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Combined Effects of Hillslope-Concentrated Flows and Riverine Stream Waves on Soil Erosion in the Reservoir Riparian Zone

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Citation: Bao, Y.; Yu, Y.; Tang, Q.; He, X.; Wei, J.; Hu, Y.; Li, J. Combined Effects of Hillslope-Concentrated Flows and Riverine Stream Waves on Soil Erosion in the Reservoir Riparian Zone. *Water* **2021**, *13*, 3465. <https://doi.org/10.3390/w13233465>

Academic Editor: Dominic E. Reeve

Received: 30 October 2021

Accepted: 5 December 2021

Published: 6 December 2021

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Abstract: During the exposed season, the water level fluctuation zone of the Three Gorges Reservoir has suffered from hillslope-concentrated flows and riverine stream waves, which considerably complicates the processes and magnifies the rate of bank erosion. This study depicts the forms and patterns of integrated bank erosion in this reservoir marginal landscape, decouples the evolutionary processes involved, explores the underlying mechanisms, and quantifies the magnitude through a case study on a fine-grained sandy bank. Hillslope-concentrated flows over rainfall storm events developed continuous gullies starting from uplands and extending throughout the entire slope of the reservoir bank, characterized by relatively larger depths and widths compared with discontinuous gullies on the lower slope developed by riverine stream waves.

Keywords: bank erosion; hillslope-concentrated flow; wave action; water level fluctuation zone; Three Gorges Reservoir

1. Introduction

The riparian zone is defined as all stream-adjacent landforms likely to be inundated or saturated by riverine overbank discharges [1]. It delivers dynamic and complex interactions with river channels via bank erosion and sediment deposition (Figure 1), acting as an important structural and functional component of river systems [2–4]. More specifically, bank erosion has been recognized as a contributor to suspended sediment load transported by global rivers [5,6]. For instance, bank erosion was found to contribute to 5–15% of the suspended sediment load in British rivers, and the proportion was even larger than 40% in many catchments [7]. A three-year field measurement regime indicated over 90% of the total sediment load in a 486 km² catchment in Denmark originating from bank erosion [8]. Fine-grained suspended sediment in rivers has many negative consequences to stream ecology (e.g., fish reproduction, benthic community, and rotifers density), water quality (diffuse contaminants input, mobilization, and transfer), and flooding and sedimentation risk [9,10]. Lateral adjustment of river channels following bank erosion threatens the sustainable use of fertile upland agricultural lands, degrades riparian landscapes, disrupts vegetation succession by the loss of favorable habitat, and impairs ecosystem services such

as biodiversity maintenance, bank stabilization, sediment retaining, diffuse agricultural contaminants filtering and abatement, and runoff regulation [11–13].

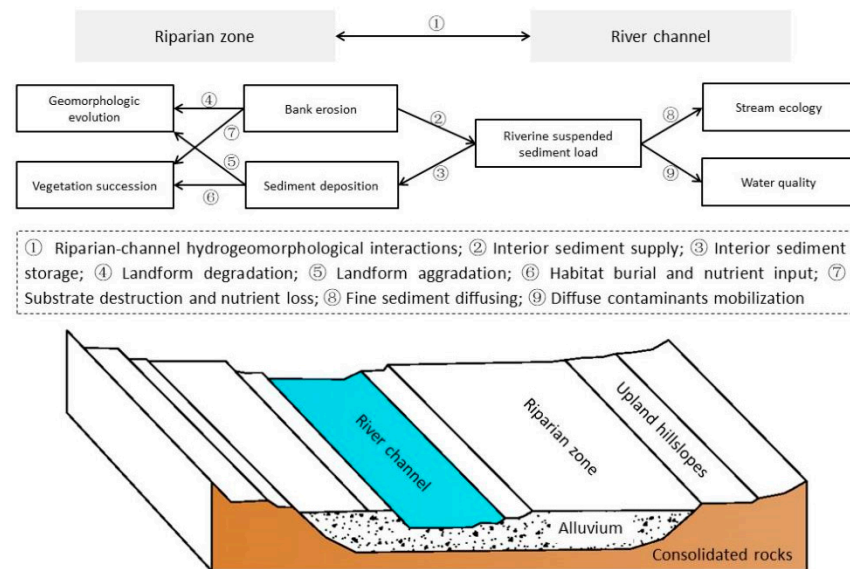


Figure 1. The components of interactions between the riparian zone and river channel (partly modified from [14]).

