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The water-level fluctuation zone of Three Gorges Reservoir — A unique geomorphological unit

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ABSTRACT

Three Gorges Reservoir (TGR) has provoked a series of unprecedented environmental problems, many of which are related to the transitional area between the base and capacity water levels of the reservoir, commonly referred to as the water-level fluctuation zone. We proposed here that this zone serves as a unique geomorphological unit playing an important role of influencing the life of the TGR and named it as the TGR disturbance zone because it has been intensively interrupted by various human activities. Based on its geomorphological characteristics, we divided this zone into three types that have hillside profiles with distinct shapes and gradients, grain components and sizes, and land uses. Although the three types of the zone have experienced the same set of geomorphological processes under the new annually cyclic hydrological regime, their responses and the associated morphologies are distinguishable. Thus we depicted them separately. Accompanied with these processes are geochemical and biological processes that bring about exacerbated pollution and destroyed ecosystem in this zone. We elaborated these problems and indicated the potential research directions toward fully understanding the complex geomorphological, geochemical, and biological processes prevalent in the zone.

Contents

1. Introduction

Three Gorges Dam (TGD) is the world's largest hydroelectric project with the designed generation capacity of 22,500 MW and the most important water control project along Yangtze River (Nilsson et al., 2005;

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Shi, 2011; Xu et al., 2011; Yuan et al., 2012; Xu et al., 2013). The TGD subsequently formed a reservoir covering the reach of Yangtze River between Chongqing and Yichang with a total water surface area of 1080 km^2 at the water level of 175 m and a storage capacity of 39.3 billion m^3 (Wu et al., 2003b; Fu et al., 2010a). The reservoir, commonly known as Three Gorges Reservoir (TGR), was impounded step by step to the elevations of 135 m, 156 m, and 175 m above the sea level in late 2003, late 2006, and late 2010, respectively (Jackson and Sleigh, 2000; Fu et al., 2010a; Morgan et al., 2012; Yuan et al., 2013).

Although the TGR may provide important services such as flood control and power generation (Changjiang Water Resource Commission, 1997), its significant environmental costs have caught the attention of researchers around the world (Du and Yan, 1999; Wu et al., 2003b; Chen, 2004; Huang, 2004; Stone, 2008; Gleick et al., 2009; Tullos, 2009; Fu et al., 2010a; Periodic Assessment Group of Three Gorges Project, 2010; Stone, 2011) and made it one of the most controversial hydraulic projects in China (Xu et al., 2013). Particularly, contentious environmental issues aroused by the TGR have centered on water quality (Bi et al., 2010; Ma et al., 2011), climate (Kent, 2011; Liu et al., 2012; Zhang et al., 2012b), biodiversity (Park et al., 2003; Wu et al., 2003a; Xie, 2003; Wu et al., 2004; Duan et al., 2009; Gao et al., 2010), sedimentation and downstream riverbed erosion (Yang et al., 2006; Yang et al., 2007; Lu et al., 2011; Dai and Liu, 2013; Wang et al., 2013), geomorphologic processes (Yuan et al., 2012; Dai et al., 2014), impact of reservoir regulation on downstream lakes (Feng et al., 2012; Feng et al., 2013; Guo et al., 2012a; Wang et al., 2014), reservoir-induced seismicity and geological instability (Wang et al., 2014), health risks to the population (Boyle, 2007), and human displacement and carrying capacity of the environment in the reservoir area (Tan et al., 2008; Xu et al., 2011). Many of these issues pertain to the water-level fluctuation zone, an artificial boundary created by the full impoundment of the TGR at the level of 175 m with a vertical height of 30 m, a length of 662 km^2, and a total area of 349 km^2 (Bao and He, 2011). While knowledge of the existing environmental problems in the water-level fluctuation zone of many reservoirs and lakes in both China and other countries of the world (New and Xie, 2008; Wu et al., 2009b; Cheng et al., 2010) is valuable for understanding those in the same zone of the TGR, the latter has larger extent and area with a longer anti-seasonal inundation period and suffers the most intensive disturbance due to the high population density in its surrounding areas (Tian, 2006; Zhang, 2009; Periodic Assessment Group of Three Gorges Project, 2010). Therefore, it is a unique landform that resulted from human intervention.

The geomorphological concern on the TGR thus far has largely focused on the response of the reservoir as a whole to the environmental changes of the upstream river and the associated basin (i.e., Upper Yangtze River Basin) and its downstream impact (Higgitt and Lu, 2001; Yang et al., 2006; Wang et al., 2007; Xiong et al., 2009; Xu et al., 2013). For the water-level fluctuation zone, massive (e.g., rockfalls and landslides) and diffusive (e.g., erosion and deposition) physical processes have been dabbled (Xu et al., 2008; Zhou et al., 2010; Bao et al., 2012). However, the coupled effect of these processes on the water-level fluctuation zone and its response to them remain unaddressed, which also thwarts the progress of understanding the geochemical and biological processes that are linked to the deteriorated pollution and destroyed ecosystem in the zone. The complex interactions among geomorphological, geochemical, and ecological processes have made the zone a unique geomorphologic unit in the world. Understanding these processes will provide profound insights into the effect of the zone on water quality and the ecological environment of the TGR, which may help to give the birth of new environmental policies.

This review summarized the geomorphological nature of the water-level fluctuation zone in the TGR and its crucial roles as the interface between the artificial lake and the terrestrial uplands. We first defined the zone after comparing it with several similar concepts. Then, we described its geological and geographical patterns. Next, we classified the zone into three types from the geomorphological perspective and characterized the dominant processes of each type, which is followed by elaboration of the challenges these three types of the zone are facing regarding to geomorphological, biochemical, and ecological processes. Finally, we proposed the future research directions about this zone. It should be noted that the water-level fluctuation zone also has significant roles in tourism by serving as a nation's famous attraction and in the culture tradition by holding many historical sites (Tan, 2008). Yet, this review concentrated on its geomorphological, geochemical, and biological functions.

