The Hydrological Regimes Brought by the Three Gorges Project Affected Riparian Vegetation Distribution and Diversity in 2009 and 2010

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Abstract Post-dam riparian vegetations affected by the new hydrological regimes in the Three Gorges Reservoir (TGR) were investigated in 2009 and 2010, respectively. The investigation in 2009 showed that about 231 vascular plant species belonging to 169 genera of 61 families were distributed in the water-level-fluctuation zone (WLFZ) of the (TGR). Three vegetation types, including Chuanjiang, Gorge, and other vegetation types, were classified efficiently via cluster analysis. Alpha diversity analysis indicated that species richness gradually decreased with decreasing elevation. Beta diversity analysis indicated that high environment heterogeneity was existed between the lower section and the other two sections, and environment homogeneity was also existed between middle section and upper section. Using the analysis of the field growth in the 2009 and 2010 field surveys as bases, we proposed a list of perennial herb species and woody species that may potentially occurred in the WLFZ of the TGR. In addition, we predicted plant community structural changes in the different altitude sections of WLFZ in the future.

1. Introduction
The Three Gorges Project (TGP), as the largest hydropower project in the world, was initiated in 1994. The closure of the Three Gorges Reservoir (TGR) and the first impoundment was occurred in 2003. The water level of the reservoir rose to 135 m from about 60 m of the original riverbank in June
2003[1]. The second impoundment was impounded in October 2006, and the water level rose to 156 m. The third impoundment in October 2008 resulted in a sustained water level at above 170 m for five months. Normally, the natural peak flows in the river occur during July, August, and September (summer flooding) with low flows in January, February, and March [2]. However, the full functional Reservoir would have a water level fluctuating between 145 m and 175 m, i.e., 145 m in summer (May–October) for flood control and 175 m in winter (November–April) for energy generation [3, 4]. The analysis of hydrological regimes of the TGR is illustrated in another paper [4]. Thus, the new hydrological regime brought about by the TGP is the absolute opposite of the natural flood rhythms of the Yangtze River.

Although the TGP offers many benefits such as controlling flooding, generating motive power and electricity, facilitating navigation, and stimulating the development of local tourism, it simultaneously imposes negative and irreversible effects on the ecology and environment, especially on riparian ecosystems[3, 5]. The new hydrological regime from the TGP dramatically altered the conditions in the riparian ecosystems. The area between the high (175 m) and low (145 m) water level is called the water-level-fluctuation-zone (WLFZ)—a new kind of wetland[3]. According impounded conditions and the seasonal hydrological regimes in TGR [4], WLFZ was divided three sections. Upper section is an area between altitudes of 165 m-175 m, the middle section is an area between altitudes of 156 m-165 m, and the lower section is an area between altitudes of 145 m-156 m. Therefore, the riparian vegetation located within the WLFZ of the TGR suffered from different gradient flood stress. Of particular concern to us is determining the effect of the TGP on the riparian vegetation through new hydrological regimes. Therefore, the objectives of this paper are to (1) understand plant species composition and dynamic distribution of riparian vegetation in the WLFZ of the TGR; (2) determine the plant diversity in the different altitude sections of WLFZ; (3) provide useful information on selecting plant species with tolerance to winter flooding, and suggestions for revegetation in the WLFZ of the TGR; (4) predict plant community structural changes in the different altitude sections of WLFZ in the future.

2. Methods

2.1 Study area

The portion of the Yangtze River Basin between Chongqing and Yichang City (where the Three Gorges Dam is located at Sandouping) has a distance of approximately 600 km. The total area of the Three Gorges Reservoir Area (TGRA, 106°20′–111°50′ E, 29°16′–31°25′ N) is approximately 58,000 km² [5], and the total surface area of the reservoir is 1,045 km². When water level was artificially regulated between 145 and 175 m, the WLFZ with an area of 348.93 km² was formed in the TGRA. The TGRA has a humid subtropical monsoon climate, with a mean annual temperature of 15–19°C, mean annual precipitation of 1,250 mm, and relative humidity of 76% [5]. Although the climate of the region is considered to be monsoonal subtropical, the flora is characterized by a mix of tropical, subtropical and temperate species[2]. Little affected by the quaternary glaciations, the TGRA is one of the richest areas in biodiversity in China[3, 6].

