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Quantifying the Distribution and Diversity of Fish Species Along Elevational Gradients in the Weihe River Basin, Northwest China

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Abstract: In this study, species compositions, distributions, and diversity patterns of fish assemblages were investigated at 50 sampling sites in the Weihe River and its two largest tributaries, the Jinghe River and the Beiluo River, under high- and low-flow conditions in 2017. For every condition tested and in the all rivers tested, *Cyprinidae* was the richest family, containing 17 of the 39 identified fish species. *Carassius auratus* was the most common species, accounting for 11.3% of the total individuals. Nonmetric multidimensional scaling (NMDS), analysis of similarities (ANOSIM), and similarity percentage analysis (SIMPER) revealed that fish species composition differed significantly among rivers ($p < 0.05$), with dissimilar species assemblages found in the different rivers. Variation was influenced by a combined effect of habitat conditions, environmental factors, and human impact. Canonical correspondence analysis (CCA) identified variables explaining the variation in fish species ($p < 0.05$), and elevation contributed the most under both flow conditions. Alpha diversity decreased with increasing elevation within rivers as a result of changing environmental conditions, especially for wetted width. Alpha and beta diversities of rivers increased with increasing drainage area, which is related to habitat heterogeneity. The decrease in alpha diversity and the increase in beta diversity with increasing elevation can be explained by variations in habitat and geographic features.

Keywords: distribution; diversity; elevation; ecological habitats; fish species; Weihe River Basin

1. Introduction

With population growth, rapid socio-economic development, and unreasonable development and utilization of biological resources, natural aquatic ecosystems, such as rivers and lakes, have experienced challenges, including declining biodiversity and degradation of ecological service functions [1]. Water quantity and quality in a drainage basin are also affected by certain construction activities, such as dredging and channel migration, which can lead to further degradation of the river ecosystem and have a detrimental impact on biodiversity [2]. Fish communities are important indicators of the health of river ecosystems [3]. Understanding the diversity of fish species and the drivers of diversity change can help scientifically manage and protect river ecosystems [4].

Elucidation of spatial composition, distribution, and diversity patterns of species along elevational gradients at different spatial scales is essential in biogeography and ecology [5,6]. Fish diversity is an important component of biodiversity, providing fish resources that are indispensable for human survival and sustainable development [7]. The presence, absence, and distribution of fish species are influenced by interactive abiotic and biotic processes, such as geographic isolation, hydrological regimes, and competitive relationships [8]. Analysis of fish species distributions and diversity patterns in freshwater ecosystems plays a crucial role in understanding how local organisms respond to biotic and abiotic changes along ecological gradients [9,10]. Elevation is one of the most prominent ecological gradients impacting biodiversity and is considered a major factor constraining the dispersal of fish species in river systems [11–13].

Fish species composition is affected by habitat heterogeneity, environmental gradients, and human activity [14,15] at local and regional scales [16–18]. Natural river structures and varying habitat conditions can form geographic barriers that constrain the dispersal potential of fish species [19]. Since fish assemblages are sensitive to environmental changes, species distributions and diversity are affected by variation in environmental variables [8,20].

The distribution and diversity of fish species may also be affected by human interventions, because river ecosystems are intimately relevant to anthropogenic activities. Excessive human activities modify local habitats and hydrological conditions that threaten fish assemblages in riverine ecosystems [21,22]. Agricultural activities are related to nutrient and sediment loading in rivers, contributing to poor habitat conditions for aquatic organisms, especially for sensitive fish species [20]. Urbanization and industrial processes alter hydrological conditions, resulting in a deteriorated water quality that influences fish habitat heterogeneity and the diversity of fish species [23]. Anthropogenic activities generally lead to changes in the composition of fish species assemblages and the loss of fish diversity [9].

Species diversity is essential for maintaining ecosystem functions [24]. Alpha diversity is used to measure species richness within a community while beta diversity quantifies the degree of differentiation in species composition among communities [25]. Species diversity patterns vary along environmental gradients [26,27]. These patterns may vary across organisms, regions, and scales [16]. Elevational diversity patterns have been widely investigated in freshwater ecosystems for biota, including fish [6,28,29], microbes, macroinvertebrates [30], and aquatic insects [31].

Elevational alpha diversity patterns of fish species in river systems typically include monotonic decline with increasing elevation [26,29], increasing then decreasing diversity with the highest value occurring between 1700 and 2200 m [32], and decreasing diversity with a slight increase above 2000 m [28]. However, the beta diversity of fish species has received less attention, although its values vary with elevation. Beta diversity decreases and then increases from upstream to downstream [33] and gradually increases with greater elevation [26,28]. Such different diversity patterns can result from a combination of processes, including geographic isolation, species-specific dispersal limitations, habitat size, and environmental heterogeneity at different scales [5,34].

Habitat variation contributes to elevational patterns of fish distributions and diversity by modifying local conditions and hydrological regimes [28,35,36]. Large rivers that cover wide areas and complex terrain contain multiple habitats and hydrological features, resulting in variation in fish species distributions [37].

Worldwide, freshwater fish species diversity is dwindling [38]. Studies of the distributions and diversity patterns of fish species are urgent in northwest China, especially in the Weihe River Basin, which is facing environmental degradation induced by climate change and anthropogenic activities [23]. Fish species in this basin belong to the upper-midstream Yellow River aquatic ecoregion [39,40]. The Weihe River flows west to east through the Loess Plateau, Qinling Mountains, and Guanzhong Plain, covering a transitional region with substantial change in elevation. The Weihe River Basin is the most important agricultural, industrial, and economic region in northwest China. Drinking water, agricultural irrigation, and industrial water are extracted from the Weihe River [41]. However, the basin is severely affected by anthropogenic activities, especially in the downstream reaches, where the Weihe

River flows across the Guanzhong Plain, a densely inhabited area including 35 counties and 5 cities with a population of 24 million and area of 5.3×10^4 km^2. The Jinghe River and Beiluo River carry large amounts of sediment and receive effluent from nearby industrial plants [42]. Water quantity and quality in the basin are also affected by several construction activities, such as dredging and channel migration, which have led to further degradation of the river ecosystem and detrimentally impacted biodiversity [22]. The research results in this paper directly reflect the ecological process of the impact of the ecological environment on the fish community, which is of great scientific value for the management of fish resources in different geographical regions and is very important for the development and testing of community ecology theory.