The riparian zone of the Three Gorges Reservoir is a unique artificial landscape created by flow regulation following regular dam operations, where bank erosion differs substantially from that in the conventional natural riparian zone of unregulated rivers in terms of driving forces, forms, evolutionary processes, and magnitude [15]. The combination of hillslope-concentrated flows and riverine stream waves over the exposed season has complicated the processes and magnified the rate of soil erosion in the reservoir marginal landscape. Loss of original terrestrial vegetation by extreme flooding stress further facilitates soil erosion, given the key role that vegetation plays in bank stabilization through land surface protection by aboveground biomass and soil consolidation by root structure. Change of soil geophysical properties makes the soil bank more susceptible to erosion by a collection of external forces. Given the key role that the reservoir riparian zone plays as a critical buffer strip or ecological corridor, knowledge of the form, evolutionary processes, mechanisms, and magnitude of soil erosion is critical for restoration purposes.

Our previous study carried out field measurements using traditional erosion pins and reported the temporal trend of total bank erosion rates since the formation of this landscape and its spatial variability between the mainstream and tributary reaches [16]. In this study, we describe the forms and patterns of integrated bank erosion in the riparian zone of the Three Gorges Reservoir, analyze the evolutionary processes involved, explore the underlying mechanisms, and quantify the magnitude, through a case study performed on a fine-grained sandy bank. Major results obtained may enhance our current knowledge on integrated bank erosion in the reservoir riparian zone, which has been significantly disturbed by flow regulation, and provide implications for potential measures for bank consolidation and vegetation restoration.

2. Methodology

2.1. Study Area

The Three Gorges Dam on the upper Yangtze River has a full storage capacity of 34.3 billion m³ and a flood regulation capacity of 22.4 billion m³, which allows it to supply multiple services including hydropower generation, flood control, and navigation improvement. The Three Gorges Reservoir extends 661 km long and impounds a water area of 1080 km² (Figure 2). A specific operational strategy defined as “impounding clean

water and draining turbid water” has been adopted, generating a specific schedule for water level fluctuating. On a hydrological year basis, water level fluctuates between the base level of 145 m in the rainy season (May–September) and the peak level of 175 m in the dry season (October–April). A unique reservoir riparian zone with a vertical height of 30 m and a total area of 349 km² has been created [16–19].

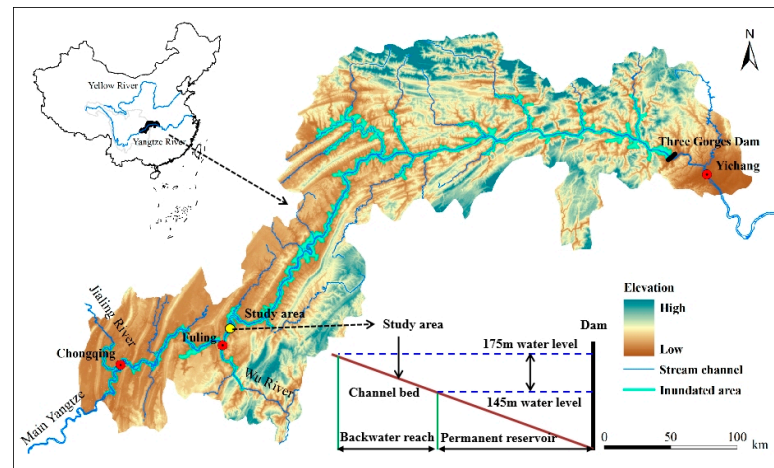


Figure 2. Map of the Three Gorges Reservoir and location of study area.