2.2 Field surveys
A survey on plant species distribution was carried out between July and August 2009. 22 sampling sites were set up in 10 typical areas along both sides of the Yangtze River in Zigui, Badong, Wushan, Fengjie, Yunyang, Wanzhou, Zhongxian, Fengdu, Fuling, and Changshou Districts of Chongqing City. The spatial distributions of these counties in the TGRA were shown in Yang et al. (2015). Three sampling belts (200 m in length, and 5 m in width) in each sampling sites were designed in the lower section, middle section and upper section of WLFZ, respectively, total 66 sampling belts. The plant species catalogue was recorded in detail.

A survey on plant community was carried out between June and July 2010. Sixteen sampling sites were listed in table 1. Three big quadrats (10 m × 10 m) were designed in the lower section, middle section and upper section in each sampling site, respectively. In addition, four small quadrats (1 m × 1 m) for herb species were designed in a big quadrat along the diagonal line. A total of 192 quadrats were used (Table 1). Basic parameters, such as altitude, slope degree, and vegetation coverage of each unit were recorded. For herbs and shrubs, species, abundance, coverage, and average height were investigated.

Table 1. The coordinate data of 192 quadrats of the water-level-fluctuation zone in the Three Gorges Reservoir in 2010

2.3 Hierarchical cluster analysis of plant species from different sampling sites.
Hierarchical cluster analysis was used to compare the similarity of plant species composition among different sampling regions. The plant species in each sampling site were scored as present (1) or absent (0). The coefficients of inter-sampling sites were generated. Hierarchical cluster analysis was performed with the SPSS 16.0 for Windows statistical software package.

2.4 Plant diversity index
Relative frequency = frequencies of a plant species/ frequencies of all plant species×100%;
Relative height = heights of a plant species/total heights of all plant species×100%;
Relative coverage = coverage of a plant species/ total coverage of all plant species×100%;
Important value = (relative frequency+ relative height+ relative coverage)/3.

The α-diversity parameters were calculated for each plot, and the average value of the plots at each site was accepted as the diversity indices of each site. The Shannon information index was used to
measure diversity on the basis of importance value, the Pielou’s index for the relative species evenness and the Simpson’s index for the concentration of species dominance were also calculated, and richness was calculated as the species number. Different diversity indexes were calculated using the following equations [7, 8]:

- **Richness index (S):** the amount of species in the plot;

- **Shannon-Wiener diversity index:** \( H' = - \sum_{i=1}^{s} P_i \ln P_i \); 

- **Simpson’s diversity index:** \( D = 1 - \sum_{i=1}^{s} P_i^2 \);

- **Pielou evenness index:** \( J_{sw} = \frac{1}{\ln S} \sum_{i=1}^{s} \frac{P_i}{\ln(S)} \);

- **Population encounter incidence:** \( P_{IE} = \frac{1}{\ln(N)} \sum_{i=1}^{s} \left( \frac{N_i}{N} (N - N_i) \ln(N - 1) \right) \).

Where \( P_i \) is the relative importance values of the \( i \)th species, \( N_i \) is an importance of the \( i \)th species; \( N \) is total amount of importance values of each species in \( i \)th species present squadrat, and \( S \) is the total amount of the species in each squadrat.

The \( \beta \)-diversity for each section was calculated on the basis of data from all plots. The \( \beta \)-diversity values thus reflect habitat heterogeneity between sections. Different diversity indexes were calculated using the following equations [7, 8]:

- **Whittaker index:** \( \beta_W = \frac{S}{\alpha} - 1 \);

- **Cody index:** \( \beta_C = \frac{\ln(g(H)) + \ln(l(H))}{2} \);

- **Routledge index:** \( \beta_R = \frac{S^2}{2r+S} - 1 \);

Where \( S \) is total amount of plant species in studied system, \( \alpha \) is mean numbers of species in individual squadrat, \( g(H) \) is increased species number along the environmental gradient, \( l(H) \) is lost species numbers along the environmental gradient, and \( r \) is log of repeated species in each squadrat.

2.5 Statistical analysis

One-way analysis of variance (ANOVA) was used to test differences (\( P<0.05 \)). Statistical analyses using the Duncan’s method were performed with the SPSS16.0 for Windows statistical software package.

