



Sediment Particle Size Composition in the Riparian Zone of the Three Gorges Reservoir

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The riparian zone is a transitional zone of terrestrial ecosystems and aquatic ecosystems, which is one of the main sources of reservoir sediment and pollutants. The sediment loss has an increasing trend in the riparian zone of the Three Gorges Reservoir (TGR), which was closely related to sediment particle size composition change in the riparian zone, but its distribution and factors are still unclear. Hydrological conditions, sediment particle size composition and vegetation properties in the riparian zone were investigated in 3 mainstream and 8 tributary sections along the Yangtze River within the TGR across 450 km. On the one hand, both sediment sand content and median particle size (D_{50}) showed a horizontal raising trend from the upstream to the dam region of the TGR at the mainstream and tributary sites. On the other hand, compared to the upper-middle mainstream and the tributaries of Longxi, Wu, Longxi, Pengxi, Daning, Tongzi rivers, the D_{50} was much higher in the lower altitudes of the riparian zone in the tributaries of Wubu, Ruxi, and Xiangxi and the mainstream in the lower reaches of the Yangtze River. With the raising of the riparian zone slope, D_{50} decreased in the mainstream riparian zone sites, while increased in the tributary riparian zone sites ($p < 0.05$). Besides, D_{50} was 2.3 times higher in the south aspect relative to the north aspect of the riparian zone in the TGR. No significant relationship was found between root biomass of a local dominate species-*Cynodon Dactylon* (Linn.) and D_{50} . Hydrological and geographical variables could predict 64%–67% of the D_{50} variance, and thus could be regarded as the main predictor of D_{50} in the riparian zone of the TGR.

Keywords: particle size composition, water-level fluctuation, Three Gorges Dam, Yangtze River, sediment

INTRODUCTION

The Three Gorges Dam (TGD) is a critical hydro-electric project in China, which completed the 175 m trial impoundment since 2010, forming the 660 km Three Gorges Reservoir (TGR) strip from Zigui County to the central district of Chongqing (Su et al., 2017). The drainage area is about 1×10^6 km² in the TGR, which intercepts the outlet of the upper reaches and the main channel of the Yangtze River (Tang et al., 2016; Pei et al., 2018). Based on the flow regulation, the water-level in the TGR gradually rises to 175 m in September and kept constant until the following January for power generation and irrigation. Thereafter, it recedes to the lowest level

(145 m) in late June for flood control (Ye et al., 2011), which disordered the natural balance of sediment transport in the TGR (Bing et al., 2016).

The reverse seasonal hydrological process has led to the formation of a riparian zone in the TGR with an area of ~349 km² and a vertical drop of 30 m (Wu et al., 2004; Zhang et al., 2020). It represents a critical transitional zone between an aquatic and terrestrial environment. Thus, it could alternate between being sediment “source” or “sink” based on the periodic water-level fluctuations in the TGR (Fei Ye et al., 2019). The sediment in the riparian zone of the TGR mainly originates from water impoundment and bank erosion (Panwar et al., 2016; Wang et al., 2016a). The sediment particle size composition largely depends on the responses of sediment stability to hydrological stresses (Ran et al., 2020). The finer particles in sediment may be easily moved by fluid flow, forming a layer of solid particles in the riparian zone’s surface layer (Knighton 1980; Rhoads 1989). Further, the finer particles in sediments can be released to the water-column via hydrodynamic disturbance under variable sedimentary conditions, causing potential risk to aquatic biota or the TGD operation (Tang et al., 2016). In the torrent streams of the Mediterranean environment, investigating the effects of check dams on riparian vegetation, relationships were found between synthetic vegetation parameters (such as, global canopy cover and weighted canopy height) and the number of species (Bombino et al., 2008).

Fundamentals of sediment transport pointed out that the sediment transport regime is mainly controlled by the chemical composition of the fluid, the physicochemical properties of cohesive sediments, and the hydrodynamics, which can effectively affect the processes of deposition, settling, erosion, advection, dispersion, and flocculation, etc (Hayter and Gailani, 2014). The periodic hydrologic fluctuation is one of the crucial driving factors for sediment transportation (Lin et al., 2018). First, the impoundment turned the natural river into a lake by reducing flow velocity and increasing the flow displacement. Second, the enlarged width of the river channel can increase the dam storage (Yang et al., 2015). The sediment in riparian zone may be relocated between the mainstream and tributaries, the upstream and downstream areas, or among riparian zone altitudes (Lu and Higgitt, 2001). However, the sediment particle size distribution in the riparian zone of the Yangtze River on the basin-scale under periodic flood has not received adequate attention and empirical investigation. Therefore, it is critical to clarify the distribution and its influencing factors of sediment particle size composition in the riparian zone of the TGR for the security operation of the Three Gorges Dam.

This study aimed to 1) investigate the distribution of sediment particle size composition in the riparian zone in the TGR and 2) clarify the factors that regulate sediment particle size composition in the riparian zone of the TGR. We hypothesize that 1) sediment median particle size (D_{50}) in the riparian zone horizontally increases from the upstream of the Yangtze River to the TGD; 2) D_{50} are primarily driven by hydrological and geographic variables.

