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Flooding Depth and Flooding Duration with the Zonation of Riparian Plant Communities in the Three Gorges Reservoir of China

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Abstract: The hydraulics of flows, especially the flooding process, influence the patterns of riparian plant zonation. Different characteristics of the flooding process should be analyzed to correlate plant zonation with flooding due to their different effect modes. The effects of flooding characteristics on riparian plants have yet to be studied, especially in the field. Thus, two elements of the flow regime, flooding duration and depth, were analyzed in relation to the riparian plants of the Three Gorges Reservoir. The taxonomic indices and the functional diversity of the riparian plants in three seasons in 2019 and the corresponding inundation character were surveyed. Our results showed that the riparian plant diversity and functional diversity varied by season. A significant negative relationship between plant diversity and flooding depth was observed, while flooding duration was not a significant predictor in different seasons. The greater explanatory capacity of flooding depth than that of flooding duration suggests that flooding depth could be a better indicator of the zonation of the riparian vegetation in this area. Concerning the vital component of flow hydraulics, growing opportunities to study flooding depth and strategies that consider both flooding time and flooding depth in a reservoir should be offered, as they will assist in refining process-based river restoration.

Keywords: flooding depth; flooding duration; riparian zone; plant zonation; Three Gorges Reservoir

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1. Introduction

Riparian zones serve as a framework for understanding how the organization, diversity, and dynamics of communities associated with fluvial ecosystems represent an unusually diverse mosaic of landforms, communities, and environments within a larger landscape [1,2]. The water regime of a riparian zone is a significant determinant of plant zonation patterns and is essential to river life, but it can also be a source of stress. Flow spatial- temporal patterns from local to regional scales exert direct and indirect control over plant communities [3]. River regulation affects riparian plants by modifying water level fluctuations via altering flow regimes [4,5], especially for the large dams.

With intensive human intervention and occupation, natural river regimes are gradually being replaced by regulated flow, thereby dramatically affecting riparian zones and stoking international concern [6–8]. The impacts caused by dam construction include changing river sediment transportation and scouring–silting patterns and effects on biological activities, downstream fluvial geomorphology, and sedimentary environments [9,10]. The Three Gorges Dam (TGD) has entered its twentieth year after its first turbine operation in June 2003. The dam, which has 20 times the power generation capacity of the Hoover Dam in the United States, has been hailed as a key component of solving China's energy crisis [11]. However, major concerns about this large-scale engineering project's social consequences and catastrophic environmental repercussions, especially with respect to its impact on the nearby riparian ecosystem, have been expressed despite its benefits.

After a dam's construction, the habitat-changing characteristics of the neighboring riparian zone are significantly related to the magnitude and frequency of flow duration [12]. The Three Gorges Dam, the biggest dam in China, caused the Three Gorges Reservoir (TGR) to experience a seasonal reversal of its hydrological regime [13]. The riparian plants of the TGR then faced inundation for up to several months [14], which resulted in a typical degree of plant zonation. Plant species zonation is a characteristic feature of water depth gradients in wetland environments and lake shorelines due to the wide availability of water for growth in these areas [15]. It has been reported that plant diversity and species richness are negatively affected by frequent flooding [16]. With the severe stress of a riparian zone, riparian vegetation species must complete their life cycles under a limited growth period, which can be as short as three months [17]. Riparian plants appear to have more distinctive preferences and distribution patterns after twenty years of reversed hydrological regime adjustment.

Different life-history strategies are needed to allow riparian plants to adapt to a varying environment. Flow hydraulics influence the vegetation distribution and zonation in riparian zones. This is especially the case for flooding processes, which bring about scour and deposition [18,19]. Flooding and water level fluctuations disturb riparian landscapes by determining the amount of exposed land and affect riverine vegetation by imposing physiological constraints and precipitating losses in cover and species diversity [20]. How hydrological characteristics interact with and affect riparian zones is complex, particularly with respect to seasonal variations in flow and alternating wet and dry cycles [21]. Flow regulation can lead to changes in the responses of riparian plant species guilds [20,22,23], it has motivated research on the link between hydrologic alterations and biota [3,24,25]. Different life-history strategies are needed for riparian plants to adapt to varying environments.

With intensifying human demands for water and the continued alteration of rivers by humans, there is a growing need to predict vegetation responses to flow alteration [26], including responses related to the flooding process. The different aspects of flooding dynamics should be analyzed separately to correlate riparian plant zonation with flooding [27]. Flooding duration has attracted more attention than other factors in riparian plant research because of the unnatural long-term flooding of the TGR, where high-level water fluctuations result in an extremely high flooding depth. Such flooding depths change the physical and chemical composition [28] of a riparian zone's soil, which affects the area's riparian plants. Research linking flood factors with riparian vegetation have shown the importance of flooding depth [29,30]. Current research focuses on the effects of long-term flooding [16,31] on riparian plants and the effects of flooding depth on plant traits in the laboratory [32,33], but the plant community's response to flooding depth lacks attention in the field, especially regarding the extreme flooding caused by big dams. Inundation with seasonal variation presents a different impact compared to flooding events over a long period [34]. Whole-year data, including on seasons, appear to be more explanatory than growing season data [27].

