Soil erosion in the riparian zone of the Three Gorges Reservoir, China

Yuhai Bao, Qiang Tang, Xiubin He, Yunhua Hu and Xinbao Zhang

ABSTRACT

The riparian zone of the Three Gorges Reservoir (TGR) has experienced substantial erosion that may severely deteriorate the reservoir ecosystem. To calculate soil erosion characteristics, field investigations have been conducted in the TGR area and 12 erosion-monitoring transects have been set in the middle TGR. The results showed that the dominating drive forces are water wave, gravity and surface runoff. In summer when the reservoir ran at lower water levels, wave erosion led to bank instability and bank collapses. Simultaneously, due to a number of heavy storms, surface runoff erosion was also severe. In other seasons when the reservoir ran at relative higher levels reaching the highest level in winter, water wave prevailed due to the wide range of water surface and heavy waterway transportation. Soil erosion was the most severe in the mainstream where higher frequency and intensity of waves occurred. The rates of wave erosion were around 37 mm/year with the highest being 53 mm/year, and surface runoff erosion was up to 15 mm/year in the main stream riparian zone.

Key words | bank collapse, hydrological alternation, riparian zone, soil erosion, Three Gorges Reservoir, wave erosion

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INTRODUCTION

The riparian zone, which spatially refers to the transitional zone from fluvial flow regime to upland regions, is characterized by a distinctive hydrogeomorphological process (Naiman & Decamps 1997; Yang *et al*. 2012). With a great variety of ecosystem benefits, the riparian zones has been recognized as a key area for installing buffer strips to abate contaminants, enhance biodiversity, protect water quality, and maintain aquatic ecosystem diversity (Lowrance *et al.* 2000; Anbumozhi *et al*. 2005; Mander *et al*. 2005; Kenwick *et al*. 2009; Cheng *et al.* 2010). However, with a significantly high degree of hydrological, biological and physical variation, the riparian zone formed in the reservoir is ecologically fragile (New & Xie 2008; Chang *et al.* 2011). Of the many negative consequences, geomorphologic transformation due to severe soil erosion, bank collapse and the associated sediment mobilization is particularly significant (Cyberski 1973; Born & Stephenson 1973). The process of soil erosion may be in the form of crumbling, transferring, scattering, slumping, or sliding. Additionally, soil erosion in the dam-formed riparian zone is more dynamic with the degree of the erosion several orders higher than that during the initial impoundment because channel bank stability could be rapidly disturbed by highly variable and intensive fluvial hydrodynamics due to reservoir impoundment (Zhang 2009).

With multiple social and economic objectives of electricity generating, flood mitigation, navigation improvement, and tourism, the Three Gorges Dam, which is located about 30 km upstream from the outlet of the upper Yangtze River basin (Yichang) and controls a watershed of more than 1.05 million km^2, began being constructed in 1993 and started to function in 2009. Several impoundment trials were conducted during this period. The first was in 2003 when the reservoir water level increased to 135 m above sea level (a.s.l.), the second was in 2006 when the water level reached 156 m a.s.l., and the third was in 2008

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when the water level reached a height above 170 m a.s.l. (Yang *et al*. 2012). Impoundment of the Three Gorges Reservoir (TGR) to the full storage capacity of 3.93 billion m^3 resulted in a riparian zone with a vertical height of 30 m and a total area of 349 km^2 along a 660 km mountainous reach from Yichang to upstream Chongqing (Lu & Higgitt 2001; Shao 2008). According to the TGR's designed annual operation schedule, the water level rises to the maximum level of 175 m a.s.l. during the dry season for generating hydropower and falls to the flood control level of 145 m a.s.l. Consequently, substantial environmental changes have taken place within the riparian zone in response to the hydrological alternation between the period of exposure (May–September) and the inundation period (October–April) (Zhang & Lou 2011). In particular, the cyclic hydrological change, which leads to frequent and intensive hydrological disturbance and vegetation depletion, makes the riparian land extremely susceptible to erosion and losses (Bao *et al*. 2010).

Severe soil erosion in the riparian zone of the TGR may potentially cause a series of social and environmental problems as follows: (1) providing a source for sediment mobilization which leads to reservoir siltation and depletion of storage capacity (Hagan & Roberts 1972; Seversona *et al.* 2009); (2) facilitating mobilization and transfer of sediment-associated contaminants, causing complex inner-source water pollution; (3) reducing habitats and biodiversity in the riparian zone; (4) landscape fragmentation; and (5) interrupting ecosystem integrity. Therefore, successful management of the documented environmental problems related to TGR should heavily depend on controlling soil erosion in the riparian zone of the TGR (Wu *et al*. 2004; He *et al.* 2007; New & Xie 2008), although this is still poorly understood. Thus far, little knowledge concerning the impact of water impounding on ecosystem stability of the riparian zone is available. The present study provides necessary knowledge of soil erosion in the TGR's riparian zone during the initial impounding period. It aims to characterize the processes, magnitude, and patterns of soil erosion in the riparian zone of the TGR through extensive field survey and a five-year-long *in situ* monitoring at Zhong County, Chongqing Municipality in the middle reaches of the TGR.