2. Characteristics of the water-level fluctuation (WLF) zone

2.1. *Definition of the zone*

The WLF zone refers to the area along TGR banks bounded by the minimum (145 m) and maximum (175 m) water levels of the TGR. It is a physical area undergoing an annually cyclic inundation and exposure due to the TGR operation. Serving as a transition between aquatic and terrestrial environments, the WLF zone in the TGR is akin to the transitional zones in other reservoirs (Leyer, 2005; Fu et al., 2008a; Thompson and Ryder, 2008; Liu et al., 2009). It is also comparable to the transitional zones along banks of many lakes and rivers (Riis and Hawes, 2002; Junk and Wantzen, 2004; Jansson et al., 2005; Leira and Cantonati, 2008). Nonetheless, the WLF zone of the TGR bears many unique characteristics that distinguish it from three relevant terms used in lakes, rivers, and reservoirs. The first is the littoral zone, which contains four sections, from higher to lower on a shore: wooded wetland, wet meadow, marsh, and aquatic vegetation, and is commonly used in freshwater ecosystems (Keddy, 2010). The second is the riparian zone, which refers to the surface area that is inundated or saturated by the bankfull discharge of a river (Hupp and Osterkamp, 1996; Naiman and Decamps, 1997) or more broadly the transitional areas between terrestrial and aquatic ecosystems that can be distinguished by gradients in biophysical conditions, ecological processes, and biota (National Research Council, 2002; Nilsson and Svedmark, 2002). The third is the riparian ecotone, which refers to as “a three-dimensional space of interaction that include terrestrial and aquatic ecosystems that extend down into the groundwater, up above the canopy, outward across the floodplain, up the near-slopes that drain to the water, laterally into the terrestrial ecosystem, and along the water course at a variable width.” (Verry et al., 2004). These three terms focus on the areas that are mainly influenced by natural hydrological processes. The WLF zone of the TGR, however, is subject to the intensive anthropogenic disturbance (i.e., the cyclic submergence and exposure caused by the reservoir operation) combined with the natural impact (i.e., rainfall during the wet season when the water level is relatively low). Therefore, its morphology is shaped by both aquatic processes due to oscillatory flows (i.e., flows driven by surface waves) and terrestrial fluvial processes due to storm flows. The WLF zone is a unique reservoir component herein termed the *TGR disturbance zone*.

2.2. *Geographic characteristics and geological patterns of the zone*

Geographically, the TGR disturbance zone covers the lower sections of 18 administrative units neighboring the TGR (Fig. 1), commonly referred to as Three Gorges Reservoir Region (TGRR) (Lu and Higgitt, 2001; Cao et al., 2011). Administratively, 87.8% of the total area (i.e., 306.33 km^2) is located in Chongqing City. The other four units that have relatively high percentages of the TGR disturbance zone are Kai (12.62%), Fuling (11.43%), Yunyang (9.67%), and Zhong (8.61%) Counties (Zhou et al., 2011). Geomorphologically, the TGR disturbance zone is distributed along both the main course and tributaries of the Yangtze River. It extends laterally with variable extents because gradients of hillsides along the TGR banks alter prominently, leading to an elevation-dependent distribution of this zone. The area of the TGR disturbance zone within the 145–150 m elevation is 55.83 km^2,

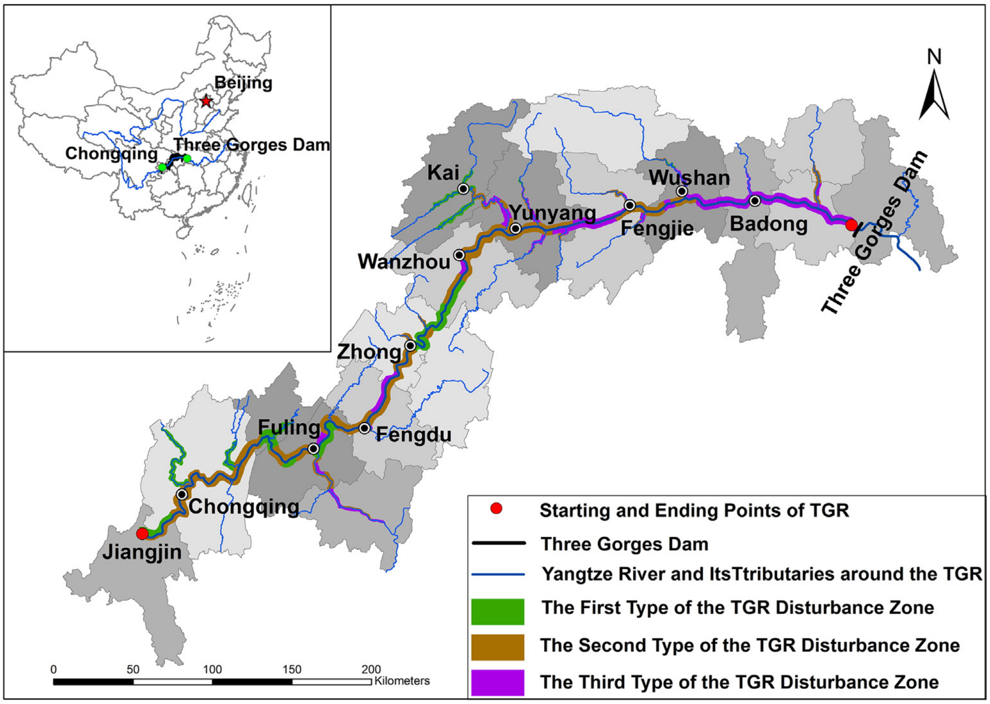

Fig. 1. Location and types of the TGR disturbance zone. The shaded area represents Three Gorges Reservoir Region (TGRR) that contains 18 administrative units. Because of the elongate shape of the TGR, the TGR disturbance zone appears as thick lines, though it actually represents an area of 348.92 km^2.

followed by that of 108.93 km^2 within the 150–160 m elevation, 119.03 km^2 within the 160–170 m elevation, and 65.13 km^2 within the 170–175 m elevation (Sun and Yuan, 2012).