Based on the hypothesis that habitats that vary in natural characteristics and human activities have different effects on fish composition, distribution, and diversity, this project investigated the composition, distribution, and altitude diversity of fish in different hydrological seasons in the Weihe River Basin under high- and low-flow conditions. First, patterns of fish species composition and distribution were described. Second, alpha and beta diversity were measured in each river at both high- and low-flow conditions. Fish species composition was analyzed in three rivers to examine whether there were significant differences across rivers in the two conditions. Two sets of environmental variables that affect species changes were explored under two hydrological conditions by forward selection. Third, relationships between fish species and environmental variables were determined by CCA analysis (Canonical Correlation Analysis). Finally, we analyzed variation in alpha and beta diversity along elevational gradients analyzed at the river scale and at the elevation class scale.

2. Materials and Methods

2.1. Study Area

The Weihe River is one of the largest tributaries of the Yellow River and the most important river in northwest China (Figure 1). Having an overall length of approximately 818 km, it originates from the Niaoshu Mountains and flows eastward into the Yellow River [43]. The Weihe River Basin (104°00′ E–110°20′ E, 33°50′ N–37°18′ N) has a drainage area of approximately 1.34×10^5 km^2 and its elevation range spans from 320 to 3600 m. The basin is located in a semi-humid area with a warm temperate continental monsoon climate. The average annual temperature is 13.3 °C and the average annual rainfall ranges from 558 to 750 mm. Approximately 60% of the annual precipitation falls between May and September [44]. The northern tributaries of the Weihe River originate from the Loess Plateau, having large sediment loads compared to the southern tributaries from the Qinling Mountains. The three major rivers are the Weihe River, Jinghe River, and Beiluo River. The Jinghe River is the largest northern tributary, with a total length of 455 km and a drainage area of 4.54×10^4 km^2 [45]. The Beiluo River is the longest and second largest northern tributary, with a length of 680.3 km and a total area of 2.69×10^4 km^2.

2.2. Fish Sampling

Fish sampling was conducted at low- and high-flow conditions in May and September 2017, respectively. The 50 sampling sites were chosen at elevations ranging from 335 to 2266 m in the basin. A total of 19, 19, and 12 sites were selected in the Weihe River, Jinghe River, and Beiluo River, respectively (Figure 1). The sampling sites were chosen below the confluences of the main channels and tributaries in the three rivers. The sampling point W2 was located 100 m downstream of the dam. To identify the relationship between elevation and fish diversity, all sampling sites were divided into four elevation classes at 500 m intervals. The elevation classes included low elevations (below 500 m, 13 sites), middle elevations (between 500 and 1000 m, 16 sites; between 1000 and 1500 m, 15 sites), and high elevations (above 1500 m, 6 sites).

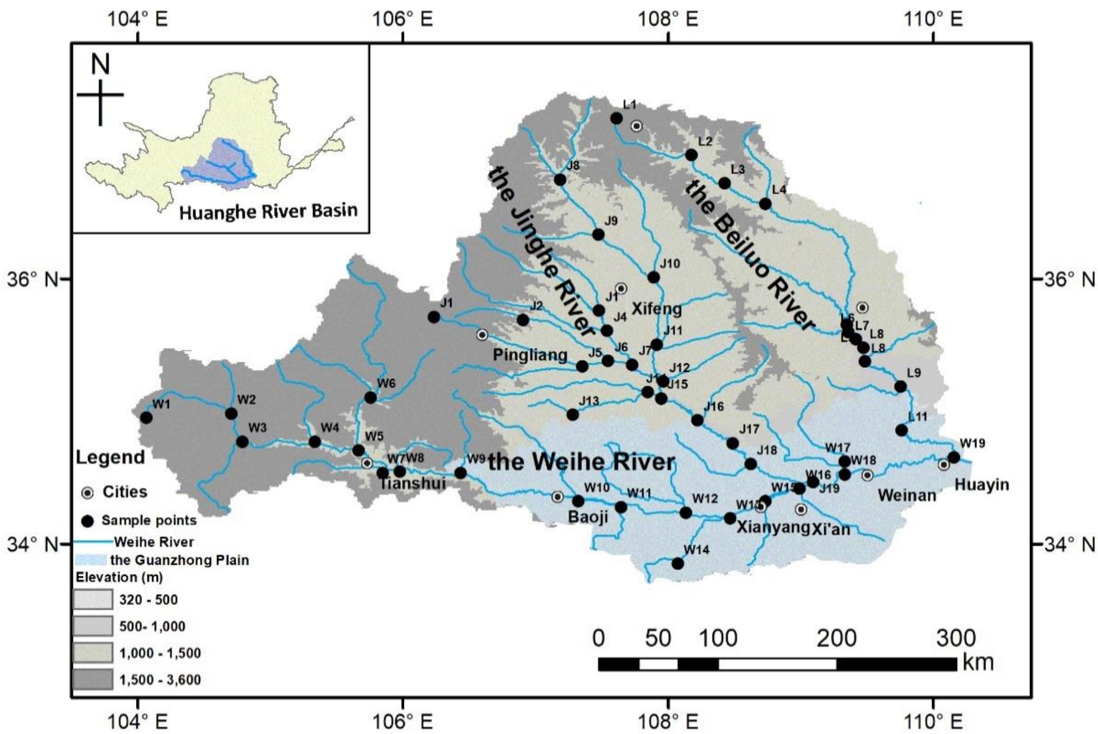

Figure 1. Map of the Weihe River Basin and location of 50 sampling sites.

