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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 ± 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 $0.35\ m \cdot d^{-1}$. The water level consistently decreased to 153.7 m by 11th April 2010 (138 days in length), with a daily average decease rate of $0.13\ m \cdot d^{-1}$. 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