The Three Gorges Reservoir area is dominated by northeast–southwest paralleling mountains and valleys (Figure 2). Regional landform is dominated by hills and low mountains in the western–central section, where the channel width is large and slope gradient is low, and by high mountains in the eastern section, where channels are narrow with steep slopes and bare rocks. The study area is located in the backwater reach of the Three Gorges Reservoir (Figure 2). The selected riparian reach is a fine-grained sandy bank. This area has a humid subtropical monsoon climate, with an annual precipitation of 1072 mm, a significant portion of which falls during the rainy season from May to September.

2.2. Field Measurement

Field measurement was carried out in late May 2013, when local riverine water level was kept at around 152 m and river channel exhibited a natural flow state. Previously, a storm event with daily precipitation larger than 50 cm and a natural flood event with water level rising to 155 m has occurred (Figure 3), giving rising to the cooccurrence of hillslope-concentrated flow erosion and fluvial wave entrainment in the selected riparian zone.

A typical observation plot (with length 5 m and width 5 m) was set up in the selected riparian zone. The length (L), depth (D), and width (W) of the gully were measured by a measuring tapes and ranging poles. The measuring section was set at 0.5 m intervals in each of the erosion gullies. The gully length was obtained by multiplying the number of intervals points by 0.5 [20]. For measuring the widths of the bottom and shoulders, each interval points were successive marked by a ranging pole, and then the gully bottom and shoulder width were measured with the measuring tape at each point. The mean width (W) of each gully was calculated using the following formula [20]:

$$\text{Mean bottom width, } W_b = \frac{\text{Sum of bottom width readings}}{\text{Number of interval points}} \quad (1)$$

$$\text{Mean shoulder width, } W_s = \frac{\text{Sum of shoulder width readings}}{\text{Number of interval points}} \quad (2)$$

$$\text{Mean gully width, } W = \frac{W_b + W_s}{2} \quad (3)$$

The average gully depth (D) was estimated using the following procedures: (1) placing one of the poles at the deepest part of the gully floor, (2) measuring the bed and shoulder widths at the same interval point, (3) deploying the tape at ground level and stretching across the gully channel over the ranging pole, and (4) using the below equation to calculate D value.

$$D = \frac{\text{Sum of interval depths}}{\text{Number of interval points}} \quad (4)$$

The volume of each gully (V) was calculated by the following formula presented by Kaczmarek (2016) [21]:

$$V = \sum \left(\frac{S_i + S_{i+1}}{2} \times L_{i-i+1} \right) \quad (5)$$

where V is gully volume, L_{i-i+1} is distance between two adjacent profiles, and $S_i + S_{i+1}$ is cross-sectional area of the measured profiles i and $i + 1$.

