



Soil types differentiated their responses of aggregate stability to hydrological stresses at the riparian zones of the Three Gorges Reservoir

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Abstract

Purpose The aim of this study was to investigate the resistance of aggregates to flooding stresses for different soil types and present implications for the restoration of eroded soils.

Materials and methods Twelve field sites for three soil types were selected and separated into four hydrological stress levels at the riparian zones of the Three Gorges Reservoir. Soil samples were collected randomly, followed by lab analysis of soil mechanical composition, soil aggregate and stability, and soil carbon and nitrogen contents in the bulk soil and different sizes of aggregates.

Results and discussion Clay and silt migrated from the upper water level sites to lower water level sites for Regosols under hydrological stresses; however, the mechanical compositions were not changed for Anthrosols and Luvisols. Total carbon content (TC), total nitrogen content (TN), and carbon and nitrogen ratio (C/N) were highest under strong hydrological stress for all-sized aggregates and bulk soils. Aggregate disintegration under hydrological stresses made organic matter exposed, but the anaerobic environment created by flood avoided organic matter from being decomposed. Most TC and TN in aggregates and bulk soils were negatively correlated with stability. Compared with Anthrosols and Luvisols, Regosols had lower aggregate stability due to its low large macro-aggregate proportions for each stress level. Therefore, much attention should be given to Regosols which has a high potential for erosion. Resistances of aggregates to strong and intermediate hydrological stress were higher for Anthrosols than other tested soils. However, Luvisols had the highest resistance to hydrological stresses because of its higher stability above the elevation of 165 m, due to its highest small macro-aggregate proportion. Therefore, anthropogenic restorations are recommended to stabilize the structure of Anthrosols and Luvisols under weak and strong hydrological stress, respectively.

Conclusions The operation of the Three Gorges Reservoir forced the riparian ecosystem to undergo periodical flooding stresses. The resistance of soil aggregates to hydrological stresses was lowest for Regosols, which should be concerned urgently to reduce soil losses. Under strong and intermediate hydrological stresses, Anthrosols had greater stability to maintain its original structure. However, the aggregate stability of Luvisols was higher for weak and none hydrological stress levels. Hence, anthropogenic restorations are recommended to take priorities for Anthrosols and Luvisols to reduce soil erosion under weak and strong hydrological stress, respectively.

Keywords Anthrosols · Flooding · Soil aggregate stability · Soil composition · Three Gorges Reservoir

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1 Introduction

Soil aggregate is the basic unit of soil structure and storage of soil nutrients (Bronick and Lal 2005). Aggregates play a crucial role in the dynamics of soil erosion and soil nutrients, during which aggregate turnover is a fundamental process (Torri et al. 1998). The aggregate formation is described by aggregate hierarchy theory (Tisdall and Oades 1982; Oades 1984). Micro-aggregates are first formed freely by combining

soil primary particles with metal ions and then serve as the building blocks for the formation of macro-aggregates glued by roots and hyphae. Since roots and hyphae are temporary binding agents, they do not persist and decompose into micro-aggregates when soils are disturbed by external condition including tillage, wetting-drying, flooding, etc. (Six et al. 2004). The mechanism of soil aggregate stabilization varied significantly from different soil types, and the differences are probably ascribed by soil composition and aggregation factors (Bronick and Lal 2005). In Ultisols and Oxisols, large macro-aggregates could be stabilized solely by sesquioxides (Zhang and Horn 2001), which are dense and resistant to mechanical stresses but not stable under hydraulic stress (Zhou et al. 2012). Solonetz has poorer structure than Chernozems and Gleysols, and Chernozem is considered to be a well-structured soil because of the presence of cementing agents (CaCO_3 and moderate clay content) (Ciric et al. 2012). As an important cementing agent, organic carbon plays a primary role in stabilizing aggregate which has been documented (Six et al. 2000). However, organic carbon shows distant contents for different soil types (Cameron 1905). Wetland soils are able to sequester large amounts of organic carbon due to high primary productivity and slow organic matter decomposition at wetland (De La Cruz 1986). The organic carbon plays probably a primary role in stabilizing soil aggregates at wetland (Huo et al. 2018).

Aggregate stability is influenced by environmental conditions including climate, tillage, flooding, and raindrop (Schoonover and Crim 2015). Hydrological stress, induced by water level fluctuation, is certainly an important environmental factor which has crucial effects on changes in soil structure and composition in the riparian ecosystem (Hefting et al. 2004). However, the influence of hydrological stress on soil properties at river shores is still controversial. Banach et al. (2009) indicated that hydrological stress promoted soil particles depositing on river shores and changed soil properties. However, Campbell et al. (2002) reported that hydrological stress washed smaller soil particles away and degraded soil texture. These contradictory results were probably caused by ignoring the variances of hydrological stress (hydrological regimes) and soil types at riparian ecosystems (Saint-Laurent et al. 2014; Ye et al. 2014; Wang et al. 2018). For certain, hydrological stress impacted the dynamics of soil properties, however, we still do not know how the soil type influences the resistance of aggregates to hydrological stress and it is also extremely crucial for soil management at riparian zones.

As an indicator of the ability of soil resistance to external disturbance (Arthur et al. 2012), aggregate stability is commonly described by the mean weight diameter (MWD), the geometric mean diameter (GMD), and the aggregate stability index (ASI) (Castro Filho et al. 2002; Obalum et al. 2019). Each index has a different evaluation purpose. The MWD is impacted by the proportion of large macro-aggregates; the GMD is an estimate of the size of the dominant aggregate-

size classes; the ASI is a measure of the total macro-aggregation of the soil (Kemper and Rosenau 1986; Castro Filho et al. 2002). These indices varying according to the influences on soils show if physical conditions are being affected.

Three Gorges Reservoir (TGR), one of the well-known reservoirs in the world, has been operated officially since 2009. Annually, the water level was manipulated at the lowest elevation at 145 m during summer seasons and reached to the highest elevation at 175 m in the winter, resulting in the formation of the riparian hydro-fluctuation zone with a total area of 350 km² (Zhong and Qi 2008). The operation of the TGR has altered the original riverine ecosystem (Nilsson and Berggren 2000), changed soil properties, and triggered soil erosion (New and Xie 2008). The aims of this study, therefore, were to investigate the resistance of aggregates to periodical flooding for different soil types as well as the potential mechanisms and uncover the carbon, nitrogen content in aggregates which represents organic cementing agents of aggregates, additionally, present some implications to the management of eroded soils.