Fish species were captured using a backpack electrofishing unit (China, 12 V, 60 A, DC.). At each site, a stretch of 100 m of the river including all available microhabitats (pools, riffles, and runs) was sampled for fishes. Fish collections were carried out by the same two researchers at all sites using identical sampling efforts. In the areas where water depths exceeded 1.5 m, a 10 m seine net with a drop of 1.5 m and mesh size of 30 mm was used. Fish sampling was conducted in an upstream direction, and the collection time was limited to within 30 min. In the field, fish species were identified according to the fishes of the Yellow River [46]. After identification and counting, live fishes were released to the river. Fish that were not identified to the species level were euthanized with eugenol and fixed in 10% formalin (Sino pharm Chemical Reagent Co., Ltd) for identification in the laboratory.

2.3. Environmental Variables

In total, 17 environmental variables were measured at each sampling site. The latitude, longitude, and elevation (m) of each site were determined by GPS (GM 101). Aquatic physiochemical variables, including water temperature (°C), pH, electric conductivity (μs/cm), dissolved oxygen (mg/L), oxidation-reduction potential (mV), and total dissolved solids (mg/L), were measured using a portable water quality analyzer (HACH HQ40d) before fish sampling. The water transparency (m) was measured using a Secchi disk (Beijing Purity Instrument Co., Ltd). Hydrological variables included the width, depth, water velocity, and flow. The wetted width (m) and depth (m) of the river were determined using a laser distance meter (AK600H) and tape measure, respectively. The water velocity (m/s) was measured at each site with a portable velocity meter (MGG/KL-DCB). In addition, the river flow (m^3/s) was calculated using the wetted-area-velocity method [47]. In the field, the variables were measured three times, recorded, and then averaged per visit for the analyses. Water samples were collected in polyethylene bottles at each site for analyses of the dissolved nutrients, including total nitrogen (TN, mg/L), total phosphate (TP, mg/L), ammonia nitrogen (NH_4-N, mg/L), nitrate nitrogen (NO_3-N, mg/L), and nitrite nitrogen (NO_2-N, mg/L), and analyzed in the laboratory with an Auto Discrete Analyzer (Clever Chem 200).

2.4. Data Analysis

A total of 49 sites were used for the analyses. One site in the Weihe River was not included because no fish were collected, potentially due to eutrophication (TP content higher than 0.02 mg/L). All analyses were performed for both the high-flow condition and low-flow condition. Fish diversity was assessed at two spatial scales: River (within the three rivers) and elevation class (in each class across rivers). The diversity of fish species was measured with alpha diversity and beta diversity.

Species richness, the number of fish species at each site, was considered to be alpha diversity [48] and was calculated for each site, within each river class and elevation class. Beta diversity was determined as the change in species composition and indicated the dissimilarity among rivers and classes [49]. Binary presence-absence data were used to calculate multiple-site beta diversity with the function "beta. multi" from the package "betapart" in R software, version 3.2.2 [50]. Multiple-site beta diversity was used to estimate compositional differentiation by the Sorensen dissimilarity index among all sites within each river and elevation class [49,51]. Introduced species were excluded from the beta diversity calculation to eliminate the influence of non-native fish species. Beta diversity values ranged from 0 to 1, representing strong to weak similarity in species composition. The Kruskal–Wallis test was used to examine the differences in fish diversity among river classes and among elevation classes [52].

Fish species composition was compared among rivers using nonmetric multidimensional scaling (NMDS) and analysis of similarities (ANOSIM) [53]. Similarity percentage analysis (SIMPER) was used to identify the contribution of fish species to the average dissimilarity between rivers [54]. SIMPER was also used to determine the contribution to similarity within each river. Fish abundance data from both high- and low-flow conditions were log (x + 1) transformed and then analyzed with the PRIMER 5.0 package [53].

To investigate the relationship between environmental variables and variation in fish species composition, canonical correspondence analysis (CCA) was applied to the species abundance data [55]. In a CCA biplot, the importance of environmental variables to fish species is described by the length of the arrows. The length of the environmental vector indicates the strength of correlation, and its direction indicates its relationship with the species. Fish species plotted in the same direction from the origin as an environmental vector are positively correlated with the variable, and a species plotted in the opposite direction indicates a negative relationship [23]. Fish abundance data and environmental variables (except pH) were log (x + 1) transformed. The introduced species were excluded from the CCA. The minimal number of explanatory variables to be included in the CCA, explaining statistically significant ($p \leq 0.05$) proportions of variation in the fish assemblage data, were identified using the forward-selection option of CCA, which is analogous to the forward-selection process used in stepwise multiple regression [56,57]. A Monte Carlo test with 499 permutations was used to determine whether the variables significantly ($p < 0.05$) explained the variation in fish species composition [58].

3. Results

3.1. Overall Fish Species Composition in the Weihe River Basin

A total of 3521 individual fish were collected from 49 sampling sites in the Weihe River Basin at high-flow and low-flow conditions (by hydrological season). In high-flow conditions, collected fish belonged to 34 species, 22 genera, 10 families, and 4 orders, whereas 32 species, 23 genera, 9 families, and 3 orders were collected under low-flow conditions (Figure 2). The overall captured fish species included 39 species from 26 genera, 10 families, and 4 orders (Table 1). In total, 32, 29, and 23 species were captured from the Weihe River, the Jinghe River, and the Beiluo River, respectively. Moreover, the numbers of fish species found in the four elevation classes were 27, 29, 24, and 16. Among all 39 species, *Misgurnus anguillicaudatus*, *Cyprinus carpio*, and *Oreochromis mossambicus* were introduced species. The criterion for designating a species as introduced was based on the length of time they had appeared locally [59,60].

Table 1. List of the fish species captured in the Weihe River Basin.