Despite the importance of flooding depth for the riparian plants in the TGR, little information is available about the effects of flooding depth on this plant community as assessed in the field, particularly when considering seasonal variation. Therefore, a study of inundation characteristics and the corresponding plant community was conducted in the riparian zone of the TGR. The taxonomic indices and the functional diversity of the riparian plant communities surveyed in different seasons in 2019 were analyzed. The relationship between the inundation characteristics and the plant community in the riparian zone affected by the dam was studied. This study explores the correlation between the inundation factor and riparian plants to provide greater insight into riparian ecosystem management with flow regulation.

2. Materials and Methods

2.1. Study Sites

The study was conducted at the TGR of the Yangtze River in China (Figure 1). This area has a humid, subtropical monsoonal climate [35]. The area's average annual temperature is approximately 18 °C, and its annual precipitation level is about 1100 mm [36]. Monthly precipitation levels vary between 18.72 cm and 197.32 cm, with the maximum in July and the minimum in January (influenced by monsoons), presenting strong seasonality and significant inter-annual changes. Relative humidity ranges between 75.98% and 81.66%, and wind velocity ranges between 0.9 m/s and 1.24 m/s without a clear seasonal pattern [37]. The average annual frost-free period is 268 days, accounting for 73% of the total days in the year.

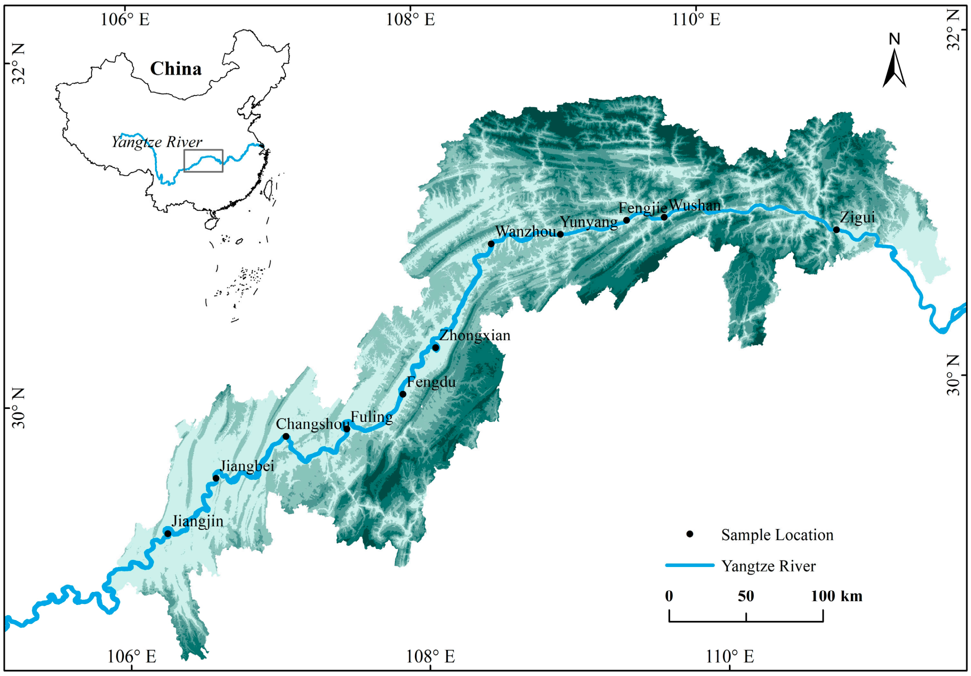

Figure 1. Location of the study site.

2.2. Vegetation Investigation

Twelve sites in the TGR ranging from Jiangjin (Chongqing) to Zigui (Hubei) were chosen to include a wide range of hydrologic and geomorphic conditions and vegetation types. At each site, three transects (145–155 m, 155–165 m, and 165–175 m for the sites from Changshou to Zigui and 155–165 m, 165–175 m, and 175–185 m for Jiangjin and Jiangbei) were delineated along an elevation gradient from the river to the band. Three quadrats measuring 1 m×1 m were established in each transect. The elevation of each quadrat was determined by applying their GPS positions to digital elevation maps using ArcGIS software 10.5 (ESRI Inc., Redlands, CA, USA). Detailed observation and sampling were conducted in three different seasons of 2019 based on the period when the riparian zone emerged from the flood (April, the early period; July, the middle period; and September, the end period). All plant species in the quadrats were identified at each quadrat. The number and coverage of each plant species were recorded. The plant species richness and plant species abundance were estimated. To avoid bias, the same botanist performed all of these vegetation assessments during the project. The site's topography, soil type, and ground cover were recorded along with these vegetation assessments.

Herbaceous plants, including *Cynodon dactylon*, *Cyperus rotundus*, *Echinochloa crusgalli*, *Bidens pilosa*, *Setaria viridis*, *Xanthium strumarium*, etc., are the dominant plants in the Three Gorges Reservoir riparian zone. Only a few arborvitae seedlings were found in the upper part of the riparian zone. They were not counted due to the predictably short period of their emergence. Functional traits such as dispersal type, growth form, life cycle, shoot height, and flowering phenology [38] (Table S2), which are considered to determine a plant's role in ecosystems and associated ecosystem services [39], were selected. The analyzed plant species' life forms and functional traits were recorded from the "Flora of China" (http://www.iplant.cn/, accessed on 7 September 2022).

