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Sedimentation and associated trace metal enrichment in the riparian zone of the Three Gorges Reservoir, China

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HIGHLIGHTS

- Sedimentation and associated trace metal enrichment in the riparian zone were preliminarily studied.
- Significant sedimentation and enrichment of trace metals in the riparian sediments were observed.
- Sedimentation and concentrations of trace metals demonstrated spatial variance with elevation.
- The hydrologic regime principally influenced sediment redistribution and trace metal enrichment.

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ABSTRACT

Impoundment of the Three Gorges Reservoir has created an artificial riparian zone with a vertical height of 30 m and a total area of 349 km^2, which has been subjected to seasonal inundation and exposure due to regular reservoir impoundment and the occurrence of natural floods. The significant alteration of hydrologic regime has caused numerous environmental changes. The present study investigated the magnitude and spatial pattern of sedimentation and metal enrichment in a typical section of the riparian zone, composed of bench terraces with previous agricultural land uses, and explored their links to the changed hydrologic regime. In particular, we measured the total sediment depths and collected surface riparian sediments and down-profile sectioned riparian soils (at 5 cm intervals) for trace metal determination. Our analysis showed that the annual average sedimentation rates varied from 0.5 to 10 $cm \cdot yr^{-1}$ and they decreased significantly with increasing elevation. This lateral distribution was principally attributed to seasonal variations in water levels and suspended sediment concentrations. Enriched concentrations of trace metals were found both in the riparian sediments and soils, but they were generally higher in the riparian sediments than in riparian soils and followed a similar lateral decreasing trend. Metal contamination assessment showed that the riparian sediments were slightly contaminated by Ni, Zn, and Pb, moderately contaminated by Cu, and moderately to strongly contaminated by Cd; while riparian soils were slightly contaminated by As, and moderately contaminated by Cd. Trace metal enrichment in the riparian sediments may be attributed to external input of contaminated sediments produced from upstream anthropogenic sources and chemical adsorption from dissolved fractions during pure sediment mobilization and after sink for a prolonged flooding period due to reservoir impoundment.

1. Introduction

The riparian zone generally refers to all stream-adjacent geomorphologic features (e.g., river banks, floodplains, lateral benches, point bars, and islands) that may be inundated or saturated by fluvial overbank discharges (Hupp and Osterkamp, 1996). Geomorphologic evolution of the riparian landforms depends heavily on the dynamic equilibriums between bank erosion and sediment accretion controlled by the interactions between channel morphology (e.g., planform and topography), bank composition (e.g., substrate type and vegetation presence), fluvial hydrodynamics (e.g., local stream hydraulics and sediment regime) and human disturbances (e.g., cultivation, grazing, sand dredging, and dam construction) (Gurnell et al., 2001; Steiger and Gurnell, 2003).

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Laterally, the riparian zone serves as an ecotone between local terrestrial and aquatic ecosystems with sharp gradients in environmental variables (Gregory et al., 1991; Naiman and Decamps, 1997), which provides multiple ecosystem benefits, such as bank stabilization (Pollen, 2007), biodiversity conservation (Mander et al., 2005), retention of upland diffuse sediment and agricultural pollutants (Collins et al., 2010; Pearce et al., 1998; Salemi et al., 2012), and runoff regulation (Herron and Hairsine, 1998; Salemi et al., 2012). Longitudinally, it forms an ecological corridor with a specific vegetation composition and distribution (Nilsson and Svedmark, 2002), which filters fluvial suspended sediment and aquatic contaminants through sedimentation processes during flood events when the riverine discharge enters the riparian zone, as well as significantly reduces in-channel delivery of terrestrial materials (e.g., organic compounds, nutrients, trace metals; Noe and Hupp, 2009; Steiger and Gurnell, 2003; Walling and Owens, 2003).

The riparian zone exists either in unmanaged river channels shaped by the natural water level fluctuations or within dammed reaches primarily affected by reservoir impoundment (de Alcantara et al., 2004). Previous studies have primarily focused on the various aspects of natural riparian zones, such as geomorphologic delineation (Clerici et al., 2013; Gurnell et al., 2001; Verry et al., 2004), hydrologic influence (Brosofske et al., 1997; Wantzen et al., 2008), vegetation colonization (Hupp and Osterkamp, 1996), biogeochemical interaction (Smith et al., 2012; Zhang et al., 2012), ecological services (Sparovek et al., 2002; Stutter et al., 2012) and many interacting processes (Gregory et al., 1991; Gurnell et al., 2012; Osterkamp and Hupp, 2010; Polvi et al., 2011). However, dam effects on the hydrological and biogeochemical processes in reservoir riparian zones may be much more complicated due to the marked alteration of hydrologic regimes varying considerably with the specific modes of dam operation. The construction of increasing numbers of dams on Asian rivers (particularly, large cascade dams on the main stem and major tributaries of the Upper Yangtze River in China) calls for a better understanding of how dam regulation affects the individual processes in the reservoir riparian zones and what these effects mean for reservoir management.

The Three Gorges Reservoir in China intercepts the main channel of the Yangtze River at the outlet of the upper sub-basin and controls a drainage area of nearly 1.0×10^6 km^2. The full reservoir impoundment with the storage capacity of 39.3 billion m^3 in 2009 has created an artificial riparian zone with a vertical height of 30 m and a total area of 349 km^2. A series of post-dam environmental changes in the riparian zone has been documented as a primary response to the dramatic change of hydrologic regime (Fu et al., 2010; Xu et al., 2013; Zhang and Lou, 2011). The magnitude and spatial patterns of sedimentation and trace metal enrichment in the riparian zone after full impoundment of the reservoir have been inadequately studied, and their links to the highly dynamic hydrologic regime are still not well understood. The present study attempts to fill this gap by determining the total sediment depths and collecting both surface riparian sediments and deeper riparian soils for trace metal measurement in a typical section of the riparian zone in the middle reaches of the Three Gorges Reservoir. Specifically, we (1) determined the magnitude and spatial distribution of sedimentation and the concentrations of trace metals in the riparian sediments and soils; (2) assessed the enrichment status of trace metals in both riparian sediments and soils; and (3) revealed the links between sedimentation and trace metal deposition in the riparian zone and the specific hydrologic regimes.

