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Dynamic changes of soil erosion in a typical disturbance zone of China's Three Gorges Reservoir

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ABSTRACT

The water level fluctuation region in China's Three Gorges Reservoir (TGR) represents a disturbance zone that experiences cyclic exposure and inundation due to reservoir operations. This area has also been subjected to long periods of flooding and wave-induced scouring. Thus, soil erosion in the disturbance zone has greatly intensified since the reservoir was first filled in 2006. In this study, soil erosion rates along nine transects in the mainstream disturbance zone (MDZ) and three transects in a tributary disturbance zone (TDZ) were continuously measured between 2008 and 2016 using erosion pins. The results showed that the average erosion rate in the MDZ was 32 mm yr^{-1}, which was more than six times greater than that in the TDZ. Spatially, the soil erosion rates in the MDZ displayed higher variability than those in the TDZ. The highest rate was found for the altitude range of 170–175 m in the MDZ, and the rates in the altitude ranges decreased in the order of 145–150 m, 160–165 m, and 165–170 m. However, the spatial variation of soil erosion rates in the TDZ was less significant than that in the MDZ. Furthermore, soil erosion rates in the MDZ displayed a small decreasing trend over the first six years and a much greater decreasing trend in the following three years. In contrast, these rates decreased significantly and continuously from 2008 to 2016 in the TDZ. The mean reduction rate of soil erosion in the MDZ was statistically higher than that in the TDZ. The annual average value of soil erosion rate reduction from all transects in the MDZ was 4.1 mm yr^{-1}, whereas it was only 1.7 mm yr^{-1} in the TDZ. Changes in hydrological regime, vegetation cover, and slope gradient were the main factors that governed the spatial and temporal patterns of soil erosion in the disturbance zone of the TGR.

1. Introduction

A reservoir disturbance zone (RDZ) generally refers to all landforms along river banks that fall between the peak and base water levels produced by regular dam operation (Bao et al., 2015a). RDZs have also been used to refer to shorelines, beaches, and banks in many studies as they denote similar types of water level fluctuation areas around reservoirs and lakes throughout the world (e.g., Cyberski, 1973; Buckler and Winters, 1983; Carter et al., 1986; Lawrence, 1994; Tommaselli et al., 2014; de Moraes et al., 2016; Sadeghian et al., 2017). RDZs typically have sharp biological and physical gradients along bank slopes. RDZs represent a hydrogeomorphological and biogeochemical ecotone between aquatic and terrestrial ecosystems and have been well recognized as a key area for maintaining ecosystem goods and services, including bank stabilization, biodiversity conservation, runoff regulation, pollutant interception, and amenity value (Naiman and Decamps, 1997; Lowrance et al., 2000; Anbumozhi et al., 2005; Mander et al., 2005; Kenwick et al., 2009; Cheng et al., 2010; Yang et al., 2012; Bao et al., 2015a).

However, RDZs are ecologically fragile due to issues caused by frequent water level fluctuations (New and Xie, 2008; Chang et al., 2011). One of these issues is related to the highly dynamic morphological changes resulting from soil erosion and sediment deposition. Soil erosion is an overall consequence of multiple complex processes, such as crumbling, scouring, scattering, and slumping (Cyberski, 1973; Born and Stephenson, 1973). Field monitoring and modeling have revealed that soil erosion in the RDZ is complex and highly variable (Pincus, 1962; Gatto and Doe, 1987; Carter and Guy, 1988; Hubertz et al., 1991; Saint-Laurent et al., 2001; Siqueira et al., 2015). Soil erosion rates may be extremely high during the initial period of reservoir impoundment when reservoir banks become unstable under changing fluvial hydrodynamics (Nilsson et al., 1997; Zhang, 2009; Vilmundardóttir et al.,

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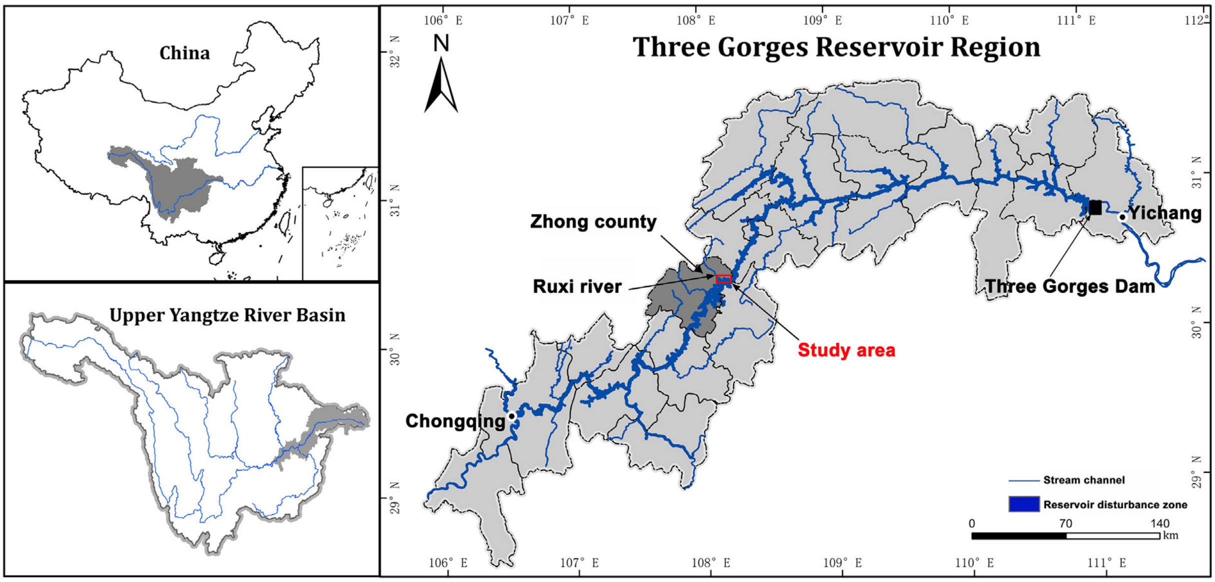

Fig. 1. Location of China's Three Gorges Reservoir and the study area.