2 Material and methods

2.1 Study area

This study was conducted in the hydro-fluctuation area of the TGR, (106°–111° 50' E, 29° 16'–31° 25' N), located at the upstream of the Yangtze River in Chongqing municipality and Hubei province, China. The water level in the TGR falls to 145 m during summer and is held at 175 m during winter, annually (Fig. 1a). The Three Gorges Reservoir Area (TGRA) has a humid subtropical monsoon climate, with a mean annual temperature ranging between 15 and 19 °C. And the average precipitation is 1400 mm, with 80% occurring from April to October (Zhang et al. 2019). Regosols (purple soils, developed from the Trias-Cretaceous system of sedimentary rocks), Anthrosols (rice paddy soils, recognized by soils on which irrigated rice is chronically cultivated), and Luvisols (yellow soils, derived from sand shale and the dominant clay mineral is vermiculite) (FAO Taxonomy) are main soil types in the TGRA (China soil database, <http://vdb3.soil.csdb.cn>). According to our field investigation, sediments concentrated in the upper reach of the TGR, from Jiangjin to Fuling district, and soils are covered hardly at middle hydro-fluctuation zone of the TGR, while from Fuling to Wanzhou District of Chongqing, the topography is a sharp slope, and bare rocks were the main landscape.

2.2 Sample collection

Soil samplings were conducted from August 26 to September 8, 2017, when the water level of the TGR was the lowest

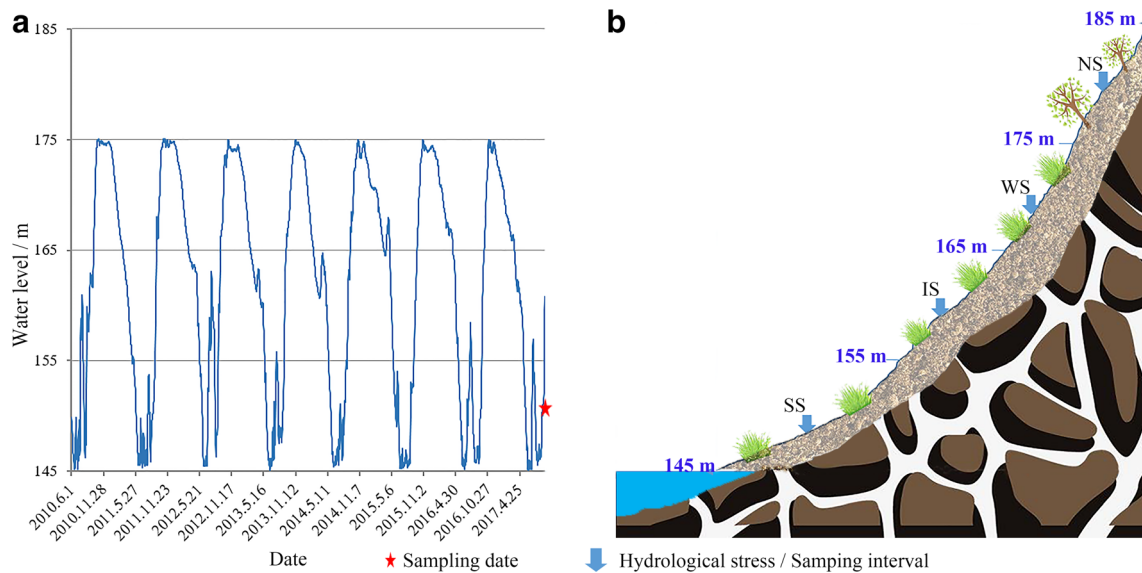


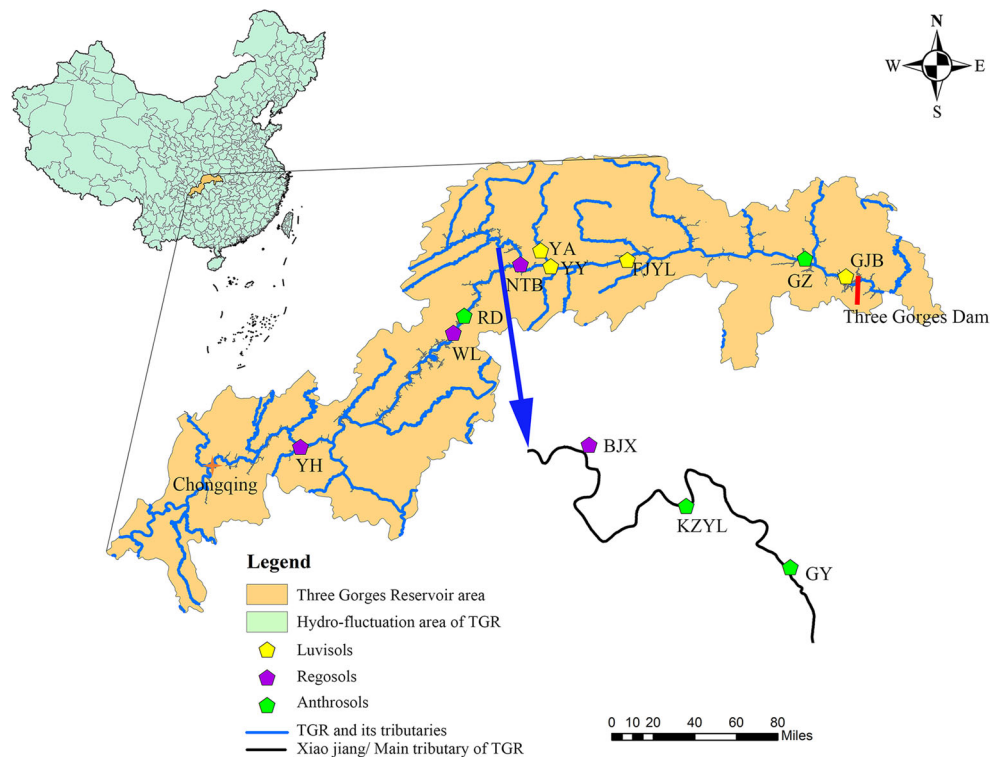
Fig. 1 Water level fluctuation in the Three Gorges Reservoir (a) and schematic diagram for sampling intervals along the riparian zones (b). Four intervals (145–155, 155–165, 165–175, and 175–185 m) were set at each site based on water level fluctuation and flooding duration,

representing four hydrological stress levels—strong (SS), intermediate (IS), weak (WS), and none stress (NS), respectively. Data for daily changes in water level were obtained from the China Three Gorges Corporation (<http://www.ctg.com.cn/>)

around 145 m. Twelve sampling sites (Fig. 2) were totally selected from the mainstream and a typical tributary at this study area, based on the three main soil types before the impoundment of TGR: Regosols (Purple soils), Anthrosols (Rice paddy soils), and Luvisols (Yellow soils). Four intervals (145–155, 155–165, 165–175, and 175–185 m) were set at each site based on water level fluctuations (hydrological stress)