MATERIALS AND METHODS

Study Area

The TGR is located in the upper reaches of the Yangtze River (N28° 10′–N31° 13′ and E105° 11′–E110° 38′), which represents the inundated and migratory area affected by the TGR backwater after the completion of the TGD (Figure 1 and Table 1). The administrative area extends from Yichang in Hubei Province in the East to Jiangjin in Chongqing in the west, including 4 counties in Hubei Province and 22 districts (counties) in Chongqing City, with an area of 5.8×10^4 km² (Ming-feng Wang et al., 2020). The region is characterized by rolling hills and valleys in the transition zone (from the second to the third step) of the terrain in China (Tang et al., 2016). It has subtropical monsoon and humid climate, with an average annual precipitation of 1120 mm, an average annual temperature of 16.3–18.2°C, numerous high-temperature days, a frost-free period of 300–340 days, and an annual sunlight period of 1200–1600 h in most areas (Lin et al., 2019).

Sampling

Surface sediment (0–20 cm) was collected from 3 mainstream sites and 8 tributary sites in the riparian zone (145–155, 155–165, and 165–175 m altitudes) and non-flooding area (175–185 m altitude) of the Yangtze River in July 2019 (Figures 1, 2). Each sample was consisted of three random sampling plots (1 × 1 m) at each altitude. Thus, there were 132 samples in total, including 11 transects × 4 altitudes × 3 replicates. All soil samples were immediately stored in a 5°C incubator and then brought to a laboratory within 24 h. All of them were air-dried and passed through a 2-mm sieve after removing plant residues. In each plot, the shoot of dominant species of *Cynodon Dactylon* (Linn.) was removed and the root part as belowground biomass was carefully collected by shaking, and then brought back into the laboratory immediately. Root samples were washed and 60°C oven-dried and weighed.

Laboratory Analysis

Particle size composition was measured using the hydrometer method (Gee and Bauder, 1979). Bulk samples were grouped into clay (<0.002 mm), silt (0.002–0.02 mm) and sandy (0.02–2 mm) fractions. Median diameter size (D_{50}) was quantified by the particle-size distribution curves (Gee and Or, 2002). Soil moisture and bulk density were measured by 100 cm³ soil core (McKenzie et al., 2002).

Data Acquisition and Processing

The daily water-level in the TGR was obtained from www.ctgpc.com.cn, reported by the China Three Gorges Group Limited Company. The flooding duration was obtained from the hydrological data (2015–2018) using GetData (V2.20) with a 3 m interval. Structure equation modelling (SEM) was used to assess potential causal relationships of D_{50} with hydrological and geographic variables. The overall goodness of fitting for the model was tested by chi-square (χ^2). The model is satisfying when χ^2/df within 0–2, non-significant χ^2 test ($p > 0$).