Order	Family	Genus	Species	* Code
Cypriniformes	Cobitidae	*Cobitis*	*Cobitis sinensis*	S1
		Misgurnus	*Misgurnus anguillicaudatus*	S2
			Misgurnus mohoity	S3
		Paramisgurnus	*Paramisgurnus dabryanus*	S4
	Cyprinidae	*Abbottina*	*Abbottina rivularis*	S5
		Acanthorhodeus	*Acanthorhodeus macropterus*	S6
		Carassius	*Carassius auratus*	S7
		Chanodichthys	*Chanodichthys erythropterus*	S8
		Ctenopharyngodon	*Ctenopharyngodon idellus*	S9
		Cyprinus	*Cyprinus carpio*	S10
		Gnathopogon	*Gnathopogon imberbis*	S11
		Gobio	*Gobio coriparoides*	S12
			Gobio rivuloides	S13
		Hemiculter	*Hemiculter leucisculus*	S14
			Hemiculter lucidus	S15
		Opsariichthys	*Opsariichthys bidens*	S16
		Pseudorasbora	*Pseudorasbora parva*	S17
		Rhynchocypris	*Rhynchocypris lagowskii*	S18
		Rhodeus	*Rhodeus lighti*	S19
			Rhodeus sinensis	S20
		Squaliobarbus	*Squaliobarbus curriculus*	S21
	Nemacheilidae	*Triplophysa*	*Trilophysa bleekeri*	S22
			Triplophysa brachyptera	S23
			Triplophysa dalaica	S24
			Triplophysa kungessana	S25
			Triplophysa pappenheimi	S26
			Triplophysa robusta	S27
			Triplophysa sellaefer	S28
			Triplophysa stoliczkai	S29
Perciformes	Channidae	*Channa*	*Channa argus*	S30
	Cichlidae	*Oreochromis*	*Oreochromis mossambicus*	S31
	Gobiidae	*Favonigobius*	*Favonigobius gymnauchen*	S32
		Rhinogobius	*Rhinogobius brunneus*	S33
			Rhinogobius cliffordpopei	S34
			Rhinogobius giurinus	S35
	Odontobutidae	*Micropercops*	*Micropercops swinhonis*	S36
Salmoniformes	Salmonidae	*Brachymystax*	*Brachymystax lenok*	S37
Siluriformes	Bagridae	*Tachysurus*	*Tachysurus nitidus*	S38
	Siluridae	*Silurus*	*Silurus asotus*	S39

* S1–S39 represent fish species and the full names refer to Figure 5.

Overall, Cyprinidae was the richest family, comprising 14 genera and 17 species, and accounted for 61.9% of the total individuals, followed by Nemacheilidae and Cobitidae, which together accounted for 34.2% of the total individuals. The families Cyprinidae, Cobitidae, and Nemacheilidae together contain 29 of the 39 total species. The most widespread and abundant species was *Carassius auratus*, which was found at 31 sampling sites and accounted for 11.3% of the total individuals. The next most abundant species were *Pseudorasbora parva* and *Misgurnus anguillicaudatus*, both of which appeared at 30 sites and accounted for 6.5% and 5.2% of the total individuals, respectively. Only the three abovementioned species were present at more than 50% of the sampling sites. The species with the most individual captures was *Triplophysa dalaica*, accounting for 11.6% of the total individuals.

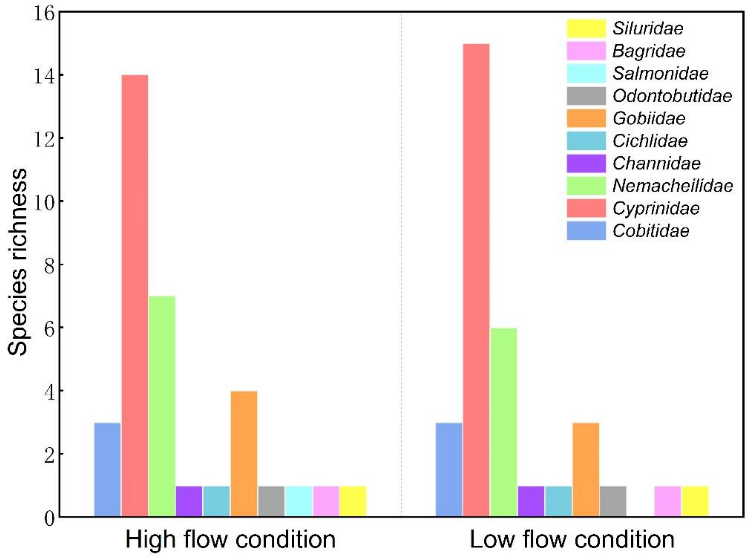

Figure 2. Summary of fish species composition and richness in the Weihe River Basin in high-flow conditions and low-flow conditions.

3.2. Patterns of Fish Species Diversity and its Distribution

Alpha diversity (Figure 3) and beta diversity (Figure 4) varied among rivers under both high- and low-flow conditions. Under the two hydrological conditions, the alpha and beta diversity for the entire Weihe River Basin were the highest. In high-flow conditions, the alpha diversity and beta diversity were highest in the Jinghe River and lowest in the Beiluo River. Under low-flow conditions, maximum alpha diversity occurred in the Weihe River. Beta diversity showed different patterns, with the highest value in the Weihe River under both conditions.

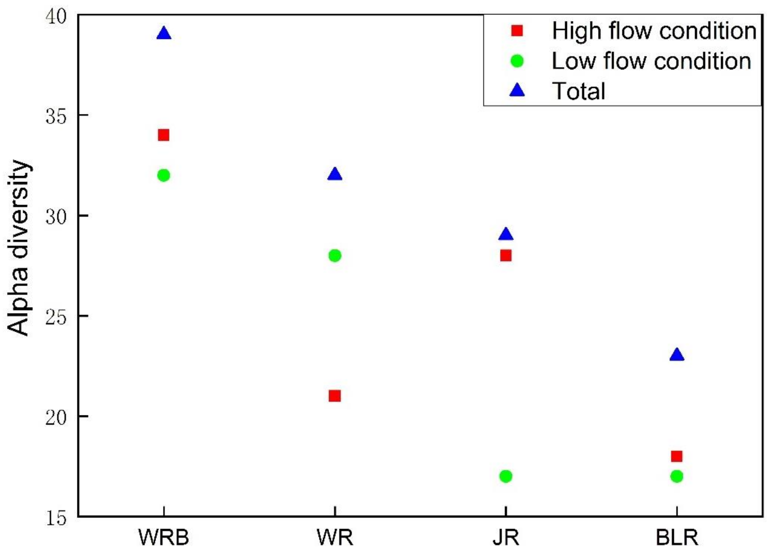

Figure 3. Fish species diversity patterns under high-flow conditions, low-flow conditions, and the combination of flow conditions: Alpha diversity in the Weihe River Basin (WRB), the Weihe River (WR), the Jinghe River (JR), and Beiluo River (BLR).