2.3. Inundation Characteristics

The water levels of the TGR varied as a result of anti-seasonal impoundment (the water level was highest (175 m) in the winter and lowest (145 m) in the summer), thus producing a Water Level Fluctuation Zone (WLFZ) of approximately 350 km^2 between the minimum and maximum water level lines. Located at the end part of the reservoir, the water levels of Jiangjin and Jiangbei range from 160 m to 190 m. The water level in front of the TGD is based on the Wusong Elevation System. The water level at the closest hydrological station to the study sites was used as the site's river water level (Table S1). The flooding times were calculated using the total number of flooded days in one year (i.e., 365 days, ranging from the investigated date to the same date of the last year). The average flooding depth was defined as the average inundation depth in meters, which was averaged over the different inundation events within a year (from the investigated day to the same day of the previous year).

2.4. Data Analysis

Species richness, total coverage, and Shannon–Wiener Index H were used to analyze the plant community. Species richness is the number of different plant species recorded in the quadrats. Total coverage is the sum of the species coverage, which is the percentage of the quadrat area that is covered by one species. The Shannon–Wiener Index is a measure of the diversity of species in a community. The higher the value of H, the greater the species diversity in a given community. This index is calculated as follows:

$$\mathrm{H} = -\sum p_i * ln p_i \tag{1}$$

where H is the Shannon–Wiener diversity Index, and p_i is the relative proportion of individuals belonging to one of the species found. The lower the value of H, the lower the diversity. A value of H = 0 indicates a community with only one species.

The Rao's quadratic diversity index Q [40,41] accounts for the trait differences between species pairs. This index is defined as the expected dissimilarity between two individuals of a given species assemblage selected at random with replacement. The dissimilarity ranges from 0 to 1 and is based on specified functional traits or phylogenetic dissimilarity:

$$\mathrm{Q} = \sum_{ij}^{S} d_{ij} p_i p_j \tag{2}$$

where p_j is the relative abundance of species j (j = 1,2,. . .,S), while d_{ij} is the dissimilarity between species i and j ($d_{ij} \geq 0$, $d_{ii} = 0$).

The relationship between plant species richness and functional diversity was tested using three models [42], namely, linear, exponential, and sigmoid logistic models, to understand the consequences of disturbing the functioning of a given ecosystem. Model selection was performed according to Akaike's Information Criterion (AIC). The overall responses to flooding duration and flooding depth for riparian plant species richness and total coverage were examined via regression analysis and by using a set of linear models. Regression coefficients describe the relationship between a predictor variable and a response. In linear regression, coefficients are values that multiply the predictor values.

The data were analyzed using SPSS for Windows, Version 12 (SPSS. Inc., Chicago, IL, USA). Raw data of all the variables were checked for normal distribution rates using the one-sample Kolmogorov–Smirnov test as well as for homogeneity of the variances using Levene's test. A *t*-test and Analysis Of Variance (ANOVA) followed by Tukey's post hoc tests were used to compare the means between the different seasons. Pearson's correlation test was used to determine the associations between variables. Data were analyzed using R 4.1.2 (The R Foundation for Statistical Computing, Vienna, Austria), with statistical significance determined at $\alpha = 0.05$.

3. Results

The riparian plant community varied with the seasons (Figure 2). The diversity index was lowest in April and highest in September. Species richness in July and September was significantly higher than that in April. The lowest Shannon–Wiener Index value was observed in April, and it was significantly lower than that in September. The functional diversity was highest in September, and July had a significantly higher index than April. The total coverage in April was significantly lower than that in July and September. The plant communities presented the lowest species richness and total coverage in April; diversity and the functional diversity were also lower in this month.