2. Materials and methods

2.1. Study area

The Three Gorges Reservoir extends 660 km upstream from Yichang to Chongqing along the main channel of the Upper Yangtze River and its tributaries (Fig. 1a). The region is characterized by arrays of rolling hills and valleys. The riparian zone is typically composed of bench terraces on valley slopes previously used as farm lands. One such typical riparian zone, located at Zhong County in the middle section of the Three Gorges Reservoir (geographically at 30°26′N, 108°11′E), was selected as study area. The area is covered by sandstones, siltstones and mudstones of the Jurassic Shaximiao Group (J2s), mixed with widely distributed "purple soil", which is the early weathering products of the Jurassic rocks. The purple soil contains 18% clay, 30% silt and 52% sand and is classified as an Orthic Entisol in the Chinese Soil Taxonomic System, a Regosol in the FAO Taxonomy and an Entisol in the USDA Taxonomy (He et al., 2009). The average soil pH is 6.2 ± 0.9 (mean value $\pm$ standard error, the same applies to all following values) and the average water content is 20.0 ± 0.7% (Ye et al., 2012). The vegetation in the riparian zone is dominated by annuals, such as *Setaria viridis*, *Digitaria ciliaris*, and *Leptochloa chinensis*, perennials, such as *Cynodon dactylon*, *Hemarthria altissima*, and *Capillipedium assimile*, and woody plants, such as *Ficus tikoua*, *Pterocarya stenoptera*, and *Vitex negundo* (Ye et al., 2012). The regional mean annual temperature and precipitation are 18.2 °C and 1172 mm, respectively, and a major proportion of precipitation occurs in the rainy season from May to September (Wang et al., 2012).

2.2. The hydrologic regime

Designed for multiple purposes of hydropower production, flood mitigation and navigation improvement, the Three Gorges Reservoir has adopted an operational strategy termed as "impounding clear water and discharging turbid water" (Zhang and Lou, 2011). According to this strategy, the reservoir is impounded to the maximum level of 175 m in the dry season (October–April) for energy generation and subsequently emptied to the base level of 145 m in the rainy season (May–September) for flood control. Before its full operation in 2009, there were three stages of water impoundment to different heights. The water level was first raised to 135 m in 2003, followed by increases to 156 m and 172 m in 2006 and 2008, respectively (Fig. 2).

Reservoir impoundment has turned the natural river flow of the dammed reaches into a man-made lacustrine regime (Xu et al., 2011). A typical hydrologic year was created that consists of four stages: (1) increasing water level due to water filling, (2) an approximately constant maximum level around 175 m at the full impoundment, (3) decreasing water level due to reservoir emptying, and (4) high variable water levels caused by natural floods around the base level of 145 m. During the 2009–2010 hydrologic year (i.e., the first full operation cycle), reservoir filling began on 15th September 2009, and the water level was increased from 146.4 m to 171.4 m by 25th November 2009 (71 days of impoundment length), with a daily average increase rate of 0.35 m·d^{-1}. The water level consistently decreased to 153.7 m by 11th April 2010 (138 days in length), with a daily average decease rate of 0.13 m·d^{-1}. Several natural floods occurred in the rainy season, which disturbed the falling limb of the hydrograph and caused several local water-level peaks, with the highest one reaching 162.3 m.

2.3. Sampling and data acquisition

In this study, we refer suspended sediments as those collected from the water regime, riparian sediments as those collected on the riparian surfaces, and riparian soils as the down-profile original soils in the riparian zone. Field sampling was conducted along five representative transects in the August 2010 when the water level remained almost around the base level such that the riparian zone was mostly exposed and had experienced one complete cycle of water level fluctuation. Along each transect, sampling plots of 1×1 m grids were selected based on the topographic variation (Table 1, Fig. 1b). These sampling plots were on flat terraces at different elevations and covered the entire studied riparian zone. The boundary between riparian sediments and soils was identified by comparing the vertical and horizontal compositions (color and texture) of the profiles with those in locations with

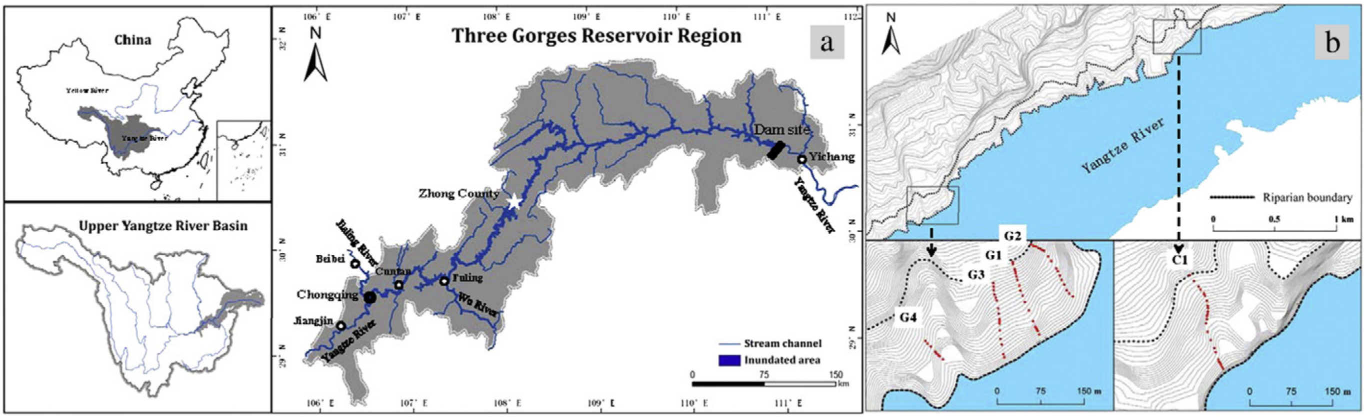

Fig. 1. (a) A sketched map of the Three Gorges Reservoir in the upper Yangtze River Basin; and (b) location of sampling transects in the studied riparian zone.