MATERIALS AND METHODS

Study area

The study area is located at Zhong County, Chongqing Municipality in the middle reach of the upper Yangtze River (30°23′N, 108°07′E) (Figure 1). The climate is dominated by a humid subtropical monsoon with mean annual precipitation from 886 to 1,614 mm. A substantial proportion of annual precipitation occurs during the rainy season from May to September (Ye *et al*. 2012). The land of the study area is covered by sandstones, siltstones, and mudstones of the Jurassic Shaximiao Group (J2 s) and is dominated by 'purple soil', a fast weathering product of the Jurassic rocks susceptible to erosion with 18% clay, 30% silt, and 52% sand, which has been classified as Orthic Entisols in the Chinese soil taxonomic system, Regosols in FAO taxonomy or Entisols in USDA taxonomy and is susceptible to detachment and erosion (He *et al*. 2009). The riparian zone specifically refers to the water level fluctuation zone (145–175 m) within the study area (Figure 1). Original vegetation in the riparian zone was dominated by annuals such as *Setaria viridis*, *D. 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*. However, annual plants such as *S. viridis*, *D. ciliaris*, and *L. chinensis* became the dominant species after inundation (New & Xie 2008).

The riparian zone of a 15 km stretch along the upper Yangtze River and Ruxi tributary was selected as the observation field. The Ruxi River is a first-order tributary on the left bank and has a drainage catchment of 720 km^2. A 15 km long inundated area was formed along the Ruxi tributary. Previous land uses of the selected riparian zones were sloping dry farmland, paddy field, and grassland. The current land use is grassland and bare land. To quantify the spatial variations of erosion rates, we selected 12 surface erosion monitoring transects (SM1–SM9 along the mainstream and ST1–ST3 along the tributary) (Figure 2) and 18 bank collapse monitoring transects (BM1–BM9 along the mainstream and BT1–BT9 along the tributary) (not shown in Figure 2