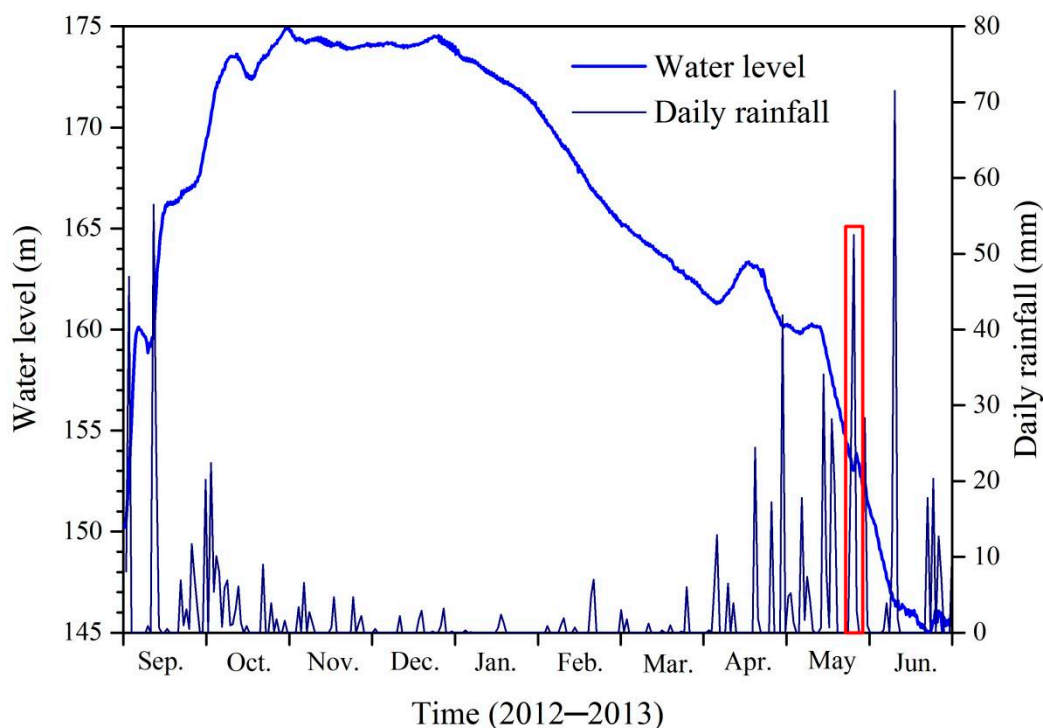


Figure 3. Change of reservoir water level and daily rainfall over the hydrological year of 2012–2013, and the study period is indicated using a red rectangle.

2.3. Data Acquisition

The daily water level operated by the Three Gorges Dam and daily rainfall in the study area are depicted in Figure 3. The data of daily rainfall and reservoir water level were assembled to interpret potential function of extreme storms and stream flood pulses on gully formation in the study riparian zone. Daily data of water level (inundation height) of the Three Gorges Reservoir was collected from the China Three Gorges Corporation (www.ctgpc.com.cn (accessed on 31 December 2013)). Daily rainfall recorded at nearby Fengdu Station is available from the National Meteorological Information Center (<http://cdc.cma.gov.cn> (accessed on 31 December 2013)).

3. Results

3.1. Morphologic Features of Soil Erosion in the Reservoir Riparian Zone

Our field visit showed that the landform of the riparian zone was homogeneous due to sedimentation in the previous inundation period by reservoir impoundment, and bank erosion was mainly performed in the form of gullying. Two categories of gullies can be

generally identified based on their morphological features, showing different lengths and cross-section profiles. Two continuous gullies were observed with lengths ranging from 38 to 46 m, which started from upland hillslopes, extended throughout the entire slope of the riparian zone, and collected with the reservoir regime (Figure 4a). Six discontinuous gullies were found with lengths ranging from 3.1 to 3.8 m occurring in the lower portions of the riparian zone (Figure 4b). The cross-section profile of continuous gullies was characterized by relatively larger depths varying between 0.3–1.9 m and lower widths varying between 0.2–0.8 m, compared with that of the discontinuous gullies, with depths and widths varying between 0.1–0.4 m and 0.4–1.6 m, respectively (Table 1).



Figure 4. Photographs: (a) continuous gullies start from upland hillslopes and extend throughout the entire slope, (b) discontinuous gullies occur in lower portions, and slope gradient transition around the flooding level.

Table 1. Morphologic features of gullies developed in the water level fluctuation zone.

| Morphologic Features | Number | Lengths (m) | Widths (m) | Depths (m) |
|-----------------------|--------|-------------|------------|------------|
| Continuous gullies | 2 | 38–46 | 0.2–0.8 | 0.3–1.9 |
| Discontinuous gullies | 6 | 3.1–3.8 | 0.4–1.6 | 0.1–0.4 |

A distinctive line showing the deposition of woody debris indicates the peak level of a previous overbank flood event (Figure 4b). Sheeting occurs on the inter-gully surface which was subjected to repeated stream wave flushing during the flood. Surface erosion caused loss of large quantity of bank materials, leading to a larger bed slope compared with that in the riparian zone without flooding disturbance (Figure 4b).