The geographic diversity of the TGR disturbance zone is relevant to the distribution of the underlying bedrocks, which are made up of three major types, purple and red (74%), carbonate (19%), and other rocks (7%) (Ma, 2002; Wang and Jiang, 2006; Liu et al., 2007) (Fig. 2). Purple and red rocks are comprised of sandstone and mudstone, and primarily distributed in the upper and middle sections of the zone (i.e., the area between Jiangjin City and Fengjie County) (Fig. 2). They are highly permeable and susceptible to weathering. Thus, soils in these areas are easy to be eroded. In particular, these areas are subject to wave and gully erosion because of the combined effect of long-time submergence during the high water-level period and surface erosion caused by storms during the low water-level period. Carbonate rocks are dominated by limestone and dolomite and mainly distributed in

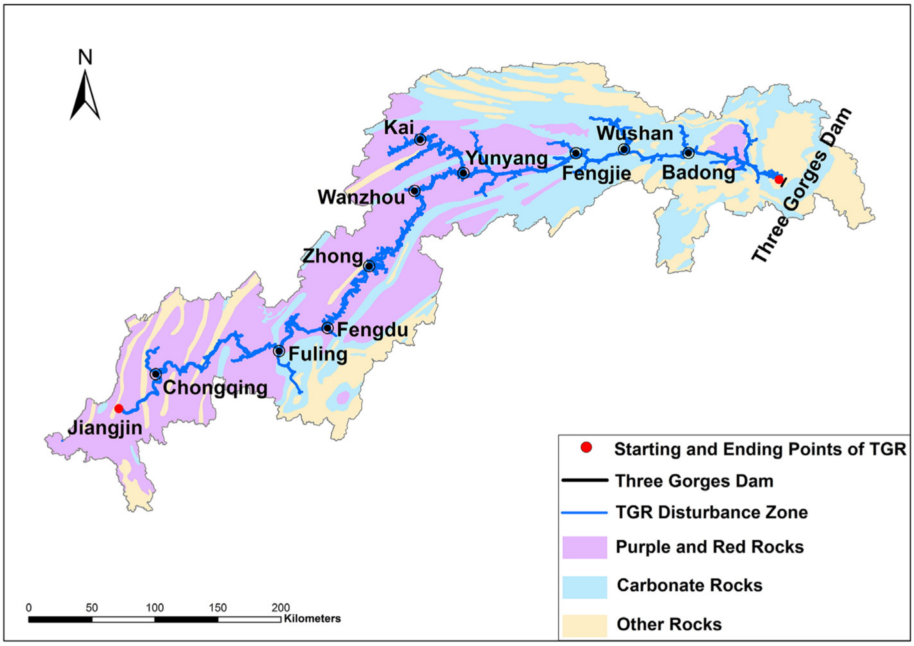

Fig. 2. Spatial distribution of bedrocks in TGRR (simplified from the original stratigraphic subdivisions (Liu et al., 2007; Ma, 2002)). Bedrock types within the TGR disturbance zone may be better identified by referring those in the entire TGRR. Names of the cities and counties along the TGR are consistent with those in Fig. 1.

the low section of the zone (i.e., the area between Fengjie and Badong Counties) (Fig. 2). These areas are featured by steep bedrock hillslopes and typically subject to Karst erosion due to both surface wave and runoff, which subsequently leads to landslides and rockfalls. Other types of rocks are primarily formed by granite, quartz diorite, and metamorphic rocks. These rocks are mainly distributed in the area toward the dam and sporadic locations around Chongqing City and Zhong County with steep slopes (Fig. 2).

2.3. Geomorphological processes within the zone

Before the emergence of the TGR, more than 50% of the TGR disturbance zone was cultivated and the population density of this zone was greater than 400 people/km^2 (Zhang, 2009). The construction of the TGR forced local residents of this zone to give up their crop (or paddy) lands, which were subsequently turned into grass or bare lands. Thus, a large proportion of this zone has been disturbed by intensive human activities (He et al., 2003). The even more substantial human disturbance is highlighted by the influence of an artificial hydrological pattern, which led to a unique flow regime significantly different from the well-known nature flow regime (Poff et al., 1997; Harris et al., 2000; Lytle and Poff, 2004). It is characterized by the annually cyclic water-level variation superimposed by additional changes caused by rainfall events during the wet season (i.e., from May to September). In particular, the magnitude and frequency of the flow in this zone are controlled by the dramatic change of the water level from the lowest of 145 m to the highest of 175 m during one annual cycle. This new flow regime may be featured by a hydrograph with a blunt but round top curve, a series of low-magnitude serrated curves near the bottom, and two very steep limbs (Fig. 3). The low end of the ragged curves at the bottom of the hydrograph represents the lowest water level of 145 m, while the top irregular curve reflects water levels around the maximum of 175 m during the dry season (i.e., from October to April). The multiple local peaks with variable magnitudes were mainly distributed along the bottom and the falling limb, signifying the contribution of storm events to the reservoir water during the wet season. The magnitudes of these peaks are much less than that of the main hydrograph, suggesting the dominance of the water-level fluctuation in the new flow regime. The time and duration of the water level at different elevations are controlled by the operation of the TGR (Fig. 4).

Influenced by this hydrological pattern, the original plant species within the zone have been reduced drastically (Huang, 2001). In the meantime, species that can sustain different inundation periods at different elevation levels survived. This adjustment catalyzes the development of a new trend displaying an elevation-dependent gradient of vegetation distribution in the TGR disturbance zone (Wang et al., 2011a; Wang et al., 2012d). The new flow regime also gives rise to unique geomorphological processes shaping the TGR disturbance zone in different times of a year via different mechanics. Between October and April when the water level stays around the maximum of 175 m and then drops to the minimum of 145 m, the TGR disturbance zone is fully submerged at the beginning for a relatively long time period and then exposed step by step from the top. During this period, it is subject to three major geomorphological processes. The first is wave erosion induced by oscillatory flows due to wind and frequent transportation of ships. This process directly affects the upper section of the zone. The second is deposition occurring in the lower section of the zone because of possible landslides and soil collapse in the submerged portion. The third is deposition of suspended sediment transported longitudinally from the Upper Yangtze River Basin (UYRB), though the magnitude of such deposition is relatively low due to the relatively less degree of sediment supply. Between May and September when the water level remains around the minimum level of 145 m for the most of the time and rises relatively fast toward the end of the season, the TGR disturbance zone is completely exposed for a prolonged period, which makes it subject to four different major processes. The first is seepage due to high ambient ground water level. This seepage generates an outward pressure that could initiate landslides and collapse of the hillslope bodies in the TGR disturbance zone. The second is fluvial processes caused by rainfall events during this season. These processes involve sheet, rill, and gully erosion on sloppy surface, and channel banks and bed erosion. The third is deposition of sediment supplied either laterally from the higher-elevation lands connecting to the zone or longitudinally from the UYRB. During the rising period of the water level, the duration of the water level at different elevation levels (see Fig. 4) affects the degrees of sediment deposition. The fourth is wave erosion confined to a belt around the level of 145 m, which may create ‘scars’ along the exposed banks.