(Fig. 1b). These four intervals were averagely flooded by 246, 131, 38, and 0 days per year (the wetting–drying ratios were 2.07, 0.56, 0.12, and 0, respectively). They also represented four hydrological stress levels—strong (SS), intermediate (IS), weak (WS), and none stress (NS). Samplings within the elevation of 175–185 m were set as control. The intact soil samples were randomly collected from three plots from

Fig. 2 Locations of sampling sites in the water level fluctuation area of Three Gorges Reservoir. The purple, yellow, and green pentagons represent Regosols, Luvisols, and Anthrosols, respectively



0–20 cm of the soil profile at each interval after removing litter, totally 144 soil samples were collected. All samples were transported intact to the laboratory and split manually into small pieces < 8 mm before air drying. Soil samples for determining basic soil properties were mixed completely after collecting randomly at three plots in each interval, totally 48 mixed samples. Soil bulk density was determined by the method of cutting rings.

2.3 Lab analysis

Bulk density (BD) was determined from the soil core with a fixed volume of 100 cm³ by weight method (Wei et al. 2015). The soil pH was determined in a 1:2.5 soil-water suspension by using pH meter (Fe20-K, METTLER TOLEDO, China). Soil total carbon content (TC), total nitrogen content (TN), and carbon and nitrogen content in aggregate fractions were detected by an elemental analyzer (CHNS analyzer, vario EL cube, Germany). Soil mechanical composition was detected by a laser particle analyzer (Mastersizer 3000, Malvern Panalytical, UK). Aggregate-size fractions were isolated by wet sieving technique as described by Yoder (1936) and Márquez, Garcia et al. (2004). Briefly, 80 g of air-dried soil through an 8-mm mesh was sieved manually by mesh sizes of 2 mm, 0.25 mm, and 0.053 mm for each soil sample. Water-stable aggregates were physically separated in four aggregate-size fractions: (1) large macro-aggregates (LM) > 2 mm in diameter, (2) small macro-aggregates (SM) between 0.25 and 2 mm in diameter, (3) micro-aggregates (MI) between 0.053 and 0.25 mm, and (4) the slit- and clay-sized aggregates (SC) < 0.053 mm in diameter, after wet sieving; all water-stable aggregates were dried at 70 °C to balance weight (Zhu 1989; An et al. 2013; Cheng et al. 2015). Soil aggregate stability was expressed by MWD, GMD, and ASI, which were calculated following equations, respectively.

MWD (Barral et al. 2007; Nie et al. 2018):

$$\text{MWD} = \frac{\sum_{i=1}^4 \bar{d}_i w_i}{\sum_{i=1}^4 w_i} \quad (1)$$

GMD (Castro Filho et al. 2002):

$$\text{GMD} = \text{Exp} \left(\frac{\sum_{i=1}^n w_i \ln \bar{d}_i}{\sum_{i=1}^n w_i} \right) \quad (2)$$

ASI (Nichols and Toro 2011):

$$\text{ASI} = \frac{M_{\text{usa}}}{M_{\text{ta}}} \times 100\% \quad (3)$$

where \bar{d}_i is the average diameter of i th size fraction of the aggregate (mm); w_i is the mass of the i th size fraction of the aggregate

(g); and w_t is the total mass of all size aggregate fraction (g); $i = 1, 2, 3, 4$ represent the size > 2 mm, 2–0.25 mm, 0.25–0.053 mm, and < 0.053 mm, respectively; M_{usa} is the mass of water-stable aggregates > 0.25 mm and M_{ta} is the mass of all water-stable aggregates.

2.4 Statistical analysis

The significant differences among different stress levels and soil types were statistically analyzed using a two-way analysis of variance (ANOVA) followed by Fisher's test ($p < 0.05$) for multiple comparisons, as well as ANOVA ($p < 0.05$) was carried out to test the effects of soil type, hydrological stress, and their interaction on soil properties. The effect of hydrological stress on soil composition and aggregate stability was uncovered through the analysis of changes in soil particle composition among hydrological stresses. Pearson test ($p < 0.05$) was conducted to analyze the correlations between carbon, nitrogen contents in bulk soils, and aggregates and stability as well as correlations between aggregates and their stability. The response of different soil types to hydrological stress at reservoir shores was further discussed. All data were analyzed using R (version 3.5.1) software.

3 Results

3.1 Soil mechanical compositions varied from different soil types under hydrological stresses

Soils were mainly composed of silt particles for all samplings. Silt proportion ranged from 60.15 to 75.64%, 65.47 to 71.48%, and 62.18 to 65.54% for Regosols, Anthrosols, and Luvisols, respectively, under the gradient of hydrological stresses. However, silt proportion distributed differently under different stress levels for these soils. Silt proportion increased with stress levels for Regosols and Anthrosols. Clay was the minor fraction, accounting for 7.70 to 12.55%, 10.79 to 12.99%, and 9.36 to 10.52% of the total soil particles respectively for Regosols, Anthrosols, and Luvisols. Resembled with silt, clay proportion increased with hydrological stresses for Regosols and Anthrosols. Inversely, very fine sand and fine sand decreased with the decreasing stress levels for Regosols and Anthrosols. No obvious variation was found for Luvisols composition with different stress levels. The pH varied from 7.06 to 7.29 and 7.01 to 7.37, respectively, for Regosols and Anthrosols, which were mainly neutrality and alkalescence. And the pH for Luvisols ranged from 6.80 to 7.10, which was mainly neutrality and acidity. The BD had a significant difference among these hydrological stresses ($p < 0.001$); hydrological stress decreased BD excluding Argosols (Table 1).