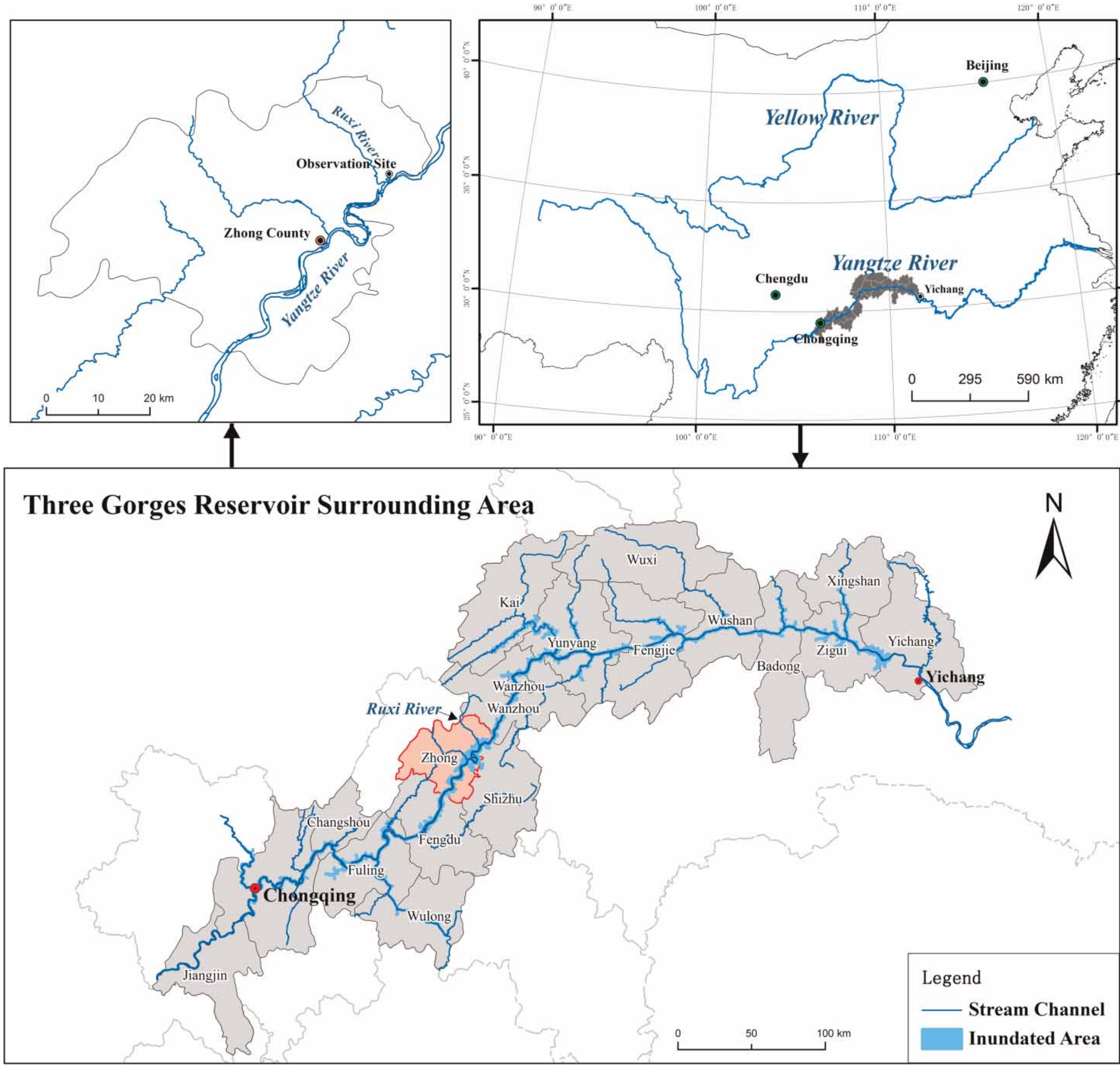

Figure 1 | A sketch map of the TGR in southwestern China. The case study site at Zhong County, Chongqing Municipality in the middle reaches of the TGR is also indicated.

due to limited space). These transects contain diverse soil types, previous land uses, topography, and vegetation (Table 1).

Methods

In these transects, soil erosion rates were measured using erosion pins during 2007–2012. The data set on water level was collected from the website of China Three Gorges Corporation (http://www.ctgpc.com.cn) and the water level fluctuation schedule is depicted in Figure 3. In 2007, along each transect, metallic and plastic erosion pins of a fixed length (40 cm) were installed on the ground's surface with a fixed exposed length (10 cm). To assure the quality of the data, we kept soil disturbance to a minimum during pin installation. The exposed

