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Effect of Environmental Factors on Macrobenthic Community Structure in Chishui River Basin

Shuo Feng [1], Hongtao Wang [2], Jing Zhang [1,*], Xianfu Zhao [3], Jinyong Zhao [1], Feng Mao [4], Wenqi Peng [1] and Quchang Chen [1]

[1] China Institute of Water Resources and Hydropower Research, Beijing 100044, China
[2] School of Water Conservancy Engineering, Yellow River Conservancy Technical Institute, Kaifeng 475004, China
[3] Institute of Hydroecology, MWR&CAS, Wuhan 430079, China
[4] School of Earth and Environmental Sciences, Cardiff University, Cardiff CF10 3AT, UK
* Correspondence: zhangjing@iwhr.com

Abstract: Tributaries flowing naturally play an important role in maintaining the biodiversity of aquatic organisms in dammed rivers. The Chishui River is currently the only undeveloped first-level tributary and an important habitat for aquatic organisms in the upper reaches of the Yangtze River. Understanding the distribution of the community structure of macrobenthos in the Chishui River and its influencing factors is crucial for the conservation and restoration of aquatic biodiversity in both the Chishui River and the Yangtze River. This study analyzes the community structure characteristics of macrobenthos in the Chishui River using four indicators, i.e., Margalef richness index, EPT taxon richness (the number of taxa in the pollution-sensitive Ephemeroptera, Plecoptera, and Trichoptera), Simpson dominance index, and Shannon diversity index, examining differences among different types of environmental factors (physical, chemical, and biological) in the upper, middle, and lower reaches. Subsequently, RDA (Redundancy Analysis) is used to analyze the main influencing factors of different types of environmental factors on macrobenthic community structure. VPA (Variance Partitioning Analysis) is employed to assess the relative importance of different types of environmental factors and their joint effects on the characteristics of macrobenthic community structure. The results indicate that physical environmental factors explain 68.7% of the variation in macrobenthic community structure indicators, chemical environmental factors explain 79.3%, and biological environmental factors account for 36.2%. The interaction among chemical, biological, and physical factors is the most significant explanatory variable, accounting for 41.7% of the variation in macrobenthic community structure characteristics. For EPT taxon number and Shannon diversity index, the interaction among chemical, biological, and physical factors is also the most important explanatory variable, accounting for 42.1% and 42.5% of the variation. For the Margalef richness index and Simpson dominance index, the interaction between chemical and physical factors is the most significant, accounting for 45.0% and 85.3% of the variation. Therefore, the impact of multiple environmental factors on aquatic organisms should not be overlooked, and attention should be paid to the contributions of various environmental factors in the conservation of macrobenthos in the Chishui River Basin.

Keywords: Chishui River; macrobenthos; environmental factors; joint effects

Academic Editors: Francisco Guerrero, Juan Diego Gilbert and Andreas Reul

Received: 14 November 2024
Revised: 29 December 2024
Accepted: 31 December 2024
Published: 9 January 2025

Citation: Feng, S.; Wang, H.; Zhang, J.; Zhao, X.; Zhao, J.; Mao, F.; Peng, W.; Chen, Q. Effect of Environmental Factors on Macrobenthic Community Structure in Chishui River Basin. *Sustainability* **2025**, *17*, 469. https://doi.org/10.3390/su17020469

1. Introduction

The habitat characteristics of rivers are closely related to biodiversity [1]. River habitats shape the biodiversity, biomass, and productivity of rivers [2]. Human disturbances such as agricultural activities, urban sewage, dam construction, and water flow management can impact the aquatic environment and hydrological connectivity, leading to the degradation of the structure and function of river ecosystems and altering the spatial structure of aquatic communities [3–5]. To mitigate the negative impacts of these disturbances, research aimed at understanding the response relationships between aquatic community characteristics and environmental factors that can guide river ecological restoration [6–8]. However, multiple environmental factors often operate simultaneously, necessitating an understanding of the hierarchical structure of different types of environmental factors [9].

Biological indicators have been widely used to evaluate the health of river ecosystems [10]. Macrobenthos have become the most widely used aquatic biota in river ecosystem condition surveys and river health assessments due to their relatively sessile lifestyle, ease of collection, and ability to respond to the effects of human disturbance in an integrated manner [11]. Therefore, macrobenthos is a good indicator for studying different types of environmental factors.