no distinguishable riparian sediments (Fig. 3; Belyaev et al., 2005). At each sampling plot, the thickness of the riparian sediments was identified first and then its total depth was measured using a vernier caliper. The values of these depths were then used, together with the average bulk density of 1300 $kg \cdot m^{-3}$ in the Yangtze River (Li et al., 2011) and the adjustment for elevation-dependent durations of sedimentation, to calculate the annual average sedimentation rates. Riparian sediments (less than 10 cm in depth) and down-profile sectioned riparian soils (upper soils from 0 to 5 cm and lower soils from 5 to 10 cm) in individual plots were sampled randomly with a plastic shovel and mixed to form a composite sample. A total of 27 composite samples were obtained. In addition, 4-hour integrated suspended sediment samples at Beibei (the outlet of the upstream tributary Jialing), Jiangjin (the outlet of the Yangtze mainstream upstream of the reservoir), Fuling (the backwater reach of the reservoir) and Zhong (the study area) were collected on-site using a centrifugal sampler (Cao and He, 2013). All samples were sealed in polyethylene bags and brought back to the laboratory, air-dried at room temperature, manually disaggregated, and sieved through a 2 mm sieve.

The daily water level data for the Three Gorges Reservoir were obtained from the China Three Gorges Corporation (www.ctgpc.com.cn). The monthly averaged data on the suspended sediment concentration at Cuntan were calculated using the water discharge and sediment load data provided by the Yangtze River Water Conservancy Committee of the Ministry of Water Resources of China.

2.4. Laboratory analysis

Absolute grain size distribution measurements were performed by laser diffraction granulometer (Malvern Mastersizer 2000) on riparian sediments and soils as well as suspended sediments. Before measurement, all samples were pre-treated with hydrogen peroxide to remove the organic fraction and dispersed with hydrochloric acid. The percentages of particle sizes in terms of clay, silt and sand were calculated. The concentrations of trace metals (Cr, Ni, Cu, Zn, As, Cd and Pb) were determined using flame atomic absorption spectrometry (FAAS) following direct digestion using aqua regia (1 part HNO_3 to 3 parts HCl) (Allen, 1989). The measurement accuracy was assessed by analyzing standard reference materials. The organic matter was measured after $K_2Cr_2O_7$–H_2SO_4 low-temperature digestion using an UV/visible spectrophotometer (Lu, 1999). The carbonate content was measured as the weight difference after ignition in a furnace at 550 °C for 4h and then at 850 °C for 1 h (Dean, 1974). All the standard solutions were prepared from analytical grade compounds. For quality control, blank and duplicate

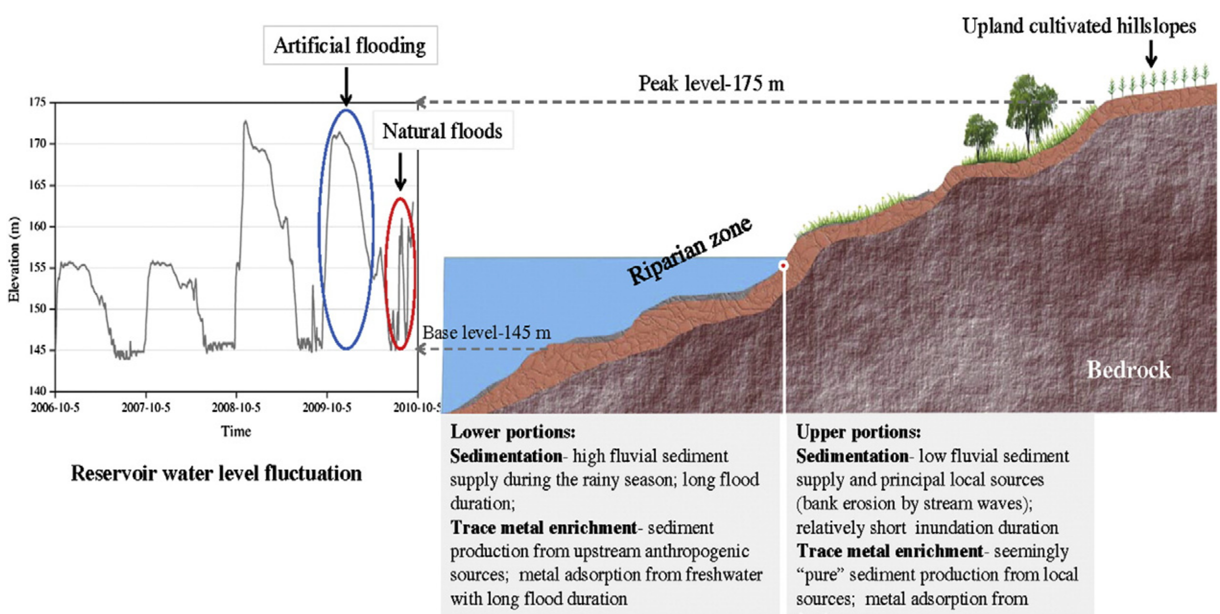

Fig. 2. The changes in water level by regular dam operation since 2006 in the riparian zone, as well as the contrasting processes of sedimentation and trace metal enrichment at different portions of the riparian zone were illustrated.

Table 1
Summary of the characteristics of the selected transects in the studied riparian zone.