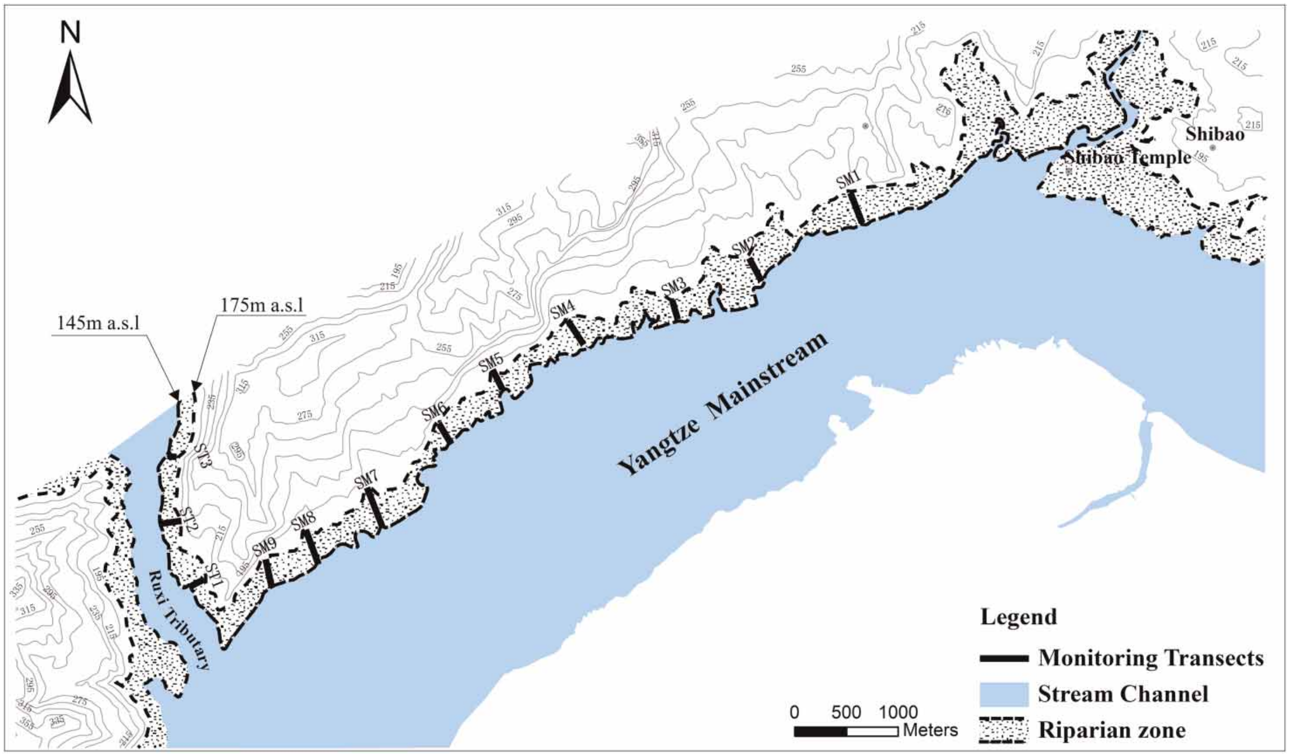

Figure 2 | Schematic representation of selected soil erosion monitoring transects along the mainstream and Ruxi tributary.

Table 1 | Summary of characteristics of the selected soil erosion observation transects along the Yangtze mainstream and the Ruxi tributary

Stretch	No.	Soil type	Previous land use	Vegetation	Slope morphology	Slope gradient
Yangtze mainstream	SM1	Purple soil	Dry land	Natural meadow, coverage: 45%	Slope + terrace	5°–20°
	SM2	Purple soil	Dry land	Natural meadow, coverage: 55%	Slope + terrace	2°–15°
	SM3	Purple soil	Dry land	Crop, natural meadow, coverage: 60%	Slope + terrace	2°–10°
	SM4	Purple soil	Grassland, dry land	Natural meadow, coverage: 45%	Slope + terrace	10°–20°
	SM5	Purple soil	Grassland, dry land	Natural meadow, coverage: 45%	Slope + terrace	5°–30°
	SM6	Purple soil	Grassland, dry land	Natural meadow, coverage: 45%	Slope + terrace	20°–30°
	SM7	Purple soil	Grassland, dry land	Natural meadow, coverage: 60%	Slope + terrace	10°–22°
	SM8	Purple soil	Dry land	Crop, natural meadow, coverage: 50%	Slope + terrace	2°–25°
	SM9	Purple soil	Bare land	No vegetation	Slope	20°–38°
Ruxi tributary	ST1	Purple soil	Dry land, grassland	Natural meadow, coverage: 55%	Slope + terrace	2°–20°
	ST2	Purple soil	Dry land, grassland	Natural meadow, coverage: 50%	Slope + terrace	5°–22°
	ST3	Purple soil	Dry land, grassland	Natural meadow, coverage: 60%	Slope + terrace	2°–15°

length of erosion pins reflects time-integrated changes in microtopography caused by soil erosion. It was measured with a vernier caliper and recorded twice a year, once during the impounding season before the pins were submerged and then during the water level retreat season shortly after the pins were exposed. Wave erosion and runoff erosion were subsequently separated and quantified by comparing the exposed lengths of the pins recorded at different times, based upon the assumption that wave erosion occurred at the water–bank interface during

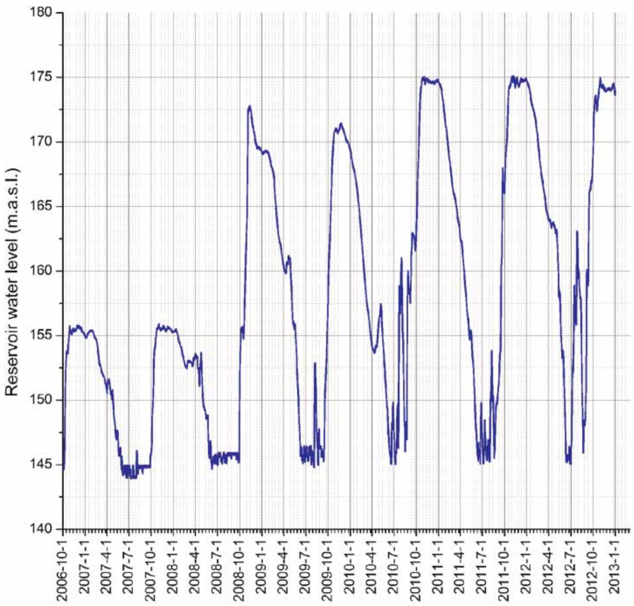

Figure 3 | Water level fluctuating schedule in the riparian zone of the TGR during 2006–2012.

inundation and runoff erosion mainly occurred during the exposed period:

$$Q_{wi} = P_{i,2} - P_{i,1} \quad (1)$$

$$Q_{ri} = P_{i+1,1} - P_{i,2} \quad (2)$$

where Q_{wi} is observed wave erosion rate during the i impounding season, Q_{ri} is observed runoff erosion rate during the i impounding season, $P_{i,1}$ is the pin exposed length before inundation at the i impounding season, $P_{i,2}$ is the pin exposed length after reservoir water level lowering at the i impounding season; i represents the sequence of monitored years.