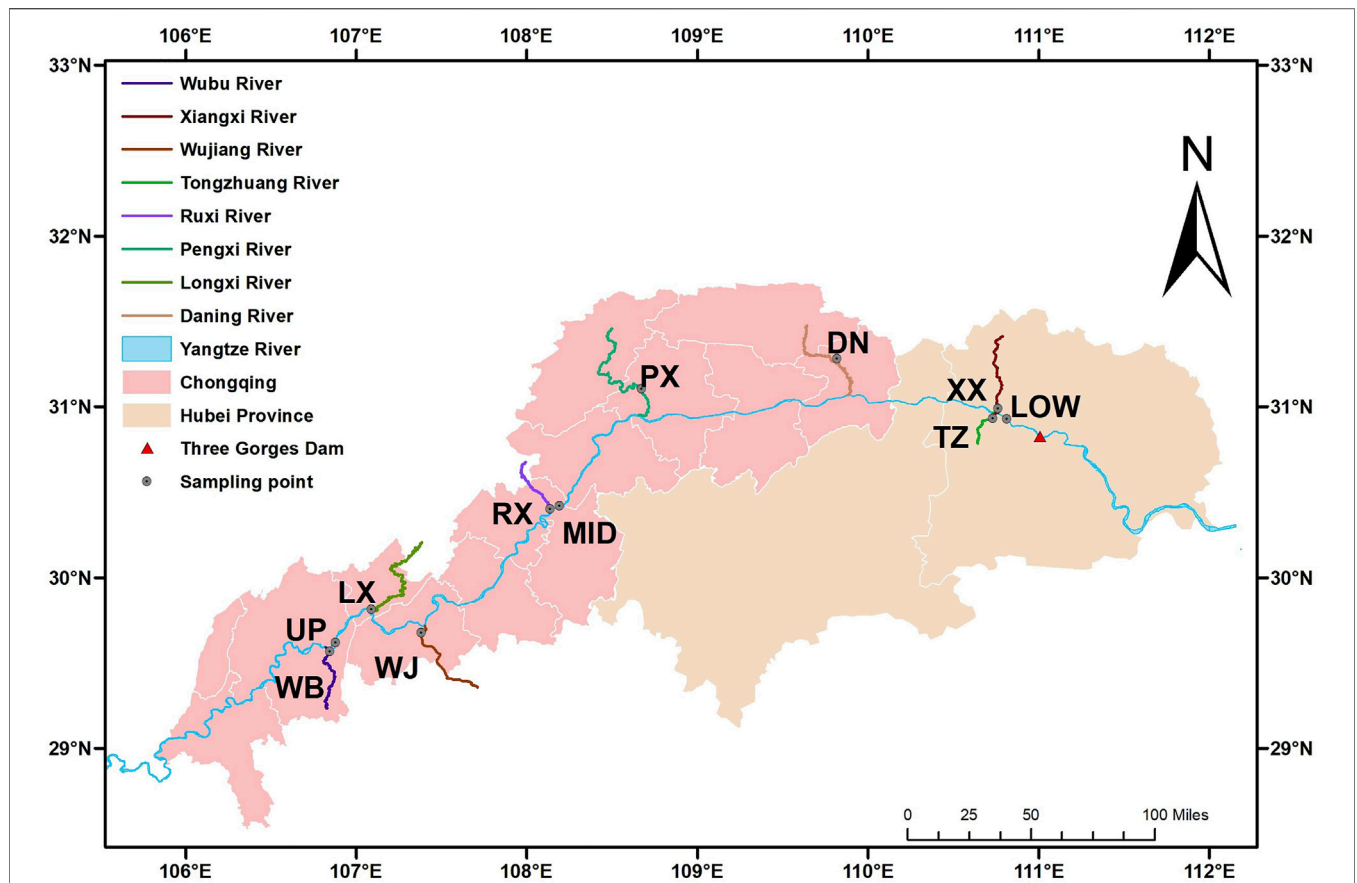


FIGURE 1 | Sampling sites in the Three Gorges Reservoir. Wubu (WB), Longxi (LX), Wujiang (WJ), Ruxi (RX), Pengxi (PX), Daning (DN), Tongzhuang (TZ), and Xiangxi (XX) rivers; upstream (UP), middle (MID), and lower (LOW) sections of the Three Gorges Reservoir.

TABLE 1 | Characteristics of sampling transects in the mainstream and tributaries of the Yangtze River. Wubu (WB), Longxi (LX), Wu (WJ), Ruxi (RX), Pengxi (PX), Daning (DN), Tongzhuang (TZ), and Xiangxi (XX) rivers; upper (Up), middle (Mid), and lower (LOW) reaches of the mainstream of the Yangtze River.

No.	Sampling location	GPS coordinate	Region	Relative to the mainstream of Yangtze River	Distance to TGR (km)	Channel attributes
1	WB	N29°34'03.00", E106°50'38.00"	Banan	First-order, South	426.13	Backwater
2	LX	N29°48'50.00", E107°05'16.00"	Changshou	First-order, North	394.39	Backwater
3	WJ	N29°40'31.00", E107°22'55.00"	Fuling	First-order, South	372.74	Backwater
4	RX	N30°24'07.00", E108°08'13.00"	Zhong	First-order, North	279.16	Permanent
5	PX	N31°06'11.00", E108°40'23.00"	Kai	First-order, North	224.29	Permanent
6	DN	N31°16'51.00", E109°49'04.00"	Wuxi	First-order, North	123.81	Permanent
7	TZ	N30°55'50.00", E110°43'42.00"	Zigui	First-order, South	29.01	Permanent
8	XX	N30°59'17.00", E110°45'31.00"	Zigui	First-order, North	29.79	Permanent
9	Up	N29°37'08.00", E106°52'42.00"	Banan	—	420.94	Backwater
10	Mid	N30°25'11.00", E108°11'22.00"	Zhong	—	273.82	Permanent
11	LOW	N30°55'34.00", E110°48'47.00"	Zigui	—	21.62	Permanent

05) and low values of root mean square error of approximation, χ^2 , and akaike information criterion (Schermelleh-Engel et al., 2003), and indicate that the difference between the observed and modelled values is acceptable.

Statistical Analysis

One-way ANOVA was used to examine variations in particle-size composition and D_{50} between altitudes. All statistical analyses and plots were obtained using SPSS 20.0 for Windows and SigmaPlot 12.5, respectively.

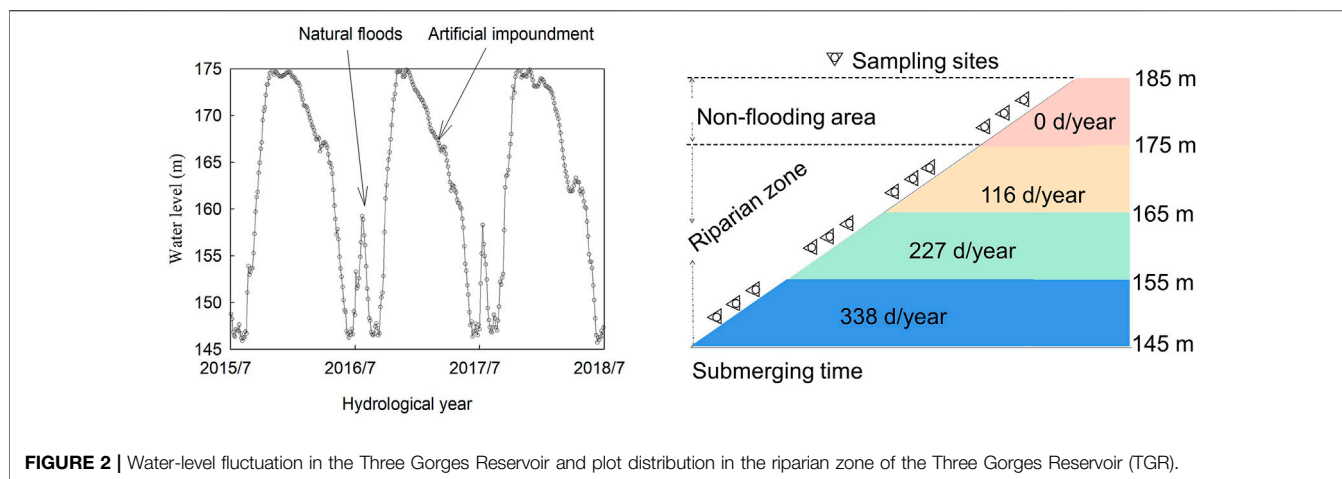


FIGURE 2 | Water-level fluctuation in the Three Gorges Reservoir and plot distribution in the riparian zone of the Three Gorges Reservoir (TGR).