The structure of macrobenthic communities varies considerably in different rivers. Various ecological processes at different spatial scales (watershed, reach, microhabitat, etc.) result in corresponding community structures [12]. Early studies primarily focused on small-scale analyses, with most research suggesting that riverbank and riverine habitats are the main factors influencing the distribution of large macrobenthos [13,14]. Since the 1990s, some scholars have begun to pay attention to factors at a larger scale, believing that landscape-scale and watershed-scale factors play an important role in the riverine macrobenthos macroinvertebrate community [15]. Currently, most scholars believe that riverine biodiversity is influenced by multi-scale, multitype factors, and research is focused on the effects of the coupling of multiple environmental factors on the community [9,16].

The Chishui River is currently the only undeveloped first-order tributary in the upper reaches of the Yangtze River and is of great significance in maintaining biodiversity and ecosystem stability in the surrounding watershed. Scholars have made great progress in exploring the relationship between fishes and the watershed ecosystem in the Chishui River Basin and the protection countermeasures for rare and endemic fish resources [17]. Fewer studies on the benthos of the Chishui River have been reported, mainly exploring the driving mechanism and stress factors of the Chishui River Basin in the distribution of macrobenthos, developing the macrobenthos-based multi-parameter index (CSMMI) to evaluate the ecological status of the Chishui River, etc. [18–20]. However, the corresponding relationship between macrobenthic community structure and multiple environmental factors in the Chishui River Basin is still not adequately studied.

In order to understand the distribution and influencing factors of the macrobenthic community structure in the Chishui River, we compare and analyze the effects of different types of environmental factors on the macrobenthic community structure and analyze the corresponding relationship between macrobenthic and multiple environmental factors. This study will provide technical support for the conservation and restoration of aquatic biodiversity in the Chishui River and even the Yangtze River.

2. Materials and Methods

2.1. Study Area

The Chishui River is a first-class tributary on the right bank of the upper reaches of the Yangtze River, and it is the only undeveloped first-class tributary on the upper reaches of the Yangtze River [21]. The whole basin (except for some tributaries) basically maintains the natural attributes of a natural river, with relatively little interference from human activities, and its diversified geomorphological units provide a suitable living space for macrobenthos organisms, and it is an important habitat or spawning ground for endemic fish and a variety of aquatic organisms in the upper reaches of the Yangtze River [21]. It has a total length of 436.5 km and a total drop of 1475 m, with an average gradient of 3.4‰. The annual sediment transport is 7.18 million tons, and the sediment content is 0.927 kg/m^3. As a typical meandering river in the southwest mountainous area, the Chishui River is a national nature reserve of rare and endemic fish species in the upper reaches of the Yangtze River. It has a special topography, a rich geomorphic pattern, and diversified hydraulic characteristics, providing a physical habitat for a variety of endangered fish [22].

2.2. Sample Collection and Processing

Considering the feasibility of macrobenthos collection, combined with the hydrological characteristics of the Chishui River, and on the basis of previous research, the time of investigation and sampling was spring. Firstly, this is the dry season of the Chishui River Basin, which is favorable for benthos collection in terms of sampling method; secondly, the biomass of macrobenthos is large in spring, which can ensure the quality of collected samples. The distribution of sample points is shown in Figure 1, and the locations of sample points in the river basin are provided in Table 1.

