The vertical heterogeneity of soil detachment by overland flow on the water-level fluctuation zone slope in the Three Gorges Reservoir, China

Ping Guo [1, 2], Hai Xiao [1, 2, *], Feng Gao [1], Zijuan Li [2], Huan Hu [1], Qianheng Zhang [1], Zhenyao Xia [1, 2, *], Mingyi Li [1, 2], Yueshu Yang [1]

[1] Key Laboratory of Geological Hazards on Three Gorges Reservoir Area (China Three Gorges University), Ministry of Education, Yichang 443002, People's Republic of China

[2] Engineering Research Center of Eco-environment in Three Gorges Reservoir Region, Ministry of Education, China Three Gorges University, Yichang 443002, People's Republic of China

*Corresponding author:

Correspondence address: China Three Gorges University, No.8 Daxue road, Xiling district, Yichang City, Hubei Province 443002, China.

E-mail address: oceanshawctgu@163.com (Hai Xiao); xzy_yc@126.com (Zhenyao Xia)

Abstract

Submersion and exposure from the operation of the Three Gorges Reservoir (TGR) can alter soil properties and plant characteristics at different elevations of the water level fluctuation zone (WLFZ), possibly influencing soil detachment capacity (D_c), but the vertical heterogeneity of this effect is uncertain. Soil samples were taken from 6 segments (5 m elevation per segment) along a slope profile in the WLFZ of the TGR to clarify the vertical heterogeneity of D_c. Scouring experiments were conducted at 5 slope gradients (17.63%, 26.79%, 36.40%, 46.63%, and 57.74%) and 5 flow rates (10, 15, 20, 25, and 30 L min^{-1}) to determine D_c. The results indicate that the soil properties and biomass parameters of the WLFZ are strongly affected by elevation. D_c fluctuates with increasing elevation, with maximum and minimum average values at elevations of 145-150 m and 165-170 m, respectively. Linear equations accurately describe the relationships between D_c and hydrodynamic parameters. τ, ω, and E perform much better than U. Furthermore, a clear improvement is seen when using the general index of flow intensity to estimate D_c. D_c is significantly negatively correlated with *MWD* ($p < 0.05$) and organic matter ($p < 0.01$) but not significantly correlated with other soil properties ($p > 0.05$). At elevations of 145-150 m and 170-175 m, rill erodibility was greater than at other elevations. The critical hydraulic parameters were highest in the 165-170 m segments, both showing obviously fluctuation in the vertical direction of slope surface. This research highlighted the vertical heterogeneity of the soil detachment and was helpful to understand the mechanisms of soil detachment processes in the WLFZ of the TGR.

Keywords:

Soil detachment capacity, Vertical variation, Rill erodibility, The water level fluctuation zone, The Three Gorges Reservoir

1. INTRODUCTION

Soil erosion is the main cause of land degradation, continues to be the greatest threat to global soil health and its ecosystem services, and is regarded as the greatest challenge to sustainable soil management (FAO, 2019; Li, Zhang, Wang, & Meng, 2020). The soil erosion process includes three subprocesses: soil detachment, sediment transport and deposition (Zhu et al., Zhu, Fu, Wu, & Wang, 2020). As the initial process of soil erosion, soil detachment creates loose, non-cohesive soil particles and aggregates for sediment transport (Xiao et al., 2017; Shen, Wang, Zhang, Chen, & Wu, 2019). Clear water can produce maximum rates of soil detachment and defines the soil detachment capacity (D_c) (Nearing, Bradford, & Parker, 1991; Shen et al., 2019), the key parameter of process-based erosion models (Nearing, Foster, & Lane, 1989). Accurate estimation of soil detachment is important for soil erosion simulations and is important in establishing process-based erosion models.

D_c is strongly influenced by soil properties, such as particle composition, the mean weight diameter of aggregates, bulk density, and organic matter, and by plant factors, such as root density (Zhang, Tang, Sun, & Zhang, 2014; Vannoppen, Vanmaercke, De Baets, & Poesen, 2015). In general, D_c decreases with bulk density, the mean weight diameter of aggregates, sand content, organic matter, root density, and vegetation cover but increases with clay and silt contents (Zhang, Liu, Tang, & Zhang, 2008; Zhang, Tang, & Zhang, 2009; Knapen, Smets, & Poesen, 2009; Wang et al., 2013; Wang, Zhang, Yang, Li, & Liu, 2018a; Wang, Zhang, Li, Zhang, & Yang, 2018b; Yu, Zhang, Geng, & Sun, 2014; Parhizkar et al., 2020). Clay content, the mean weight diameter of aggregates, organic matter, bulk density, and root density are consistently the most effective characteristics for predicting D_c (Morgan et al., 1998; Zhang et al., 2008; Scherer, Zehe, Träbing, & Gerlinger, 2012; Wang et al., 2013). Tillage operations, vegetation restoration models, land use, and restoration age affect soil detachment by altering soil properties and plant characteristics (Scherer et al., 2012; Li, Zhang, Geng Wang, H., & Zhang, 2015; Dou, Yang, An, & Zhu, 2020; Liu, Zhang, Sun, & Li, 2020a). In the course of the operation of the Three Gorges Reservoir (TGR), soil properties and plant characteristics are altered by the submersion and exposure of plants in the water level fluctuation zone (WLFZ). However, soil detachment under these conditions has been rarely reported.

D_c is sensitive to slope gradient and flow rate and always increases with slope gradient and flow rate (Xiao et al., 2017; Li et al., 2019b; Ma, Zhang, Cao, Wei, & Yang, 2020). The power function of either slope gradient or flow rate has been shown to be useful for forecasting D_c (Nearing et al., 1991; Zhang, Liu, Nearing, & Huang, 2002; Zhu et al., 2020). In many cases, overland flow hydraulic parameters are also used to estimate D_c (Nearing et al., 1991). The shear stress (Nearing et al., 1991), stream power (Hairsine & Rose, 1992a; Hairsine & Rose, 1992b), unit stream power (Morgan et al., 1998; Govers, Rafael, & Oost, 2007), and unit energy of water-carrying sections (Xiao et al., 2017; Li et al., 2019b) are commonly employed to estimate D_c. Shear stress is the most common hydraulic parameter for estimating D_c and has been adopted in the Water Erosion Prediction Project (WEPP) (Nearing, et al., 1989). Stream power performs better than other parameters in many simulation studies of D_c (Zhang et al., 2002; Ma et al., 2020; Zhu et al., 2020) and is used as the hydraulic parameter for estimating D_c in the Griffith University Erosion System Template (GUST) (Misra & Rose, 1996). Unit stream power is regarded as the most appropriate parameter to describe the D_c in some studies (Nazari, Qiuwen, Shahram, James, & Reza, 2016; Yang et al., 2018) and is used to calculate D_c in the European Soil Erosion Model (EUROSEM). In addition, the unit energy of water-carrying sections has been applied to estimate D_c in recent decades (Wang, Wang, Shen, & Chen, 2016; Xiao et al., 2017; Li et al., 2019b). Thus, the choice of the most suitable overland flow hydraulic parameter for describing D_c, especially in special areas such as the WLFZ, is still inconsistent.