TABLE 2 | Descriptive statistics of sediment particle size composition, moisture, and bulk density in the riparian zone of the TGR.

Item	Moisture (%)	Bulk density (g/Cm ³)	Clay (%)	Silt (%)	Sand (%)
N	132	132	132	132	132
Minimum	3.00	0.59	7.00	9.00	10.00
Maximum	59.00	1.6	43.00	65.00	81.00
Mean	26.38	1.21	26.41	34.77	38.80
Std. D	11.08	0.18	7.24	12.30	16.78
Variance	1.20	0.03	0.50	1.50	2.80
Skewness	0.58	-0.37	-0.54	0.04	0.49
Kurtosis	0.46	-0.03	0.09	-0.58	-0.45
C.V. (%)	42.00	15.23	27.41	35.36	43.25

RESULTS

Sediment Moisture, Bulk Density and Particle Size Composition

The sediment moisture, bulk density, and proportions of clay, silt, and sand varied from 3.00 to 59.00%, 0.59–1.60 g cm⁻³, 7.00–43.00%, 9.00–65.00%, and 10.00–81.00%, respectively (Table 2). The coefficient of variation (C.V.) of sand content was the highest (43.25%), while that of bulk density was the lowest (15.23%). The C.V. of moisture, silt, and sand were >30%, thus showing a strong variation (Table 2). The proportion of clay decreased ($r = 0.41$ $p < 0.05$, Figure 3A), and that of sand (Figure 3C) and D_{50} increased from upstream of the Yangtze River to the TGD at both mainstream (Figure 3D) and tributary (Figure 3E) sites across 450 km, while no significant trend was observed for the proportion of silt content in the riparian zone of the TGR (Figure 3B).

Sediment Particle-Size Distribution Along the Riparian Zone Altitudes

D_{50} was totally the highest for the TZ River (Figure 4J) and the lowest for the Wu River (Figure 4F). The D_{50} and the percentage of sand (coarser particle) decreased in the upper (Figure 4A) and middle (Figure 4B) sites and increased in the lower mainstream site (Figure 4C) with the decline of the riparian zone altitude.

Besides, the proportion of sand and D_{50} decreased in the LX (Figure 4E), WU (Figure 4F), PX (Figure 4H), DN (Figure 4I), and TZ (Figure 4J) rivers, while it increased in the WB (Figure 4D), RX (Figure 4G), and XX (Figure 4K) rivers with the decline of the riparian zone altitudes.

Linking D_{50} to the Slope, Aspect, and Root Biomass of the Riparian Zone

The D_{50} was negatively correlated with the riparian zone's slope in the mainstream (Figure 5A, $p < 0.05$) and positively correlated with the slope in the tributaries (Figure 5B, $p < 0.05$). D_{50} of the riparian zones located in the southern aspect of the Yangtze River was 2.3 times higher than that in the northern aspect (Figure 6). No significant relationship was found between D_{50} and root biomass of local dominant species-*Cynodon Dactylon* (Linn.) (Figure 7).