3.2. The Evolutionary Process of Bank Erosion in the Riparian Zone

The development of continuous and discontinuous gullies was driven by different forcing agents and went through contrasting processes. Original drainage networks in the riparian zone remained unmanaged after water inundation and were gradually silted by sediments and, consequently, the draining capacity was lost. Concentrated flows collected from upland hillslopes in storms events directly entered the riparian zone. During the initial runoff period, flow path in the riparian zone migrated frequently when the shear stress was still below the erosion threshold of the bank. Flow path would be fixed if denudation force exceeds resistance strength, and continuous gullies were initiated. A large quantity of sediments was detached through subsequent processes of gully wall failure and bed scouring, creating discontinuous gullies characterized by relatively high depths and narrow widths.

The discontinuous gullies were initiated in the riparian zone where the erosive force of concentrated flows exceeds the resistance force of bank material, and further developed by riverine stream waves over a flood period.

Concentrated overland flows and natural flood pulses simultaneously operated on bank erosion in the riparian zone. The processes of gully initiation and development

which led to significant bank erosion are interpreted in Figure 5. Originally, the gullies were initiated by concentrated shallow flows generated in the upper reach of the riparian zone during the extreme storm event. Fluvial entrainment had greatly contributed to the development of the gullies through widening and downslope mass movement. The presence of concentrated overland flows subsequently contributed to head-cutting and, thus, up-moving of gullies head. This can explain large gullies with head at relatively high elevation level (Figure 6).

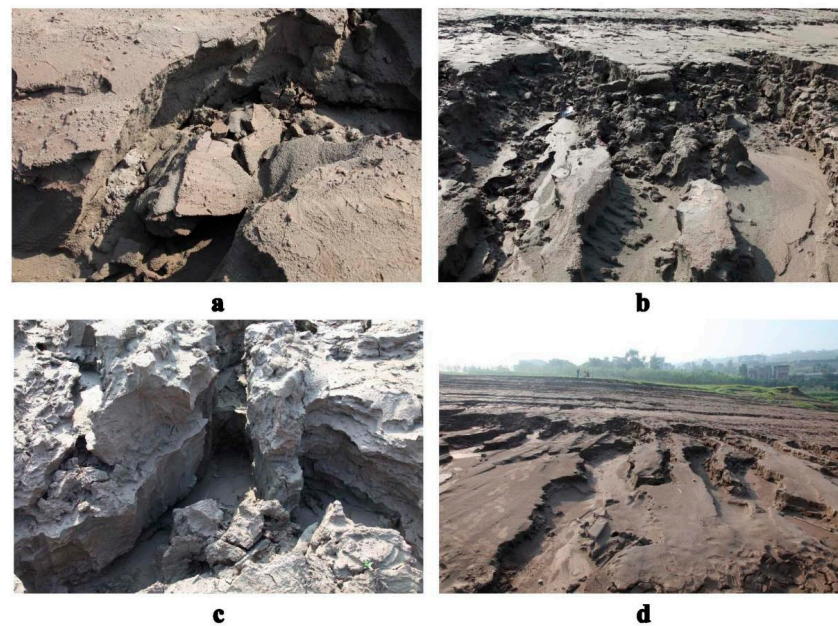


Figure 5. The evolutionary processes for discontinuous gullies in the riparian zone: (a) wall failure, (b) head retreat, (c) bed deepening, and (d) width enlargement.