The operation of the TGR is characterized by anti-seasonal water level regulation, resulting in the maximum water level (175 m) from October to April and the minimum water level (145 m) from May to September (Bao, Gao, & He, 2015a). These unnatural fluctuations result in a zone with a length of 5578 km and an area of 348.93 km^2 (Su et al., 2017). The WLFZ has suffered severe soil erosion due to wave erosion and surface runoff erosion (Bao, Tang, He, Hu, & Zhang, 2015b). The mean annual soil erosion rates in the mainstream WLFZ range from 32,383 to 69,593 t km^{-2} yr^{-1}, with an average of 54,050 t km^{-2} yr^{-1}, and those in the tributary WLFZ range from 8107 to 10,360 t km^{-2} yr^{-1}, with an average of 9191 t km^{-2} yr^{-1} (Bao et al., 2018). In the WLFZ, the soil properties and plant characteristics of plants at different elevations are altered by submersion and exposure because of the operation of the TGR (Baldwin & Mitchell, 2000; Tang et al., 2014; Tang et al., 2018), possibly influencing D_c at different elevations in the WLFZ.

This study was conducted to determine the vertical heterogeneity of D_c in the WLFZ of the TGR. Soil samples were taken in the same time period from 6 segments at elevations of 145-150 m, 150-155 m, 155-160 m, 160-165 m, 165-170 m, and 170-175 m along a slope profile across the WLFZ of the TGR area and were subjected to a scouring experiment. The purposes of this study were (i) to quantify the effects of the vertical position on the spatial variation of D_c and (ii) to identify the factors influencing these variations in the WLFZ of the TGR. This study will improve the understanding of the soil erosion process and provide a scientific basis for controlling soil erosion in the WLFZ of the TGR．

2. DATA AND METHODS

2.1 Soil and experimental design

Soil samples were collected on August 22, 2019, when the entire WLFZ was exposed (Fig. 1). A typical WLFZ in Zigui County (30°38′-31°11′ N and 110°18′-111°00′ E), Yichang City, Hubei Province, China, was selected as the sampling site. The area is characterized as having a subtropical continental monsoon climate with an average annual temperature, average annual rainfall, and average annual sunshine time of approximately 18.9 °C, 1100 mm and 1631.5 h, respectively.

Six segments with elevations of 145-150 m, 150-155 m, 155-160 m, 160-165 m, 165-170 m, and 170-175 m were defined along the elevation gradient of the WLFZ.

Three 0.5 × 0.5 m^2 quadrats for each segment were placed at random, and samples of the uppermost 5 cm of soil were collected after removing aboveground plant parts and litter. Soil samples from different quadrats in the same segment were mixed and brought back to the laboratory. Impurities (roots and gravel) in soil were removed by gently passing it through a 5 mm sieve after air drying. Soil was then packed into a 10.05 cm diameter and 5 cm deep steel cylinder. The mass of each sample were determined using the target bulk density and moisture content of the air-dried soil. The target bulk density at each elevation was determined according to the field values at each elevation. The steel cylinders with air-dried soil were saturated with water before being subjected to a scouring experiment.

A slope-adjustable (ranged from 0 to 60.00%) steel hydraulic flume 4 m in length, 0.4 m wide and 0.2 m deep was used to conduct the scouring experiment to determine D_c (Fig. 2). Based on our field investigation, 5 slope gradients of 17.63%, 26.79%, 36.40%, 46.63%, and 57.74% were chosen. Five flow rates of 10, 15, 20, 25, and 30 L min^{-1} were used to calculate different flow conditions. In all, twenty-five combinations were performed to determine D_c according to the overland flow for each elevation, and each combination was repeated three times. Thus, in this study, 450 samples with 6 segments × 5 slope gradients × 5 flow rates × 3 replicates were tested.

The designed slope gradient was set by adjusting the steel hydraulic flume before each test. The overland flow was supplied to the upstream end of the flume using a pump, and the discharge of the water flow was controlled by a flowmeter (error < 5%). The dye tracing method (potassium permanganate as tracer) was used to measure the velocity of each flow (Zhang, Luo, Cao, Shen, & Zhang, 2010). The velocity between cross sections at transects 0 to 1 m from the soil chamber was measured in five replicates. The mean travel time of the dye tracer was determined to estimate the surface flow velocity for each flow. The mean flow velocity was obtained by multiplying the surface flow velocity by a correction factor of 0.67 (Li, Abrahams, & Atkinson, 1996). The steel cylinders containing soil samples were inserted into the chamber of the flume to ensure that soil sample surfaces were at the same level relative to the flume bed and were covered by a sliding plate to prevent detaching when removing the pipe from the flume. Overland flow was introduced into the flume and the sliding plate was removed; then, after the overland flow reached a steady state, the test was initiated. The test was stopped when the scouring depth reached approximately 2 cm to prevent boundary effects from the steel cylinder (Wang et al., 2017), and the scouring duration was measured using a stopwatch. All the sediment was collected and weighed after complete oven drying.

The aboveground biomass in each quadrat was collected after cutting using scissors, and the underground biomass in the uppermost 5 cm was measured by means of three self-made annulus samples (10.05 cm diameter and 5 cm deep). The aboveground and underground biomasses were oven-dried at 65 °C and weighed. Soil bulk density was measured using a steel ring with a volume of 100 cm^3 in three replicates. A precision acidity meter (Rex Electric Chemical PHS-3E, Shanghai Precision Scientific Instrument Co., Ltd, China) was used to determine the soil pH. The potassium dichromate oxidation-external heating method was used to determine soil organic matter. The wet-sieving method was used to measure the water stable aggregate in triplicate. Approximately 100 g of soil was placed on filter paper and capillary-wetted for 30 min. A series of sieves with grid sizes of 5, 2, 1, 0.5, and 0.25 mm, stacked from top to bottom, were immersed in distilled water, and each soil sample was introduced into the top sieve (5 mm). The soil particles captured on each sieve were collected after shaking up and down 30 times over 1 min. The collected soil in each sieve was dried and weighed for analysis.

2.2 Data analysis

The stability of soil aggregates is expressed as the mean weight diameter (*MWD*), which is estimated using Equation (1):

$$MWD = \sum_{i=1}^{n} \bar{x}_i w_i \tag{1}$$

where w_i is the weight fraction of aggregates in size class i with an average diameter $\bar{x}_i$. A larger *MWD* value indicates greater stability of the soil aggregate (Dou et al., 2020).

D_c (kg m^{-2} s^{-1}) is the mass of detachment per area per time under clear water, which is estimated using Equation (2):

$$D_c = \frac{m}{At} \tag{2}$$

where m is the mass of sediment for each test (kg), A is the test area of the soil sample (7.93×10^{-3} m^2) and t is the duration of the test (s).