Transect no.	Sampling plots	Sample numbers	Slope gradient	Previous land use	Vegetation
G1	18	Sediment: 5 Soil: 36	3–8	Paddy field	*Paspalum distichum* L.
G2	17	Sediment: 2 Soil: 34	4–10	Paddy field	*Hemarthria compressa* (L.F.) R. Br.
G3	16	Sediment: 5 Soil: 32	3–14	Dry land	*Cynodondactylon* (Linn.) Pers.
G4	8	Sediment:8 Soil: 16	3–9	Dry land	Mixed
C1	25	Sediment: 7 Soil: 56	2–12	Paddy field	Mixed

samples were analyzed in each analysis batch. Replicate samples were made for all extractions and analyses and the average values were used in the calculations. The analytical results based on quality control indicated a satisfactory performance for trace metals and organic matter determinations, with overall uncertainties varying between 5% and 15%.

2.5. Contamination assessment

The degree of trace metal contamination was assessed by comparing the measured metal concentrations of sediments and soils with their background levels (defined as the concentrations of samples with low anthropogenic influence) to focus on the trace metal enrichment in the riparian after water inundation. The regional background concentrations in soils obtained by Tang et al. (2008) through extensive sampling and statistical analysis were adopted in this study as the background levels (Table 3).

Based on these concentrations, the Geoaccumulation index (I_{geo}) developed by Müller (1969) was calculated to assess the contamination degree of trace metals in sediments and soils in the riparian zone using the following equation:

$$I_{geo} = Log_2\left(\frac{C_i}{1.5B_i}\right) \quad (1)$$

where C_i and B_i are the measured concentration and the associated background value for metal i, respectively. The I_{geo} includes 7 grades (Table 2) based on the ranges of the calculated values (Ghrefat et al., 2011).

The potential ecological risk index (RI) proposed by Hakanson (1980) was used to evaluate the trace metal contamination from the perspective of sedimentology by considering the potential toxic effects of the trace metals on exposed organisms:

$$RI = \sum_{i=1}^{n} E_{ri} = \sum_{i=1}^{n} T_{ri}C_{fi} = \sum_{i=1}^{n} T_{ri}\frac{C_i}{C_{bi}} \quad (2)$$

where E_{ri} is the individual coefficient reflecting the potential ecological risk for metal i, T_{ri} is the toxicity response coefficient for metal i, C_{fi} is the contamination factor for metal i, C_i is the measured concentration for metal i, and C_b is the background value for metal i. T_{ri} accounts for both the exposure level and the potential toxic response effect, and has been established as 2 for Cr, 2 for Ni, 5 for Cu, 1 for Zn, 10 for As, 30 for Cd and 5 for Pb (Ye et al., 2010; Xiao et al., 2013).

3. Results

3.1. Magnitude and lateral distribution of sedimentation in the riparian zone

According to field measurements, detectable sediment deposition in the studied riparian zone mainly occurred within the portion approximately below 167 m. The measured total sediment depths, which reflect the multi-year cumulative sedimentation amounts since the initial water inundation, varied at different elevations from 1.1 to 39.9 cm, with an average of 9.9 cm. The annual average sedimentation rates differed

Fig. 3. A typical view of: (a) the riparian zone composed of bench terraces in the Three Gorges Reservoir; (b) sediment accretion in the riparian zone; and (c) a sediment–soil profile in the riparian zone.

Table 2
Contamination level and potential ecological risk corresponding to the calculated indices.

I_{geo} value	≤0	0–1	1–2	2–3	3–4	4–5	>5
I_{geo} class	0	1	2	3	4	5	6
Contamination level	UC	UC-MC	MC	MC-SC	SC	SC-EC	EC
E_{ri} value	≤ 40	40–80	80–160	160–320	> 320		
RI value	≤ 150	150–300	300–600	> 600			
Ecological risk degree	Minor	Moderate	High	Very high	Serious		

UC: uncontaminated; UC-MC: uncontaminated to moderately; MC: moderately contaminated; MC-SC: moderately to strongly; SC: strongly contaminated; SC-EC: strongly to extremely; EC: extremely contaminated.

from 0.5 to 10 $cm \cdot yr^{-1}$, with an average of 2.7 $cm \cdot yr^{-1}$. The corresponding annual average specific sedimentation rates fell in the range of 6.5–130 $kg \cdot m^{-2} \cdot yr^{-1}$, with an average of 35.1 $kg \cdot m^{-2} \cdot yr^{-1}$. The magnitude of sedimentation demonstrated an elevation-dependent trend — that is, the amount of sedimentation decreased significantly with increasing elevation (Fig. 4). The decreasing trend showed two different linear rates of change that merged at the elevation of approximately 155 m. The total sediment depths in the lower portion of the riparian zone (below the water level of 155 m which represents inundation heights operated during the rainy season) decreased at the rate of 4.1 $cm \cdot m^{-1}$, with an averaged value of 14.9 cm. In the riparian zone of 155–167 m, the decrease rate was 0.2 $cm \cdot m^{-1}$, with a mean sediment depth of 2.6 cm.

3.2. Sediment characteristics and metal contamination assessment

Absolute grain size distribution measurements indicated the dominance of clay and silt fractions, which accounted for 63.6% to 95.0% of the bulk riparian sediment volume, 68.1% to 92.2% of the bulk suspended sediment volume, and 77.0% to 87.6% of the bulk riparian soil volume. The riparian sediments demonstrated a coarser tendency laterally across the riparian zone with the increase of elevation, according to the grain-size compositions (Fig. 5). Suspended sediments retrieved from upstream river channels (Beibei and Jiangjin) and the upper reach of the Three Gorges Reservoir (Fuling) had larger proportions of sand fraction than in the downstream area (Fig. 5). The carbonate content of the riparian sediments ranged between 1.5 and 5.5%, with an average of 3.6%. The organic matter in riparian sediments differed from 1.4 to 2.7%, with an average of 2.0%. Both variables demonstrated elevation-dependent trends. A negative linear correlation existed between carbonate content and elevation, while a positive linear relationship existed between organic matter and elevation (Fig. S1).

