the increasing order was Cr (−0.75) < Ni (−0.09) < Pb (0.11) < Zn (0.19) < Cu (0.28) < As (0.31) < Hg (0.63) < Cd (1.63). It implied that Cr and Ni had no contamination, while Pb, Zn, Cu, As, Hg and Cd contaminated soil/sediment mildly to moderately. Parts of I_{geo} values for Cd ranged 3 to 5, reflecting

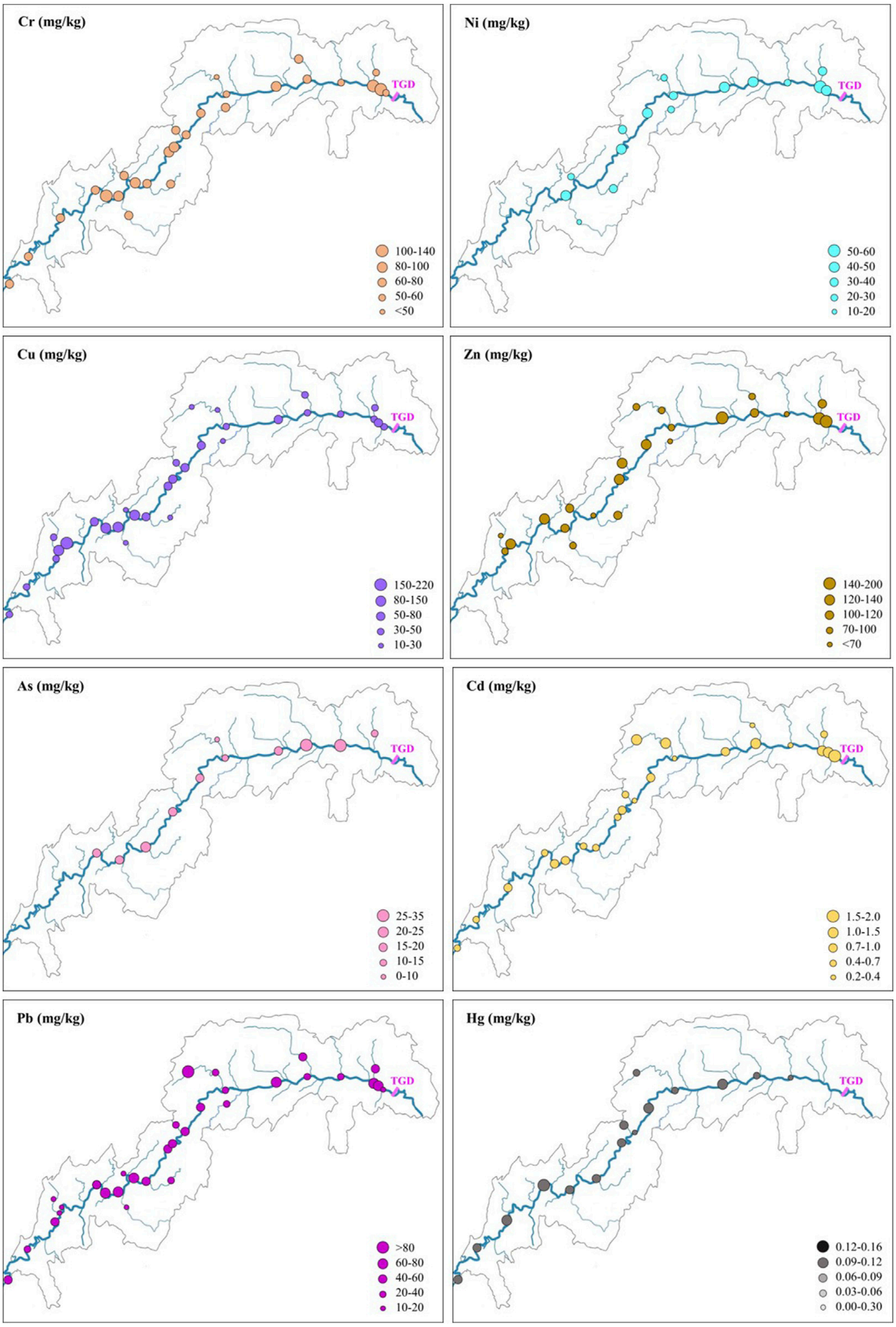

FIGURE 3
The Spatial distribution patterns of heavy metals in soil/sediment of the TGR from 2008 to 2020.

highly to extremely polluted levels. The labile percentage of Cd with high bioavailability was reported to exceed 50%, followed by Zn (10%–20%), Cu (5%–15%), Pb (around 5%), Ni (<5%) and Cr (<1%) (Bing et al., 2022). Thus, Cd was the most polluted metal in the TGR, which is the key factor of ecological risk in the TGR (Gao et al., 2019; Bing et al., 2022).