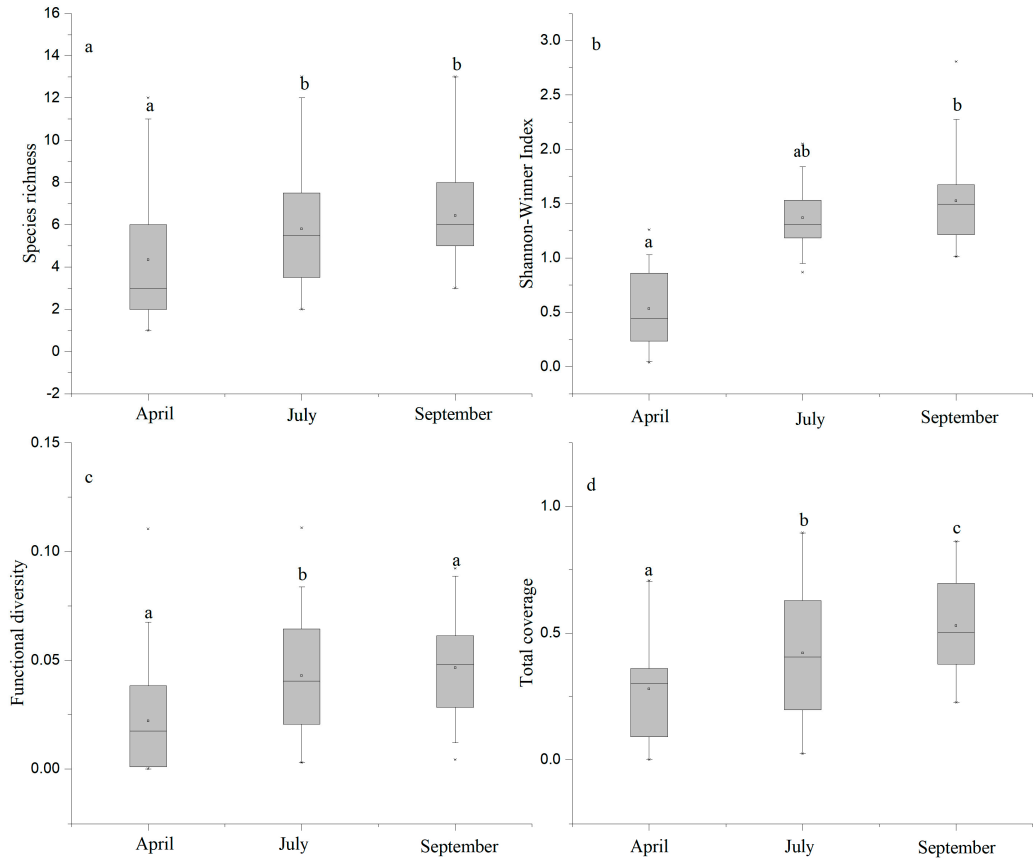

Figure 2. Species richness (**a**), Shannon Winner Index (**b**), Functional diversity (**c**) and total coverage (**d**) of riparian plants in different seasons (bars with different letters indicate statistically significant differences, bars with the same letters indicate differences that are not significant, and bars with “ab” indicate that there are no significant differences from the bars of both a and b ($p \leq 0.05$)).

The test showed a sigmoidal relationship between plant species richness and functional diversity in April, while a linear relationship was shown in July and September (Figure 3). The sigmoidal relationship in April showed a functional redundancy at low levels of species richness, followed by a rapid increase at intermediate levels until functional diversity reached an asymptote at a relatively high level. This linear relationship indicated that functional diversity increased as the species richness increased with a relatively steady functional redundancy.

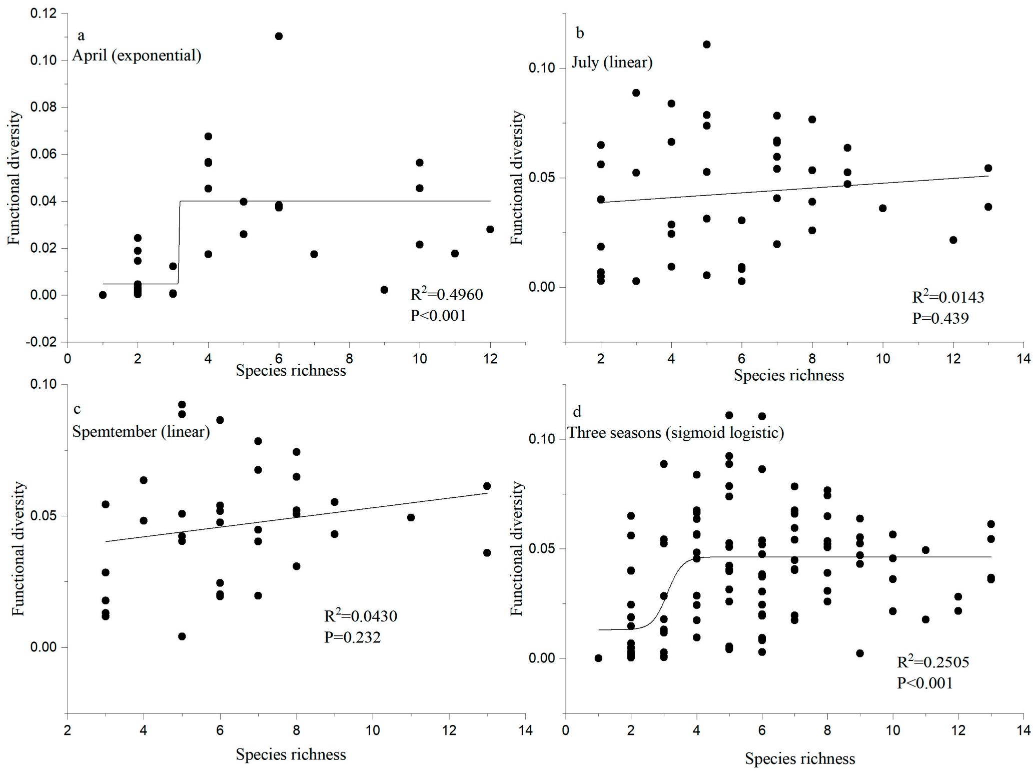

Figure 3. Relationship between species richness and functional diversity in different seasons ((**a**)—April, (**b**)—July, (**c**)—September, (**d**)—three seasons).

A significant negative relationship between the plant community and inundation characteristics was observed, as revealed via linear regression (Figure 4). Species richness and the total coverage of riparian plants decreased with increasing flooding days and depth. Aside from July, the correlation coefficient was higher between species richness and flooding time than total coverage. The total coverage of April was more correlated, i.e., had a higher correlation coefficient, with flooding depth than species richness. Flooding depth had a higher correlation coefficient in relation to plant communities than flooding duration, except for species richness in April and total coverage in July. The correlation coefficient was highest between flooding depth and species richness in April (R^2 = 0.4636, $p < 0.001$) and lowest between flooding duration and total coverage in September (R^2 = 0.1128, $p < 0.05$).