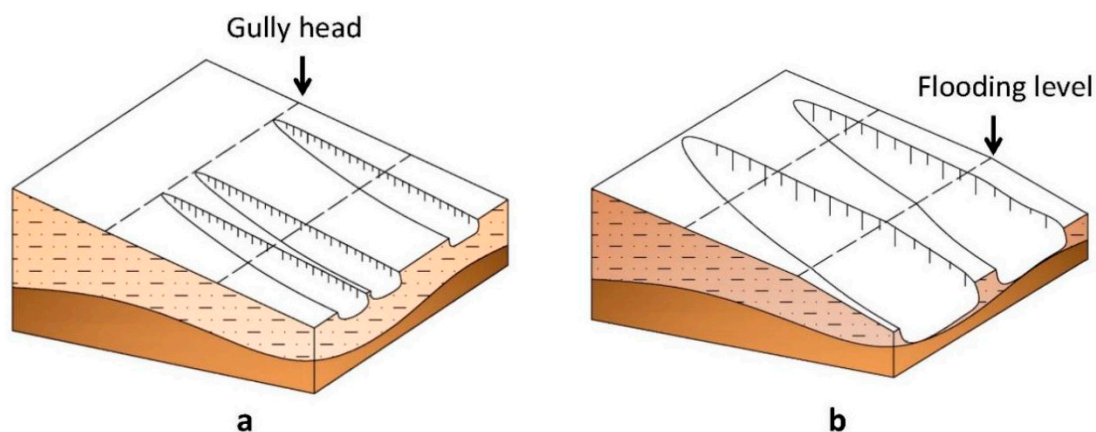


Figure 6. Gully development by head movement, width enlargement, and inter-gully area sheeting below the flooding level: (a) gully initiation, and (b) gully development.

Furthermore, it can be observed that the averaged gradient of the slopes above the flood level was relatively larger than that of the slope below the flood level. This means that the inter-gully area had been degraded due to erosion caused by stream forces. Consequently, the processes that contributed to the occurrence of gullies in the lower parts of the riparian zone include gullying, scouring, mass failure, sheeting, and sediment transport.

3.3. Quantifying the Magnitude of Bank Erosion in the Riparian Zone

In this study, a typical observation plot was set up in the reservoir riparian zone, and six gullies in total were studied, and parameters analyzed. Table 2 shows the parameters of both gullies in the observation plot. From the observations, one can notice that the gullies were extremely developed, an area which accounts for 52.96% of the observing area. The depth and width have a significant difference between the two gullies, while there was no significant difference in the mean bed gradient (p -value of statistical significance < 0.05). The mean gully width in the study area ranges from 0.30 m to 0.68 m, while the mean depth ranges from 0.10 m to 0.21 m. The gully was dominated by type of wide–shallow, and the ratio of width to depth was ranged from 2.95 to 3.75, with an average ratio of 3.31. The volume of total gully erosion was 1.01 cubic meters in the typical observation plot. It was hence estimated that the 0.040 cubic meters of soil may be supplied to the stream per square meter of observation plot by the gully erosion.

Table 2. Bank erosion rate estimated by measuring the size of gullies.

| Map Area (m ²) | Surface Area (m ²) | Gully Length (m) | Mean W (m) | Mean D (m) | W/D | Gradient (%) | Eroded Volume (m ³) |
|----------------------------|--------------------------------|------------------|------------|------------|------|--------------|---------------------------------|
| 25 | 1.36 | 2.37 | 0.45 | 0.12 | 3.75 | 16.30 | 0.096 |
| | 2.67 | 3.88 | 0.62 | 0.21 | 2.95 | 16.80 | 0.21 |
| | 1.35 | 3.45 | 0.30 | 0.10 | 3.00 | 16.20 | 0.085 |
| | 2.65 | 3.90 | 0.62 | 0.20 | 3.10 | 16.40 | 0.20 |
| | 2.36 | 3.85 | 0.55 | 0.15 | 3.67 | 16.30 | 0.16 |
| | 2.85 | 3.95 | 0.68 | 0.20 | 3.40 | 16.60 | 0.26 |
| Total | 13.24 | 21.40 | 0.54 | 0.16 | 3.31 | 16.43 | 1.01 |