3. Results

3.1 Plant composition

The riparian vegetation survey in 2009 indicates that 231 vascular plant species belonging to 169 genera of 61 families were found in the investigated area. As far as family was concerned, family with over 30 species was not found. 29 families with one species and 26 families with 2-9 species were found, respectively, and their individual ratio to all families is 47.5% and 42.6%, respectively. As far
as genus was concerned, genus with over 10 species was not found. 134 genera with one species and 33 genera with 2-5 species were found, respectively, and their individual ratio to all genera was 79.2% and 19.5%, respectively. As far as life form of plant species was concerned, 105 annual herb species and 75 perennial herb species was found, respectively, and their individual ratio to total species was 45.5% and 32.5%, respectively. In addition, 39 woody plant species including 12 tree species and 27 shrub or subshrub species were found.

3.2 Cluster analysis of vegetation types on various sites
The hierarchical cluster analysis indicated that the coefficient of vegetation types among different sampling sites. Figure 1 shows the results of the analysis. The results infer that vegetation types among different sampling sites may be differentiated. Thus, three vegetation types were differentiated efficiently. Type 1 was located in the Chuanjiang River sections (sites 1, 2, 3, 4, 5, 6, 9, and 10; from Chongqing to Fengjie); type 2 was located in the Gorges River sections (sites 14, 15, 16, 18, and 20; from Fengjie to Zigui); type 3 was located the experimental base (sites 22, 7, and 21) or other micro-topography (8, 11, 12, 13, 17, and 19) belonging to untraversed sites.

![Figure 1](image)

**Figure 1.** Hierarchical cluster analysis of vegetation distribution in 22 sampling sites in the water-level-fluctuation-zone in the Three Gorges Reservoir in 2009.

Note: 1, Longxi River in Changshou; 2, Changming Port in Changshou; 3, Wu River in Fuling; 4, Yangtze River in Fuling; 5, Yangtze River in Fengdu; 6, Long River in Fengdu; 7, Experiment base in Zhongxian; 8, Xintian Town in Wanzhou; 9, Wanzhou Port in Wanzhou; 10, Pengxi River in Yunyang; 11, Yangtze River in Yunyang; 12, Yangtze River in the old location of Yunyang; 13, Yangxi River in the old location of Yunyang; 14, Meixi River in Fengjie; 15, Yangtze River in Fengjie; 16, Daling River in Wushan; 17, Yangtze River in the Badong; 18, Badong Port in Badong County; 19, Shennong River in Badong; 20, Xiangxi River in Zigui; 21, Lanling River Experiment base in Zigui; 22, Experiment base in Three Gorges Dam in Zigui.

3.3 Alpha diversity analysis among different altitude sections
The mean species richness based on the squadrats in 2010 was listed in Table 2. From upper section to
lower section, species richness and diversity was gradually decreased with the decline of altitude. The best and the worst species richness were found in the upper section and lower section of WLFZ, respectively. Significant differences in species richness were found between middle section and lower section. However, significant differences in species richness were found between upper section and middle section. As far as diversity indexes were concerned, $H'$ and $D$ diversity indexes in the lower section were obviously lower than that in the middle and upper sections. However, significant difference in $H'$ and $D$ diversity indexes were not found between middle section and upper section. As far as evenness indexes were concerned, $Jsw$ evenness index in the upper section was significant higher than that in the lower section, and $Jsw$ evenness index in the middle section was not significant different from these in the upper section and lower section. As far as PIE was concerned, PIE in the lower section was significant higher than these in the middle and upper sections, and significant differences were not found between the middle and upper sections.

**Table 2.** The comparison of $\alpha$ diversity index in the different sections of the water-level-fluctuation zone in the Three Gorges Reservoir. Values are means ± SE. Within a column, values followed by different letters are significantly different at $P < 0.05$ according to Duncan’s test.

|         | S       | $H'$         | D          | $Jsw$      | PIE         |
|---------|---------|--------------|------------|------------|-------------|
| Upper section | 16.9±6.3a | 2.574±0.349a | 0.907±0.031a | 0.932±0.016a | 1.465±0.192b |
| Middle section | 14.1±5.6a | 2.386±0.415a | 0.885±0.054a | 0.928±0.033ab | 1.532±0.322b |
| Lower section | 5.5±5.0b  | 1.312±0.643b | 0.647±0.180b | 0.898±0.057b | 2.467±1.211a |

3.4 **Beta diversity analysis among different altitude sections**

As far as vertical direction, $\beta$ diversity in the lower section are significant different from upper section and lower section (Table 3). $\beta_W$, $\beta_C$ and $\beta_R$ in the upper section and middle section were significant higher than that in the lower section, and significant differences in these indexes were not found between upper section and middle section.