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3.2 Temporal and spatial variations of heavy metals

Most trace metals (except Ni and As) in soil/sediment were observed an evident increase after the full impoundment stage of 2008–2014, and then showed dynamic fluctuation change (Figure 2). Despite the high levels of Cr and Hg were observed in 1985, this might be attributed to the difference of sampling sites (Xu et al., 1999). In comparison with the monitoring data before impoundment, the concentrations of all trace metals have increased to some extent, especially As and Cd were about doubled (Figure 2). This might be attributed to the dam construction of the TGR that promoting the sediment adsorption effects for trace metals (Wei et al., 2016; Bing et al., 2022). After impoundment, notable decreased water flow velocity and increased water retention time accelerated the sinking process of suspended particulate matter and attached heavy metals (Wang et al., 2017; Bing et al., 2022). Moreover, the effects of damming on river ecosystems are long-lasting and likely to persist for few decades (Porvari, 1998; Bodaly et al., 2007). The correlation analysis for Cu, Zn, Cd and Pb clearly identified a consistent positive correlation with each other (Supplementary Table S4, $p < 0.05$), and studies have shown that they were primarily from industrial effluents or intensive fertilizer use (Chen et al., 2011; Zhu et al., 2019; Shui et al., 2020). Meanwhile, Pb was confirmed to come from ore mining and smelting, coal combustion, aerosols and traffic exhaust by isotope ratios (Bing et al., 2016; Zhu et al., 2019). Ni generally had a close correlation with all other trace metals ($p < 0.05$), indicating diverse sources.

For spatial patterns, metal contents largely depended on the sampling sites (Lin et al., 2020). There were no obvious changing trends for trace metals from upstream to the Three Gorges Dam (TGD) (Figure 3). In previous studies, the concentrations for some trace metals in the soil/sediments generally appeared a rising trend towards the dam, suggesting the "self-purification" of the reservoir (Gao et al., 2019; Zhu et al., 2019; Lin et al., 2020; Bing et al., 2022), whereas the opposite result was simultaneously discovered (e.g., Cd) (Zhu et al., 2019). In the upper section, most metals (Cu, As, Cd, Pb and Hg) had relatively low levels in S1 and S2 (Figure 3). But in and around the main urban area of Chongqing City with intensive human activities, Cr, Cu, Zn, Pb and Hg exhibited comparatively high values (Figure 3). Traffic exhaust and industrial effluents were recognized as the main sources, reflecting anthropogenic effects on trace metal contamination in sediments (Chen et al., 2011). After that, agricultural activities and animal husbandry industries probably contributed to the metal accumulation in the soil/sediment of the middle section (Bing et al., 2022). Near the dam, high values were observed for some trace metals (e.g., Cr, Cd, Zn and Pb) that might be connected with the high geological background levels in the host rock (limestone) (Bing et al., 2022). Furthermore, the average concentration of trace metals in the soil/sediment of the main stream was commonly higher than that of the tributaries (Supplementary Figure S3), indicating the higher metal pollution inputs in main stream (Gao et al., 2015; Gao et al., 2019). The concentrations of Ni, Cu and Zn were found significant differences between main stream and tributaries (Supplementary Figure S3, Mann-Whitney U test, $p < 0.05$).