The concentrations of trace metals in riparian sediments fell in the ranges of 76.4–106 (92.3 ± 1.3) mg/kg for Cr, 41.4–57.6 mg/kg (49.0 ± 0.7) for Ni, 53.8–102 (80.9 ± 2.0) mg/kg for Cu, 115–189 (163 ± 3.4) mg/kg for Zn, 11.4–20.9 (17.0 ± 0.5) mg/kg for As, 0.60–1.17 (0.91 ± 0.02) mg/kg for Cd and 36.7–81.1 (61.9 ± 1.8) mg/kg for Pb. The concentrations of trace metals in riparian sediments showed an overall decreasing trend with increasing elevation (Fig. 6). All trace metals had relatively higher concentrations in riparian sediments than in the down-profile riparian soils (Table 3), and those in the upper soils (0–5 cm) were generally higher than those in the lower soils (5–10 cm). Significant correlations were obtained for all measured metals in sediments, according to the Pearson's correlation analysis (Table S1).

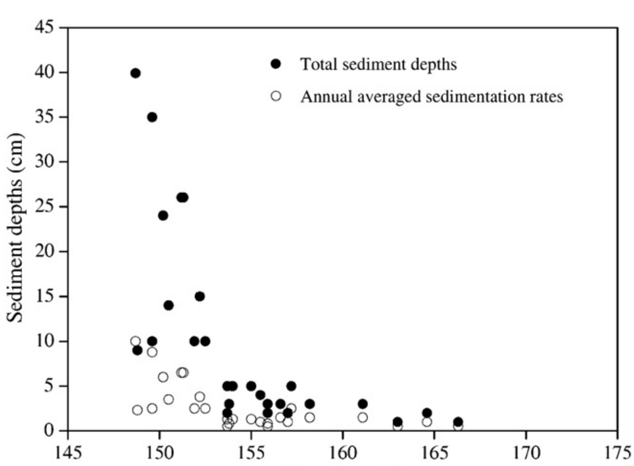

Fig. 4. The observed variation of the total sediment depths and annual average sedimentation rates with elevation in the riparian zone.

The I_{geo} values calculated using Eq. (1) for the riparian sediments, upper soils, and lower soils with contamination categories indicated that riparian sediments were not contaminated by Cr, were slightly contaminated by Ni, Zn and Pb, and were moderately to strongly contaminated by Cu and Cd. Riparian soils were not contaminated by Cr, Ni, Cu, Zn and Pb, were slightly contaminated by As, and were moderately contaminated by Cd (Fig. S2).

Given the same exposure levels, the potential toxic risk of the trace metals to organisms varies considerably with element-specific toxicology. The potential ecological risk index defied by Eq. (2) was used to give a quantitative assessment of the potential detrimental effects of the trace metals in both the riparian sediments and soils on local ecosystem. The degree of potential ecological risk was interpreted according to the calculated E_r value for a specific metal and the integrated RI value for a composite sample. The results indicated that Cr, Ni, Cu, Zn, As and Pb in sediments and soils are a potentially minor risk, whereas Cd is a very high risk in riparian sediments and is a high risk in riparian soils (Fig. S3). The riparian sediments were of moderate risk to the local ecosystems, while the riparian soils represented a minor risk (Fig. S4).

4. Discussion

4.1. Effects of the hydrologic regime on sedimentation in the riparian zone

Sediment storage on riparian landforms is an important attribute of natural river channels, and the magnitude varies spatially with local sedimentary environment and demonstrates high inter-event variability with flood characteristics (Benjankar and Yager, 2012; Nicholas and Walling, 1997; Steiger and Gurnell, 2003). Significant sedimentation has occurred in the riparian zone of the Three Gorges Reservoir since the initial water impoundment, particularly in the lower portions of riparian zone (mainly below water levels operated during the rainy season). Although sedimentation in the reservoir riparian zone may vary longitudinally, our findings that sedimentation rates decreased markedly with increasing elevation can represent a general lateral tendency of sedimentation in the riparian zone. This distribution pattern of sedimentation was performed by contrasting hydrologic processes acting on the entire riparian zone with different elevations. The alteration of hydrologic regime created by regular reservoir impoundment interacting with the natural hydrodynamics of the Upper Yangtze River was responsible for sedimentation and this lateral distribution pattern in the riparian zone.

Understanding the different hydrologic processes occurring at different elevations of the riparian zone requires identifying possible sources supplying sediment to deposition in the riparian zone and

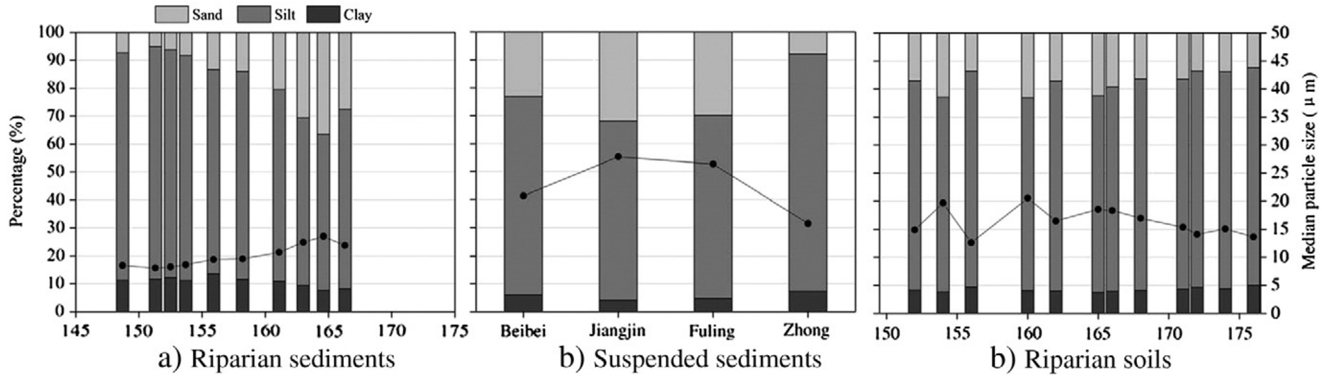

Fig. 5. The absolute grain size distribution of riparian sediments, suspended sediments and riparian soils.