Commonly used hydrodynamic parameters, shear stress (τ, Pa or N m^{-2}) (Nearing et al., 1991), stream power (ω, N m^{-1} s^{-1}) (Hairsine & Rose, 1992a; Hairsine & Rose, 1992b), unit stream power (U, m s^{-1}) (Morgan et al., 1998; Govers et al., 2007), and unit energy of water-carrying section (E, m) (Xiao et al., 2017; Li et al., 2019b), were employed in this research. These parameters can be calculated using the following equations:

$$\tau = \rho g h J \tag{3}$$

$$\omega = \tau V = \rho g q J \tag{4}$$

$$U = VJ \tag{5}$$

$$E = \alpha \frac{V^2}{2g} + h \tag{6}$$

where ρ is the water density (kg m^{-3}), g is gravitational acceleration (m s^{-2}), h is the flow depth for each test (m), J is the slope gradient for each test (m m^{-1}), q is the unit discharge per unit width for each test (m^2 s^{-1}), V is the mean flow velocity for each test (m s^{-1}), and a is the correction factor, usually equal to 1, for kinetic energy (Xiao et al., 2017).

Flow depth (h, m) is very difficult to accurately monitor due to shallow depths (usually only a few millimetres) and its dynamic condition (Guo, Wang, Li, & Wu, 2010). Hence, flow depth is calculated based on the assumption of a uniform condition across the flow width, which is calculated using Equation (7):

$$h = \frac{Q}{Vb} \tag{7}$$

where Q is the flow rate for each test (m^3 s^{-1}) and b is the flow width, which is equal to the width of the hydraulic flume (0.4 m).

The slope of the regression line and the intercept on the x-axis were taken as soil erodibility and critical hydrodynamic parameters according to the linear function between D_c and the flow hydrodynamic parameters (Li et al., 2019b):

$$D_C = K_r \left(F - F_c \right) \tag{8}$$

where K_r is the soil erodibility, F is a hydrodynamic parameter, and F_c is a critical hydraulic parameter corresponding to a hydraulic parameter.

The experimental data presented in the tables and figures represent the mean values of each segment. Differences between segments were determined using one-way ANOVA with the least significant difference (LSD) test at a significance level of 0.05. The correlations of the soil properties, biomass properties and measured influencing factors were determined using Pearson correlation analysis. All statistical analyses were performed using SPSS version 21.0 and Excel version 2010.

3. RESULTS

3.1 Soil and biomass properties at different elevations

All the soil and biomass properties measured showed significant spatial variation in the WLFZ (Table 1). The soil bulk density, pH, clay content, silt content, sand content, soil aggregate stability, organic matter, aboveground biomass, and underground biomass ranged from 1.08-1.29 g cm^{-3}, 6.64-7.49, 14.02-19.91%, 39.77-54.25%, 25.84-46.15%, 0.91-1.17 mm, 16.31-30.31 g kg^{-1}, 369.47-1750.97 g m^{-2}, and 1.03-22.44 kg m^{-3}, respectively. The soil bulk density at elevations of 145-150 m and 170-175 m was significantly higher than at other elevations. The soil pH values at low elevations (145-160 m) were significantly higher than those at high elevations (160-175 m). With increasing elevation, the clay and silt contents showed decreasing trends, while the sand content exhibited the opposite trend, suggesting that soil particles coarsen with increasing elevation. A significantly greater *MWD* was observed at elevations of 160-165 m and 165-170 m than at the other elevations, and the organic matter contents at elevations of 145-150 m and 170-175 m were significantly less than those at the other elevations. The aboveground biomass and underground biomass at 160-165 m were significantly greater than those at the other elevations, suggesting that the greatest plant biomass was in the middle part of the WLFZ.

Pearson correlations (Table 2) indicated that clay content was significantly positively correlated with silt content ($p < 0.05$) and significantly negatively correlated with sand content ($p < 0.01$). A significant negative correlation was found between silt content and sand content ($p < 0.01$). The *MWD* was found to be significantly positively correlated with organic matter and underground biomass ($p < 0.05$) but not with aboveground biomass, although a significantly positive correlation existed between aboveground biomass and underground biomass ($p < 0.01$).

3.2 Soil detachment capacity (D_c) at different elevations

D_c varied from 0.068 to 1.151, 0.040 to 0.983, 0.041 to 0.911, 0.058 to 0.804, 0.047 to 0.864, and 0.055 to 1.023 kg m^{-2} s^{-1}, with averages of 0.443, 0.391, 0.385, 0.383, 0.325, and 0.415 kg m^{-2} s^{-1} for elevation segments of 145-150 m, 150-155 m, 155-160 m, 160-165 m, 165-170 m, and 170-175 m, respectively. Generally speaking, D_c

fluctuated with increasing elevation, reaching a maximum average value at the elevation segment of 145-150 m and a minimum average value at the elevation segment of 165-170 m. No significant differences in D_c were observed among all the elevation segments due to the amplitude of the variation and the large overlap in the D_c of different elevation segments. However, the average D_c at elevation segments of 145-150 m, 150-155 m, 155-160 m, 160-165 m and 170-175 m was 36.50%, 20.33%, 18.59%, 18.08% and 27.88% higher than that at the elevation segment of 165-170 m, respectively. The vertical heterogeneity of D_c was further assessed for different elevations at the same slope gradient and flow rate to account for the influence of their effects. D_c values at different elevations with a slope gradient of 36.40% and a flow rate of 30 L min^{-1} were taken as examples due to the similar pattern of change of D_c in each treatment (Fig. 3). The differences in D_c among elevation segments of 150-155 m, 155-160 m and 160-165 m were insignificant but were significantly different than those of the other elevation segments. The D_c of the 145-150 m and 170-175 m elevation segments were significantly greater than that at the other elevation segments, while the D_c of the 165-170 m elevation segment was significantly less than that the other elevations segments, suggesting obvious vertical heterogeneity for D_c in the WLFZ of the TGR.

D_c increased with τ (Fig. 4a), ω (Fig. 4b), U (Fig. 4c) and E (Fig. 4d) for the all elevation segments, as expected. The relationship between D_c and hydrodynamic parameters can be accurately described by linear equations, the determination coefficients (R^2) of which ranged from 0.855 to 0.950, 0.842 to 0.950, 0.366 to 0.697, and 0.877 to 0.935, with average values of 0.908, 0.901, 0.511 and 0.905 for τ, ω, U and E, respectively, indicating that τ, ω, and E can be better employed to determine D_c than U.