At the river scale, the total alpha and beta diversities increased with the increasing drainage area in the Weihe River Basin (Weihe River Basin >Weihe River > Jinghe River > Beiluo River). However, the highest values of alpha and beta diversity were measured in the Jinghe River under high-flow conditions. The Kruskal–Wallis test showed that the alpha diversity and beta diversity did not show significant variation ($p > 0.05$) among the three rivers under either high- or low-flow conditions.

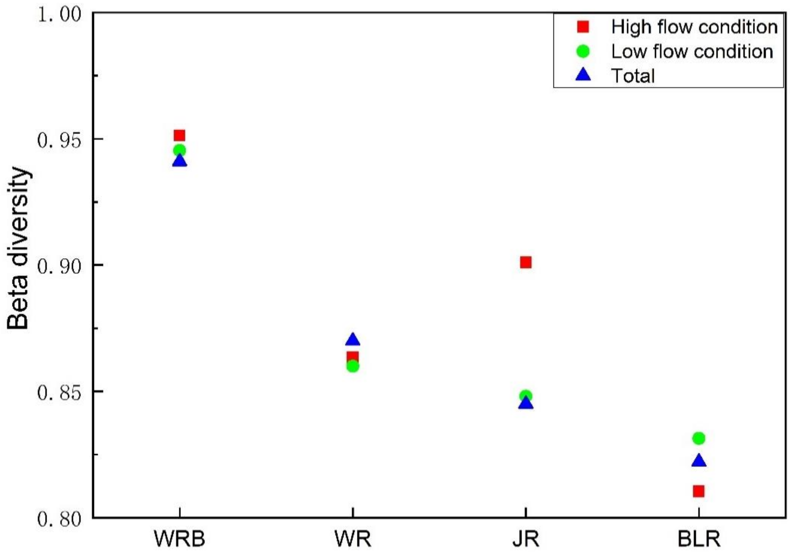

Figure 4. Fish species diversity patterns under high-flow conditions, low-flow conditions, and the combination of flow conditions: beta diversity in the Weihe River Basin (WRB), the Weihe River (WR), the Jinghe River (JR), and Beiluo River (BLR).

Fish species composition showed different patterns in the three rivers based on NMDS (Figure 5) and ANOSIM under high- and low-flow conditions. Under high-flow conditions, NMDS with a stress of 0.17 and one-way ANOSIM indicated that fish species composition significantly varied within each site across rivers (Global R = 0.142, $p = 0.001$). Significant pairwise differences in species composition were also observed among the three rivers (Table 2). Moreover, under low-flow conditions, NMDS with a stress of 0.16 and one-way ANOSIM also indicated that fish species composition significantly varied among rivers (Global R = 0.074, $p = 0.041$). Significant pairwise differences were also present, except for the Jinghe River and Beiluo River, which showed no significant difference in fish species composition ($p > 0.05$).

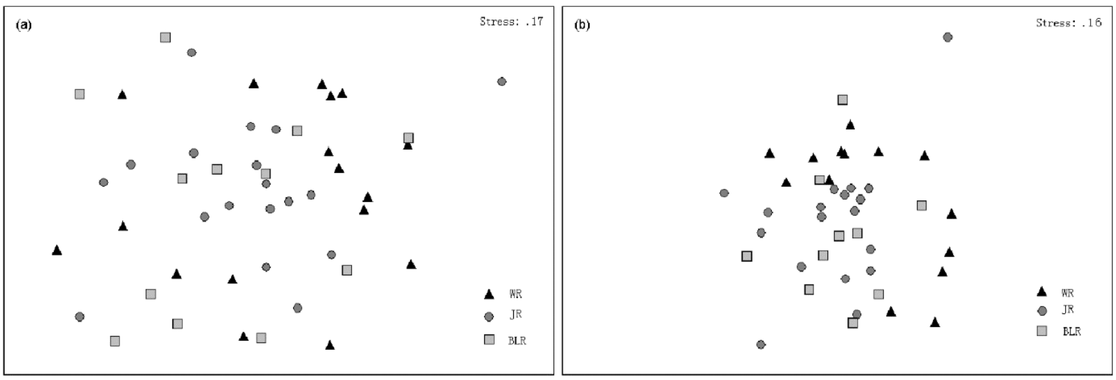

Figure 5. Ordinations of sampling sites by nonmetric multidimensional scaling (NMDS) based on the Bray–Curtis similarity matrix using fish species abundance data from three rivers under (**a**) high- and (**b**) low-flow conditions. The sites in the Weihe River (WR), Jinghe River (JR), and Beiluo River (BLR) are indicated with black triangles, dark gray circles, and light gray squares, respectively. The stresses are goodness-of-fit metrics.

SIMPER revealed that *Pseudorasbora parva* (contribution of 7.65%), *Carassius auratus* (7.53%), and *Abbottina rivularis* (7.24%) contributed the most to the dissimilarity between the Weihe River and Jinghe River under high-flow conditions. *Triplophysa brachyptera* (8.03%) contributed the most to the dissimilarity under low-flow conditions. *Pseudorasbora parva* (9.10%) and *Triplophysa brachyptera* (7.31%) exhibited the greatest contributions to the differences between the Weihe River and Beiluo

River under both high- and low-flow conditions, respectively. In the Jinghe River and Beiluo River, the most dissimilar species were *Carassius auratus* (8.71%) and *Triplophysa brachyptera* (9.78%) under high- and low-flow conditions, respectively. *Pseudorasbora parva* and *Gobio coriparoides* contributed the most to species similarity within the Weihe River under high- and low-flow conditions, respectively; *Carassius auratus* and *Abbottina rivularis* contributed the most within the Jinghe River under the two conditions; and *Triplophysa dalaica* contributed the most within the Beiluo River under both conditions.