3.3 Impact of the hydrological regime on heavy metal distribution

The water level scheduling mode of "impoundment in winter and effusion in summer" in the TGR created a WLFZ with a total area of 349 km^2 (Bao et al., 2015). The WLFZ demonstrated spatially diverse patterns that responded differently to hydrological regimes. There were three common types (Supplementary Table S5), of which type 1 and type 2 represented the most dynamic part of the TGR disturbance zone. Type 1 (the gradient less than 15°) comprised of purple and red rocks and a generally thick soil layer with sparsely distributed vegetation, and type 2 consisted of the lower section that similar to type1 and the upper section that had shallow soil layer with the gradient greater than 25° (Bao et al., 2015). During the warm season, rills and gullies generated by overland flow during storm events were scattered throughout these areas so that erosional particulates attached to heavy metals flowed into the water and deposited in sediments (Bao et al., 2015; Zhu et al., 2019). Type 3 (the gradient greater than 45°) was relatively stable that dominated by bedrocks with a thin layer of bare soils (Zhang et al., 2009; Bao et al., 2015). The cycling rising and falling of water level could bring about rockfalls and bedding landslides that rock-forming elements were significantly correlated with heavy metals in submerged sediments of the TGR (Chen et al., 2011; Bing et al., 2016; Zhu et al., 2019). Hence, different WLFZ patterns affected the spatial distribution of trace metals in the TGR.

In the WLFZ, the distribution patterns of heavy metals with water level elevation were ambiguous (Supplementary Figure S4). No significant differences were observed among three kinds of water level elevations (145–155 m, 155–165 m and 165–175 m) for all trace metals (Kruskal–Wallis test, $p > 0.05$). As a whole, concentrations of trace metals in soil/sediment in the submerged zone (SUB) were all higher than those in the WFLZ (Figure 4). Levels of Cr, Cu, Zn and Pb showed statistically significant difference between the SUB and the WFLZ (*t*-test, $p < 0.05$). During the low water-level period, soil/sediment in the WLFZ suffered from the intensive anthropogenic activities (e.g., improper agricultural activities, industrial and residential wastes) encouraged the enrichment of heavy metals, but contaminants were likely transferred through the complex geochemical process (e.g., soil erosion or flushing effects of wet deposition), and ultimately accumulated in the sediments (Gao et al., 2016; Wang et al., 2017). Thus, submerged sediment seemed to act as a major sink of heavy metals.

Hydrological regime brought great changes to the WLFZ and affected the redistribution of various pollutants (e.g., heavy metals). Firstly, the drought-rewetting cycles controlled the physiochemical characteristics of soil/sediment, such as pH, oxidation-reduction potential (OPR), organic matter, particle size, element contents, the functional groups and crystal structure (Lin et al., 2018; Pei et al., 2018; Fu et al., 2020). The contents of NO_3^--N, pH and element (except C element)