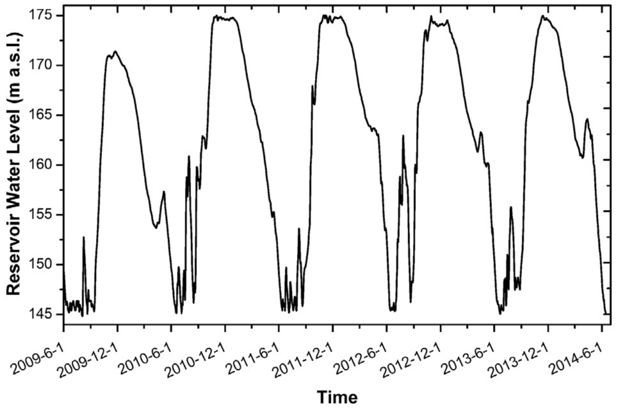

Fig. 3. The new hydrological regime in the Three Gorges Reservoir. The generally similar shape of annual hydrograph indicates the impact of reservoir operation.

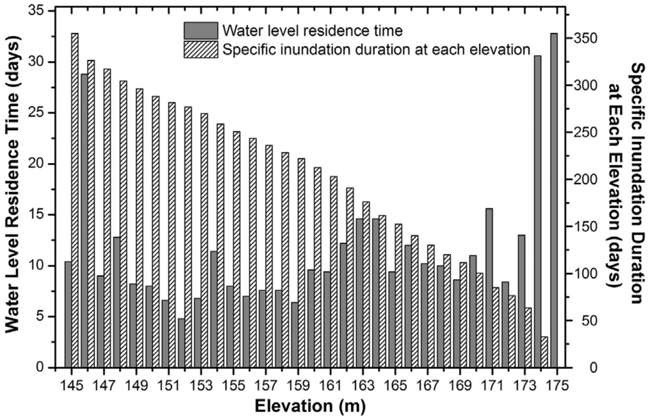

Fig. 4. Water level residence time and inundation duration at different levels of elevation within the TGR disturbance zone. Water stays around the minimum and maximum levels significantly longer than at other levels. The lower the elevation, the longer time the associated area is inundated during one year cycle.

Since the full impoundment of the TGR in 2010, the TGR disturbance zone has been subject to the combination of all these processes annually. Its response to these processes is extremely complex, which is reflected by the significant spatial and temporal variations of its morphology. Therefore, this zone forms a new and unique synthetic geomorphological unit that is worth special attention.

3. Types and spatial distribution of the TGR disturbance zone

The morphology of the TGR disturbance zone demonstrates spatially diverse patterns, which may be generally categorized into three types (Fig. 1). The first refers to the areas that have an approximately linear slope profile with the gradient less than 15° and large lateral extents (i.e., the horizontally projected width of a typical slope is more than 100 m) (Fig. 5a). Geomorphologically, these areas belong to floodplains, first and second terraces, or lower hilly areas neighboring the TGR banks with a generally thick soil layer. This type is underlaid by purple and red rocks and primarily distributed in the section between Jiangjin City and Fuling County, and that between Zhong County and Wanzhou City (Figs. 1 and 2). These lands typically have bare soils with sparsely distributed vegetation. Each year right after the water level is dropped around the base level of 145 m, some grass or shrubs may sporadically develop on these bare soils. During this season, these areas are subject to all abovementioned fluvial processes and hence represent the most dynamic part of the TGR disturbance zone. Rills and gullies generated by overland flow during storm events are dispersed over these areas as they are completely exposed in this season. Along with them are small stream channels running through the areas from the top to the bottom. The size, shape, and location of these rills and gullies vary after each cycle of the new flow regime. Although channel width and depth are generally greater in the downstream section than those in the upstream, the net effect of multiple fluvial processes in these small stream channels could be either erosion or deposition.

The second is the areas comprised of both soils and rock fragments, typically with the horizontally projected width of a slope between 60 and 100 m (Fig. 1). The slope profile is characterized by an inflection point that separates the steeper upper section with the gradient greater than 25° from the gentler lower section with the gradient less than 15° (Fig. 5b). The thickness of the soil layer varies along the profile with a tendency of a greater soil depth in the lower section. This type is also within the area dominated by purple and red rocks and spreads downstream from Jiangjin to Wushan Cities and some main tributaries (Figs. 1 and 2). Before the building of the TGR, the upper section of this type was covered by annuals, perennials and woody plants such as *Ficus tikoua*, *Pterocarya stenoptera*, and *Vitex negundo* (Lu et al., 2010a), while the lower section was commonly used as terraced croplands or grass lands. After the full impoundment, a discernable layer of deposited fine sediment was overlaid on the lower section of the profile, which further reduced its gradient and enhanced the inflection point. To adapt the new flow regime in the TGR, the original vegetation species on the upper section of this type were gradually replaced by annual plants such as *Setaria viridis*, *Digitaria ciliaris*, and *Lobelia chinensis*, and a few alien invasive plants, such as *Eupatorium adenophorum* and *Alternanthera philoxeroides* (Zhong and Qi, 2008; Lu et al., 2010b). The sporadically distributed vegetation species in the upper section of this type facilitated gravity-induced mass movement, which resulted in loosely accumulated rock fragments on the surface (Fig. 5b). Prevailing geomorphological processes acting on the bare lands in the lower section of this type are similar to those described in the first type of the zone.