Table 2. Global R and *p*-values of the ANOSIM analyses (analysis of similarities) for the pairwise differences in species composition among the three rivers, the Weihe River (WR), the Jinghe River (JR), and the Beiluo River (BLR) under high-flow condition and low-flow conditions.

		High-Flow Condition			**Low-Flow Condition**		
	R	**WR**	**JR**	**BLR**	**WR**	**JR**	**BLR**
WR	Global R	–	0.153	0.183	–	0.101	0.111
	p	–	0.004	0.007	–	0.020	0.046
JR	Global R	0.153	–	0.101	0.101	–	0.002
	p	0.004	–	0.05	0.020	–	0.460
BLR	Global R	0.183	0.101	–	0.111	0.002	–
	p	0.007	0.05	–	0.046	0.460	–

3.3. Relationships between Environmental Variables and Fish Species

Forward selection revealed different subsets of environmental variables under different flow conditions (Figure 6). Under high-flow conditions, forward selection in CCA selected a subset of 7 significant explanatory variables from the 17 total variables (Figure 5a). CCA indicated that the correlation between fish species and environmental variables was significant (F = 1.6, $p = 0.002$) as estimated by a Monte Carlo permutation test, with the first two axes explaining 45.2% of the variation in fish species composition. Elevation had the greatest variability, followed by wetted width, water temperature, NO_3-N, electric conductivity, TN (total nitrogen), and velocity (TN was defined as the total amount of various forms of inorganic and organic nitrogen in the water). In the CCA biplot, elevation (canonical coefficient, r = 0.89) and river wetted width (r =−0.84) exhibited the strongest correlations with axis 1 while water electric conductivity (r = 0.55) and NO_3-N (r =−0.48) were more relevant to axis 2. Under low-flow conditions, six environmental variables were selected as significant contributors (F = 1.4, $p = 0.013$) in the CCA ordination (Figure 5b). The selected variables included elevation, wetted width, water depth, velocity, pH, and NO_3-N. According to the ordination biplot, elevation (canonical coefficient, r =−0.82) and river wetted width (r =−0.81) showed the strongest correlations with axis 1 while pH (r =−0.65) and NO_3-N (r =−0.32) were more related to axis 2. Under both high- and low-flow conditions, elevation was related to fish species occurrence and tightly related to other variables. River water temperature, wetted width, and NO_3-N displayed trends opposite to that of elevation.

The CCA results revealed that some fish species, such as *Triplophysa brachyptera*, *Triplophysa dalaica*, and *Paramisgurnus dabryanus*, were positively associated with elevation and velocity and negatively associated with wetted width. The species *Hemiculter leucisculus*, *Rhodeus sinensis*, and *Silurus asotus* were positively related to water depth and width, were negatively associated with elevation, and occurred at low elevations. *Paramisgurnus dabryanus*, *Gobio coriparoides*, and *Triplophysa stoliczkai* were all positively related to TN and NO_3-N.

3.4. Alpha Diversity and Beta Diversity of Fish Species along Elevational Gradients

Although no significant differences in alpha and beta diversity have been previously identified among the rivers, alpha diversity varied with elevation within the three rivers under both high- and low-flow conditions. Overall, the mean alpha diversity exhibited a decreasing trend with increasing elevation. Regression analysis illustrated that alpha diversity had a negative relationship with elevation in the Weihe River Basin under both high- and low-flow conditions (p = 0.05), decreasing gradually from 12 to 0 (Figure A1).

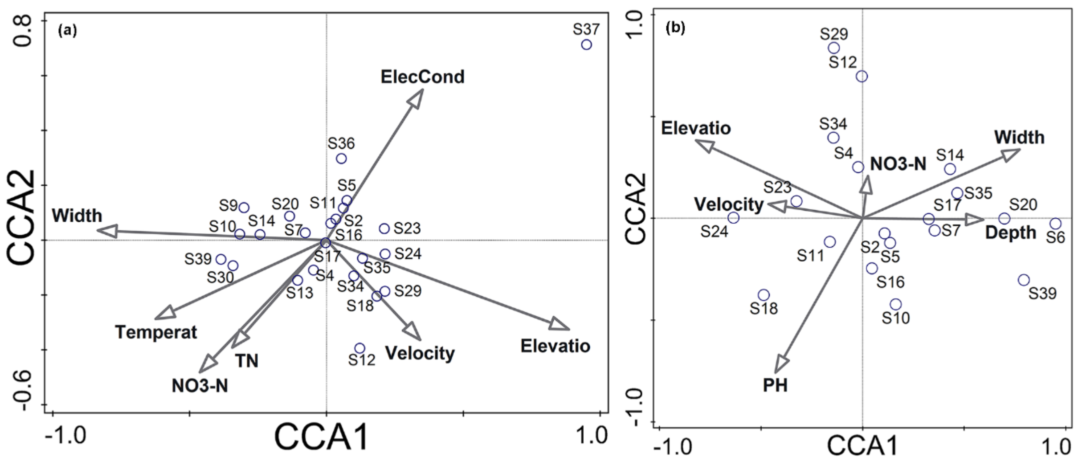

Figure 6. Biplots of canonical correspondence analysis (CCA) displaying the relationship of fish species (circles) and environmental variables (arrows) for all sampling sites under: (**a**) High-flow conditions and (**b**) low-flow conditions. The length of the arrows indicates the strength of the correlation. The selected subset of environmental variables includes Elevation, Elevatio; Width; Depth; Temperat, water temperature; ElecCond, Electric conductivity; Velocity; pH; TN, total nitrogen; and NO_3-N, nitrate nitrogen. The S1–S39 represent fish species and the full names are summarized in Table 1.