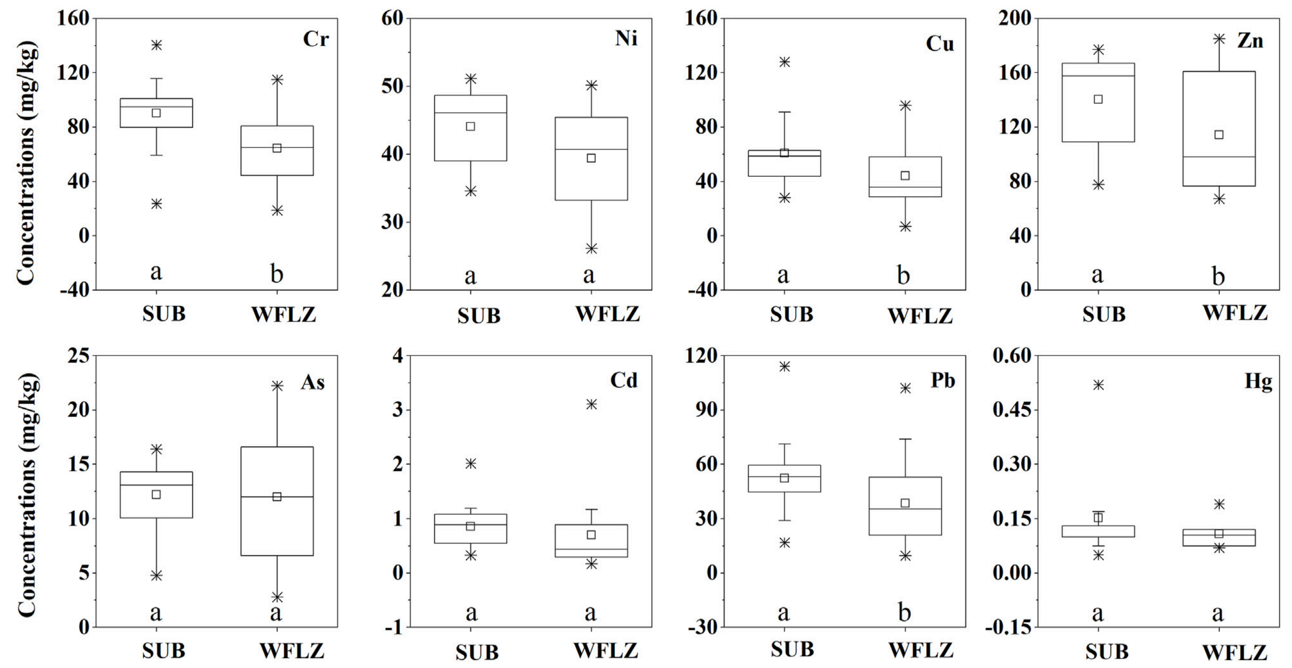

FIGURE 4
Concentrations of heavy metals in soil/sediment in submerged zone (SUB) and water-level-fluctuating zone (WFLZ) of the Three Gorges Reservoir from 2008 to 2020 (" ", the minimum and maximum value; " ", mean value; "——", mid-value; a and b show significant levels after *t*-test; the data sets were log-transferred when they were not normal.).

in sediment were discovered to increase with the elevation of water level, whereas the OPR, TC, TN, C/N, NH_4^+-N, clay, silt and some trace metals (e.g., Cr, Cd, Cu and Pb) simultaneously decreased (Lin et al., 2018; Fu et al., 2020). Moreover, the Fourier transform infrared spectroscopy (FTIR) spectra of sediments were significantly different at various lateral altitudes, suggesting diverse active functional groups (like hydroxyl), some of which were susceptive to heavy metal ion binding (Fu et al., 2020). Due to rainfall runoff and riverbank erosion, sediment in lower altitude frequently tended to be coarser, more porous, and had a higher ratio of silt to clay componence (Tang et al., 2016; Wang et al., 2016; Lin et al., 2018). Particularly, there are more crystalline minerals in fine and silty sand that allows heavy metal contaminants to be easily adsorbed and fixed on mineral surfaces (Maity and Maiti, 2016; Fu et al., 2020). Additionally, plant diversity and species richness decreased markedly under the long-term periodic hydrodynamic disturbance (Ye et al., 2020). The flooding-tolerant plants survived to become the dominant species, and differed significantly at different elevations in some belt transects (e.g., Zhong County, Kaizhou and Xiangxi river) (Yin et al., 2020; Zhu et al., 2020). The vegetated area presented an upward trend with increasing water level elevation (Zhu et al., 2020). Here plants have been recognized as an important contributor to heavy metals in soil/sediment, and their well-developed root systems were primarily responsible for the uptake and accumulation of pollutants (Hall and St. Louis, 2004; Wang et al., 2022). During the high water-level period, flooded plants decomposed to aggravate anaerobic states and release nutrients that altered the morphology and bioavailability of heavy metals (Hall and St. Louis, 2004; Yin et al., 2020). However, microbial community properties of soil/sediment seemed to be less affected by the hydrological regimes, suggesting that microbes were more resilient than plants (Ye et al., 2020).

4 Conclusion

Levels of trace metals were apparently higher than the soil background values in the TGR (except for Cr) and China, in which Cd was the most polluted metal in the TGR. The dam construction of the TGR promoted the sediment adsorption effects resulting in an evident increase for trace metals (except Ni and As) after the full impoundment. Intensive anthropogenic activities largely contributed to the trace metals of soil/sediment from upstream to dam, and higher metal pollution inputs were found in the main stream. In the WLFZ, hydrological regime altered the physiochemical characteristics and vegetation coverage of soil/sediment, disrupting the distribution of heavy metals. Ultimately, trace metals were accumulated in submerged sediment resulting greater concentration than that in the WLFZ.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

QX: Conceptualization, Data curation, Methodology, Writing–original draft. KZ: Supervision, Validation, Writing–review and editing. BW: Funding acquisition, Writing–review and editing.

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Conflict of interest

KZ was employed by Shanghai Municipal Engineering Design Institute (Group) Co. Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1269138/full#supplementary-material

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