The third is the areas consisting of carbonate and other bedrocks with a thin layer of bare soils (Figs. 1 and 2). This type commonly has a steep slope or cliff with the gradient greater than 45° (Fig. 5c). Thus, it has the narrowest horizontally projected width of slope, which is normally less than 60 m. The hillslope surface is either covered with meager vegetation or has no vegetation at all. This type of the zone is typically distributed around the Fengjie County and the section between the Wushan City and the dam, as well as the deep valleys of the tributaries (Fig. 1). Even before the construction of the TGR, this type of the zone is not suitable for cultivation and residence. Therefore, the areas have mostly remained their natural status. After the full impoundment, the annually cyclic water level fluctuation has resulted in the distinction of most original vegetation species in this zone. Furthermore, the steep and thin layer of surface soils prevented new species from succession. Consequently, a sharp vegetation line was formed between the area of this type and that above, marking the maximum water level of 175 m (Fig. 5c). In this bedrock-dominated zone, mass movement is the prevailing geomorphological process that typically involves rockfalls and bedding landslides along faults or joints of the bedrocks. The cyclic rising and falling of water level introduce additional

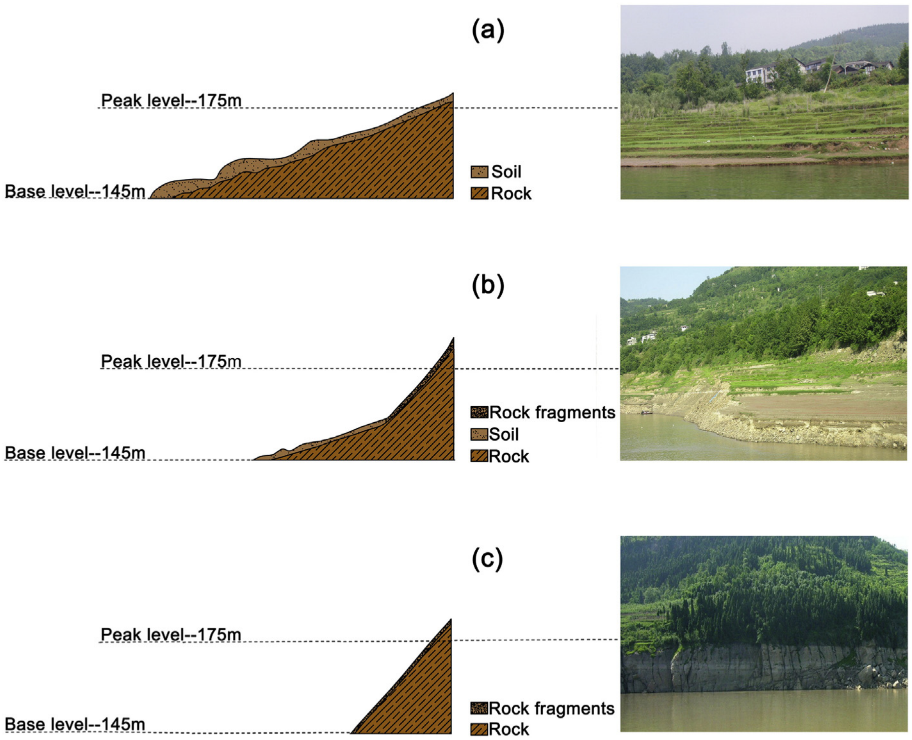

Fig. 5. Morphological characteristics of the three types of the TGR disturbance zone. (a) A conceptual profile of the type one zone. The picture shows an example of this type located in the central part of Zhong County; (b) a conceptual profile of the type two zone. The picture shows an example of this type located in the southern part of Fengjie County; (c) a conceptual profile of the type three zone. The picture shows an example of this type located in the eastern part of Fengjie County.

hydrodynamic and hydrostatic pressures during the dry seasons and interstitial water pressure during the wet season. These forces, together with the change of rock mechanical properties caused by the water-level fluctuation, have triggered more mass movement, which may be evidenced by fresh talus-like deposits with poorly sorted sizes (Fig. 5c). As the remaining part of the hillslope is relatively stable, the frequency of mass movement will gradually reduce and the areas in this type of the TGR disturbance zone will gradually become stable (Zhang, 2009).

4. Existing problems

4.1. Geomorphological processes and the associated challenges

The morphology of the TGR disturbance zone is constantly changing by the active erosion and deposition processes. During the dry season with a high water level, more frequent navigation because of wider and deeper reservoir water creates more powerful waves that may result in the collapse of the banks through sheet, creep, and/or undercutting erosion (Chen et al., 2002). The eroded materials move downslope forming talus-shape deposits along the upper part of the slope profile in the second type of the zone (Fig. 6a). During the wet season when water level is low (close to or at the 145 m), banks in the lower parts of the TGR disturbance zone may still be subject to wave erosion (Fig. 6a), though the water level is more dynamic due to the occurrence of variable storm events (Fig. 3). Although the sparsely distributed invasive vegetation species within the zone might offset the impact of wave erosion, this effect is very limited as rehabilitation of ecosystem in the TGR disturbance zone is a gradual and slow process. Hence, wave erosion will continue to undermine the stability of the zone for a long time.

While wave erosion is primarily constrained to the areas around the minimum and maximum water levels, fluvial erosion caused by storm events during the wet season may affect most areas of the first and second types of the zone. The storm flow running laterally from Three Gorges Reservoir Region into the zone carves the surface, generating rills and gullies of variable sizes, or enlarges the small intermittent creeks across the zone (Fig. 6b). Different from those on hillslopes, rills and gullies on the disturbance zone are simultaneously affected by deposition of the suspended sediment carried longitudinally from UYRB. Therefore, the morphological changes of landforms in the zone are ascribed to the comprehensive effect of both erosion and deposition.

Deposition processes also strongly influence the morphology of the zone. The average flow velocity in the TGR is reduced to the range between 0.2 and 0.3 m/s with the maximum no more than 0. 5 m/s (Luo et al., 2006). During the wet season when the water level is low, storm flows carry a large amount of suspended sediment, a proportion of which is easily deposited on the lower parts of the type-one and type-two zones because of the reduced flow velocity (Wang et al., 2004; Luo et al., 2006). The variable magnitudes of erosion and deposition form the following unique vertically distributed geomorphologic pattern. In the area between 145 and 155 m with gentle slopes, deposition process dominates along the gentle, linear slopes with the sedimentation rate varying between 1 and 40 cm (Bao et al., 2010; Tang et al., 2014). The areas above 155 m are commonly characterized by a cascade of artificial terraces, whose ridges have experienced the highest degree of erosion (Bao and He, 2011), turning the morphology of stepwise slopes into wavelike slopes with the annual average of the erosion rate ranging from 0.1 to 20 cm (Fig. 6c). Quantifying these processes is essential for projecting the potential trend of the morphological changes in the future, especially, that caused by the increased trend of extreme weather due to climate change (Foulds et al., 2014).