Moreover, for the elevation classes in the Weihe River Basin, alpha diversity and beta diversity showed opposite trends in high- and low-flow conditions (Figure 7). Under high flow, the highest value of alpha diversity occurred within the elevation range of 500–1000 m, followed by below 500 m, 1000–1500 m, and above 1500 m. However, beta diversity peaked within the elevation range of above 1500 m, followed by 1000–1500 m, 500–1000 m, and below 500 m. In addition, under low-flow conditions, alpha diversity showed a decreasing trend with increasing elevation classes. Beta diversity declined with increasing elevation classes, with the highest value at above 1500 m. The Kruskal–Wallis test showed that alpha diversity shows significant variation (p = 0.002) within elevation classes under low-flow conditions but no differences (p > 0.05) under high-flow conditions. No significant variation in beta diversity was found among elevation classes in either flow condition.

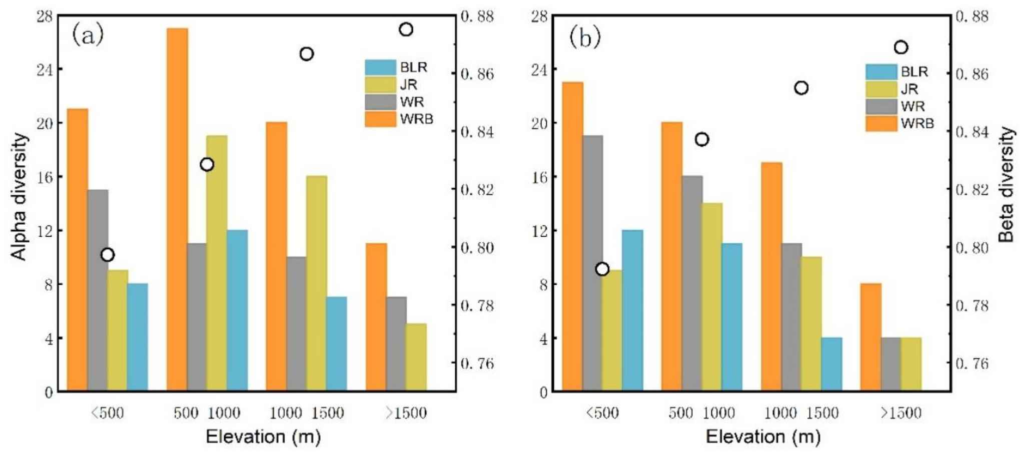

Figure 7. Variations of alpha diversity and beta diversity within each elevation class under (**a**) high-and (**b**) low-flow conditions. The columns show alpha diversity in the Weihe River Basin (WRB), the Weihe River (WR), the Jinghe River (JR), and the Beiluo River (BLR). The circles represent the beta diversity at each elevation class.

4. Discussion

4.1. Variation in Fish Species Composition and Distribution

Two investigations of fish species have previously been carried out in the entire Weihe River Basin. The first complete study was in 1984, with the collected fish species belonged to 58 species in 42 genera, 9 families, and 5 orders [61]. The second, carried out in 2011, found 36 species representing 27 genera, 6 families, and 4 orders [52]. Cobitidae and Cyprinidae were the most common and numerically dominant families in the previous surveys. In this study, fish species were investigated in the whole basin, including three rivers. The fish species compositions observed were similar to those from the aforementioned records, with the richest family being Cyprinidae. Variation in the composition and distribution of fish species among rivers results from the combined effects of habitat conditions, various environmental factors, and human interference. According to the above results, *Pseudorasbora parva*, *Carassius auratus*, and *Triplophysa dalaica* can be considered as indicator species in the Weihe River, Jinghe River, and Beiluo River, respectively.

The species turnover along the elevational gradient in the basin may be explained by increasing elevation; fishes varied from riverine species that live in smooth areas and nutrient-rich conditions to plateau species adapted to cold and harsh surroundings at high altitudes [40,62]. In the low elevations of the Weihe River Basin, fish assemblages included Gobioninae and Cultrinae of the Cyprinidae family, such as *Hemiculter leucisculus*, while fish assemblages were mainly composed of *Triplophysa* at higher elevations. The most common species, *Carassius auratus*, was found at elevations ranging from 350 to 1505 m in all three rivers, with the broadest elevation range. The species *Triplophysa dalaica*, *Triplophysa stoliczkai*, and *Triplophysa sellaefer* were mainly present in the highlands above 1500 m in the three rivers while being absent in lowlands below 500 m. *Brachymystax lenok*, a typical landlocked cold-water species [63], was caught only in the headwaters of the Jinghe River. Fish species differ in tolerance and ecological demands. In the Weihe River Basin, the three most common species, *Carassius auratus*, *Pseudorasbora parva*, and *Misgurnus anguillicaudatus*, are all omnivores with flexible food and habitat options, present in all three rivers.

Human disturbances impact the spatial heterogeneity of fish species [15,22]. A previous study revealed that approximately half of the land use in the Guanzhong Plain was agriculture [64]. The mid-low elevations of the Weihe River are polluted with high TN and NO_3-N due to emissions from agriculture and large cities, such as Baoji, Xianyang, and Xi'an. Fish in these reaches are considered to be extremely tolerant species that can tolerate a variety of environmental conditions, because they are very common in most regions of the catchment and are tolerant of a variety of pollutants [65]. Species with a higher tolerance to pollution, *Paramisgurnus dabryanus* and *Gobio coriparoides*, are present under this condition. The composition and distribution of fish species are also influenced by the availability of feeding habitats and food sources [66]. The Jinghe River flows through the Loess Plateau and carries a sediment load that combines with runoff from agriculture. Therefore, the production of plankton and algae are inhibited, which threatens the food sources of fish species. The Beiluo River has a heavy TN load compared to other rivers. All five contamination variables (TN, TP, NH_4-N, NO_2-N, and NO_3-N) in the Beiluo River are positively related to elevation ($p < 0.05$), owing to the highlands being heavily polluted by petroleum plants [42]. These different human activities in the three rivers have changed the local environmental characteristics, leading to variations in the distribution and diversity of fish species. In addition, damming is the most dramatic human factor affecting the freshwater environment, but since only one of the sampling sites W2 has a dam, it is clear that other human activity, particularly water pollution, must be the key factor, not damming.