Table 1 Soil mechanism composition, pH, and bulk density of different soil types along the water level elevation of Three Gorges Reservoir. Numbers in the brackets represent standard deviation. Similar letters indicate non-significant differences between hydrological stresses ($p < 0.05$)

Soil type	Elevations m	Clay % < 2 μm	Silt % 2–50 μm	Very fine sand % 50–100 μm	Fine sand % 100–250 μm	Medium sand % 250–500 μm	Coarse sand % 500–2000 μm	pH	BD (g/cm ³)
Regosols	145–155	12.55 (1.69) a	75.64 (3.33) a	7.13 (1.93) a	3.48 (1.62) a	0.99 (0.66) a	0.21 (0.21) a	7.06 (0.33)	1.41 (0.10) a
	155–165	11.19 (4.27) ab	67.80 (7.18) ab	11.00 (6.70) a	8.34 (5.42) a	1.42 (0.86) a	0.25 (0.41) a	7.19 (0.24)	1.47 (0.12) a
	165–175	7.70 (2.62) b	60.15 (11.63) b	15.93 (6.72) ab	13.15 (6.28) ab	2.92 (2.43) a	0.16 (0.19) a	7.29 (0.17)	1.62 (0.11) b
	175–185	7.98 (1.38) b	62.67 (3.83) b	15.18 (1.43) b	12.36 (3.54) b	1.80 (0.90) a	0.01 (0.02) a	7.13 (0.13)	1.67 (0.03) b
Anthrosols	145–155	12.99 (1.16)	71.48 (3.40)	8.80 (0.78)	5.15 (1.90)	1.46 (0.60)	0.12 (0.12)	7.08 (0.33)	1.38 (0.03) b
	155–165	11.43 (3.51)	69.23 (4.46)	11.31 (5.00)	6.91 (4.26)	0.86 (0.58)	0.25 (0.51)	7.17 (0.33)	1.47 (0.17) ab
	165–175	10.79 (1.96)	65.47 (7.75)	12.93 (4.16)	9.54 (5.31)	1.26 (1.32)	0.02 (0.03)	7.37 (0.27)	1.64 (0.15) a
	175–185	9.56 (2.17)	65.75 (4.10)	13.78 (2.58)	9.79 (1.01)	1.11 (1.09)	0.01 (0.02)	7.01 (0.33)	1.60 (0.09) a
Luvisols	145–155	9.36 (4.44)	62.18 (19.67)	12.12 (5.79)	11.13 (11.46)	4.84 (7.53)	0.38 (0.49)	6.96 (0.32)	1.43 (0.17)
	155–165	10.23 (6.63)	63.38 (19.25)	10.65 (6.02)	6.82 (7.49)	5.88 (9.66)	3.04 (4.59)	7.10 (0.24)	1.56 (0.08)
	165–175	10.52 (3.58)	65.59 (7.01)	11.50 (3.03)	7.30 (3.90)	4.09 (3.74)	1.00 (1.05)	6.94 (0.70)	1.49 (0.22)
	175–185	11.08 (5.30)	63.24 (11.07)	12.90 (6.82)	9.01 (7.59)	3.22 (2.40)	0.55 (0.76)	6.80 (0.93)	1.58 (0.11)

3.2 Soil aggregates and stability for different soil types under hydrological stresses

LM and MI proportions both had a significant difference among the three tested soil types at $p = 0.005$ and 0.017 , respectively. SM and SC proportion had significant difference among hydrological stresses at both $p = 0.009$. No interactions were found between soil type and hydrological stress. LM proportion followed a sequence of Anthrosols > Luvisols > Regosols for each stress level (Table 2). And it was highest at 155–165 m under hydrological stress for all soil types. Generally, SM proportion decreased and SC proportion increased with stress levels for all soil types. SM proportion was higher for Luvisols than Anthrosols and Regosols above 165 m. MI proportion was lower for Luvisols than Anthrosols and Regosols above 155 m. Anthrosols had higher SC proportion than Regosols and Luvisols excluding 155–165 m (Fig. 3). In addition, MWD was significantly different among soils at $p = 0.039$, and GMD and ASI were both significantly different among these hydrological stress at $p = 0.019$ and 0.018 , respectively (Table 2). Table 4 shows that MWD, GMD, and ASI were all positively correlated with LM and SM and negatively related to MI and SC for Anthrosols. MWD was only positively correlated with LM proportion, GMD was positively correlated with SM proportion and negatively correlated with SC proportion, and ASI was positively correlated with SM proportion and negatively correlated with MI and SC proportion for Regosols. Additionally, MWD was positively correlated with LM and SM proportion and negatively correlated with MI and SC proportion, and GMD and ASI were both positively correlated with SM proportion and

negatively correlated with MI and SC proportion for Luvisols. Totally, Fig. 4 shows that the aggregate stability of Regosols was lower than Anthrosols and Luvisols. GMD and ASI both were highest above 165 m and decreased with wetting–drying ratio for Luvisols. MWD, GMD, and ASI were higher for Anthrosols than other soils below 165 m.

Table 2 ANOVA results for effects of soil type, hydrological stress, and their interaction on aggregate fractions and stability. HS, hydrological stress; ST, soil type; HS × ST, interaction of soil type and hydrological stress, ** $p < 0.01$, otherwise $*0.01 < p < 0.05$

Aggregate and stability	Source	d.f.	F	Significance
LM	HS	3	0.987	0.410
	ST	2	6.226	0.005**
	HS × ST	6	0.095	0.990
SM	HS	3	4.461	0.009**
	ST	2	2.193	0.126
	HS × ST	6	1.076	0.395
MI	HS	3	1.132	0.349
	ST	2	4.587	0.017*
	HS × ST	6	1.319	0.274
SC	HS	3	4.415	0.009**
	ST	2	0.473	0.627
	HS × ST	6	0.592	0.734
MWD	HS	3	1.556	0.217
	ST	2	3.567	0.039*
	HS × ST	3	0.231	0.964
GMD	HS	6	3.747	0.019*
	ST	2	2.911	0.067
	HS × ST	6	0.716	0.639
ASI	HS	3	3.835	0.018*
	ST	2	1.553	0.225
	HS × ST	6	0.838	0.549