In the third type and the upper part of the second type of the TGR disturbance zone, bedrock banks and slopes largely consist of sandstone, mudstone, and weathered, alluvial, or fluvial materials. Together with the steep slopes, these areas are susceptible to landslides and rockfalls even before the construction of the dam. For example, the total of 1208 (old and new) landslides, as well as rockfalls, debris flows, and surface sinks were recorded along banks of the Chongqing section, the tail of the TGR (Liao, 2009). Large and rapid fluctuation of the water level since 2003 resulted in a greater range of rise and fall of groundwater level, which changes significantly the original distribution of infiltration capacity. It also weakens the resistance of and disintegrates the submerged rocks, resulting in a considerable number of new landslides and rockfalls (Zhou et al., 2007; Xu et al., 2008). For example, in 2006 after the water level was raised to the 156 m, 248 old landslides became active by showing vertical cracks, local collapses, and distortion (Periodic Assessment Group of Three Gorges Project, 2010). In 2010 after the full impoundment, 75 landslides and rockfalls were recorded (Ministry of Environmental Protection, 2011). Controlling these mass-wasting processes is a challenge for the sustainable reservoir management.

4.2. Geochemical processes and the associated challenges

Geochemical processes in the TGR disturbance zone vary at different stages of the new flow regime. During the low water-level period of the wet season, suspended sediment is transported by flood flows either longitudinally from UYRB or laterally from TGRR (Periodic Assessment Group of Three Gorges Project) and a proportion of which is deposited within the zone (Tang et al., 2014). With their already high population density, both UYRB and TGRR have to accommodate a large amount of relocated people moved out of the TGR disturbance zone (Tan and Yao, 2006), leading to intensive agricultural activities and fast expansion of towns and cities. These anthropogenic activities encouraged the increased use of fertilizers and accelerated production of industrial and residential wastes. Consequently, nutrients (typically P and N) and heavy and trace metals, traveled either with fine sediment in the solid form or with the flow in the dissolved form (Lv et al., 2007) may be deposited in the TGR disturbance zone (Ye et al., 2011). The abandoned towns and factories in the TGR disturbance zones and the

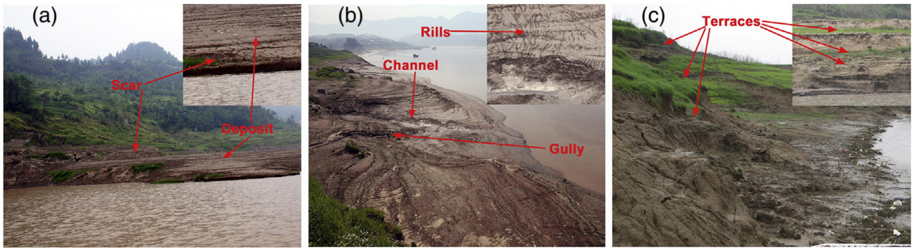

Fig. 6. Illustration of various landforms in the TGR disturbance zone. (a) Evidence of downslope deposits of the eroded materials happened during the dry season in the type-one zone located in Fengjie County (inset shows a scar on the bank due to wave erosion); (b) examples of rill, gullies, and channels within the type-one zone located in Zhong County (inset shows the details of multiple rills). The channel extends upstream even above the top of the TGR disturbance zone. The gully head shows a tendency of moving upstream and part of it has already connected to an upslope rill; (c) a cascade of artificial terraces located in Zhong County (inset shows the cascade from a different perspective). Erosion may be clearly identified on the edge of the top terrace and lower terraces show round edges.

direct discharge of the untreated industrial and residential wastewater also contribute to the enrichment of geochemical materials in the soils of the zone (Su and Zhang, 2010; Xian et al., 2013). Because of the relatively low water level, these geochemical materials tend to accumulate in the middle and low sections of the first and second types of the disturbance zone with relatively gentle slopes, taking the area of 204.59 km^2 that accounts for 66.7% of the total area of TGR disturbance zone (Yuan et al., 2013). During the high water-level period of the dry season, the accumulated nutrients and heavy and trace metals may be partially released to the TGR through various physical and chemical processes such as dissolution, diffusion, and exchange (Xian et al., 2013), accompanied with the decomposition of dead animals and plants, and litters. The significantly degraded ecosystem in the TGR disturbance zone undermines its self-cleaning ability, facilitating the increase of nutrients and metals in the TGR. Furthermore, the reduced flow velocity during this period encourages the enrichment of dissolved pollutants such as nitrogen and phosphorus, particularly in the backwater areas of tributaries within the TGR, triggering more frequent eutrophication incidents (Tan et al., 2008; Fu et al., 2010a). Therefore, this zone becomes the secondary source of pollution deteriorating water quality of the TGR.

In addition to the aggravated pollution, the TGR disturbance zone also suffers the deteriorated sanitary condition that threatens the health of densely distributed local residents. Each year during the wet season with the low water level, local morphological sinks become widely distributed ponds filled with standing water, which encourages the reproduction of bacteria, parasites, and mosquitoes, possibly leading to the breakout of epidemics (Wang et al., 2013). The relatively long period of the low water level also allows the continuous exposure of polluted surface soils in the zone under insolation, which may generate fetor and promote decomposition of some toxic chemicals adsorbed by the soils, exacerbating the neighboring dwelling condition (Chetham, 2002; Tan, 2008).