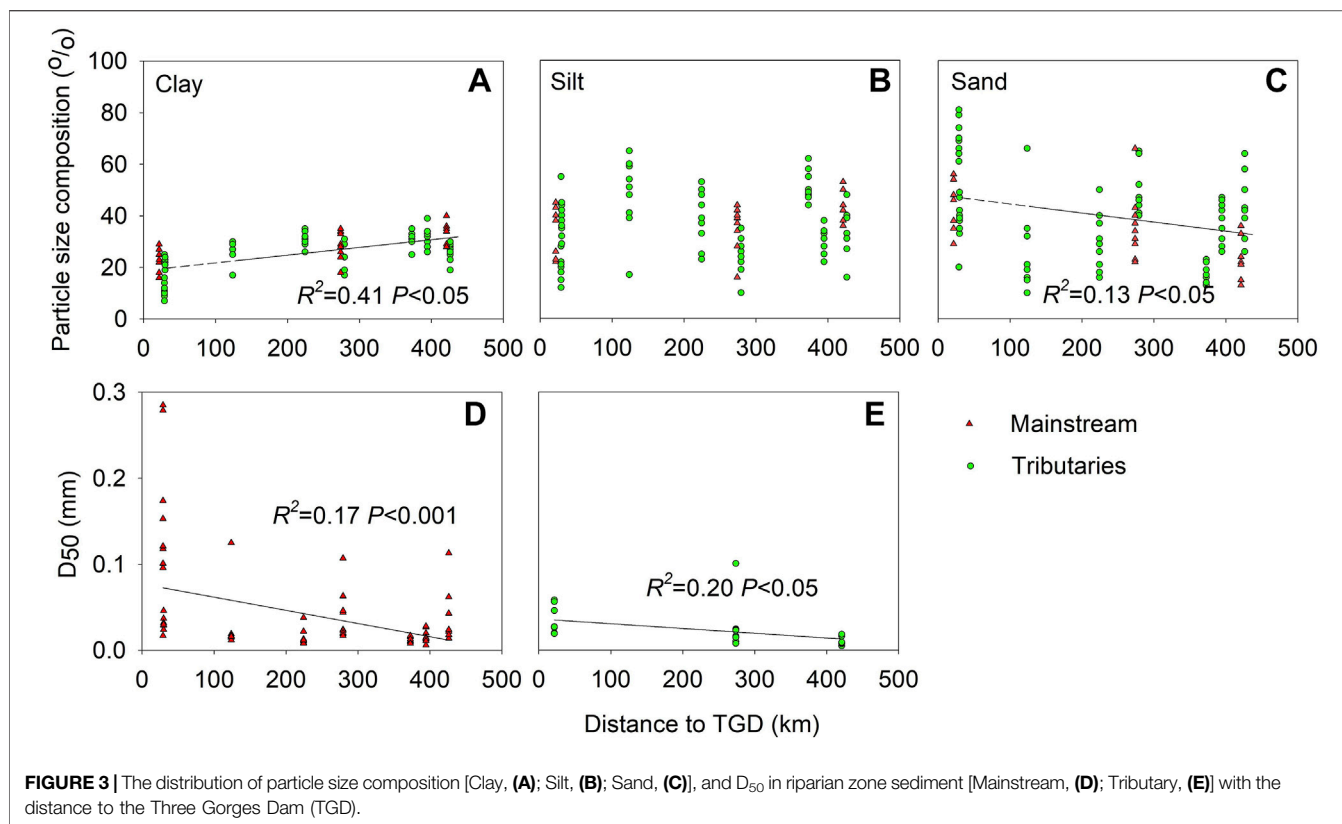
Modelling Drivers of D_{50}

The SEM analysis showed that the submerging time had a direct positive effect on sediment bulk density and moisture. Further, the sediment bulk density negatively affected sediment clay content, while clay content had a direct negative effect on the D_{50} variation (Figure 8A). Besides, the geographical location of the riparian zone (the distance to the Three Gorges Dam) had a direct positive effect on sediment clay and the slope of riparian zone, while both of them had a direct negative impact on D_{50} variation (Figure 8B). The hydrological condition (submerging time) and geographical location could explain 64%–67% of D_{50} variation (Figure 8). Considering the total effect of direct and indirect effects, riparian zone slope and sediment bulk density could be regarded as the most critical predictors shaping the D_{50} variation (Figure 9).

DISCUSSION

Horizontal Trend of Sediment Particle Size Composition

A horizontal coarsening trend of sediment particle size in the riparian zone from upstream of the Yangtze River to the TGD