3.3 Soil erosion resistance at different elevations

Rill erodibility and the critical hydrodynamic parameter can be used to describe soil resistance to rill erosion (Geng, Zhang, Ma, & Wang, 2017). The rill erodibility corresponding to U and the critical value of U were not analysed because of the relatively poor relationship between D_c and U (Table 3). The rill erodibility coefficients that corresponded to shear stress were 0.120, 0.112, 0.103, 0.103, 0.094 and 0.120 s m^{-1}; those corresponding to stream power were 0.173, 0.163, 0.149, 0.147, 0.137 and 0.173 kg m^{-3}; and those corresponding to the unit energy of a water-carrying section were 63.092, 58.234, 52.824, 52.836, 48.623 and 62.524 kg m^{-3} s^{-1} for the elevation segments of 145-150 m, 150-155 m, 155-160 m, 160-165 m, 165-170 m, and 170-175 m, respectively (Table 3). The critical τ, critical ω and critical E were 1.950, 2.162, 1.883, 1.932, 2.191 and 2.167 Pa, 0.208, 0.368, 0.187, 0.170, 0.409 and 0.370 N m^{-1} s^{-1}, and 0.006, 0.006, 0.006, 0.006, 0.007 and 0.007 m for the elevation segments of 145-150 m, 150-155 m, 155-160 m, 160-165 m, 165-170 m, and 170-175 m, respectively. With increasing elevation, rill erodibility showed a decreasing trend, followed by an increase, and the critical hydraulic parameters exhibited an increasing trend, followed by a reduction and a subsequent increase.

3.4 Relationship between soil erosion resistance and soil properties

Pearson correlations (Table 4) indicated that D_c was significantly negatively correlated with the *MWD* ($p < 0.05$) and organic matter ($p < 0.01$) but was not significantly correlated with the other soil properties ($p > 0.05$). Moreover, correlation analysis suggested that the rill erodibility coefficients corresponding to the shear stress, stream power and unit energy of a water-carrying section were also negatively related to the *MWD* ($p < 0.05$) and organic matter ($p < 0.05$) but not to the other soil properties ($p > 0.05$). Surprising, no significantly correlation was found between the critical hydrodynamic parameter and soil properties.

4. DISCUSSION

In the WLFZ, soil properties were strongly heterogenous at different elevations (Table 1). Small particles fill the space between soil skeletons during compaction and consolidation of reservoir water during submersion, and human activity during exposure could explain the significant high soil bulk density at the 145-150 m and 170-175 m elevation segments, respectively (Lv, Tang, Zhang, He, & Bao, 2018; Ye et al., 2019b). In addition, the higher aboveground and underground biomasses at the other elevation segments may have reduced the soil bulk density because of the ameliorating effects of plants on the soil structure (Gu et al., 2019). Longer submersion in water results in more dilution (Guo et al., 2019) and is presumably related to the observation that soil pH at low elevations was higher than at high elevations. This study confirmed that soil particles coarsen with increasing elevation (Tang et al., 2018; Li et al., 2019a). The deposition of clay and silt particles from the upstream riverbank during submersion and washing by runoff from high elevations during exposure may partly explain this phenomenon (Li et al., 2019a; Wang et al., 2018c). The significantly high organic matter at the 150-170 m elevation segment may also be explained by the high aboveground and underground biomasses possibly enhancing the accumulation of plant litter in soil, the deposition of which is conducive to the accumulation of soil organic matter (Liu, Li, Liu, & Flanagan, 2020b). The significantly high *MWD* at the 160-170 m elevation segment may be explained by the high amounts of organic matter and roots (Table 2; Kořenková & Matúš, 2015; Bachmann et al., 2020). Surprisingly, the *MWD* was negative, although not significantly correlated with the clay content (Table 2), which was also the cementing agent for the formation of the aggregate, and the *MWD* increased the stability of the aggregate (Xiao et al., 2018). The effects of increases of organic matter and roots may have overridden the effects of the decrease in clay content in terms of aggregate stability. The highest plant biomass was found in the middle part of the WLFZ, in agreement with Ye, Zhang, Deng, & Zhang, (2013), who found the highest plant biodiversity and biomass under intermediate stress levels in the WLFZ.

The results of this study suggest that τ, ω, and E much better describe D_c than U, confirming previous findings (Xiao et al., 2017; Li et al., 2019b; Li et al., Li, Li, Liang, He, & Bush, 2019c). Hydrodynamic parameters have different physical meanings and expressions. τ represents the drag force of water flow on the soil surface, while ω, U and E express the effects of the energy of the flow on soil erosion. Based on Equations 3 to 6, τ is proportional to the flow depth and slope gradient; ω is proportional to the flow depth, slope gradient and flow velocity; U is proportional to the slope gradient and flow velocity; and E is proportional to the quadratic of the flow velocity and flow depth. The lack of flow depth in E could be the reason for its poor performance in describing D_c. Flow depth seems to have a strong influence on soil detachment (Nearing et al., 1991; Xiao et al., 2017). Furthermore, the calculations of these hydrodynamic parameters indicate the connections among them. Generally, a combination of flow depth, slope gradient and flow velocity is responsible for the values of these parameters. Therefore, a general index of flow intensity that was used to predict the sediment transport capacity by Li et al. (2020) was used to estimate D_c in this research. This general index of flow intensity can be calculated as:

$$\phi = gV^{a_1}h^{a_2}J^{a_3} \tag{9}$$

where φ is the general index of flow intensity, g is the gravitational acceleration (m s^{-2}), V is the flow velocity (m s^{-1}), h is the flow depth (m), J is the slope gradient (m m^{-1}), and a_1, a_2, and a_3 are the flow pattern exponents.

The results of the relationship between D_c and φ for the different elevation segments are presented in Table 5. The high correlations between the measured and predicted D_c calculated using equations (Table 5) at the different elevation segments are shown in Fig. 5. All the data points are distributed near the 1:1 line. The values of R^2 ranged between 0.937 and 0.970, with an average value of 0.957. The average value of R^2 for equations related to φ increased by 5.40%, 6.22%, 87.65%, and 5.75%, respectively, compared to the results of τ, ω, U and E in Table 3. Therefore, a clear improvement exists when using the general index of flow intensity in estimating D_c, suggesting that the general index of flow intensity is a good parameter for predicting

D_c.

The rill erodibility coefficients corresponding to shear stress were all between 0.04 and 0.22 s m^{-1} in purple soils studied by Li et al. (2019c). The rill erodibility measures at the 145-150 m and 170-175 m elevation segments were higher than those at the other elevation segments (Table 3). This finding shows that the soils in these two elevation segments are more susceptible to detachment by flowing water than those at the other elevation segments, which may be a partial explanation of the result obtained by Bao et al. (2018). Bao et al. (2018) quantified the erosion rates in the mainstream and tributaries of the WLFZ in the TGR using erosion pins and observed that the highest erosion rates were at elevations between 170 and 175, m followed by elevations between 145 and 150 m, and were significantly higher than the erosion rates at other elevations for the mainstream of the WLFZ. They thought that this phenomenon was caused by the significantly longer residence time of water around the minimum and maximum levels than at other levels. However, higher erodibility could be another reason for this phenomenon.