4. Discussion

4.1. The Specificity of Soil Erosion in This Reservoir Marginal Landscape

Gully erosion is one of the major types of soil water erosion in many parts of the world [22,23]. Traditional gully erosion studies mainly focus on the hillslopes, where gullies generally form due to the scoured process in the aeolium, colluvium, eluvium, weak sedimentary rock, or other weathered rock [24]. In this study, the reservoir riparian zone gullies originate from the relatively gentle alluvial terraces in the adjacent banks of the river channel (Figure 4). Their characteristics rather agree with the description in the literature of alluvial gullies, valley-bottom gullies, and bank gullies [25–27]. Similar to the alluvial gullies [26], these gullies here have relatively young topographic characteristics, and usually cut into alluvium (Figure 4). Alluvial gullies are commonly found in large alluvial deposits along main streams or other large bodies of water such as inlets or lakes (e.g., Figure 6). Therefore, they have high sediment transport rates and are the main sources of fine suspended sediment [28]. In contrast to the gullies in the reservoir riparian zone, traditional gullies in the hillslope are not always connected directly to the channel system downstream, with the eroded sediment deposited in a floodplain or low-lying land of small valley [29]. In this case, the contribution of traditional hillslope gullies to the stream sediment transport is much less than if they were completely connected to the drainage system (i.e., riparian bank gully). Because of the lack of structural control over their lateral expansion, the riparian bank gully generally expands in longitudinal and lateral direction until it develops a new stable bed slope. In the meantime, it erodes large amounts of floodplain alluvial deposits [26,27,30]. In term of geomorphic features, the gullies in this study are usually as wide as deep or wider than deep (Tables 1 and 2).

Many researchers worldwide have attempted to investigate the gully retrogressive erosion rates and to quantify the eroded volumes using the repeated measures over different periods [31–34] or the remote sensing image of time series [35]. General morphology characteristics of gully channels are important for determining gully retrogressive erosion rates and soil erosion amount [31]. The accurate measurement of the geomorphological parameters of the gully is important not only for the calculation of the amount of soil

erosion [34,36] but also for understanding erosion dynamics [31,37]. The most commonly measured parameters are gully width, depth, length, bottom gradient, and ratios between these parameters [31,38,39], and the parameters proportion (i.e., the relationship between width and depth) is an important morphology characteristic of gully cross sections [31]. Many studies have indicated that gully eroded volume (V) has a positive correlation with the aspect ratio (W/D) [20,26]. In addition, higher W/D values reveal relatively wide and shallow cross sections of the gully, while lower values indicate narrow and deep cross sections. [31,38]. The ratio of W/D were reported in Table 3. W/D in each of the investigated six gullies ranged from 2.95 to 3.75, with an average of 3.31. Based on the statistical analysis of field survey of gully dimensions, the US-SCS observed that the width of gullies formed on cohesive soils is three times their depth, while on frictional soils, the W/D ratio is 1.75 [20,31]. The results were also comparable with those reported in the Upper Yangtze River Basin and Loess Plateau [34,39], where the ratio of W/D was 0.84 to 3.52 and 0.24 to 1.47, respectively, with an average of 1.91 and 0.79, respectively.

Table 3. Bank erosion through gullying and sheeting processes.

| Forms | Processes | Agents | Water Level |
|-------------|---|---|---|
| Gully | Raindrop detachment, scouring, micro-scale mass failure | Raindrops, overland flows, stream waves | Higher water level or water level fluctuation |
| Inter-gully | Sheeting | Stream waves, runoff | Higher water level and low water level |

In contrast to the development of the traditional hillslopes gullies, the gully lateral erosion was a more prevalent phenomenon in the reservoir riparian zone than the gully downcutting. The difference in W/D reported in these studies may be due to different erosion mechanisms and erosion forces [26]. The erosion mechanism of the hillslopes gully erosion is generally overland flow shear stress exceeding the resisting forces [20,40,41]. Eroding force and gully head position are influenced by the slope grade and the catchment area above the gully head [20,42]. Hillslope gullies are mainly expanded by gully head erosion [20], which is the main trigger for the expansion of the gully system [43] and, to a lesser extent, by the scouring of the wall of the gully [44]. However, gully development in the riparian zone of manmade reservoirs is characterized by particular characteristics which are defined by interaction with other geomorphological processes in the context of water level fluctuations [45]. The hydrological regime of water level fluctuations and wave becomes the primary factor responsible for the development of erosion at the riparian zone [19,46]. The initiation and development of erosional landforms in the riparian zone of the reservoir show a seasonal character related to reservoir water level fluctuations (Figure 3). Gully erosion of the riparian zone is usually jointly triggered or accelerated by the extreme rainfall events, wave, gravity, and water level fluctuation. Moreover, the wave and water level fluctuation induce accelerated gully-side erosion, which is represented as gully wall failure (Figure 5).