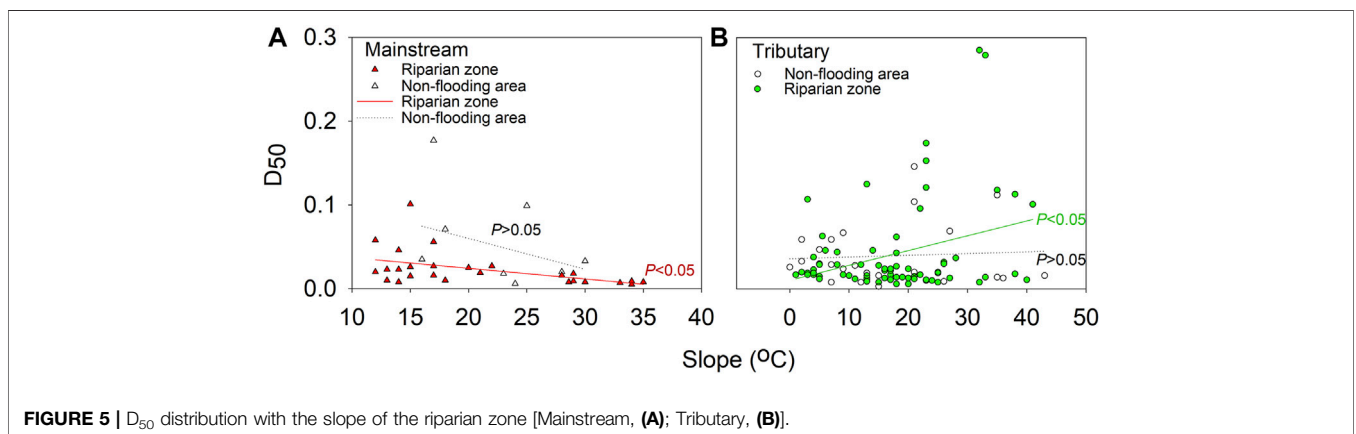
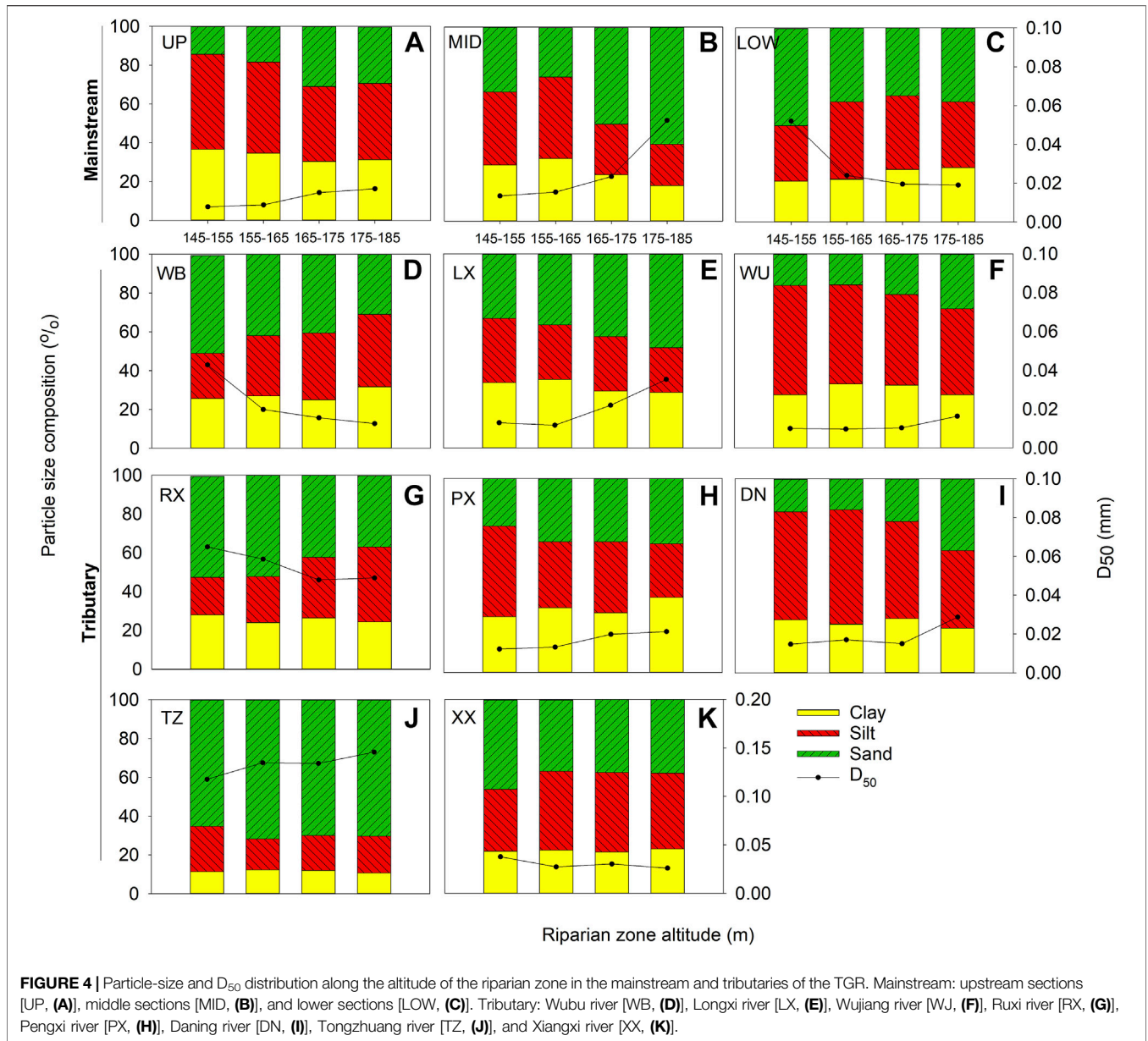


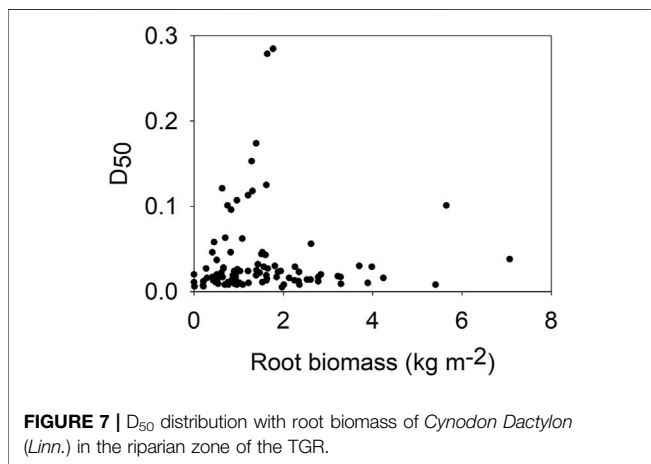
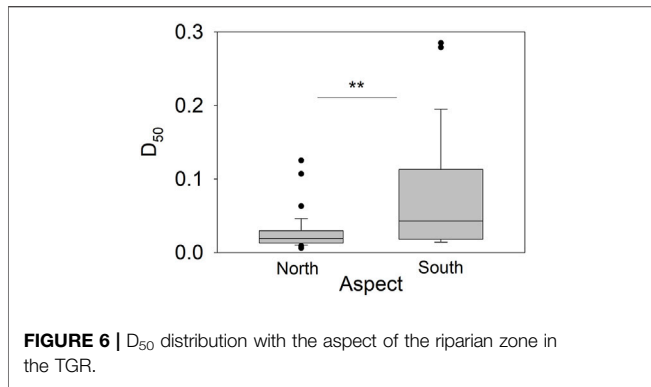
was observed in the TGR across 450 km (Figure 3). The sediment in the riparian zone mainly originates from suspended aquatic sediment deposition and surrounding basin erosion (Tang et al., 2016; Tang et al., 2018). Sediment particle-size composition is a crucial factor in determining the sediment transport capacity under the water level fluctuation condition. Besides, suspended sediment is one of the primary causes of sedimentary landform's evolution in the riparian zone (Tang et al., 2014). Further, the sink sediment with finer particles in the riparian zone can quickly enter the reservoir under drastic hydrological fluctuations (Chen Ye et al., 2019). When sediment enters the reservoir, a horizontal variation is usually seen in the sedimentation processes due to a change in hydrodynamic conditions (Xinchen Wang et al., 2020). Moreover, sediment's emptying effect due to flood discharge can result in a more severe riparian zone erosion towards the TGD (Zhang et al., 2012). Conversely, the increasing trend of finer particles (clay and silt) was found in the riparian zone towards the TGD (Bing et al., 2016), but the research only focused on the mainstream without considering the riparian zone altitudes and the tributaries. The emptying effect might be responsible for the coarsening trend in riparian zone sediment (Rice and Church, 1998; Zhang et al., 2012). Moreover, the blocking effect is relatively higher in the backwater area of the distal upstream (Huang et al., 2018). Thus, the finer sediment