To record the bank retreat rate, wooden pins were perpendicularly installed in a 1×1 m grid of the bank surface along the 10 m wide selected transects. At the locations with bank collapse, the height and width of the collapsed body were repeatedly measured to calculate the released bank volume. Site-specific soil bulk density was obtained in the laboratory based on the oven-dried weight and the sample volume. Total annual soil erosion rate (t km^{-2} a^{-1}) was subsequently calculated as the product of soil erosion thickness (mm) measured by erosion pins and bulk density (g cm^{-3}) (Bu & Liu 1995; Zaimes *et al.* 2005).

RESULTS AND DISCUSSION

Types of soil erosion

Extensive field survey since 2007 showed that soil erosion within the riparian zone of the TGR can be generally grouped into two categories: (1) surface erosion caused by wave strength during the inundated period (wave erosion) and runoff hydraulics during the exposed rainy season (runoff erosion); and (2) mass failure (i.e., bank collapse) controlled by gravitational or mechanical forces. These different types of erosion may take effect individually or collectively (Figure 4).

Stream hydrology has substantially determined the spatiotemporal co-occurrence of soil erosion in the riparian zone. Soil erosion processes during one impounding season may be described as four consecutive hydrological stages with contrasting behavior in response to varied hydrological conditions associated with riparian hydrological alternations and vegetation replacement (Figure 5).

1. Rising period (September–October): at this stage, the riparian zone suffers from intensive hydrological disturbance caused by waves associated with water level rising from 145 to 175 m a.s.l. Wave erosion and bank collapse plays a crucial role in bank detachment and sediment movement. However, the degree of erosion may be alleviated by riparian vegetation, whose roots hold bank soils and stems reduce wave strength. In other words, riparian vegetation serves as a buffer between wave regime and the riparian zone.
2. Flooding period (November–December): at this stage, the water level reaches around the maximum level of 175 m and the entire riparian zone is inundated. Soil erosion and bank collapse in the underwater riparian land are controlled by in-stream hydrodynamics. However, at the interface between surface water and riparian land, soil erosion may be much more intensive due to intensified hydrodynamics.
3. Falling period (January–May): at this stage, vegetation in the riparian zone is (almost) depleted due to prolonged inundation and bare land is exposed when the water level drops. Large quantities of soil particles can be removed by wave flushing and rainfall strength. A higher degree of wave erosion, runoff erosion, and bank collapse typically occurs during this period.