analyzing their seasonal variability in sediment production. Although the contributions of individual sources to sediment deposition in the riparian zone of the Three Gorges Reservoir have not been quantitatively described, we identified three possible sediment provenances that account for sedimentation in the riparian zone: (1) sediment yields longitudinally from major upstream watersheds (remote sources: Jinsha, Min, Jialing, and Wu), (2) sediment production laterally from local uplands and catchments which directly discharged into the Three Gorges Reservoir (regional sources), and (3) sediment generation from bank erosion in the riparian zone (local sources). The former two types of sources mainly occur in association with storm runoffs during the rainy season, while the last source occurs extending the whole hydrologic year due to the occurrence of intensive stream waves triggered by frequent navigations.

Suspended sediment concentrations (SSCs) in the reservoir water regime supplied from the individual provenance areas afford a constraint factor that determines the amounts of riverine sediment available for deposition in the riparian zone. The link between the sedimentation in the riparian zone and fluvial suspended sediment supply can be revealed by the seasonal variations of water levels (inundation heights) and SSCs during the 2009–2010 hydrologic year recorded at Cuntan (Fig. 7). During the rainy season (May to September) when the reservoir water level fluctuated at lower elevations, large quantities of suspended sediment, which are corroborated by high mean monthly SSCs between 0.11 and 1.30 $kg \cdot m^3$, were exported from the upstream watersheds and local uplands by storms. During the dry season (October to April) when the reservoir was impounded towards the maximum level, the mean monthly SSCs varied within a low range between 0.03 and 0.22 $kg \cdot m^3$ due to less sediment that was yielded from upstream watersheds and local uplands. Comparing the spatial variations of sedimentation rates (Fig. 4) with seasonal variations of SSCs and water levels (Fig. 7), it can be observed that higher sedimentation rates in the lower portions of the riparian zone are consistent with higher SSCs and lower impoundment heights in the rainy season, while lower sedimentation rates in the upper portions are in accordance with lower SSCs and higher impoundment heights in the dry season. This match clearly suggests that high fluvial sediment yields from upstream watersheds and local uplands have contributed to significant sedimentation in the lower portions of riparian zone during the rainy season when water level stayed at lower elevations, while low fluvial suspended sediment transport has constrained sedimentation in the upper portions of the riparian zone.

Comparing the grain size composition of riparian sediments with suspended sediments and riparian soils (Fig. 5), riparian sediments sampled from the lower portions of riparian zone have the similar percentages of sand fraction with suspended sediments collected from water regime in the study area (Zhong), which confirmed the fact that fluvial suspended sediment transport has played an essential role in

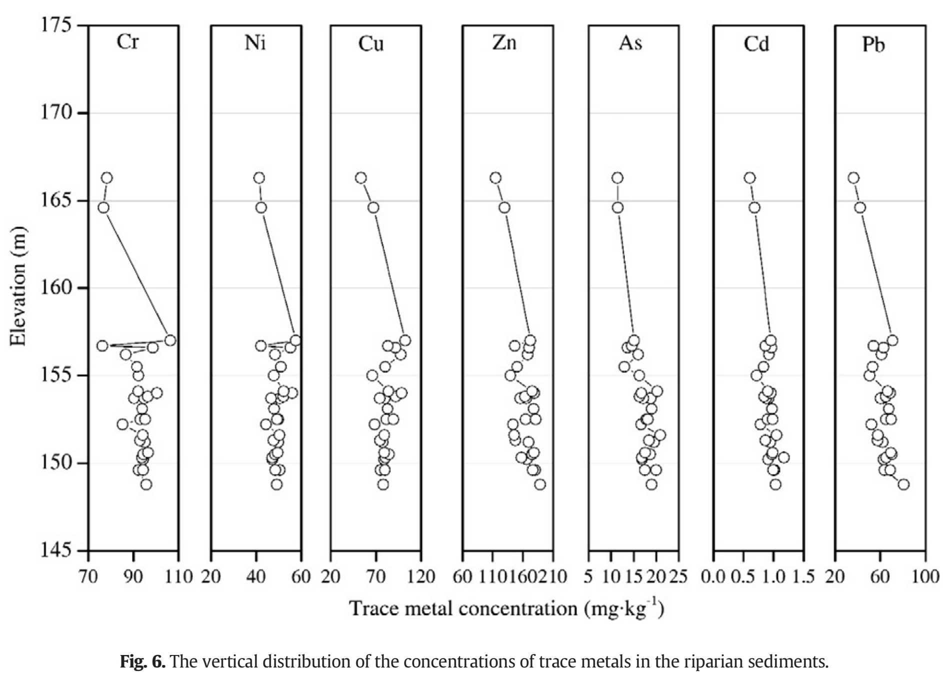

Fig. 6. The vertical distribution of the concentrations of trace metals in the riparian sediments.

Table 3
Statistics of the concentrations of trace metals in the riparian surface sediments and down-profile sectioned soils.