particle tends to deposit in the tail-end riparian zone of the reservoir rather than the surrounding of the TGD.

Hydrological Regime for Particle Size Composition Distribution

Periodic water-level fluctuations might be a potential driver for the distinct distribution of sediment particles in the riparian zone of the TGR. The SEM results suggested that submerging time was the primary driver of D_{50} (Figure 7A), which supported our second hypothesis. The more clay loss occurred in the riparian zone of the lower mainstream and the WB, RX, and XX tributaries, while more finer particles were enriched in the LX, WU, PX, DN, and TZ rivers (Figure 4). It can be explained as follows: first, the complex dynamic action of slope-runoff and current/wave/water-level fluctuations caused a distinct variation in the surface-sediment with different particle sizes in the riparian zone (Pan et al., 2017; Shmilovitz et al., 2020). Second, the flow velocity decreased with the TGR impoundment (Chen et al., 2008; Wei et al., 2016). This occurred particularly in the case of the tributaries as a result of the backwater blocking effect, which has caused numerous water quality issues associated with sediment input into the tributaries of the TGR (Li et al., 2018). Finally, the local impact of sediment load caused a temporal variability in sediment supply from different parts of the TGR (Lu and Higgitt, 2001; Bing et al., 2016).





and succession (Corenblit et al., 2009). The annual erosion of forest land, shrub, grassland, and farmland accounts for 6.19%, 10.76%, 23.05%, and 60% of the total erosion of the TGR area, respectively, while the corresponding sediment export was accounted for 5.95%, 12.42%, 35.46%, and 46.16% of the total sediment export, respectively (Shi et al., 1991). Severe sediment erosion occurs due to cultivation along steep slopes (Lu and Higgitt, 2001). Besides, vegetation density could determine the sediment deposition rate by influencing the surface roughness of the riparian zone (Nagy et al., 2018). However, the vegetation cover indicated by the root-biomass weakly impacted D_{50} distribution (Figure 7). It might be explained by the fact that biodiversity drastically decreases under the anti-seasonal flow regulation, and only a few perennial herbs survive in the riparian zone from long-term winter flooding (Lin et al., 2020).

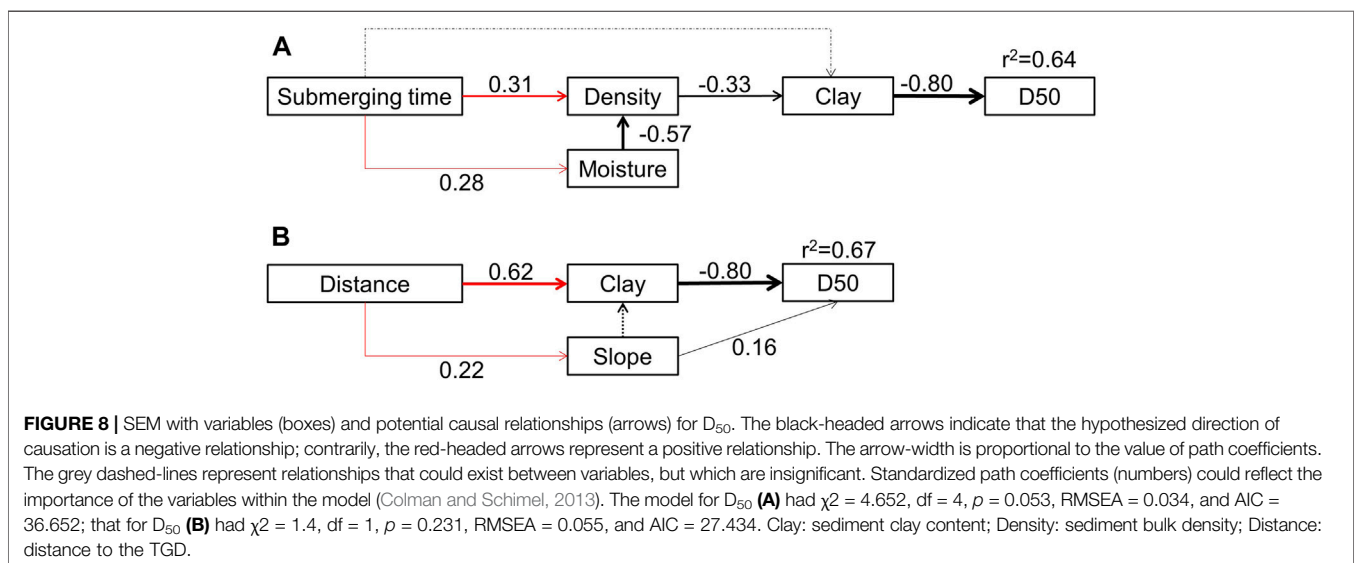
Morphology on Particle Size Composition Distribution