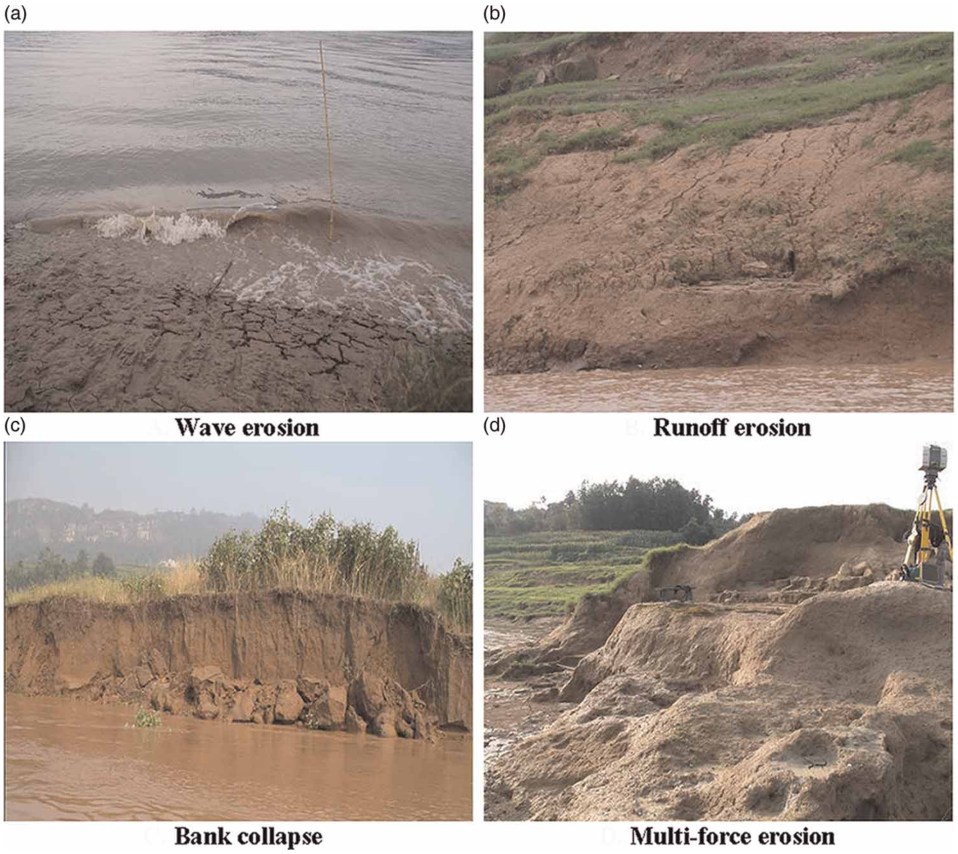

Figure 4 | Landscape view of eroded tracks subjected to diverse erosion processes in the riparian zone of the TGR.

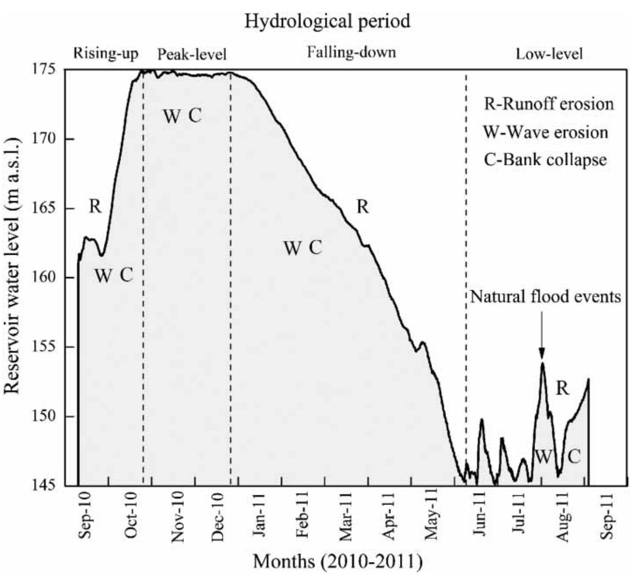

Figure 5 | Spatial-temporal co-occurrence of erosion forms (wave erosion, runoff erosion, and bank collapse) associated with hydrological fluctuation in the riparian zone of the TGR.

4. Exposing period (June–August): at this stage, the water level largely remains around the flood control water level of 145 m except for some flood events during which the riparian zone is subject to raindrop and surface runoff disturbance. In the upper and middle sections of the riparian zone, soil detachment and transport are dominated by sheet, rill, and gully erosion. However, in the lower section, both wave erosion and bank collapse are predominant due to frequent water level fluctuation and rapid change of soil moisture. Bank erosion may also be accelerated during flood events.

Magnitude, pattern, and determinants

Averaged surface erosion rates and the differentiated wave erosion and runoff erosion are summarized in Table 2. The steps of impoundment for the TGR and the seasonal water level fluctuation lead to variation in length (duration)

Table 2 | Observed annual average (2008–2012) eroded soil thickness and corresponding soil erosion rate in the riparian zone of the study site

		Annual average eroded soil thickness (mm)						
		Wave erosion		Runoff erosion				
Stretch	No.	Thickness	Contribution percentage	Thickness	Contribution percentage	Total	Bulk density (g cm^{-3})	Averaged annual erosion rate (t km^{-2} a^{-1})
Yangtze mainstream	SM1	43	72%	17	28%	60	1.41	84,600
	SM2	30	72%	12	28%	42	1.45	60,900
	SM3	23	70%	10	30%	33	1.47	48,510
	SM4	40	71%	16	29%	56	1.49	83,440
	SM5	46	79%	12	21%	58	1.46	84,680
	SM6	37	65%	20	35%	57	1.49	84,930
	SM7	36	70%	16	30%	52	1.46	75,920
	SM8	21	70%	9	30%	30	1.45	43,500
	SM9	53	71%	22	29%	75	1.49	111,750
Ruxi tributary	ST1	3	36%	5	64%	8	1.48	11,840
	ST2	3	28%	7	72%	10	1.49	14,900
	ST3	2	31%	5	69%	7	1.52	10,640