2010; Kaczmarek et al., 2016). Soil erosion in the RDZ may cause a series of social and environmental consequences, including (i) reduced reservoir storage capacity caused by siltation (Hagan and Roberts, 1972; Seversona et al., 2009; Bao et al., 2010), (ii) generation of complex sources of water pollution (Tang et al., 2014a & 2014b), (iii) reduced habitats and biodiversity in the RDZ (New and Xie, 2008), and (iv) fragmented landscapes and disturbed ecosystem integrity. To date, > 50,000 reservoirs of various sizes have been constructed in the Yangtze River basin, with many other dams proposed for construction by 2020 (Li et al., 2013). Therefore, successful management of environmental problems related to reservoirs requires an understanding of the dynamic changes in soil erosion in the RDZ (Wu et al., 2004; New and Xie, 2008).

The Three Gorges Dam on the Upper Yangtze River is a typical valley dammed reservoir, which is part of the world's largest hydroelectric power plant and is categorized by an unprecedented RDZ. Understanding the change in soil erosion in response to disturbances caused by the changed hydrological regime in the disturbance zone (DZ) of the Three Gorges Reservoir (TGR) in China is particularly vital, given that most studies have been carried out in regions outside of China, such as the northern United States, Canada, Poland, and the former Soviet Union (e.g., Kondratjev, 1966; Cyberski, 1965 & 1973; Avakyn, 1975; Shur et al., 1978; Lukac, 1982; Reid, 1985; Lawson, 1985; Gatto and Doe, 1987; Reid et al., 1988; Sadeghian et al., 2017). Most studies of reservoir bank erosion have taken place in cold or temperate regions, with only a few studies in tropical regions (Fernandez and Fulfaro, 2000; Siqueira et al., 2015). The TGR is located across subtropical climate regions; it was completed in 2006 and has been in regular operation since 2010. Since the reservoir's impoundment, an RDZ has been created as a result of controlling the water flow. The RDZ is characterized by variations in the annual cyclic water level in conjunction with additional changes caused by rainfall events during the wet season. In particular, the magnitude and frequency of the flow in this zone are controlled by the 30 m change in water level over one annual cycle. Since 2010, multiple processes, including ecological degradation in terms of vegetation loss and habitat fragmentation and geomorphological adjustments through bank erosion and sedimentation, have been evident in the RDZ of the TGR (Bao et al., 2015b). Moreover, the morphology of the RDZ has constantly changed due to active erosion and deposition processes. However, the combined effect of these processes on the RDZ and the associated morphological responses remain to be studied, which has halted the progress of understanding the geochemical and biological processes that are linked to the increasing pollution and destruction of the ecosystem in the RDZ. The complex interactions among geomorphological, geochemical, and ecological processes have made the RDZ a unique geomorphological unit. Understanding the geomorphological processes will provide new insight into the effect of the RDZ on water quality and the ecological environment of the TGR (Bao et al., 2015a), which may help to improve the management of cascade reservoirs in China as well as those in countries around the world.

The DZ of the TGR is an artificial reservoir transitional zone that significantly affects the health of the reservoir. The morphological changes in the RDZ are subjected to fluvial processes driven by the annual cyclic variation of the water level, as well as storm events. Therefore, frequent switching between erosion and deposition occurs throughout the year, making the geomorphological system extremely dynamic and complex. Little knowledge of the impact of water impoundment on soil erosion in the DZ in the TGR is currently available. Although the limited results from previous studies have demonstrated that the depth of soil erosion varies spatially and its variation is dependent on altitude (Bao et al., 2015b; Su et al., 2017), it is still not clear how this depth changes from year to year. Hydrological, topographic, soil, geological and vegetation conditions are the critical factors that influence soil erosion (Vilmundardóttir et al., 2010; Bao et al., 2015b; Kaczmarek et al., 2016;). If the endogenic agency (i.e., vegetation and topography) and exogenic agency (i.e., frequent water level fluctuations, wave action from wind and boat traffic, and overland runoff) of soil erosion change over time, then we propose that there will be spatial-temporal variability in soil erosion followed by changes in environmental variables. In order to test this hypothesis, this study quantified the spatial and temporal changes in soil erosion in the DZ of the TGR using data collected from 2008 to 2016 through an extensive field survey and a nine-year in situ monitoring program around Zhong County, Chongqing Municipality in the middle of the TGR. This study aimed to understand the soil erosion trends at different spatial and temporal scales in the DZ of the TGR and provide first-hand information for future soil conservation planning in this zone.

2. Material and methods

2.1. Study area

The TGR covers a region of the Upper Yangtze River between