Element (mg/kg)	Cr	Ni	Cu	Zn	As	Cd	Pb
(A) sediment (n = 27)							
Maximum	106	57.6	103	189	20.9	1.17	81.1
Minimum	76.4	41.4	53.8	115	11.4	0.60	36.7
Median	93.3	49.2	80.0	167	17.2	0.92	63.0
Mean[a]	92.3 ± 1.3	49.0 ± 0.7	80.9 ± 2.0	163 ± 3.4	17.0 ± 0.5	0.91 ± 0.02	61.9 ± 1.8
Extreme ratio	1.4	1.4	1.9	1.6	1.8	1.9	2.2
Std. D	6.7	3.8	10.5	17.8	2.5	0.1	9.3
Cv (%)	7	8	13	11	15	13	15
(B) Upper soil (n = 87)							
Maximum	96.7	53.7	98.0	164	18.0	1.21	67.8
Minimum	44.7	17.5	14.5	47.2	5.00	0.21	19.7
Median	74.5	38.9	30.9	86.8	11.3	0.47	25.1
Mean[a]	73.0 ± 2.0	38.0 ± 0.8	32.3 ± 2.1	89.0 ± 2.2	10.8 ± 0.3	0.49 ± 0.02	26.6 ± 0.8
Extreme ratio	2.2	3.1	6.8	3.5	3.6	5.6	3.5
Std. D	10.5	7.8	11.0	20.4	2.4	0.2	7.3
Cv (%)	14	20	34	23	22	30	27
(C) Lower soil (n = 87)							
Maximum	88.7	52.6	96.6	156	17.5	0.91	50.2
Minimum	48.0	18.7	15.8	50.5	5.20	0.14	19.5
Median	73.5	38.5	29.2	86.0	11.1	0.44	23.5
Mean[a]	71.2 ± 1.1	37.0 ± 0.9	29.4 ± 1.1	83.8 ± 1.9	10.6 ± 0.2	0.43 ± 0.01	24.6 ± 0.5
Extreme ratio	1.9	2.8	6.1	3.1	3.4	6.4	2.6
Std. D	10.5	8.2	10.3	17.7	2.3	0.1	4.9
Cv (%)	15	22	35	21	22	27	20
Background value	78.03	29	25	70	5.8	0.1	23.9

[a] Represented as mean ± standard error.

sediment deposition in the lower portions of riparian zone. However, the increasing proportions of sand fraction in the bulk riparian sediments at increasing elevations implied that the riparian sediments has received increasing input of sediment yields from local riparian bank erosion during the dry season when the water level is high and fluvial suspended sediment supply was low. During a wave erosion event, the coarser grains of eroded materials from bank erosion may deposit preferentially at relatively higher elevations of riparian zone adjacent to the erosion sites, while the finer particles may continue mobilizing with streams. The sediment sorting process may lead to the input of coarser fractions to the riparian sediments.

The dynamic variations of water levels in the riparian zone also determined the occurrence of different sedimentary processes with contrasting sediment supply at different topographic locations in the riparian zone. Compared to natural river channels, the riparian zone of the Three Gorges Reservoir has experienced prolonged flooding during the impounding (i.e., dry) season and natural floods during the discharging (i.e., rainy) season. The influence of different flooding intensities on sedimentation in the riparian zone can be illustrated by the correlation between the elevation and two hydrologic variables of water level residence time and inundation duration. The former represents the time when the water level stayed at a specific elevation of the riparian zone. The latter is defined as the time when the riparian zone was flooded since the initial formation of the riparian zone. The inundation duration generally decreases significantly with increasing elevation (Fig. 8). High sedimentation rates in the lower portions of riparian can partially be explained by the fact that this riparian area has experienced relatively longer flooding duration. The abrupt change in inundation duration at approximately 155 m in the studied riparian zone coincides with the significant change in sedimentation rates (Fig. 4), which further reflects the influence of inundation duration on sediment deposition in the riparian zone. The change of water level residence time with elevation did not show any trend, although the water level tended to stay relatively longer at elevations lower than 157 m, which was

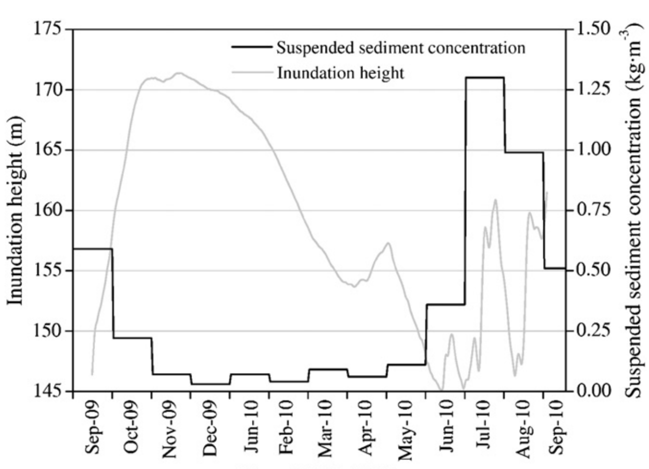

Fig. 7. The seasonal variation of monthly average suspended sediment concentrations and water levels during the 2009–2010 hydrologic year.

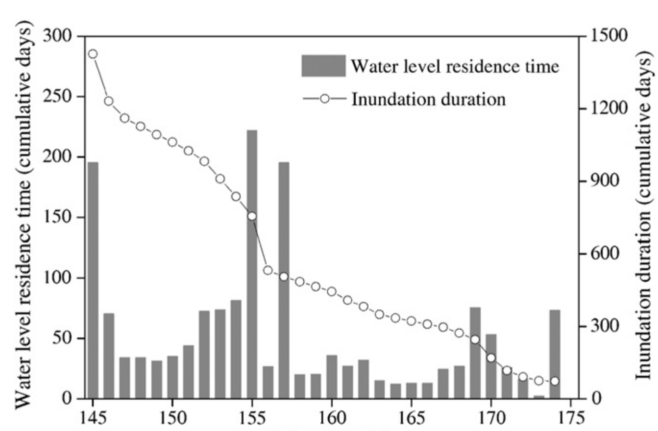

Fig. 8. The variation of water level residence time and inundation duration with elevation in the riparian zone.

partially caused by the maximum inundation heights in 2006 and 2007 that were around this level and also reflects the influence of frequent natural floods at this level during the rainy season.