of the riparian zone being subjected to hydrology and hydrodynamics disturbances. This paper took the observation data of low level (c. 155 m) since 2007 and high level (c. 175 m) since 2009, and the different impounding duration was used to calculate the mean annual soil erosion rate. Mean annual averaged surface erosion thickness ranges from 30 to 75 mm a^{-1} in the Yangtze mainstream riparian zone, with an average of 51.4 mm a^{-1}, while in the Ruxi tributary riparian zone, it ranges from 7 to 10 mm a^{-1} with an average of 8.3 mm a^{-1}. Following the same trend, mean annual averaged surface erosion rate along the Yangtze mainstream is from 43,500 to 111,750 t km^{-2} a^{-1}, with an average of 75,359 t km^{-2} a^{-1}, while in the Ruxi tributary, it ranges from 10,640 to 11,840 t km^{-2} a^{-1}, with an average of 12,460 t km^{-2} a^{-1}. Evidently, the riparian zone along the mainstream is subject to a much higher degree of soil erosion than the tributary.

Wave erosion has contributed significantly to surface erosion in the mainstream riparian zone than that in the Ruxi tributary (Table 2). In the riparian zone along the Yangtze mainstream, wave erosion rate was observed to be from 21 to 53 mm a^{-1}, with an average of 36.6 mm a^{-1}. Runoff-induced erosion thickness ranged from 9 to 22 mm a^{-1}, with an average of 14.9 mm a^{-1}. These results indicate that wave erosion, which contributed up to 72% of the total surface erosion, is a dominant process of soil erosion in the mainstream riparian zone. In the tributary riparian zone, however, wave erosion only accounted for 32% of total surface erosion, indicating the prevalence of runoff erosion. This is consistent with the observation that during the initial impounding season of 2007–2008, no

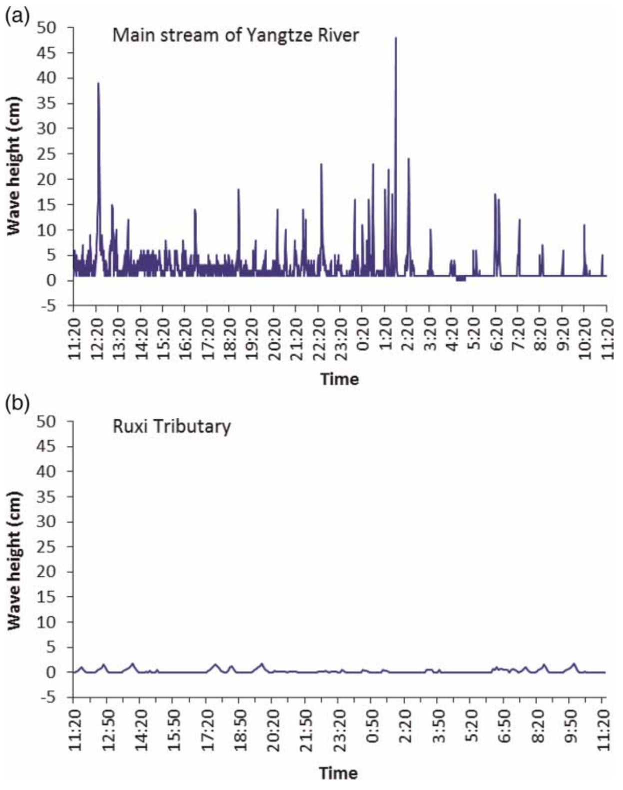

Figure 6 | Monitored wave heights in the Yangtze mainstream and the Ruxi tributary.

wave erosion occurred in the Ruxi tributary riparian zone. The much higher wave erosion rate in the Yangtze mainstream than that in the tributary agrees well with the significantly higher variations and magnitudes of water wave in the former than that in the latter (Figure 6).

The observed extent, features, and magnitude of bank collapse in the selected transects are summarized in Table 3. Bank retreat rate ranged from 0.15 to 3.50 m/a along the mainstream and from 0.05 to 0.45 m/a in the tributary. Both rate and volume of bank collapse were higher in the Yangtze mainstream than those in the tributary, and higher within the lower sections (below 150 m) than those in the upper section. The highest degree of bank collapse occurred in the bank consisting of fine sand and sandy clay materials. Wave strength and soil moisture gradient may be causal factors of bank collapse. Surface water acting duration in the lower sections of the riparian was greater than that in the upper sections.