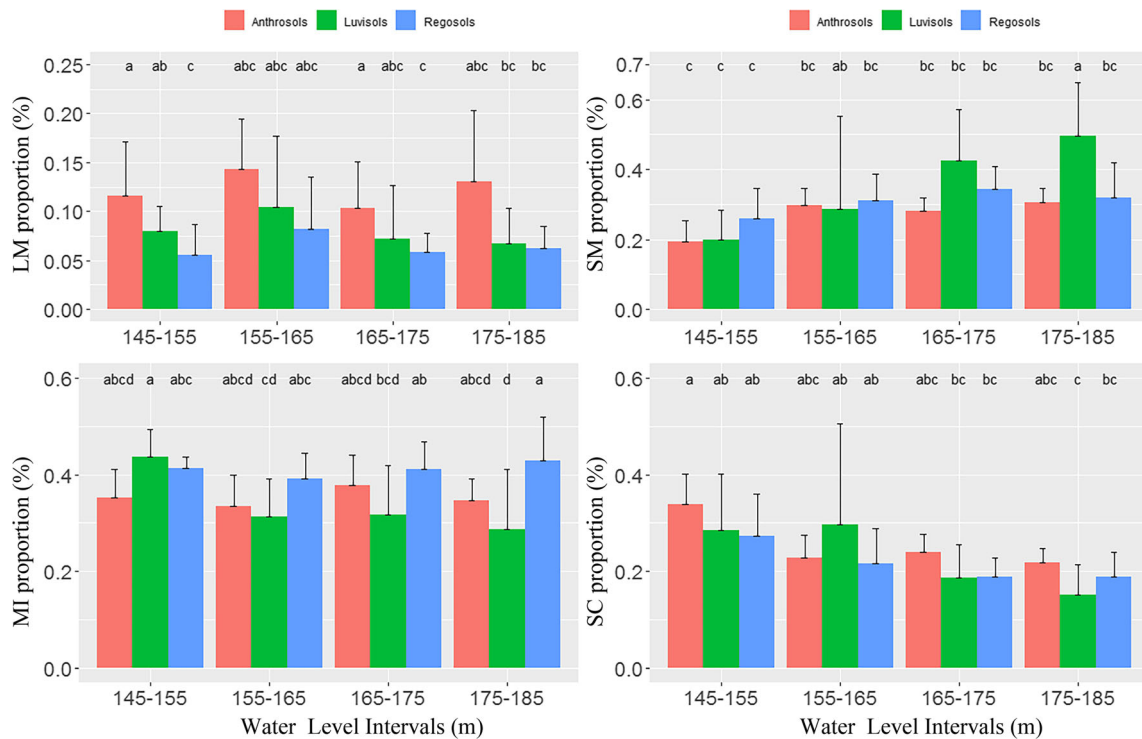


Fig. 3 Soil aggregate proportions in water level fluctuation area of Three Gorges Reservoir for different soil types. Similar letters indicate non-significant differences between soil types under the same hydrological stress ($p < 0.05$)

3.3 Carbon, nitrogen contents, and carbon/nitrogen ratios in aggregate fractions and bulk soils

Table 3 shows that TC, TN (whole soil total carbon and nitrogen contents are equivalent to organic matter and nitrogen

contents), and C/N all were highest at 145–155 m for all aggregate fractions and bulk soils. However, they did not follow the same tendency along stress levels gradient for all soil types. TC in aggregates and bulk soil were significantly different between soils below the elevation of 165 m and those

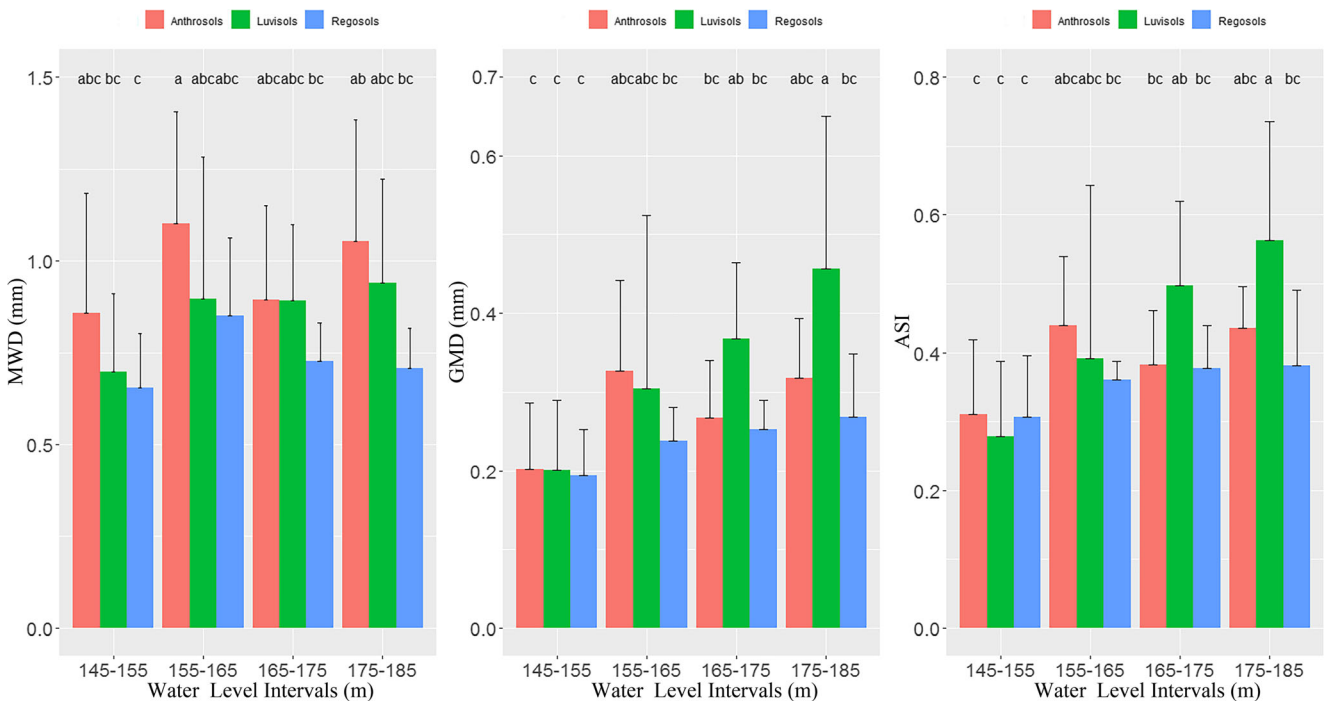


Fig. 4 Soil aggregate stability in water level fluctuation area of Three Gorges Reservoir for different soil types. Similar letters indicate non-significant differences between soil types under the same hydrological stress ($p < 0.05$)

Table 3 Carbon, nitrogen content, and C/N ratio in aggregate fractions and bulk soil along the riparian zone for different soil types. The standard deviation was shown in the bracket. Similar letters indicate non-significant differences between soil types under the same hydrological stress ($p < 0.05$)