4.2. Fish Diversity Patterns along Elevational Gradients in the Weihe River Basin

The alpha diversity and beta diversity of fish species showed varied patterns at the river scale and elevation class scale under high- and low-flow conditions. Although introduced species were not included in calculations of beta diversity in this study, at the river scale, alpha diversity and beta diversity increased with drainage size. The outliers observed in the Jinghe River in high-flow conditions may be related to the rare species and introduced species caught in high-flow conditions within elevation classes 500–1000 m and 1000–1500 m. In these two elevation classes, *Rhodeus lighti*, *Triplophysa pappenheimi*, and *Triplophysa robusta* were collected only in the Jinghe River (Table 1). Additionally, the introduced species *Oreochromis mossambicus* was caught in the Jinghe River. The increasing trend may be attributed to the increased river size and local habitat heterogeneity. Larger habitats contain various microhabitats and food sources that better support a greater species diversity [11,67]. On the other hand, small habitats usually have fewer species and therefore lower species diversity [68].

Higher alpha diversity of fish species at low elevations may reflect the contribution of the Jinghe River with higher alpha diversity while beta diversity increased with elevation. Such contrasting patterns of alpha and beta diversity can be explained by variation in environmental and geographic features with elevation [6,26]. The dispersal ability of a species is restricted by topographic isolation, and different dispersal limitations can lead to different diversity patterns [9,26]. Therefore, high elevations are inhabited by a few specialized species that are adapted only to the highlands. In the Weihe River Basin, *Triplophysa*, including *T. brachyptera* and *T. sellaefer*, were only present at high elevations while lowland assemblages were composed of greater numbers of species, such as *Misgurnus anguillicaudatus*, *Hemiculter leucisculus*, and *Carassius auratus*. The headwaters of a river are generally controlled by natural habitat processes, whereas the lowlands are more affected by coupled natural and anthropogenic activities [67]. In the lowlands, the higher-diversity lowland systems exhibit greater species similarity and therefore lower beta diversity.

5. Conclusions

In summary, in the present study, the composition, distributions, and diversity patterns of fish species were investigated at 50 sampling sites in the Weihe River Basin, including three rivers under high- and low-flow conditions. Patterns of fish species distribution and diversity were assessed. *Cyprinidae* was identified as the richest family in the number of represented species while *Carassius auratus* was the most common species. Fish species composition differed significantly among the three rivers under both flow conditions. Differences in species composition can be explained by the combined effect of habitat conditions, various environmental variables, and human disturbances. The large spatial extent of rivers provides various habitats and food availability for aquatic organisms, thus leading to variations in species composition. Under high-flow conditions, elevation was the variable that explained the most variation, followed by stream wetted width, water temperature, NO_3-N, electric conductivity, TN, and velocity. Under low-flow conditions, the subset of variables including elevation, wetted width, water depth, velocity, pH, and NO_2-N dominated. Different human activities in the three rivers with distinctive local conditions may likely influence the distributions and diversity of fish species.

Elevation is the critical variable explaining the variation in fish species composition. Elevational gradients of fish diversity were examined by river class and elevation class. Alpha diversity decreased along elevational gradients within each river under both flow conditions as a result of changing environmental conditions, especially for wetted width. Alpha diversity and beta diversity gradually increased with increasing drainage area among rivers, whereas two measures of fish diversity displayed different patterns with changing elevation. Differences in fish diversity among rivers were dominated by drainage area and habitat conditions. Alpha diversity declined with increasing elevation while beta diversity increased with increasing elevation. These contrasting altitudinal patterns can be explained by variations in habitat and geographic features with changing elevation. More data from future investigations are required to explore the combined impacts of space, topography, and anthropogenic disturbances on the distributions and diversity of fish species along elevational gradients.

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Appendix A

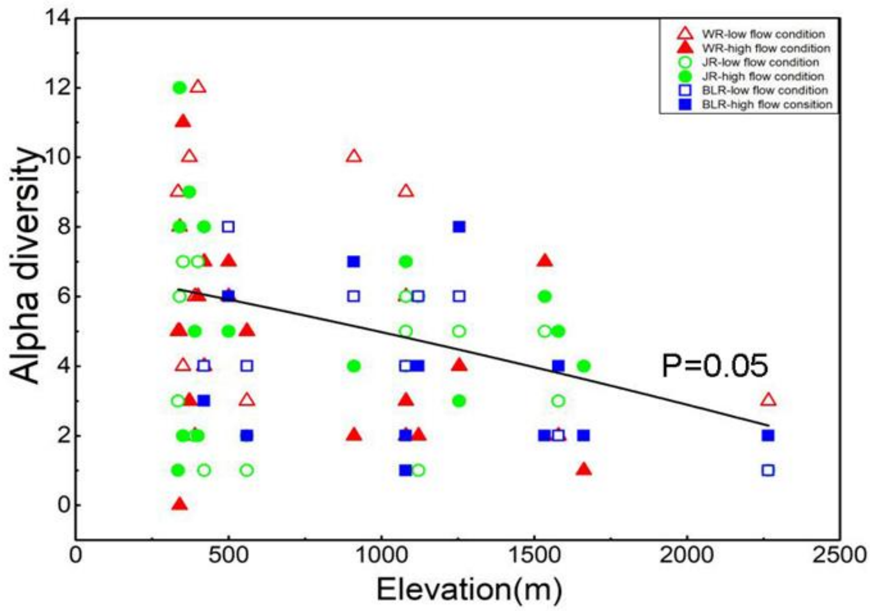

Figure A1. Variations of alpha diversity along elevational gradients within each river at high flow condition and low flow condition. The sites within in the Weihe River (WR), Jinghe River (JR) and Beiluo River (BLR) are indicated with triangles, circles and squares, respectively. $p < 0.05$ indicates a significant difference.

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