The results of this study are based on measurements of soil samples from different elevations collected during the same time period and located to show vertical heterogeneity. However, soil and plant properties varied not only at different elevations but also at different times because of the submersion and exposure of plants at different elevations and different times due to the operation of the TGR (Tang et al., 2018; Ye et al., 2019a). Therefore, the temporal and spatial variations of soil detachment in the WLFZ should be investigated to verify the results obtained in this research and to better understand of soil erosion in the WLFZ of the TGR.

5. CONCLUSIONS

The soil properties (soil bulk density, pH, particles, *MWD* and organic matter) and biomass parameters (aboveground biomass and underground biomass) were strongly heterogenous across different elevations in the WLFZ of the TGR. D_c fluctuated with increasing elevation, reaching a maximum average value at the elevation segment of 145-150 m and a minimum average value at the elevation segment of 165-170 m. The mathematical relationship between D_c and τ, ω, E, and U can be described using a linear function, and τ, ω, and E performed much better to describe D_c than U. In addition, a clear improvement was seen when using the general index of flow intensity to estimate D_c. The vertical variation in rill erodibility at each elevation segments was similar to the variations in D_c. Soil aggregate stability and organic matter were considered as the major factors responsible for the vertical variation in D_c because D_c was significantly negatively correlated with the *MWD* ($p < 0.05$) and organic matter ($p < 0.01$). Therefore, more efforts should be tried to increase the soil clay content and organic matter for suppressing the soil erosion WLFZ of the TGR in the future.

ACKNOWLEDGEMENTS

This research was jointly sponsored the National Natural Science Foundation of China (41807068, U2040207), Research Fund for Excellent Dissertation of China Three Gorges University (2020BSPY003), the CRSRI Open Research Program

(CKWV2018488/KY).

DATA AVAILABILITY

All data used during the study are available from the corresponding author by request.

REFERENCES

Bachmann, J., Goebel, M.O., Krueger, J., Fleige, H., Woche, S.K., Dörner, J., & Horn, R. (2020). Aggregate stability of south Chilean volcanic ash soils – A combined XPS, contact angle, and surface charge analysis. *Geoderma, 361*, 114022. https://doi.org/10.1016/j.geoderma.2019.114022.

Baldwin, D.S., & Mitchell, A.M. (2000). The effects of drying and re-flooding on the sediment and soil nutrient dynamics of lowland river-floodplain systems: a synthesis. *Regulated Rivers, 16*, 457-467. https://doi.org/10.1002/1099-1646(200009/10)16:53.0.CO;2-B.

Bao, Y.H., Gao, P., & He, X.B. (2015a). The water-level fluctuation zone of Three Gorges Reservoir - A unique geomorphological unit. *Earth-Science Reviews, 150*, 14-24. https://doi.org/10.1016/j.earscirev.2015.07.005.

Bao, Y., Tang, Q., He, X., Hu, Y., & Zhang, X. (2015b). Soil erosion in the riparian zone of the Three Gorges Reservoir, China. *Hydrology Research. 46*(2), 212-221. https://doi.org/10.2166/nh.2013.291.

Bao, Y.H., He, X.B., Wen, A.B., Gao, P., Tang, Q., Yan, D.C., & Long, Y. (2018). Dynamic changes of soil erosion in a typical disturbance zone of China's Three Gorges Reservoir. *Catena, 169*, 128-139.

https://doi.org/10.1016/j.catena.2018.05.032.

Dou, Y.X., Yang, Y., An, S.S., & Zhu, Z.L. (2020). Effect of different vegetation restoration measures on soil aggregate stability and erodibility on the Loess Plateau, China. *Catena, 185*, 104294. https://doi.org/10.1016/j.catena.2019.104294.

FAO. 2019. Soil erosion: the greatest challenge to sustainable soil management, in: *Food and Agriculture Organization of the United Nations*. Rome, pp. 100. (https://www.smashwords.com/books/view/939181).

Geng, R., Zhang, G.H., Ma, Q.H., & Wang, H. (2017). Effects of landscape positions on soil resistance to rill erosion in a small catchment on the Loess Plateau. *Biosystems Engineering, 160*, 95-108. https://doi.org/10.1016/j.biosystemseng.2017.06.001.

Govers, G., Rafael, G., & Oost, K.V. (2007). Rill erosion: Exploring the relationship between experiments, modelling and field observations. *Earth-Science Reviews, 84*(3-4), 87-102. https://doi.org/10.1016/j.earscirev.2007.06.001.

Gu, C.J., Mu, X.M., Gao, P., Zhao, G.J., Sun, W.Y., Tatarko, J., & Tan, X.J. (2019). Influence of vegetation restoration on soil physical properties in the Loess Plateau, China. *Jouranal of Soils and Sediments, 19*, 716–728. https://doi.org/10.1007/s11368-018-2083-3.

Guo, T.L., Wang, Q.J., Li, D.Q., & Wu, L.S. (2010). Sediment and solute transport on soil slope under simultaneous influence of rainfall impact and scouring flow. *Hydrological Processes, 24*(11), 1446–1454. https://doi.org/10.1002/hyp.7605.

Guo, Y., Cheng, R.M., Xiao, W.F., Shen, Y.F., Yang, S., Wang, N., Liu, Z.B., & Wang, X.R. (2019). Inter-Aannual Variation of Soil Chemical Properties in the Water-Level-Fluctuation Zone of the Three Gorges Reservoir. *SCIENTIA SILVAE SINICAE, 55*(4), 22-30. https://doi.org/10.11707/j.1001-7488.20190403. (In Chinese)

Hairsine, P.B., & Rose, C.W. (1992a). Modeling water erosion due to overland flow using physical principles: 1. Sheet flow. *Water Resources Research, 28*(1), 237-243. https://doi.org/10.1029/91WR02380.

Hairsine, P.B., & Rose, C.W. (1992b). Modeling water erosion due to overland flow using physical principles: 2. Rill flow. *Water Resources Research, 28*(1), 245-250. https://doi.org/10.1029/91WR02381.

Knapen, A., Smets, T., & Poesen, J. (2009). Flow-retarding effects of vegetation and geotextiles on soil detachment during concentrated flow. *Hydrological Processes, 23*(17), 2427-2437. https://doi.org/10.1002/hyp.7360.

Kořenková, L., & Matúš, P. (2015). Role of Water Repellency in Aggregate Stability of Cultivated Soils under Simulated Raindrop Impact. *Eurasian Soil Science, 48*(7), 754–758. https://doi.org/10.1134/S1064229315070054.

Li, G., Abrahams, A.D., & Atkinson, J.F. (1996). Correction factors in the determination of mean velocity of overland flow. *Earth Surface Processes and Landforms, 21*, 509-515. https://doi.org/10.1002/(SICI)1096-9837(199606)21:6<509::AID-ESP613>3.0.CO;2-Z.

Li, J.L., Bao, Y.H., Wei, J., He, X., Tang, Q., & Nambajimana, J. de D. (2019a).

Fractal characterization of sediment particle size distribution in the water-level fluctuation zone of the Three Gorges Reservoir, China. *Journal of Mountain Science, 16*, 2028-2038. https://doi.org/10.1007/s11629-019-5456-1.