Soil type	Aggregate fractions	Water level (m)	TC (%)	TN (%)	C:N	
Regosols	LM (> 2 mm)	145–155	2.77 (0.15)	0.17 (0.03)	16.88 (2.64)	
		155–165	2.38 (NA)	0.16 (NA)	16.15 (NA)	
		165–175	1.98 (NA)	0.13 (NA)	15.85 (NA)	
		175–185	1.38 (NA)	0.12 (NA)	11.50 (NA)	
	SM (0.25~2 mm)	145–155	2.33 (0.43) a	0.12 (0.02) a	18.99 (2.06) a	
		155–165	1.82 (0.75) ab	0.09 (0.03) a	21.63 (8.26) a	
		165–175	1.24 (0.70) b	0.08 (0.05) a	16.55 (3.90) a	
		175–185	1.27 (0.29) b	0.08 (0.02) a	16.50 (4.83) a	
	MI (0.053~0.25 mm)	145–155	1.92 (0.62) a	0.09 (0.03) a	21.57 (4.04) a	
		155–165	1.35 (0.97) ab	0.06 (0.02) ab	23.75 (10.21) ab	
		165–175	0.74 (0.28) b	0.05 (0.02) b	14.61 (1.70) b	
		175–185	0.74 (0.18) b	0.05 (0.01) b	14.13 (1.24) b	
	SC (0~0.053 mm)	145–155	1.64 (0.36) a	0.07 (0.02) a	25.08 (6.80) a	
		155–165	1.30 (0.93) ab	0.06 (0.02) ab	23.56 (18.91) ab	
		165–175	0.68 (0.20) b	0.06 (0.01) ab	11.26 (2.24) ab	
		175–185	0.76 (0.17) b	0.08 (0.02) b	9.17 (0.63) b	
	Bulk soil	145–155	2.07 (0.22) a	0.10 (0.01) a	20.90 (3.72) a	
		155–165	1.52 (0.84) ab	0.07 (0.02) ab	21.76 (10.95) a	
		165–175	1.06 (0.40) b	0.06 (0.03) b	18.61 (4.37) a	
		175–185	1.03 (0.19) b	0.08 (0.02) b	13.93 (2.86) a	
	Anthrosols	LM (> 2 mm)	145–155	2.50 (0.11)	0.17 (0.03)	14.80 (2.18)
			155–165	1.97 (1.01)	0.15 (0.08)	13.42 (2.84)
			165–175	1.92 (NA)	0.12 (NA)	13.94 (NA)
			175–185	1.38 (0.56)	0.13 (0.04)	10.41 (1.08)
SM (0.25~2 mm)		145–155	2.45 (0.59) a	0.15 (0.04) a	16.55 (3.00) a	
		155–165	2.04 (1.01) ab	0.14 (0.07) a	13.96 (2.79) ab	
		165–175	1.20 (0.85) ab	0.09 (0.07) a	13.50 (1.56) ab	
		175–185	1.77 (0.31) b	0.14 (0.03) a	12.47 (0.33) b	
MI (0.053~0.25 mm)		145–155	1.74 (0.71) a	0.08 (0.02) a	21.13 (8.34) a	
		155–165	1.33 (0.74) ab	0.08 (0.04) a	16.95 (4.60) ab	
		165–175	0.75 (0.52) ab	0.07 (0.05) a	11.93 (2.93) b	
		175–185	1.04 (0.12) b	0.09 (0.01) a	11.61 (1.01) b	
SC (0~0.053 mm)		145–155	1.58 (0.62) a	0.07 (0.01) a	23.11 (8.09) a	
		155–165	1.13 (0.65) ab	0.07 (0.02) b	14.94 (7.74) ab	
		165–175	0.68 (0.30) ab	0.08 (0.03) b	8.23 (1.23) b	
		175–185	0.87 (0.08) b	0.11 (0.01) b	8.00 (1.16) b	
Bulk soil		145–155	1.91 (0.50) a	0.09 (0.01) a	21.48 (6.57) a	
		155–165	1.40 (0.72) ab	0.09 (0.04) a	14.70 (4.60) b	
		165–175	0.87 (0.48) b	0.08 (0.04) a	11.18 (2.13) b	
		175–185	1.13 (0.18) b	0.10 (0.02) a	11.90 (0.99) b	
Luvisols		LM (> 2 mm)	145–155	2.43 (0.12)	0.14 (0.03)	17.87 (3.77)
			155–165	2.37 (4.12)	0.13 (0.02)	18.23 (4.12)
			165–175	2.17 (NA)	0.13 (NA)	16.69 (NA)
			175–185	1.34 (NA)	0.10 (NA)	13.40 (NA)
	SM (0.25~2 mm)	145–155	2.86 (1.00)	0.12 (0.02)	24.26 (10.34)	
		155–165	2.55 (1.10)	0.14 (0.06)	19.05 (1.77)	
		165–175	2.13 (1.17)	0.10 (0.05)	23.70 (12.27)	
		175–185	3.17 (2.02)	0.10 (0.04)	33.04 (24.34)	
	MI (0.053~0.25 mm)	145–155	1.92 (0.95)	0.08 (0.02)	22.90 (6.99)	
		155–165	1.95 (0.46)	0.09 (0.02)	23.18 (8.66)	
		165–175	1.54 (0.32)	0.10 (0.03)	17.02 (4.87)	
		175–185	2.62 (1.76)	0.14 (0.08)	19.16 (11.89)	
	SC (0~0.053 mm)	145–155	1.76 (0.62)	0.08 (0.02)	23.99 (10.39)	
		155–165	1.76 (0.46)	0.09 (0.07)	23.40 (9.97)	
		165–175	1.28 (0.23)	0.10 (0.05)	14.44 (4.25)	
		175–185	2.29 (1.49)	0.13 (0.05)	20.75 (18.88)	
	Bulk soil	145–155	2.08 (0.64)	0.10 (0.02)	21.38 (4.65)	
		155–165	1.85 (0.63)	0.08 (0.02)	24.31 (4.62)	
		165–175	1.67 (0.33)	0.09 (0.02)	20.46 (5.92)	
		175–185	2.54 (1.49)	0.11 (0.03)	23.95 (15.27)	

Table 4 The correlations between aggregates and the stability for different soils. *** $p < 0.001$, ** $0.001 < p < 0.01$, otherwise * $0.01 < p < 0.05$