4.3. Ecological processes and the associated challenges

In the TGR disturbance zone, the shift from the original flood-controlled irregular hydrology to the artificial regular hydrology turns the original terrestrial ecosystem into the seasonal wetland ecosystem, which resulted in fragmented vegetation habitats (Wu et al., 2003b). Many original vegetation species and animals failed to survive under the prolonged submergence condition during the high stage and died out (Huang, 2001; Zhou et al., 2012). Only a few gramineous plants have adapted to the new conditions of habitats. The result was the reduction of vegetation diversity and the capacity of interrestriction among local species (Lu et al., 2010a; Zhou et al., 2011; Yang et al., 2012). Survey of vegetation cover within the zone in 2009 showed that most areas except the gravel floodplains of some tributaries, artificial lands, and some steep bank slopes, were covered by herb-dominated vegetation with spatial variations (Li et al., 2011; Wang et al., 2011a; Wang et al., 2011b; Li et al., 2012). Specifically, in the lower sections of the type-one and type-two disturbance zones, soils are relatively deeper with high organic contents, giving rise to the growth of herb species. Where the inundation period is relatively long (e.g., the areas with relatively gentle slopes), herb species are less diverse and sparsely distributed; where the inundation period is relatively short (i.e., the areas with relatively steep slopes), herb species tend to be more densely distributed and individual plants are relatively tall (Wang et al., 2011b; Wang et al., 2012d). Evidently, the destroyed ecosystem in the TGR disturbance zone needs to be restored.

5. Future directions

Mobilization and movement of geochemical materials are closely related to soil erosion and sediment transport. The landforms within the disturbance zone are the habitats supporting the establishment of a new adapted ecological system. Therefore, understanding the geomorphological processes controlling erosion and deposition and the resultant morphological forms is a fundamental step toward deciphering these interactions.

5.1. Geomorphological aspects

For the first two types of the TGR disturbance zones, though their landforms are the results of the coupled effects of both erosion and deposition, characterizing these effects must rely on knowledge of mechanisms of erosion and deposition, respectively. Erosion is caused by wave impact and surface runoff that are both spatially and temporally variable. Research is needed to describe the intensity of wave erosion during the low water level of 145 m and the high one of 175 m. Empirical relationships between driving forces of wave erosion such as fetch and wind velocity (Elçi et al., 2007) and the amount of eroded materials at each elevation should be created to quantify the degree of wave erosion. It should be useful to identify or create a quantitative index (or several indices) to represent independent variable(s) in these quantitative relationships. During the wet season, storm events, in particular large ones, generate surface runoff that moves laterally along the two types of the zone and triggers erosion that leads to laterally developed rill, gully, and small channels. These erosion processes act on the low and middle parts of the two types of the zone in the direction roughly perpendicular to that of wave erosion. Determination of the amount of the eroded materials and the associated impact on rills, gullies, and channel morphology needs to focus on measuring hydraulics of surface runoff and using either existing soil-erosion models or sediment-transport equations to estimate the eroded materials. Such knowledge will shed light into the relative importance of erosion due to wave movement and surface runoff.

Deposition processes are more complex than erosion ones. During the wet season, high flows induced by storms carry a large amount of suspended sediment both from UYRB and TGRR (Periodic Assessment Group of Three Gorges Project, 2010). Our previous study has shown that the deposition depth generally decreases with the increase of elevation (Tang et al., 2014). This observation, however, was based on the point sampling that may not reflect spatial variations of deposition depths along the same elevation. More systematic sampling methods are required to characterize the spatial variations. Furthermore, the observation failed to distinguish the respective amount of deposited sediment between the lateral sources of the TGRR and the longitudinal sources of the UYRB. The third type of deposition is caused by the movement of the eroded materials due to wave erosion at the level of 175 m. It is a mechanism causing the sediment redistribution within the upper part of the two zones. Isolating these three types of deposition is critical for determining the sediment budget of the TGR disturbance zone and thus should be a pressing research direction.

The morphological structures within these two types of the zone such as rills, gullies, small channels, depressions, and modified edges of cascaded artificial terraces are resulted from the interaction among all erosion and deposition processes. These structures are both spatially diverse and temporally variable. Therefore, monitoring their patterns of annual transition will be extremely valuable for predicting the temporal trend of morphological change the TGR disturbance zone has, which will provide the benchmark for understanding the development of the future new ecosystem. The type-three TGR disturbance zone is dominated by mass-wasting processes such as landslides and rockfalls. It is well known that qualitatively the intensified mass movement after the full impoundment of TGR in 2010 will gradually slow down (Zhang, 2009). However, exactly how long it takes for these steep bank slopes to resume stable is still a mystery. Continuous inventory of the number, size, and amount of disturbed bank materials will make it possible to establish quantitative relationships that can project the future trend of bank stability.

5.2. Geochemical aspects

Geochemical materials are mobilized and travel from both UYRB and TGRR into the TGR. A significant proportion of them is deposited within the TGR disturbance zone, which may be remobilized later, continuously deteriorating water quality of the TGR. Thus, understanding the amount and spatial distribution of chemical pollutants (primarily nutrients, heavy and trace metals, and carbons) in the TGR disturbance zone is critical for Chinese central and local governments to launch tailored policies to improve the reservoir water quality. Unfortunately, biochemical processes such as adsorption and desorption processes superimposed on physical ones controlling pollutant transport lead to highly variable magnitudes and spatial distributions of these pollutants.

Attempts of characterizing the spatial distribution of nutrients and organic materials (OM) within the TGR disturbance zone and their annual variation have shown inconsistent results. While some reported that in the early years when the water level was about to reach the maximum (i.e., 2008 and 2009), the accumulated amounts of organic materials, total phosphorus (TP), and total nitrate (TN) increased (Tan et al., 2012), others showed a declined trend (Cao and Ji, 2013), which was echoed by a study using the data collected in 2010 (Guo et al., 2012c). The inconsistency highlights the importance of developing clearly-defined sampling methods in order to make meaningful interpretation of the associated outcomes. Despite of this, all studies demonstrated diverse and temporally variable distributions of OM and nutrients. This distribution reflects the coupled effect of (1) the desorption processes of these materials to reservoir water from the soils or rotten and decomposed plants because of submergence (Zhan et al., 2006; Wang et al., 2012a), (2) the decreased supply of nutrients and OM from the source regions due to the continuity of water and soil conservation policies (Xu et al., 2013), (3) the spatially variable amounts of these materials due to the change of soil layers caused by erosion and deposition processes, and (4) the absorption of nutrients from the enriched backwater of tributaries within the TGR during the dry season because of the reduced flow velocity (Wang et al., 2010a). Research is awaited for characterizing each of these processes for better understanding of the highly variable distribution.