The relationship between the Shannon–Wiener Index and inundation characteristics revealed that the Shannon–Wiener Index decreased with increasing inundation characteristics (Figure 5). Flooding times in April had the highest correlation coefficient in relation to the Shannon–Wiener Index, while the lowest was in July. The correlation coefficient for the relationship between flooding time and the Shannon–Wiener Index in three seasons was higher than that in July and September but lower than that in April. Flooding depth showed a similar trend with respect to flooding time. The correlation coefficient for the relationship between flooding depth and the Shannon—Wiener Index was higher in September (R^2 = 0.2036, $p < 0.05$) and three seasons (R^2 = 0.2075, $p < 0.001$).

A regression model comparing flooding time and flooding depth with species richness and total coverage of riparian plants was developed to determine the significance of inundation character with respect to riparian plants' diversity. The regression model showed that flooding depth explained a more significant proportion of the overall variation in the riparian plant community than that of flooding duration in July and September (Table 1). It can be noticed that the flooding depth in July had the highest significant coefficient value ($p < 0.05$) in relation to explaining the species richness and total coverage of riparian plants, while the flooding time in July had the lowest value in this regard. Aside from flooding depth in April, Negative coefficient values were observed for inundation character in three months.

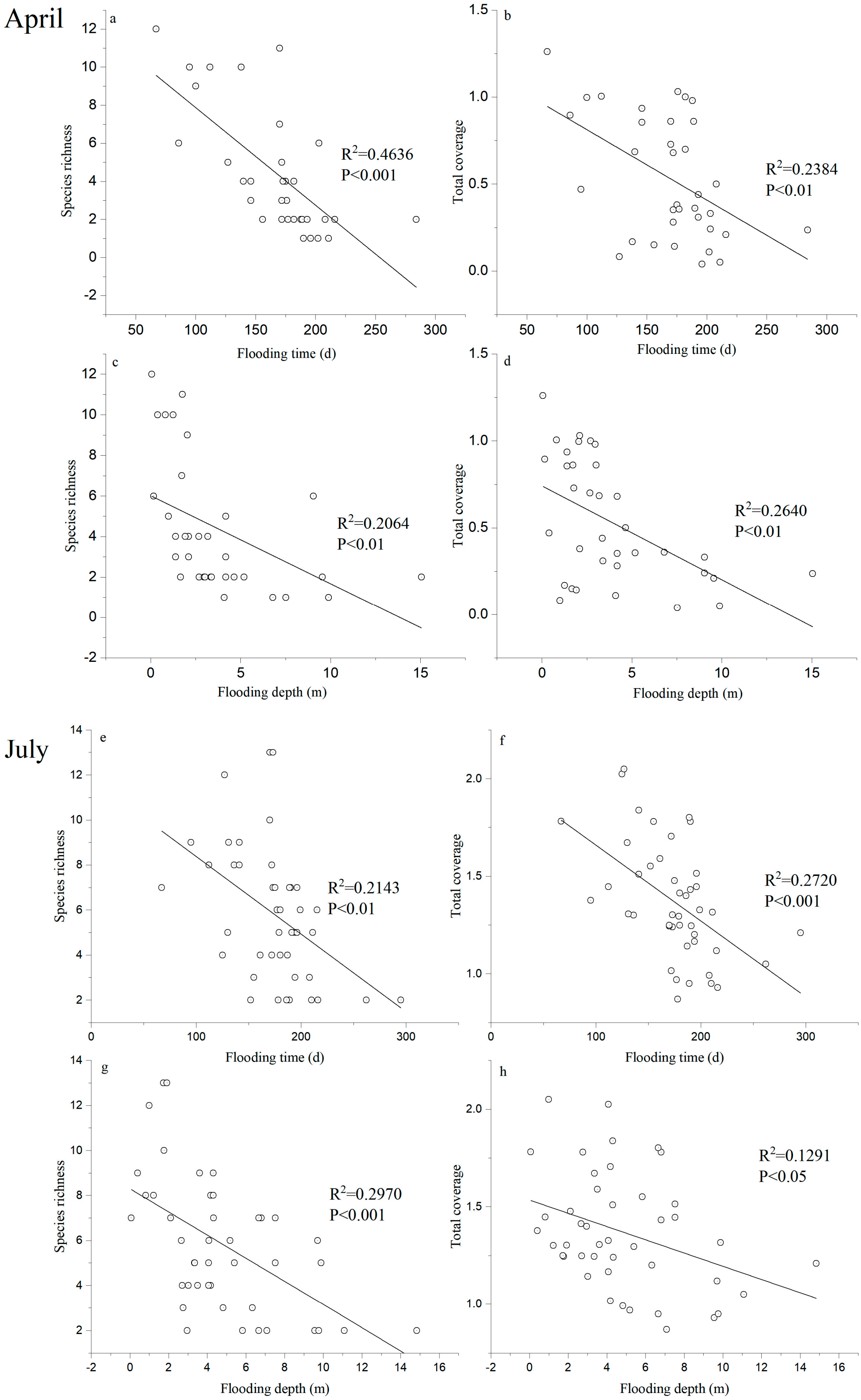

Figure 4. *Cont.*

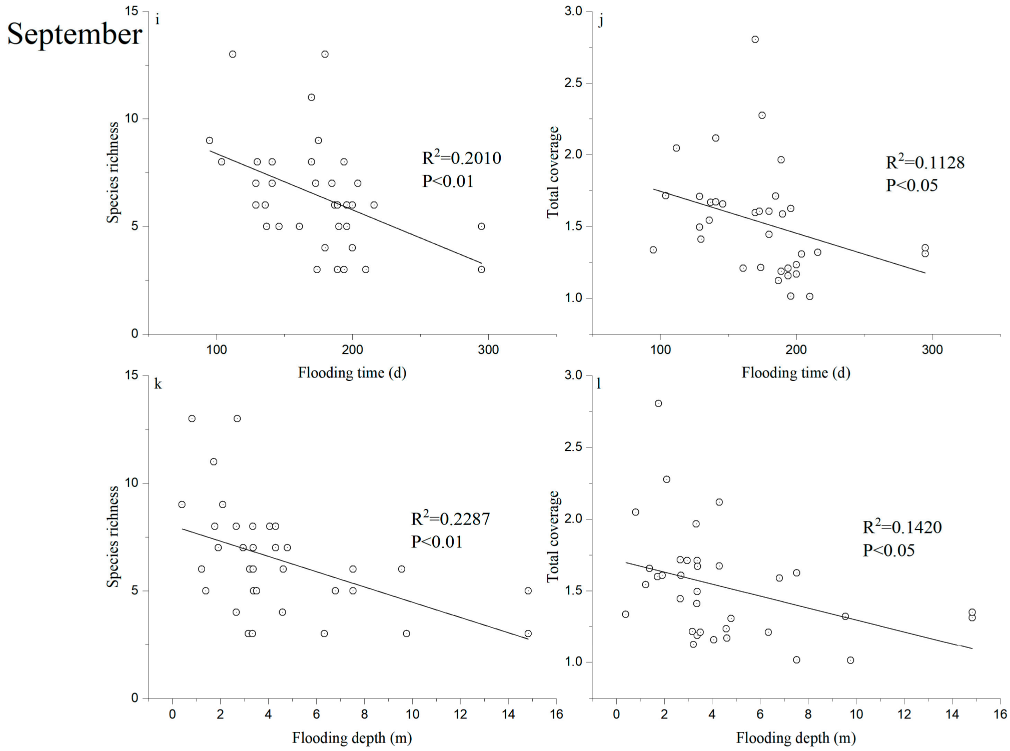

Figure 4. Species richness (**a**,**c**,**e**,**g**,**i**,**k**) and total coverage (**b**,**d**,**f**,**h**,**j**,**l**) versus inundation characteristics in different seasons.