Table 3 | Observed characteristics of bank collapse in the riparian zone of selected reaches (2007–2009)

					Characteristics of bank collapse				
Stretch	**Transect No.**	**Bank composition**	**Slope gradient**	**Vegetation coverage**	**Height (m)**	**Width (m)**	**Toe elevation (m)**	**Mean annual retreat rate (m/a)**	**Total released volume (m^3)**
Yangtze mainstream	BM1	Taupe silty clay, slightly compact	75°	40%	2.3	1.15	147	0.70	3.70
	BM2	Tawny fine sandy soil, slightly compact	85°	20%	1.8	3.65	147	2.40	31.54
	BM3	Tawny fine sand, sandy clay, slightly compact	90°	10%	4.0	6.00	149	3.50	168.00
	BM4	Taupe to tawny fine sandy soil, slightly compact	72°	36%	1.0	1.15	155	0.75	1.73
	BM5	Tawny silty clay, slightly compact	73°	37%	1.5	1.10	154	0.60	1.98
	BM6	Taupe silty clay, relatively compact	90°	10%	1.6	0.50	161	0.30	0.48
	BM7	Taupe silty clay, relatively compact	87°	20%	1.0	0.30	170	0.15	0.09
	BM8	Tawny fine sandy soil, slightly compact	50°	35%	2.0	0.70	171	0.35	0.98
	BM9	Taupe to tawny fine sandy soil, slightly compact	45°	35%	1.6	0.60	169	0.30	0.58
Ruxi tributary	BT1	Taupe silty clay, relatively compact	90°	45%	1.7	0.40	148	0.25	0.34
	BT2	Taupe silty clay, relatively compact	80°	25%	1.0	0.40	147	0.30	0.24
	BT3	Taupe to tawny silty clay, slightly compact	85°	36%	1.5	0.60	146	0.45	0.81
	BT4	Taupe silty clay, relatively compact	70°	40%	1.0	0.20	158	0.10	0.04
	BT5	Taupe silty clay, relatively compact	72°	35%	1.2	0.20	156	0.15	0.072
	BT6	Taupe silty clay, relatively compact	85°	36%	1.5	0.40	161	0.20	0.24
	BT7	Taupe silty clay, relatively compact	85°	36%	2.0	0.10	170	0.05	0.02
	BT8	Taupe silty clay, relatively compact	71°	35%	1.7	0.20	171	0.10	0.068
	BT9	Taupe silty clay, relatively compact	50°	35%	1.2	0.10	170	0.05	0.012

There are numerous factors that determine the extent, magnitude, and pattern of soil erosion and mass failure occurring within the riparian zone of the TGR, including channel morphology, topography, precipitation, vegetation, stream hydrodynamics, bank composition, and human disturbance (Nagle *et al*. 2012; Kronvang *et al*. 2013). Stream hydrological fluctuating pattern directly determines erosion types and vegetation coverage plays a key rule in the erosion intensity of soil erosion occurring within the riparian zone. Wave and runoff strength are major forces and slope morphology determines the extent and intensity of erosion. As for bank collapse, bank composition and morphology determine the extent of bank material susceptible to disturbances and vegetation functions as a resisting force.

CONCLUSIONS

Soil erosion in the riparian zone of the TGR is still poorly understood and is an emerging new research topic. Preliminary results on soil erosion obtained through extensive field measurement and *in situ* monitoring were reported in this study. Soil erosion in the riparian zone of the TGR generally occurs as either surface erosion (wave erosion and runoff erosion) or mass failure (i.e., bank collapse), and is primarily controlled by hydrological fluctuation. That is, wave erosion and bank collapse occurred during the inundation period when the riparian land suffered from stream forces, while runoff erosion took place during heavy storms in the rainy season with lower water levels. *In situ* monitoring demonstrated that annual average surface soil erosion rate in the selected riparian zone of the Yangtze mainstream ranged from 43,500 to 111,750 $t\,km^{-2}\,a^{-1}$, with an average of 75,359 $t\,km^{-2}\,a^{-1}$, while that in the Ruxi tributary ranged from 10,640 to 11,840 $t\,km^{-2}\,a^{-1}$, with an average of 12,460 $t\,km^{-2}\,a^{-1}$. The relative contribution of wave erosion to the total surface erosion ranged from 65 to 79% in the mainstream riparian zone, and from 21 to 35% in the Ruxi tributary riparian zone. Observed bank retreat rate ranged from 0.15 to 3.50 m/a along the mainstream and from 0.05 to 0.45 m/a in the tributary. Both soil erosion and bank collapse were more intensive along the mainstream than in the tributary and changed with elevation. This spatial distribution reflects the influence of stream hydrology, bank composition and morphology, and riparian vegetation. Although the results of this study demonstrate the significant bank erosion in the riparian zone of the TGR, they were limited to the study area, which is only a small portion of the entire riparian zone of the TGR and only based on five-year monitoring. Large-scale and long-term monitoring and survey are required to explicitly understand the processes of soil erosion.

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