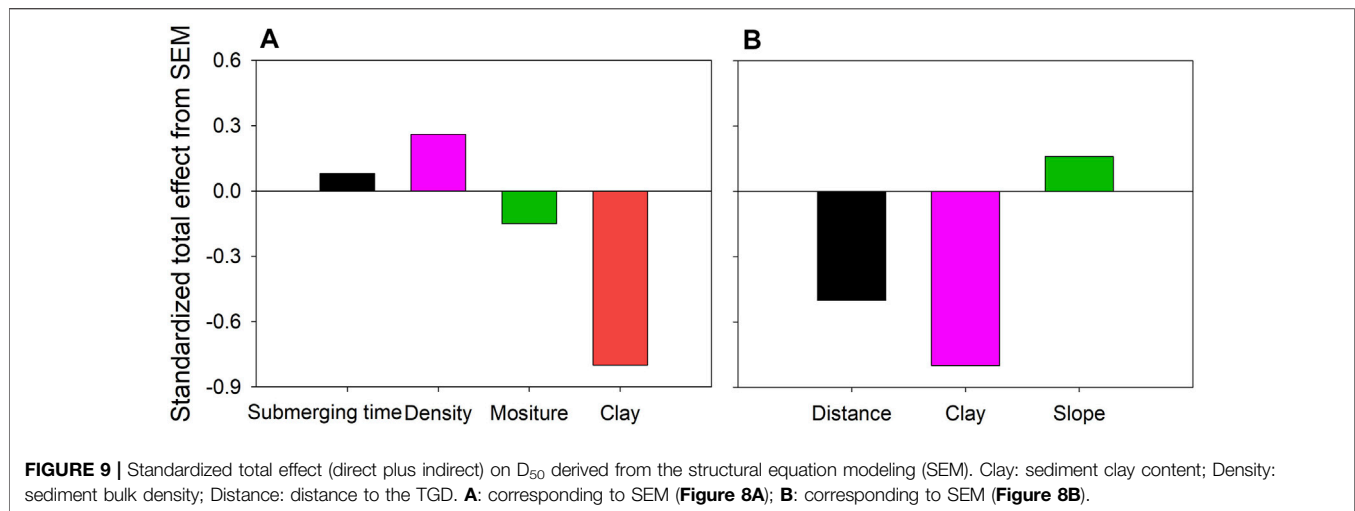
The channel morphology primarily influenced sediment particle size distribution in the riparian zone. About 40% of the riparian zone is distributed along the mainstream, while 60% is located along the Yangtze River’s tributaries. However, the riparian zone located in the Yangtze River’s southern aspect showed more severe erosion with the higher D_{50} (Figure 6). It was primarily related to the local terrain that comprises agricultural platforms (paddy fields and dry land) or steep slopes between platforms.

The slope also determines the distribution of sediment particle size in the riparian zone (Wang et al., 2016a). Sediment with more finer particle size composition tends to deposit in the riparian zone with a gentle slope, which tends to be lost in the riparian zone with a steep slope. With the slope becoming more gentle, finer sediment decreased in the riparian zone of the mainstream, and increased in the riparian zone of the tributaries (Figure 5).

Influence of Land-Use on Sediment Erosion-Deposition

Land use in the riverside basin has significantly influenced sediment particle size distribution in the riparian zone. The riparian zone erosion increased with vegetation’s destruction





The riparian zones with slopes of $<15^\circ$ and $15\text{--}25^\circ$ accounted for 60.94% and 18.56% of the total areas of riparian zone, respectively (Wang et al., 2016b). Moreover, the riparian zone slope in the mid-upper reaches of the TGR was gentle, thus benefitting finer sediment storage. Contrarily, the riparian zone slope in the lower reaches was relatively steep and composed of hillside bedrock (Bing et al., 2016), thus, it is hard to maintain relatively finer particles in the riparian zone under variable water levels (Bao et al., 2015). Thus, the slope plays a crucial role in distribution of particle size composition in the riparian zone sediment of the TGR. In addition, some studies have pointed out that lithology and climate factors play a role in determining sediment particle size (Khan and Chakrapani 2016; Daityari and Khan 2017), but they are not involved in this study.

CONCLUSION

Our investigation demonstrates that the finer sediment in the riparian zone has a decreased trend from the upstream of the Yangtze River to the TGD across 450 km. The trend was inconsistent between the mainstream and tributaries among the riparian zone's altitudes due to the differences in land-use, morphology, and hydrological condition. Hydrological and geographical variables could predict 64%–67% of the D_{50} variance, and thus could be regarded as the main predictor of D_{50} in the riparian zone of the TGR. Thus, to reduce the finer sediment input, the conservation and stabilization of riparian zone in the TGR, especially in the mainstream and the surrounding areas near the TGD, should be highly concerned for the safe operation of the TGR.

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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

JL designed the study, drew the figures and tables, and drafted the manuscript; L. Zhang, C. Yan, YL, X. Xiang, and SZ attended the field investigation and laboratory measurement; ZY, BL, AK, and DL instructed and coordinated the project, edited and smoothed the manuscript.

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