Aggregates	Anthrosols			Regosols			Luvisols		
	MWD	GMD	ASI	MWD	GMD	ASI	MWD	GMD	ASI
LM	0.98***	0.82***	0.80***	0.82***	0.39	0.21	0.67**	-0.05	-0.01
SM	0.56*	0.79***	0.86***	0.09	0.76**	0.89***	0.55*	0.96***	0.97***
MI	-0.88***	-0.71**	-0.77**	-0.29	-0.37	-0.55**	-0.62*	-0.75**	-0.76**
SC	-0.61*	-0.84***	-0.84***	-0.30	-0.76**	-0.68**	-0.58*	-0.84***	-0.86***

above 165 m for Regosols. However, no significant difference existed between 165–175 and 175–185 m for Regosols. For Anthrosols, TC was significantly different among four stress level for aggregates; no significant difference for TN among different stress level excluding SC, which showed TN was lowest at 145–155 m. C/N was significantly higher at aggregates below the elevation of 165 m than those above 165 m. Additionally, not any significant differences were found among stress levels for bulk Luvisols or aggregate fractions. However, TC and TC were lower at flooding sites than none stress at 175–185 m. In addition, most TC, TN, and C/N in aggregates and bulk soils are negatively and none correlated with MWD, GMD, and ASI, except TN in SC for Luvisols (Table 5).

4 Discussion

4.1 Variations of soil property from different soil types under hydrological stresses

Regosols and Anthrosols were mainly neutrality and alkalinescence, and Luvisols was mainly neutrality and acidity at the shores of the TGR, which were consistent with the documented results (Iqbal et al. 2010; Cheng et al. 2017). Hydrological stresses did not significantly change soil pH. BD decreased significantly with the increasing hydrological stresses for the tested soil types, which was negatively correlated with increasing carbon and nitrogen contents (Sakin 2012). However, not any significant differences were observed among soil types at the same hydrological stress level. The results of soil mechanical compositions indicated that hydrological stresses did not significantly change silt and clay proportions, which even had no difference as compared with the control sites (175–185 m) for Anthrosols and Luvisols. Similar results were found by Cui Junfang et al. (2018). However, previous studies indicated that soil mechanical composition can be modified dramatically by hydrological stresses in riverbank ecosystem (Neill 1995; Wang et al. 2018). We found clay and silt proportion were significantly higher below the elevation of 165 m than those above 165 m for Luvisols, as well as very fine sand and fine sand proportion

both were significantly different between hydrological stress and non-stress sites. Hydrological disturbance washed much smaller soil particles away and degraded soil texture (Campbell et al. 2002). Wang et al. (2018) found that the soil mechanical composition was changed by hydrological stresses and the percentage of the clay and silt ranged from 47.14 to 55.68% in the shores of the TGR, which was significantly lower than our results (Table 1). The inconsistent results may be related to the difference of detection instrument and soil texture classification (they defined soil particles between 2 and 20 μm as silt; however, we used defined particles between 2 and 50 μm as silt). Usually, the proportion and size distribution of soil particles were influenced by its parent material (internal factor) for undisturbed soils (Bakhshandeh et al. 2014). The variation of soil mechanical composition resulted also from the external factors, tillage, and fertilization for agroecosystems, vegetation for natural ecosystems, hydrological regime for riparian ecosystems, etc. (Zheng et al. 2003; Wolf et al. 2011). The hydrological regime was the major environmental factor which controlled the processes of the riparian ecosystem (Steiger et al. 2005). The variation of soil mechanical composition for Regosols was induced by around 10-year hydrological stress in the reservoir shores. Interestingly, no obvious variation for Regosols and Anthrosols was from hydrological stresses.

4.2 Responses of aggregate and stability to hydrological stresses for different soil types

Aggregate stability is described by MWD, GMD, and ASI, which are mainly controlled by the percentage of large aggregates proportion, the size of the dominated aggregate-size classes, and the total macro-aggregation of the soil, respectively, (Kemper and Rosenau 1986). There are differences among them as shown in Table 4. Considering the correlation coefficient, ASI was the more appropriate one to describe aggregate stability in this study.

The aggregate stability varied with soil types; the resistance of aggregates to the same external environment stress for different soil types is different (Bronick and Lal 2005). In this study, soils were mainly threatened by water level fluctuation. Although no statistic difference existed among soil types

Table 5 The correlations between carbon, nitrogen contents, and carbon/nitrogen ratios in aggregate fractions and bulk soils. *** $p < 0.001$, ** $0.001 < p < 0.01$, otherwise $0.01 < p < 0.05$

Soils	Stability	TC	TN	C/N	LM-C	SM-C	MI-C	SC-C	LM-N	SM-N	MI-N	SC-N	LM-C/N	SM-C/N	MI-C/N	SC-C/N
Anthrosols	MWD	-0.59*	-0.10	-0.67*	-0.57*	-0.38	-0.64*	-0.69***	-0.40	-0.06	-0.17	0.15	-0.57*	-0.78***	-0.68*	-0.70***
	GWD	-0.67*	-0.10	-0.74**	-0.60*	-0.478	-0.68*	-0.75***	-0.43	-0.12	-0.17	0.23	-0.57*	-0.85***	-0.71***	-0.79***
	ASI	-0.66*	-0.09	-0.75**	-0.57*	-0.47	-0.67*	-0.75***	-0.39	-0.11	-0.13	0.2	-0.57*	-0.86***	-0.74***	-0.79***
Luvisols	MWD	-0.44	0.199	-0.69*	-0.64	-0.62	-0.50	-0.56	0.33	-0.14	0.34	0.41	-0.88***	-0.54	-0.79**	-0.68**
	GWD	-0.75*	-0.08	-0.84**	-0.95***	-0.81***	-0.68*	-0.58	-0.12	-0.59	0.18	0.76*	-0.77*	-0.42	-0.88***	-0.83***
	ASI	-0.68*	0.06	-0.88**	-0.91***	-0.82***	-0.65	-0.58	0.02	-0.51	0.29	0.71*	-0.86***	-0.50	-0.92***	-0.83***
Regosols	MWD	-0.44	-0.44	-0.21	0.039	-0.32	-0.41	-0.28	0.27	-0.41	-0.56	-0.30	-0.21	-0.03	0.24	-0.25
	GWD	-0.62	-0.37	-0.54	-0.15	-0.58	-0.63	-0.51	0.09	-0.58	-0.52	-0.01	-0.24	-0.28	-0.28	-0.61
	ASI	-0.46	-0.11	-0.53	-0.18	-0.58	-0.51	-0.38	0.05	-0.48	-0.34	0.04	-0.23	-0.40	-0.33	-0.50