Li, M.Y., Xiao, H., Hong, H., Shao, Y.Y., Peng, D.D., Xu, W.N., Yang, Y.S., Zheng, Y., & Xia, Z.Y. (2019b). Modelling soil detachment by overland flow for the soil in the Tibet Plateau of China. *Scientific Reports, 9*, 8063. https://doi.org/10.1038/s41598-019-44586-5.

Li, P., Zhang, K.D., Wang, J.W., & Meng, H. (2020). Nondimensional sediment transport capacity of sand soils and its response to parameter in the Loess Plateau of China. *Hydrological Processes, 34*, 823-835. https://doi.org/10.1002/hyp.13634.

Li, T.Y., Li, S.Y., Liang, C., He, B.H., & Bush, R.T. (2019c). Erosion vulnerability of sandy clay loam soil in Southwest China: Modeling soil detachment capacity by flume simulation. *Catena, 178*, 90-99. https://doi.org/10.1016/j.catena.2019.03.008.

Li, Z.W., Zhang, G.H., Geng, R., Wang, H., & Zhang, X.C. (2015). Land use impacts on soil detachment capacity by over land flow in the Loess Plateau, China. *Catena, 124*, 9-17. https://doi.org/10.1016/j.catena.2014.08.019.

Liu, J.T., Zhang, J.J., Sun, R.X., & Li, L. (2020a). Effects of the conversion time of cropland into forestry on soil physical properties in loess area of western Shanxi Province of northern China. *Journal of Beijing Forestry University, 42*(1), 94-103. https://doi.org/10.12171/j.1000−1522.20180376. (In Chinese)

Liu, J.X., Li, P.P., Liu, G.B., & Flanagan, D.C. (2020b). Quantifying the effects of plant litter in the topsoil on the soil detachment process by overland flow in typical grasslands of the Loess Plateau, China. *Hydrological Processes, 34*(9), 2076-2087. https://doi.org/10.1002/hyp.13713.

Lv, F.Y., Tang, Q., Zhang, S.J., He, X.B, & Bao, Y.H. (2018). Response of Purple Soil Physical to Repeated Water Flooding in Water-Level Fluctuation Zone in the Three Gorges Reservior. *Research of Soil and Water Conservation, 25*(1), 276-281. https://doi.org/10.13869/j.cnki.rswc.2018.01.045. (In Chinese)

Ma, Q.H., Zhang, K.L, Cao, Z.H., Wei, M.Y., & Yang, Z.C. (2020). Soil detachment by overland flow on steep cropland in the subtropical region of China. *Hydrological Processes, 34*(8), 1810-1820. https://doi.org/10.1002/hyp.13694.

Misra, R.K., & Rose, C.W. (1996). Application and sensitivity analysis of process-based erosion model GUEST. *European Journal of Soil Science, 47*(4), 593-604. https://doi.org/10.1111/j.1365-2389.1996.tb01858.x.

Morgan, R.P.C., Quinton, J.N., Smith, R.E., Govers, G., Poesen, J.W.A., Auerswald, K., Chisci, G., Torri, D., & Styczen, M.E. (1998). The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. *Earth Surface Processes and Landforms, 23*(6), 527-544. https://doi.org/10.1002/(SICI)1096-9837(199806)23:63.0.CO;2-5.

Nazari, S.A., Qiuwen, C., Shahram, K., James, W.R., & Reza, R.M. (2016). Assessment of land use impact on hydraulic threshold conditions for gully head cut initiation. *Hydrology and Earth System Sciences Discussions, 20*(7), 3005-

3012. https://doi.org/10.5194/hess-20-3005-2016.

Nearing, M.A., Bradford, J.M., & Parker, S.C. (1991). Soil Detachment by Shallow Flow at Low Slopes. *Soil Science Society of America Journal, 55*(2), 339-344. https://doi.org/10.2136/sssaj1991.03615995005500020006x.

Nearing, M.A., Foster, G.R., & Lane, L.J. (1989). A process-based soil erosion model for USDA-water erosion prediction project technology. *Transactions of the ASAE (American Society of Agricultural Engineers), 32*(5), 1587-1593. https://doi.org/10.13031/2013.31195.

Parhizkar, M., Shabanpour, M., Khaledian, M., Cerdà, A., Rose, C.W., Asadi, H., Lucas-Borja, M.E., & Zema, D.A. (2020). Assessing and Modeling Soil Detachment Capacity by Overland Flow in Forest and Woodland of Northern Iran. *Forests, 11*(1), 65. https://doi.org/10.3390/f11010065.

Scherer, U., Zehe, E., Träbing, K., & Gerlinger, K. (2012). Prediction of soil detachment in agricultural loess catchments: model development and parameterisation. *Catena, 90*, 63-75. https://doi.org/10.1016/j.catena.2011.11.003.

Shen, N., Wang, Z.L., Zhang, Q.W., Chen, H., & Wu, B. (2019). Modelling soil detachment capacity by rill flow with hydraulic variables on a simulated steep loessial hillslope. *Hydrology Research, 50*(1), 85-98. https://doi.org/10.2166/nh.2018.037.

Su, X.L., Nilsson, C., Pilotto, F., Liu, S.P., Shi, S.H., & Zeng, B. (2017). Soil erosion and deposition in the new shorelines of the Three Gorges Reservoir. *Science of*

The Total Environment, 599-600, 1485. https://doi.org/10.1016/j.scitotenv.2017.05.001.

Tang, Q., Bao, Y.H., He, X.B., Zhou, H.D., Cao, Z.J., Gao, P., Zhong, R.H., Hu, Y.H., & Zhang, X.B. (2014). Sedimentation and associated trace metal enrichment in the riparian zone of the Three Gorges Reservoir, China. *Science of The Total Environment, 479-480*, 258-266. https://doi.org/10.1016/j.scitotenv.2014.01.122.

Tang, Q., Collins, A.L., Wen, A.B., He, X.B., Bao, Y.H., Yan, D.C., Long, Y., & Zhang, Y.S. (2018). Particle size differentiation explains flow regulation controls on sediment sorting in the water-level fluctuation zone of the three gorges reservoir, china. *Science of The Total Environment, 633*, 1114-1125. https://doi.org/10.1016/j.scitotenv.2018.03.258.

Vannoppen, W., Vanmaercke, M., De Baets, S., & Poesen, J. (2015). A review of the mechanical effects of plant roots on concentrated flow erosion rates. *Earth-Science Reviews, 150*, 666-678. https://doi.org/10.1016/j.earscirev.2015.08.011.

Wang, B., Zhang, G.H., Shi, Y.Y., Zhang, X.C., Ren, Z.P., & Zhu, L.J. (2013). Effect of natural restoration time of abandoned farmland on soil detachment by overland flow in the Loess Plateau of China. *Earth Surface Processes and Landforms, 38*, 1725-1734. https://doi.org/10.1002/esp.3459.