4.2. Effects of the hydrologic regime on trace metal enrichment in the riparian zone

The artificial and natural flooding of the riparian zone has led to the accumulation of trace metals in the riparian soils along both the Yangtze mainstream and its tributaries during the initial individual stages of reservoir impoundment (e.g., Ye et al., 2011). A lateral decreasing trend of the concentrations of trace metals (Cu, Zn, Pb, and Cr) in the riparian soils was further revealed, suggesting the effect of different flooding intensities induced by reservoir impoundment on trace metal enrichment in the riparian zone (Chu et al., 2011). In this paper, we conducted a comparative analysis of trace metals in the riparian sediments and soils on account of the important role of provenance area and transporting process in determining the chemical contents of riparian sediments, that is, the riparian sediments are produced from external provenance areas, and transported and deposited through fluvial processes, while the riparian soils are local weathering products without mobilization.

Although the concentrations of most trace metals (except As and Cd) in the riparian soils were not at the contamination levels, they showed discernible higher levels compared with regional background concentrations, indicating the additional input of trace metals during the natural and artificial flooding periods after dam closure. Considering that the study area is an agricultural region and the riparian soils have not subjected to anthropogenic disturbances, the augmented concentrations of trace metals in the riparian soils must be ascribed to chemical transfer from soluble fractions in the reservoir water column during the natural flooding (i.e., rainy season) and impounding (i.e., dry season) periods. The vertical transfer of trace metals along the sediment–soil profile has led to the downward decreasing trend of the average concentrations of trace metals (Table 3).

Dam closure and reservoir impoundment have physically retained the chemical loads (both in particulate and soluble forms) in the reservoir regime through reducing water volume and sediment load discharged to downstream reaches and. Song et al. (2010) carried out an extensive survey of trace metal contamination across the Yangtze River Basin and revealed enrichment of trace metals in suspended solids in the Three Gorges Reservoir. In this study, all studied trace metals demonstrated varying extents of contamination in the riparian sediments except for Cr (Fig. S2), and the bulk riparian sediments were indicative of moderate risk to local ecosystems (Fig. S4). Regarding the mobile nature of the riparian sediments and the complexity of sediment production, the excessive contents of trace metals in the riparian sediments compared with the riparian soils should be partially ascribed to external input of contaminated sediments produced from upstream anthropogenic sources, including point sources, such as mining sites in the lower Jinsha catchment, industrial effluents, domestic sewages, and waste disposal; and diffuse sources, such as urban runoffs, road dust dispersion, atmospheric deposition and agricultural solids (e.g., fertilizer, pesticides, and herbicides). Metal adsorption from dissolved fractions in the freshwater on the way of pure sediment mobilization and after sedimentation should also be responsible for the enrichment of trace metals in the riparian sediments. The dominance of fine particles with relatively large specific surface area in suspended sediments facilitates the metal transfer process during sediment suspension. Surface riparian sediments replaced the original riparian soils as a liquid–solid interface which favored direct adsorption of dissolved element on the riparian sediments other than on down-profile soils.

The lateral decreasing trend of the concentrations of trace metals in both the riparian soils and sediments may be attributed to the spatial differences in sediment origins and flooding duration. During the rainy season when the reservoir water level fluctuated around the base level, contaminated sediments with higher concentrations of trace metals were preferentially deposited in the lower portions of riparian zone. Particularly, diffuse chemical loads can be additionally exported from urban and agricultural areas during the initial several storms (Kuusisto-Hjort and Hjort, 2013; Martteila et al., 2013). During the dry season, riparian sediments produced from bank erosion in this agricultural area can be assumed as "pure" sediment with no obvious accumulation of trace metals. The increasing input of sediment from local bank erosion contributed to the decreased concentrations of trace metals in riparian sediments in the upper portions of riparian zone, which showed similar levels with the riparian soils in this riparian area. The occurrence of relatively longer flooding period in the lower portions of riparian zone may also be responsible for the more obvious enrichment of trace metals in the riparian sediments in this riparian area.

5. Conclusions

Regular impoundment of the Three Gorges Reservoir has significantly altered the hydrologic regime within the dammed reaches, which consequently has led to sedimentation and associated trace metal enrichment in the riparian zone. Discernible elevated concentrations of trace metals in both the riparian sediments and soils, and a general lateral decreasing trend of sedimentation and trace metal enrichment with increasing elevations in the riparian zone were observed. The lateral variation of sedimentation was conducted by contrasting hydrologic processes between the impounding season (i.e., dry season) and natural flooding season (i.e., rainy season) occurring at different elevations of the riparian zone. Seasonal variations in water levels (i.e., low water levels in the rainy season and high water levels in the dry season) and SSCs (i.e., high SSCs in the rainy season and low SSCs in the dry season) have led to high sedimentation rates in the lower portions of the riparian zone (mainly below the water levels operated in the rainy season around 155 m) due to a relatively longer flooding duration (both by impoundment and natural floods) and abundant fluvial sediment supply from upstream watershed and local uplands. The decreased rates of sedimentation in the upper portions of riparian zone were contributed by local riparian bank erosion triggered by strong navigation-induced waves during the dry season when fluvial sediment supply was limited. Enrichment of trace metals in the riparian sediments may be attributed to the external input of contaminated sediments produced from upstream anthropogenic sources during storms and metal adsorption during sediment suspension and after deposition. The lateral decreasing trend of concentrations of trace metals can be explained by the differences in sediment origins and flooding duration at different elevations of the riparian zone. It can be deduced that the hydrologic regime altered by the impoundment of Three Gorges Reservoir interacting with the natural hydrodynamics of the Upper Yangtze River is a predominant causing factor that determines the magnitude and spatial pattern of sedimentation and trace metal enrichment in the riparian zone.

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