under strong stress, compared with Anthrosols and Luvisols, Regosols had lower MWD, GMD, and ASI, except ASI under strong stress. However, only ASI was significantly correlated with all-sized aggregates except for LM. MWD was only correlated with LM, GMD was positively correlated with SM and negatively correlated with SC. So ASI is more reliable to represent aggregate stability for Regosols (Table 4). Additionally, high SM and SC proportions led to its lower stability for each flooding stress level (Table 4). As a consequence, Regosols was liable to be eroded under hydrological stresses, because smectite clays are the main cementing agent (Zhao et al. 2012). Regosols aggregates breakdown may occur due to differential swelling (micro-cracking) on soils threatened by hydrological stress (Le Bissonnais 1996). The increasing stress compelled the LM breaking down into SC for Regosols, naturally, and the aggregate stability decreased with the increasing stress level. Their lower stability of aggregates cannot resist being broken by hydro-fluctuation and raindrop, generating water erosion to Regosols. Therefore, much attention should be given to Regosols which has a high potential for erosion. Anthrosols is recognized by soils on which irrigated rice is chronically cultivated (Neidhardt et al. 2012). The chronically inundation and tillage determine higher resistance to water erosion of rice paddy soils (Fang et al. 2019). In this study, the resistance of aggregates to strong and intermediate hydrological stresses was higher for Anthrosols than other soil types, as shown by MWD, GMD, and ASI (Fig. 4). The three indices all followed the same tendency and all suitable to describe aggregate stability for Anthrosols; unlike Regosols, Anthrosols were significantly correlated with all-sized aggregates (Table 4). However, GMD and ASI both showed that Luvisols has the highest resistance for weak hydrological stress because of its higher stability above 165 m, determined by its highest SM proportion above 165 m (Figs. 3 and 4). Macro-aggregates are cemented by the transient and temporary cementing agents; hence, they are prone to be broken into micro-aggregates under hydrological stresses (Bronick and Lal 2005). Additionally, micro-aggregates are stabilized by persistent inorganic bonds that they are not disrupted easily (Six J et al. 2004). Therefore, anthropogenic restorations are recommended to stabilize the structure of Anthrosols and Luvisols under weak and strong hydrological stress, respectively.

4.3 Carbon, nitrogen contents, and carbon/nitrogen ratios of aggregates for different soil types under hydrological stresses

Organic matter is considered as a major binding agent that stabilizes soil aggregates (Mikha and Rice 2004). Yet soils are aggregated in different ways by different kinds of organic material (Haydu-Houdeshell et al. 2018; Heikkinen et al. 2019). No correlation between TC, TN, and C/N and

stability existed for Regosols. More interestingly, we observed that TC, TN, and C/N mostly were negatively correlated with stability for Anthrosols and Luvisols, except TN in clay- and silt-sized aggregates, when hydrological stresses were considered together (Table 5). It seems like opposite that organic matter is a major binding agent of aggregates. The reason probably is that aggregate disintegration under hydrological stresses made organic matter exposed, but the anaerobic environment created by flood avoided organic matter from being decomposed.

TC and TN content and C/N are also related to soil type (Hagedorn et al. 2001). In our study, TC in bulk soil was higher at sites below the elevation of 165 m than above 165 m for Regosols and Anthrosols, and no significant difference exists for Luvisols. TC, TN, and C/N for bulk soils increased with the increasing hydrological stress level for Regosols and Anthrosols (Table 3), which was in accord with the previous results (Chang et al. 2011; Li et al. 2013). Soils at shores were periodically inundated by the water level fluctuation of TGR, which created an anaerobic environment for edaphon. Naturally, the decomposition of organic matter proceeds much more slowly under strong hydrological stress; therefore, carbon and nitrogen generally contained higher at the area with a low water level (Davidson and Janssens 2006).

In addition, soil aggregates are storage for carbon, nitrogen, organic matter, and other nutrients; the contents of which in aggregates were related to aggregate dynamics. Usually, LM and SM were formed by combining MI transiently with organic matter (Six et al. 2000). TC and TN were higher in LM and SM than MI and SC in this study. Macro-aggregates were partly broken into micro-aggregates and silt- and clay-sized aggregates with carbon and nitrogen exposing and releasing once soils under submersion (Six et al. 2000). However, the submersion process limited oxygen diffusion by filling soil pore space and created anoxic conditions which objected to organic carbon and nitrogen mineralization (Hefting et al. 2004). When soils were dried, LM and SM reformed to stabilize both inter- and intra-aggregate carbon (Simpson et al. 2004). Inter-aggregate carbon stabilization as roots and hyphae bind SC and MI together to form LM and SM. Intra-aggregate carbon then continues to accumulate and stabilize in MI embedded within LM and SM (Tisdall and Oades 1982; Oades 1984). Although aggregates broke down under hydrological stress and made organic matter exposed, the anaerobic environment avoided organic matter being decomposed for Regosols and Anthrosols. However, Luvisols seemed no conspicuous response to hydrological stress.

5 Conclusions and implications

The operation of Three Gorges Reservoir forced the riparian ecosystem to undergo periodical threat by

hydrological stress; soils at shores are threatened by water level fluctuation. Responses of soils were different from hydrological stress with varying soil types, although all soils were mainly composed of silt particles. Regosols had the lowest large macro-aggregate and small macro-aggregate proportion; the resistance of the structure to hydrological stress was consequently lowest. Under strong and intermediate hydrological stress level, Anthrosols had higher stability to maintain its original structure. However, the aggregate stability of Luvisols was higher for weak and none hydrological stress level. Carbon and nitrogen in aggregates and bulk soils all were mainly concentrated on 145–155 m, where soils were under strong hydrological stress.

Soil type and hydrological stress both are related to soil erosion; therefore, the eroded soils cannot be treated identically. As its vulnerable structure, Regosols should be concerned urgently. Additionally, anthropogenic restorations are recommended to stabilize the structure of Anthrosols and Luvisols under weak and strong hydrological stress, respectively. Future work should focus on the variation of cementing agent and coupling mechanism between aggregate dynamics and cementing agent variation under hydrological stress in river (reservoir) shores.

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Appendix

GPS information on sampling sites for different soil types.

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