Wang, B., Zhang, G.H., Yang, Y.F., Li, P.P., & Liu, J.X. (2018a). The effects of varied soil properties induced by natural grassland succession on the process of soil detachment. *Catena, 166*, 192-199. https://doi.org/10.1016/j.catena.2018.04.007.

Wang, D.D., Wang, Z.L., Shen, N., & Chen, H. (2016). Modeling soil detachment capacity by rill flow using hydraulic parameters. *Journal of Hydrology, 535*, 473-479. https://doi.org/10.1016/j.jhydrol.2016.02.013.

Wang, H., Zhang, G.H., Li, N.N., Zhang, B.J., & Yang, H.Y. (2018b). Soil erodibility influenced by natural restoration time of abandoned farmland on the Loess Plateau of China. *Geoderma, 325*, 18-27. https://doi.org/10.1016/j.geoderma.2018.03.037.

Wang, Y., Cao, L.X., Fan, J.B. Lu, H.Z., Zhu, Y.Y., Gu, Y.L., Sun, B., & Liang, Y. (2017). Modelling soil detachment of different management practices in the red soil region of China. *Land Degradation and Development, 28*, 1496-1505. https://doi.org/10.1002/ldr.2658.

Wang, Y.J., Chen, F.Q., Zhang, M., Chen, S.H., Tan, X.Q., Liu, M., & Hu, Z.H. (2018c). The effects of the reverse seasonal flooding on soil texture within the hydro-fluctuation belt in the Three Gorges reservoir, China. *Journal of Soils and Sediments, 18*, 109–115. https://doi.org/10.1007/s11368-017-1725-1.

Xiao, H., Liu, G., Liu, P.L., Zheng, F.L., Zhang, J.Q., & Hu, F.N. (2017). Response of soil detachment rate to the hydraulic parameters of concentrated flow on steep loessial slopes in on the Loess Plateau of China. *Hydrological Processes, 31*, 2613-2621. https://doi.org/10.1002/hyp.11210.

Xiao, H., Liu, G., Zhang, Q., Zheng, F.L., Zhang, X.C., Liu, P.L., Zhang, J.Q., Hu, F.N., & Abd Elbasite, M.A.M. (2018). Quantifying contributions of slaking and mechanical breakdown of soil aggregates to splash erosion for different soils from the Loess plateau of China. *Soil and Tillage Research, 178*, 150–158.

https://doi.org/10.1016/j.still.2017.12.026.

Yang, D.M., Gao, P.L., Zhao, Y.D., Zhang, Y.H., Liu, X.Y., & Zhang, Q.W. (2018). Modeling sediment concentration of rill flow. *Journal of Hydrology, 561*, 286-294. https://doi.org/10.1016/j.jhydrol.2018.04.009.

Ye, C., Chen, C.R., Butler, O.M., Rashti, M.R., Esfandbod, M., Du, M., & Zhang, Q.F. (2019a). Spatial and temporal dynamics of nutrients in riparian soils after nine years of operation of the Three Gorges Reservoir, China. *Science of The Total Environment, 664*, 841-850. https://doi.org/10.1016/j.scitotenv.2019.02.036.

Ye, C., Zhang, K., Deng, Q., & Zhang, Q. (2013). Plant communities in relation to flooding and soil characteristics in the water level fluctuation zone of the three Gorges Reservoir, China. *Environmental Science and Pollution Research, 20*(3), 1794–1802. https://doi.org/10.1007/s11356-012-1148-x.

Ye, F., Ma M.H., Wu S.J., Jiang, Y., Zhu, G.B., Zhang, H., & Wang, Y. (2019b). Soil properties and distribution in the riparian zone: the effects of fluctuations in water and anthropogenic disturbances. *European Journal of Soil Science, 70*, 664-673. https://doi.org/10.1111/ejss.12756.

Yu, Y., Zhang, G., Geng, R., & Sun, L. (2014). Temporal variation in soil detachment capacity by overland flow under four typical crops in the Loess Plateau of China. *Biosystems Engineering, 122*, 139–148. https://doi.org/10.1016/j.biosystemseng.2014.04.004.

Zhang, G.H., Liu, B.Y., Nearing, M.A., & Huang, C.H. (2002). Soil Detachment by

Shallow Flow. *Transactions of the ASAE (American Society of Agricultural Engineers), 45*(2), 351-357. https://doi.org/10.13031/2013.8527.

Zhang, G.H., Liu, G.B., Tang, K.M., & Zhang, X.C. (2008). Flow Detachment of Soils under Different Land Uses in the Loess Plateau of China. *Transactions of the ASABE (American Society of Agricultural and Biological Engineers), 51*(3), 883-890. https://doi.org/10.13031/2013.24527.

Zhang, G.H., Luo, R.T., Cao, Y., Shen, R.C., & Zhang, X.C. (2010). Correction factor to dye-measured flow velocity under varying water and sediment discharges. *Journal of Hydrology, 389*(1-2), 205-213. https://doi.org/10.1016/j.jhydrol.2010.05.050.

Zhang, G.H., Tang, K.M., Sun, Z.L., & Zhang, X.C. (2014). Temporal variability in rill erodibility for two types of grasslands. *Soil Research, 52*(8), 781-788. https://doi.org/10.1071/SR14076.

Zhang, G.H., Tang, M.K., & Zhang, X.C. (2009). Temporal variation in soil detachment under different land uses in the Loess Plateau of China. *Earth Surface Processes and Landforms, 34*, 1302-1309. https://doi.org/10.1002/esp.1827.

Zhu, X., Fu, S., Wu, Q., & Wang, A. (2020). Soil detachment capacity of shallow overland flow in Earth-Rocky Mountain Area of Southwest China. *Geoderma, 361*, 114021. https://doi.org/10.1016/j.geoderma.2019.114021.

TABLES

TABLE 1 Soil and biomass properties at different elevation segments

Elevation (m)	Bulk density ($g\ cm^{-3}$)	pH	Soil particles composition (%) Clay (< 0.002 mm)	Silt (0.002-0.05 mm)	Sand (0.05-2.00 mm)	*MWD* (mm)	Organic matter ($g\ kg^{-1}$)	Aboveground biomass ($g\ m^{-2}$)	Underground biomass ($kg\ m^{-3}$)
145-150	1.29±0.02c	7.45±0.01c	19.91±0.24d	54.25±0.34c	25.84±0.56a	0.91±0.01a	16.31±0.38a	369.47±21.58a	1.03±0.11a
150-155	1.08±0.02a	7.48±0.01c	18.63±0.51c	44.24±1.03b	37.13±1.54b	0.98±0.03a	24.31±0.52c	1040.92±48.25c	7.99±0.11b
155-160	1.10±0.02a	7.49±0.01c	15.90±0.69b	39.77±1.18a	44.33±1.87c	0.98±0.04a	20.95±0.60b	1179.99±30.23d	10.40±0.29c
160-165	1.19±0.02b	7.00±0.01b	14.82±1.07ab	40.86±0.89a	44.32±1.95c	1.12±0.07b	23.45±0.95c	1750.97±48.65f	22.44±3.07e
165-170	1.16±0.10ab	7.03±0.04b	15.73±0.36b	40.73±0.79a	43.55±0.96c	1.17±0.04b	30.31±1.24d	1319.75±27.22e	14.66±0.86d
170-175	1.29±0.02c	6.64±0.01a	14.02±0.39a	39.83±1.04a	46.15±1.41c	0.98±0.06a	16.24±1.23a	681.33±31.94b	7.20±0.45b

Note: *MWD* denotes the mean weight diameter. Values followed by different letters in the same column indicate significant differences at the 0.05 level.