Table 1. Regression coefficient of inundation character for riparian plants in different seasons.

		Estimate	Std. Error	*p*-Value
April	Intercept	15.587	2.202	$p < 0.001$
	flooding time	−0.068	0.016	0.000206 ***
	flooding depth	0.201	0.206	0.336
	regression equation	$Y = 15.587 - 0.068X_1 + 0.201X_2$, $p < 0.001$		
July	Intercept	11.064	2.222	$p < 0.001$
	flooding time	−0.010	0.017	0.560
	flooding depth	−0.447	0.213	0.042 *
	regression equation	$Y = 11.064 - 0.\ 010X_1 - 0.447X_2$, $p < 0.001$		
September	Intercept	11.080	2.246	$p < 0.001$
	flooding time	−0.011	0.017	0.531
	flooding depth	−0.286	0.213	0.189
	regression equation	$Y = 11.080 - 0.011X_1 - 0.286X_2$, $p < 0.001$		

Notes: *** $p < 0.001$ and * $p < 0.05$.

Here, Y, denoting riparian plants, includes species richness and total coverage; X_1 denotes flooding time; and X_2 denotes flooding depth.

Std. Error is the standard error of the estimate, calculated as $S/\sqrt{n}$, where S is the sample standard deviation and n is the sample size.

A *p*-value is a standard notation used to denote probability. If the *p*-value is less than a certain significance level (e.g., $\alpha = 0.05$), then the predictor variable is said to have a statistically significant relationship with the response variable in the model.

The flooding times were calculated according to the total number of flooded days in one year (constituting the 365 days ranging from the investigated date to the same date of the previous year). Flooding depth was defined as the average inundation depth in meters, which was averaged over the different inundation events within a year (ranging from the investigated day to the same day in the previous year). The flooding time and depth were analyzed using R after a normality test.