4.2. Geomorphological Role of Gully Erosion in Bank Erosion

The main geomorphologic processes in the riparian zone are wave erosion, bluff erosion and landslides, cliff retreat, sheet erosion, and aeolian processes [15,45–47]. Accelerated gully development has been observed in the manmade reservoirs shore [48,49]. For instance, an increase in the volume of gullies formed in loess-like sediment is two to three times greater than the degradation of the shoreline due to the abrasion processes of overland flow in the Kamsk reservoir [50]. The development of a gully in a reservoir bank may be linked to those geomorphological processes controlled by the fluctuations in the water level of the reservoirs [45,50]. Moreover, gullying is important to the landform reconstruction of the riparian zone as a mechanism for slope retreat. The landform features of the gully erosion include V-shaped cutting profile in the high and steep slopes of water bodies or large river valleys in different morphoclimatic zones [45,51]. These landforms

were evolved following the erosion by surface runoff and then underwent accelerated development by the wave scouring and flooding disturbance (Figure 4b). They may quickly evolve in one storm event as a result of the increased erosion rate caused by fluctuating water levels. In addition, the shore erosion processes, especially the gully erosion, have led to a decrease in the erosion base level and the accelerated retreat of reservoir bank scarp edges [45,50]. However, the function, form, and effect of riparian gully erosion on the bank retreat is different under different reservoir water level (Table 3).

As shown in Figures 4 and 5, gully mouths were submerged in periods of higher water level or flood event. The scouring of the shore slopes by the waves has resulted in the formation of shore scarps of different heights. The failure of ground blocks over wave-cut notches induced retrogressive erosion in the gully bottoms. Thus, there is a transition of gullies from a state of decay to a growth stage at high reservoir water levels [45]. The development of bank gullies on the shore zone of the Bratsk Reservoir indicated that the reservoir water level fluctuation plays a critical role in the geomorphological processes of the reservoir shoreline [50]. Overall, riparian bank gullies are commonly related to the relatively concentrated runoff path; a system of scattered and moving forward gullies on the riparian zone can merge together to form a continuously eroding gully [28]. When the erodible soils exist, the broad gully head can quickly retreat to the mountainous slopes and higher water level zone, which is shown in the schematic diagram of channel evolution in Figure 6. The initial conditions of gully erosion and bank retreat include the effects of internal and external factors [40,52,53]. At the same time, it also has long-term factors such as climate, geology, material composition, and topography, and short-term influencing factors such as rainfall, flood process, vegetation cover, and land use [54–56].

5. Conclusions

Bank erosion in the riparian zone of the Three Gorges Reservoir has been intensified by the combined effect of hillslope-concentrated flows and riverine streams. The processes of bank erosion in the riparian zone were well evidenced in the geomorphic features (gullies) developed in a typical fine-grained riparian zone. Both upland flows and flood tides were effective in causing significant soil erosion through gullying and souring processes. However, the relative contributions of these two physical processes differed spatially and temporally. Deep flows originating from upland hillslopes contributed to form large deep-situated gullies with high amounts of soil loss. Though of relatively small quantity and low detachment power, shallow concentrated overland flows developed on the upper riparian zone were proven to be essential in gully initiation and, consequently, large quantities of bank materials were detached by flood tides and removed by streams. Subsequent repeated functions of rainfall drop, overland flow, and flood pulses rendered the formed gully area the most vulnerable for erosion and sediment loss.

Author Contributions: Conceptualization and methodology, Y.B., Q.T. and X.H.; formal analysis, J.L.; investigation, Y.B., Q.T. and Y.H.; data curation, Y.Y. and J.L.; writing—original draft preparation, Y.B. and Q.T.; writing—review and editing, X.H., J.W. and Q.T.; funding acquisition, Y.B., X.H. and J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 41977075, 41771320, U2040207, Science Fund for Distinguished Young Scholars of Chongqing, grant number cstc2019jcyj-jqX0025 and cstc2021jcyj-jqX0026.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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