**Table 3.** The comparison of $\beta$ diversity index in the different sections of the water-level-fluctuation zone in the Three Gorges Reservoir. Values are means ± SE. Within a column, values followed by different letters are significantly different at $P < 0.05$ according to Duncan’s test.

|        | $\beta_W$     | $\beta_C$     | $\beta_R$     |
|--------|----------------|----------------|----------------|
| Upper section | 2.373±0.336a | 11.800±3.516a | 19.657±6.175a |
| Middle section | 2.465±0.411a | 9.633±2.705a | 16.340±4.945a |
| Lower section | 1.562±0.595b | 3.400±2.888b | 5.685±5.367b |

4. **Discussion**

Erosion and sedimentation processes are strongly linked to the hydrology of a river and also holds
consequences for the surrounding vegetation. The riparian vegetation functions as filters between land and water and plays important roles in stabilizing riverbanks, which retains soil and decreases silt run off into rivers, and improving water quality [9, 10]. The riparian vegetation can be structured and to an extent, determined, by flood timing, duration, frequency, rate of change and magnitude, as plants often display a preference or tolerance for a specific hydrological regimes [2, 11]. The riparian ecosystems and plant diversity of the TGRA have been altered by the new hydrological regime caused by the TGP. The most serious effects on riparian vegetation are primarily caused by the opposition to the natural flood rhythms, increased flooding durations, and water level fluctuations with a 30 m magnitude. The riparian vegetation in the TGRA must not only endure winter flooding but also adapt to summer drought conditions during the growing season. Therefore, the analysis of vegetation responses to river regulation through TGP is highly important to assessing the effects on riparian ecosystems. Additionally, the data can be used as a starting point for monitoring purposes because it can be assumed that changes in vegetation will continue to occur in the future.

The investigation of pre-dam riparian vegetation in 2001 manifested that about 405 vascular plant species, belonging to 240 genera of 83 families, located in the TGRA [12]. The comparative analysis of the vascular plant family, genera, and species identified that a large proportion of the pre-dam riparian vegetation disappeared. Compared with pre-dam riparian vegetation, the family, genera and species of post-dam riparian vegetation survey were decreased to 73.49%, 70.41% and 57.04%, respectively. This suggests that most pre-dam riparian vegetation were unable to adapt to the opposition of natural flood rhythms, increased flooding durations, and water level fluctuation with a 30 m magnitude. Thus, plants gradually disappeared or died.

The comparative analysis of life forms of the vascular plant species indicated that the new hydrological regime imposed the most serious effects on shrub and perennial herb species. The survival and recovery of perennial species during or after flooding stress mainly depended on their root systems. The root systems of plant species surviving in the post-dam riparian zone must endure oxygen deficiency and low temperature resulting from winter flooding. In addition, these plant species must adapt to the dryer conditions in summer. Although the limited growth season resulting from increased flooding durations in the new riparian zone prevents certain annual species from completing their life cycles [2], their survival and emergence depends on seed germination [13]. Seeds may be dispersed from other places by wind or water flow along the riverbank [14].

The cluster analysis results indicated that the plant species distribution among different sampling regions had differences. Differences in plant species distribution between the Chuanjiang sections (from Chongqing to Fengjie) and Gorge sections (from Fengjie to Zigui) may be due to their different geographical environments. In the Chuanjiang sections, the river is wide, and the speed of the water flow is slow. Therefore, majority of plant seeds could be left in the WLFZ when the water level degrades. In addition, gentle slope and fertile soil were found everywhere in the WLFZ of the Chuanjiang sections. All these factors help in vegetation development. However, in the Gorge sections, the river is narrow, and the speed of water flow is fast. Therefore, few plant seeds could be left in the WLFZ when the water level degrades. In addition, steep slope and sandstone were found everywhere in the WLFZ of the Gorge sections. These factors go against vegetation development. The vegetation located in untraversed sites and experimental bases was different from the others because of rare
human disturbances and advantage circumstances, or revegetation activities.