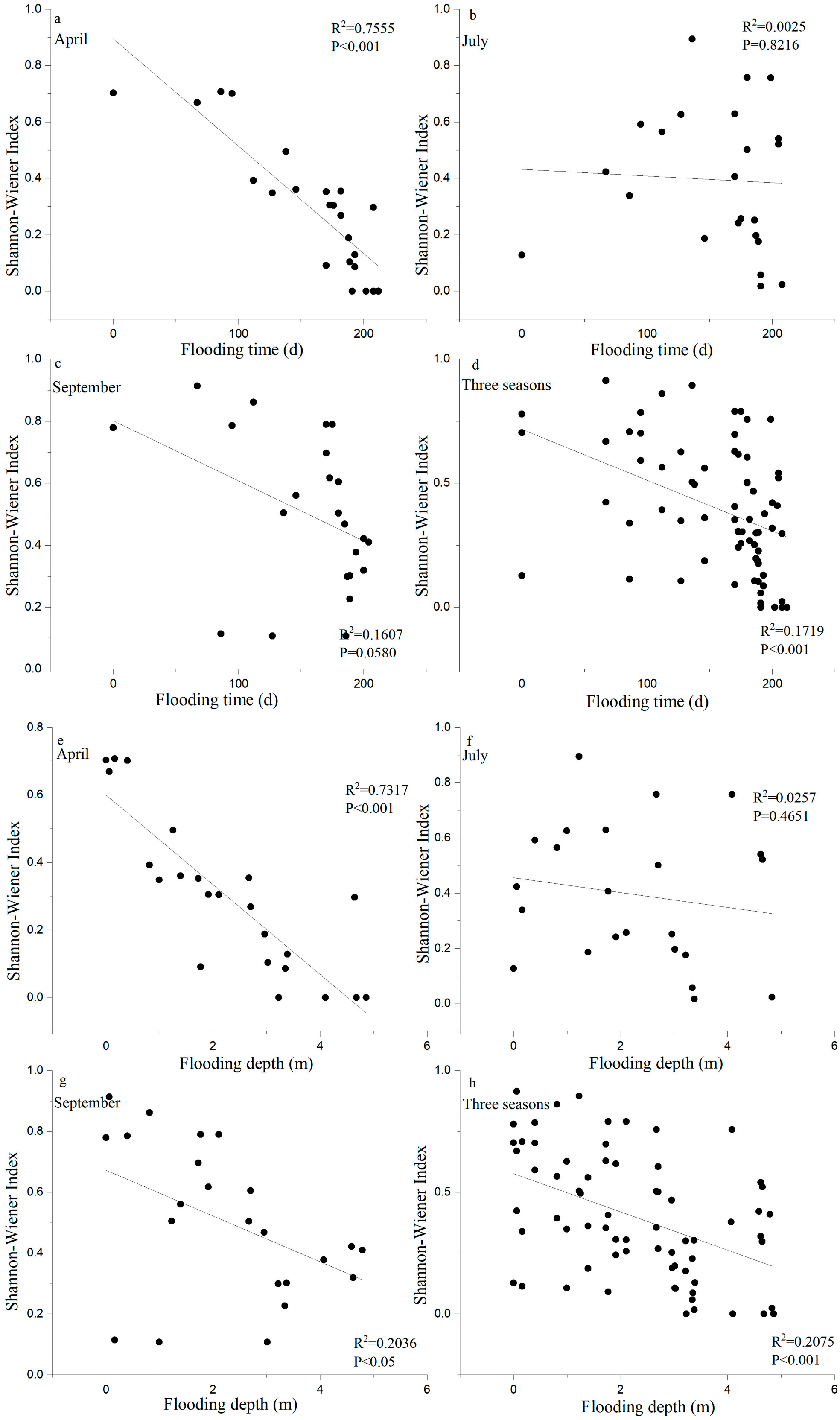

Figure 5. Shannon–Wiener Index versus inundation characteristics in different seasons ((**a**,**e**)—April, (**b**,**f**)—July, (**c**,**g**)—September,(**d**,**h**)—three seasons).

4. Discussion

Hydrological regimes are considered the main factor in determining the assembly of riparian plant communities [43,44]. When flow regulation alters flow regimes, biotic and abiotic pathways are triggered. As a result of flow regulation, riparian vegetation in the TGR area has changed in terms of its species composition, biomass, height, cover, and diversity [14]. Different vegetation types have various adaptive capacities with respect to water level fluctuations, and in general, perennial herbaceous plants are more tolerant of anti-seasonal inundation than trees [45]. The response of riparian vegetation also depends on the magnitude, frequency, and duration of water level fluctuations [46].

4.1. Plant Community Varied throughout the Seasons in the Riparian Zone

The analyzed riparian zone is subject to unnaturally prolonged flooding of up to 30 m caused by the Three Gorges Dam on submerging days. Hydrological regimes significantly impact riparian plants [21] in terms of five key flow characteristics, namely, timing, duration, frequency, rate of change, and magnitude, particularly regarding seasonal changes in flow and alternating wet and dry conditions. The length of a growing season is influenced by flow inundation characteristics, which determine the amount of exposed land during the summer or when plants can grow and reproduce. The climatic seasonal differences of a riparian zone can also affect plant growth and survival, leading to changes in species in the riparian zone. The analyzed riparian zone is drier in April, which can decrease the number of plant species that can survive in the area. The riparian zone may become wetter in July, which can increase the number of plant species that can survive in the area. The changes in plant species can have a significant impact on the ecosystem of a riparian zone and its surrounding areas. These factors can vary significantly within and between years, further increasing the disturbance of riparian ecosystems.

Flooding and water level fluctuations cause landscape disturbances that create a variety of habitats with different plant adaptations. In the emerging period of the growing season, the riparian zone is affected by dam regulation and natural seasonal flooding. The lower riparian zone is faced with a vigorous flooding intensity with a long duration, while the upper zone is faced with a relatively weaker intensity. Significant differences were observed in the riparian plant communities throughout the seasons. The highest index of plant community diversity was found in September; the most significant variation was observed in April, and the smallest variation was in July. The variability of this index shows that the variation coefficients in April were all greater than those of the other seasons. The plants' responses to the inundation varied because of their growth and survival sensitivity to timing and duration [47,48]. When emerging from inundation, few plants adapted to the flooding tended to appear in April, leading to low species richness and functional diversity. As the emerging time increased, more plant species appeared, and the diversity and functional diversity increased. The difference in the timing and duration of inundation made a difference in the riparian plant community.