The TGR disturbance zone has also received the excessive amount of trace and heavy metals from the source areas, which may be verified by the observed augment of Cd, Pb, Cu, Zn, and Hg concentrations with clear geographic and elevation-dependent variations (Pei et al., 2008; Zhang et al., 2011; Wang et al., 2012b; Tang et al., 2014). During the dry season, these materials may be partially released to the reservoir water accelerating the degradation of the water quality (Cheng et al., 2009; Fang, 2010). These results allowed for the general environment assessment of the potential detrimental impact various heavy metals might have on the TGR disturbance zone (Liu et al., 2011; Zhang et al., 2011). Nonetheless, effective and sustainable pollution management due to heavy metals calls for understanding of physical and biogeochemical mechanisms that control the dynamic changes of spatial distribution of heavy and trace metals in the TGR disturbance zone. It appeared that soil pH values are related to the migration rates of heavy metals, in particular, to their organic form, from the deposited soils to the inundated water (Fu et al., 2008b; Cheng et al., 2009; Fu et al., 2010b). Yet, the composition and bioavailability of these metals through biochemical processes (e.g., Fe–Mn redox and microbial conversion) that are tied to their migration are still poorly understood. An apparently ignored issue is the study of particle size distribution (PSD) of soils in the TGR disturbance zone and its correlation to nutrients and metals in these soils. Nutrients and (heavy and trace) metals in either the original soils of the zone or deposited suspended sediment transported from source areas are more absorbable to the chemically active fine sediment with the size less than 0.063 mm (Owens et al., 2005). Analyzing PSD of soils in the zone will enable the determination of the concentrations of contaminants based on the fraction of fine particles (Russell et al., 2001; Collins and Walling, 2007). This approach will eliminate the bias involved in the calculation of the concentrations among spatially variable soil samples with different PSDs.

5.3. Biological aspects

The greatly degraded biodiversity in the TGR disturbance zone, particularly the disappearance of indigenous vegetation significantly undermines the function of the regional ecosystem service (Cheng et al., 2010). The reported potential trend of an elevation-based distribution of new vegetation species seems to suggest that the TGR disturbance zone has the ability of developing a new ecosystem naturally, probably because the disappearance of most indigenous species due to the prolonged inundation has provided patchy habitats for the colonization of invasive species (New and Xie, 2008). Yet, a study on the dynamics of soil seed bank during the early inundation stage (Wang et al., 2012c) showed that the composition and quantity of seeds in habitats varied dramatically with elevations such that no dominant species emerge. Thus, successfully restoring vegetation in the TGR disturbance zone must rely on the artificial intervention, which requires resolving a puzzle: what kinds of (indigenous and exotic) species that can survive the prolonged inundation period while sustaining the diversity of the ecosystem? Previous studies in this zone and the similar areas of other reservoirs identified several trees and herbs (e.g., *Salix humboldtiana*, *Panicum repens*, *Eucalyptus camaldulensis*, and *Arundinella anomala* Steud.) capable of tolerating the lengthy submergence (Fang et al., 2003; Luo et al., 2006; Fu et al., 2008a; Wu et al., 2009a; Ma et al., 2010; Lu and Jiang, 2012), though the growth of these species are constrained by the fertility of soils and soil water content (Chen and Xie, 2007; Guo et al., 2012b). Particularly in the TGR disturbance zone, studies have showed that individual species such as *Cynodon dactylon* and *Mulberry* may survive effectively because of their relatively high tolerance to submergence and resistance to the prolonged drought with high temperature, and/or fast growth rates (He et al., 2007; Hong et al., 2011; Huang et al., 2012; Li et al., 2012; Zhang et al., 2012a). However, it is unknown whether these species may adapt to the highly variable surface soils in the TGR disturbance zone due to complex erosion and deposition processes. Long-term, systematic investigation of the spatial distributions of the prior species (Wang et al., 2011b) over multiple hydrological cycles in three different types of the TGR disturbance zone is a logic research direction for gaining the insight into this issue.

In addition to the ability of adapting to the new hydrological regime, the selected vegetation species should also have a well-developed root system such that they may serve as a means of green engineering in replacement of the traditional engineering construction to stabilize the landforms within the TGR disturbance zone. For instance, *Vetiveria zizanioides*, a perennial grass, has been identified as an appropriate species to facilitate soil conservation (Liu and Liu, 2004; Wang et al., 2010b; Xiong et al., 2011). More effort is needed to explore based on continuous experimental studies within the TGR disturbance zone the most appropriate density and height of the newly colonized species that may best reduce different types of erosion for stabilizing surface soils on hillsides of various gradients.

6. Conclusions

Human activities have caused environmental changes at an accelerated pace (Collins and Childers, 2014). This tendency propels geomorphologists to explore the human impact on environment, a future direction of geomorphology (Church, 2010). The TGR disturbance zone is a unique geomorphological unit that exemplifies the expansion of the purview of geomorphology toward this direction. The TGR disturbance zone is a man-made reservoir transitional zone significantly affecting the health of the TGR. Characterizing the morphologic changes of the zone is challenging because it is subject to fluvial processes driven by the annually cyclic variation of the water level, as well as storm events. Therefore, frequent alternation of erosion and deposition occurs during one year, a hydrological cycle, making the process-form response system extremely dynamic and complex. Although the results from previous studies have demonstrated that the depth of sediment deposition varies spatially and its variation is dependent of elevation, it is still not clear how this depth changes from year to year and within the two seasons of one year. New sampling strategies should be developed to characterize the relative magnitude of erosion and deposition at different elevation levels, which will enable the identification of the relative importance of different geomorphological processes acting on the TGR disturbance zone. Associated with these new sampling methods are the adoption of process-based approaches such as the timely survey of surface morphology and sediment modeling.

The morphological changes of the TGR disturbance zone profoundly affect the geochemical and biological processes that ultimately affect the water quality and ecosystem of the TGR. While movement of organic materials and chemical elements relies on biochemical processes such as decomposition, absorption, and transformation, physical processes such as traveling with the adhered fine soil particles from sources to the zone are the dominant mechanisms determining the spatial distribution and amount of the accumulative organic materials and chemical elements. Similarly, successful colonization of new vegetation species adaptive to the new hydrological regime largely depends on physical characteristics of habitats, which are directly tied to geomorphological processes. Therefore, determining the degree of pollution in and rehabilitating ecosystem of the TGR disturbance zone need new approaches involving the impact of geomorphological processes on the zone.

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