TABLE 2 Pearson correlation coefficients for the relationship between soil and biomass properties

soil and biomass properties	Bulk density	pH	Soil particle composition (%)			*MWD*	Organic matter	Above-ground biomass	Underg-round biomass
			Clay (< 0.002 mm)	Silt (0.002-0.05 mm)	Sand (0.05-2 mm)				
Bulk density	1								
pH	-0.529	1							
Soil particle composition (%) Clay	-0.062	0.788	1						
Soil particle composition (%) Silt	0.409	0.495	0.875*	1					
Soil particle composition (%) Sand	-0.280	-0.595	-0.935**	-0.990**	1				
MWD	-0.254	-0.423	-0.547	-0.570	0.579	1			
Organic matter	-0.643	0.047	-0.137	-0.408	0.339	0.828*	1		
Aboveground biomass	-0.562	-0.135	-0.521	-0.663	0.638	0.809	0.700	1	
Underground biomass	-0.337	-0.341	-0.631	-0.653	0.664	0.853*	0.610	0.967**	1

Note: * indicates a significant correlation at the 0.05 level (bilateral), and ** indicates a significant correlation at the 0.01 level (bilateral).

TABLE 3 Relationship between soil detachment capacity and hydrodynamic parameters at different elevation segments

Hydrodynamic parameters	Elevation (m)	Fitting equation	The coefficient of determination R^2	Erodibility parameter K_r	Critical hydrodynamic parameters
τ	145-150	D_c=0.120τ-0.234	0.855	0.120	1.950
	150-155	D_c=0.112τ-0.243	0.933	0.112	2.162
	155-160	D_c=0.103τ-0.194	0.950	0.103	1.883
	160-165	D_c=0.103τ-0.199	0.904	0.103	1.932
	165-170	D_c=0.094τ-0.206	0.934	0.094	2.191
	170-175	D_c=0.120τ-0.260	0.871	0.120	2.167
ω	145-150	D_c=0.173ω-0.036	0.842	0.173	0.208
	150-155	D_c=0.163ω-0.060	0.928	0.163	0.368
	155-160	D_c=0.149ω-0.028	0.950	0.149	0.187
	160-165	D_c=0.147ω-0.025	0.874	0.147	0.170
	165-170	D_c=0.137ω-0.056	0.945	0.137	0.409
	170-175	D_c=0.173ω-0.064	0.865	0.173	0.370
U	145-150	D_c=2.157U+0.088	0.366	2.157	-0.041
	150-155	D_c=2.362U+0.002	0.547	2.362	-0.001
	155-160	D_c=2.412U-0.012	0.697	2.412	0.005
	160-165	D_c=2.079U+0.041	0.486	2.079	-0.020
	165-170	D_c=2.008U-0.006	0.565	2.008	0.003
	170-175	D_c=2.232U+0.048	0.402	2.232	-0.022
E	145-150	D_c=63.093E-0.390	0.877	63.092	0.006
	150-155	D_c=58.233E-0.378	0.930	58.234	0.006
	155-160	D_c=52.824E-0.312	0.935	52.824	0.006
	160-165	D_c=52.835E-0.314	0.878	52.836	0.006
	165-170	D_c=48.623E-0.317	0.926	48.623	0.007
	170-175	D_c=62.524E-0.410	0.883	62.524	0.007

Note: D_c is the soil detachment capacity (kg m^{-2} s^{-1}), τ is the shear stress (Pa), ω is the stream power (N m^{-1} s^{-1}), U is the unit stream power (m s^{-1}), and E is the unit energy of a water-carrying section (m).

TABLE 4 Pearson correlation coefficients for the relationship between soil erosion resistance and soil properties

Factors	Bulk density	pH	Soil particle composition (%)			*MWD*	Organic matter
			Clay (< 0.002 mm)	Silt (0.002-0.05 mm)	Sand (0.05-2 mm)		
D_c	0.570	0.151	0.410	0.629	-0.581	-0.874*	-0.940**
$K_r(\tau)$	0.596	-0.028	0.363	0.551	-0.510	-0.835*	-0.868*
$K_r(\omega)$	0.582	-0.018	0.373	0.547	-0.510	-0.848*	-0.858*
$K_r(E)$	0.616	-0.025	0.383	0.578	-0.536	-0.836*	-0.863*
τ_c	0.002	-0.445	-0.127	-0.224	0.201	0.258	0.355
ω_c	-0.066	-0.373	-0.114	-0.248	0.215	0.238	0.383
E_c	0.342	-0.772	-0.552	-0.414	0.466	0.403	0.195

Note: * indicates a significant correlation at the 0.05 level (bilateral), and ** indicates a significant correlation at the 0.01 level (bilateral). D_c is soil detachment capacity. $K_r(\tau)$, $K_r(\omega)$, $K_r(U)$, and $K_r(E)$ are erodibility parameters corresponding to the stream power, stream power, unit stream power, and unit energy of water-carrying section, respectively. τ_c is the critical shear stress, ω_c is the critical stream power, and E_c is the critical unit energy of a water-carrying section.

TABLE 5 Relationship between soil detachment capacity and general hydraulic parameters at different elevation segments

Elevation (m)	Fitting equation	Coefficient of determination R^2	Erodibility parameter K	Parameters α_1	α_2	α_3
145-150		0.970	177303.296	0.123	2.171	1.226
150-155		0.947	116190.690	-0.522	2.121	1.676
155-160	$D_c = KgV^{\alpha_1}h^{\alpha_2}J^{\alpha_3}$	0.955	22.255	2.331	0.623	0.596
160-165		0.937	233.743	2.417	1.025	0.357
165-170		0.962	77917.878	-0.198	2.053	1.668
170-175		0.968	84208.134	1.051	1.997	0.999

Figure Captions

FIGURE 1 Water level changes in the Three Gorges Reservoir Area (2019) and soil sampling points

FIGURE 2 Schematic representation of the scouring experiment device

FIGURE 3. Soil detachment capacity at different elevation segments with a slope gradient of 36.40% and a flow rate of 30 L min^{-1}

FIGURE 4 Variations in soil detachment capacity and hydrodynamic parameters at different elevation segments

FIGURE 5 Comparison between the predicted and measured values for soil detachment capacity