4.2. Different Plant Community Constructions in Different Seasons of the Riparian Zone

Functional diversity was found to be sigmoidal related to species richness in April, while it was linear in July and September. Coupling flooding depth with duration, different construction processes were identified in the riparian zone. Submerged from the months of flooding, the severe stress caused by habitat change led to a subset of species having a limited number of shared functional traits of riparian plants in April. A relatively high turnover rate, a low recovery rate, and low stabilization to changes in taxonomic diversity were observed in the riparian plant community in April. Unique functions were added, with species added at a higher diversity level. This two-phase functional redundancy indicates a contrasting state caused by disturbance-resistant traits [42] appearing in April. Affected by the extremely long-term flooding, the lower riparian zone was relatively harsher for the plants than the higher riparian zone.

As the emerging time increased, more plant species with relatively unique traits entered this area, resulting in a positive linear relationship between species and functional diversity in July and September. This relationship indicates that low functional redundancy and changes in species diversity will lead to changes in functional diversity [42,49]. Located on the hillside of the reservoir side, this riparian zone tends to experience a period of drought during the exposure period. This can lead to a decrease in the number of plant species that can survive in the area. These changes in plant species can have a significant impact on the ecosystem of a riparian zone and its surrounding areas. However, it is essential to note that riparian vegetation is unique to riparian zones, and its success depends on planting at the proper elevations and seasons. The characteristics of riparian vegetation vary substantially and correspond to geographic variations in climate, hydrologic regimes, and associated geomorphology. The interval of flooding from July to September immersed this zone in a period of alternating flooding and drought. Species with unique traits were more adapted to the riparian habitat, but few differences among species resulted in low functional redundancy.

4.3. Flooding Depth: A Better Indicator for the Zonation of the Riparian Vegetation

Flooding and fluctuating water availability strongly constrain riparian plant ecological strategies, and the relationship between the two may be generalizable to diverse biomes. Human activities, such as dam construction and management for hydropower and water storage and diversion, have severely modified the natural flow regimes in many river systems. In particular, flow regimes are expected to shift under even the most conservative of climate change scenarios [50]. Extreme floods cause significant geomorphic [51] and chemical changes along the water depth gradient [28]. This changing pattern varies with flooding depth, resulting in a variety of plants in a riparian zone.

Due to the dam's regulation, the riparian plants in the Three Gorges Reservoir experienced extreme flooding, which lasted more than half a year and had a depth of 30 m. Research has shown that even slight modifications to the historic natural flow regime have significant consequences for the structure of riparian plant networks [5]. Flooding time is often used as a simple indicator of a riparian plant's water stress. However, in this study, flooding time alone did not capture the full extent of the stress, as it did not account for the depth of the water that covered the plant. When the water level rose, the plants were submerged deeper, which significantly impacted the soil properties and physiology and limited the plants' growth and survival in the flooded environment. The flooding depth contained a message: the depth to which a riparian plant submerges can affect the character of the soil and restrict plant growth.

Research has also shown that the inundation depth and frequency primarily determine riparian plant species composition [27]. A significant negative relationship between plants and flooding depth was observed in our study, while flooding duration was not retained as a significant predictor. Compared to flooding time, flooding depth presented a more proper reflection of the riparian stress experienced by the plants. The greater correlation between the flooding depth and community structure compared to that of duration suggests the better adaptability of management and restoration based on flooding depth rather than duration in environment-changing circumstances. In our study, the seasonal data showed that flooding depth could be a powerful indicator of plant zonation in the riparian zone.

5. Conclusions

River regulation, which involves managing and controlling water flowing through dams, can positively and negatively impact riparian plant communities. Riparian plants are important influencers of the flow regime of a river reservoir and are sensitive indicators of changes in the hydrological environment. Hydrological changes affect the distribution patterns, growth patterns, reproduction modes, and survival strategies of plants in riparian zones. In our study, the depth and duration of floods were analyzed in comparison with the riparian plant community's species richness and total coverage. The higher correlation between flooding depth and the riparian plant community compared to that of flooding duration suggests that flooding depth is a better indicator of the zonation of riparian vegetation affected by dam regulation. Our study emphasizes the importance of flooding depth as a determinant of ecological strategies in riparian plant communities. Regarding the key component of ecological flow, further opportunities to experiment with flooding depth should be offered, as these will assist in refining process-based river restoration. More work is needed on the interaction and influence of vegetation and local habitats on the flooding depth in the Three Gorges Reservoir.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15183228/s1, Table S1: Location and the hydrological station; Table S2: Plant functional traits and ecosystem processes and service. References [52–54] are cited in the Supplementary Materials.

Author Contributions: Conceptualization, X.Y.; methodology, X.Y.; software, X.Y., Y.H. and Y.J.; validation, X.Y. and M.M.; formal analysis, X.Y. and Y.H.; investigation, X.Y. and Y.J.; resources, S.W.; data curation, X.Y.; writing—original draft preparation, X.Y.; writing—review and editing, X.Y., M.M. and Q.C.; visualization, Q.C.; supervision, Q.C.; project administration, S.W.; funding acquisition, S.W. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to restrictions.

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

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