In the WLFZ of the TGA, the plant diversity is determined by the flood timing, flood duration and illumination intensity. Due to the water level of the TGR was artificially regulated within the altitude of 145 to 175 m [4], riparian vegetation in the lower section of the WLFZ encountered the most serious flood environment, whereas riparian vegetation in the upper section of the WLFZ encountered the slightest flood environment. The relative low S, H′ and D in the lower section indicate that only a few plant species could endure the serious flood environment. However, a relative high PIE in the lower section indicates that the plant community in the lower WLFZ was more unique than the communities in the upper and middle WLFZ.

Beta diversity can be defined as describing the extent of species replacement or biotic change along environmental gradients [8]. Significant differences in β diversity between lower section and other two sections, which indicated high environment heterogeneity was existed between lower section and other two sections. No significant differences in β diversity between middle section and upper section indicate that environment homogeneity was existed between middle section and upper section. High environment heterogeneity between lower section and other two sections was due to the most serious flood stressed environment in the lower section of WLFZ.

Most post-dam riparian vegetations were unable to adapt to the opposition of natural flood rhythms, increased flooding durations, and water level fluctuation with a 30 m magnitude. Thus, majority plant species will gradually disappear or die in the future. Therefore, information on selecting local plant species with tolerance to winter flooding is very useful for the recovery and re-establishment of the riparian vegetation in the WLFZ of the TGR. Plants selected for revegetation activities should be from remnant vegetation patches in the TGRA, rather than plants of the same species distributed outside the TGRA because of important local gene pools [2]. Fortunately, some plants from the TGRA showed high morphologic and physiologic plasticity to winter flooding and developed stable communities in the revegetation activities in the TGR WLFZ, including *Paspalum paspaloides*, *Cynodon dactylon*, *Vetiveria zizanioides*, *Hemarthria altissima*, *Capillipedium assimile*, *Artemisia atrovirens*, *Arundinella anomala*, *Polygonum perfoliatum*, *Distylium chinesis*, *M. laxiflora*, *Lycium chinense*, *Salix variegate*, *Salix babylonica*, *Populus nigra*, *Morus alba*, and *Taxodium ascendens* [15]. Meanwhile, reasonable distribution patterns of herb species and shrub species, as well as arbor species should be given attention during revegetation activities. These species will contribute to the spatial heterogeneity of the riparian WLFZ. Considering the impounded conditions and the seasonal hydrological regimes of the TGR, revegetation within the TGR WLFZ may be divided into three sections, including areas with lower altitudes (145 m to 160 m), middle section of 160 m to 170 m), and upper section of 170 m to 175 m. The revegetation of the lower areas should choose perennial creeping herb species with the strongest flood tolerance, including *C. dactylon*, *P. paspaloides*, *A. anomala*, and *P. perfoliatum*. The revegetation of the moderately elevated may choose perennial herb species with stronger flood tolerance and higher biomass aside from the aforementioned creeping herb species, including *H. altissima*, *V. zizanioides*, *C. assimile*, and *A. atrovirens*. These plants may be often used as raw materials of pastures, pulps, and other energy products, and revegetation using these plants may improve local economic development. The revegetation of high altitude areas should use herbs, shrubs, and arboreal species. The planted species may include shrub species and arboreal species with certain
flooding tolerance, aside from the aforementioned herb species, as well as the shrub species *D. chinensis, M. laxiflora, L. chinense,* and *S. variegate,* and arboreal species *S. babylonica, P. nigra, M. alba, P. stenoptera,* and *T. ascendens* [16-18].

In the future, ecological succession of plant community structure maybe have a tendency that the lower section of WLFZ had the highest plant community structural stability and the middle WLFZ had the lowest. In the upper WLFZ, the infrequent flooding stress was beneficial to a wide variety of species, allowing them to survive and compete for space. Highly competitive weeds dominated these communities. In the lower WLFZ, the surviving species were those able to deal with the strongest flooding stress. The plants were highly flood stress tolerant species which could survive and form a dominant community. The flooding stress in the middle WLFZ is intermediate between that of the upper and lower WLFZs. These mid-range WLFZ species suffered from both competitive and flooding stresses. These plant species possessed a strong competitive capacity and a strong flood tolerance and formed a dominant community. The stability of this mid-zone plant community was relatively weak, and groups of plants formed co-dominant communities. Under current conditions, the plant community in the lower WLFZ was more unique than the communities in the upper and middle WLFZs. However, it is estimated the plant community compositions in the upper and middle WLFZs will gradually stabilize and become unique as the water level stabilizes around 175 meters.

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