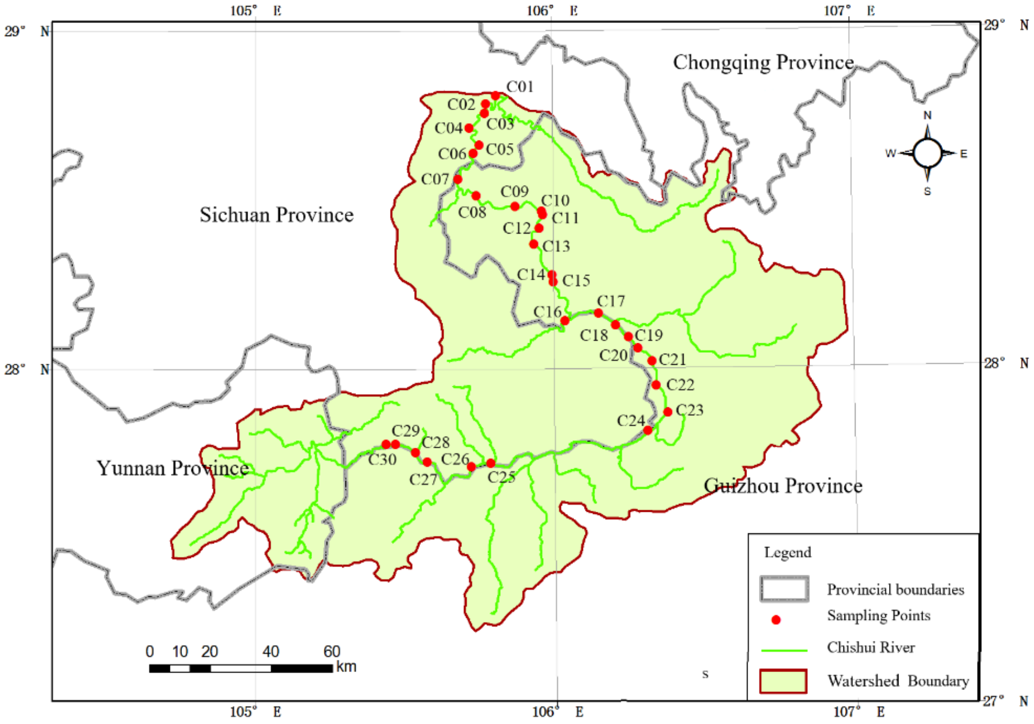


Figure 1. Study area and distribution of sampling points.

Table 1. The distribution of sampling points in the Chishui River.

Watershed	Position in the Basin [21]	Number of Sampling Points	Sampling Point Number
The main stream of the Chishui River	Upstream (from Chahe Village to Maotai Town)	7	C24–C30
	Midstream (from Maotai Town to Chishui City)	15	C08–C23
	Downstream (from Chishui City to the river estuary)	8	C01–C08

Within a range of 100 m from the selected sample point, the in situ sampling of the macrobenthos was conducted using the multihabitat method. Within 10 min, a 425-micron D-shaped hand net was used at the sampling point to sample multiple habitats at the bottom of the river areas with a water depth of less than 1.5 m. Sampling at nearshore locations with a deeper water depth was conducted. After the samples were collected, they were washed with water and placed in 500 mL wide-mouthed plastic bottles and brought back to the laboratory for sorting. After sorting, 4% formalin solution was added as a preservative. The samples were classified and counted in a laboratory by using a Leica EZ4D dissecting microscope (Wetzlar, Germany) and an Olympus BH-2 microscope (Tokyo, Japan) [23–25].

The environmental factors considered in this study include three categories of physical, chemical, and biological factors (Table 2), which were investigated for macrobenthos in the Chishui River Basin [26]. Depth (D), velocity (V), altitude (Alt), latitude (Lat), longitude (Lon), sinuosity (Sin), and channel slope (Slo) were determined using DJI Elf 4 PRO (Shenzhen, China) drone remote sensing data, a Huace i70 RTK (Shenzhen, China) (real-time kinematic), and a D390 bathymeter (Shenzhen, China) in combination with a Bigmap 2.1.8 download. The substrate was sampled using a bucket sampler, and the sampling method was the surface sampling method, with the sampling depth being about twice the median grain size of the bed sand, and the composition of the riverbed substrate was analyzed by using the ruler method and the sieve analysis method [27,28].

Table 2. Different types of environmental factors.

Types	Factors
Physical factors	Watershed scale: altitude (Alt), latitude (Lat), longitude (Lon); reach scale: sinuosity (Sin), channel slope (Slo), depth (Dep), velocity (V), and Temperature (Temp); microhabitat scale: substrate (coefficient of uniformity (Cu) and coefficient of curvature (Cc))
Chemical factors	Reach scale: pH, oxidation redox potential (ORP), salinity (Sal), electrical conductivity (SpCond), dissolved oxygen (DO), turbidity (TurbSC), photosynthetically active radiation (PAR), total dissolved gasses (TDGs), total nitrogen (TN), ammonia nitrogen (NH_3-N), nitrate nitrogen ($NO_3{}^-$-N), nitrite nitrogen ($NO_2{}^-$-N), total phosphorus (TP) orthophosphate ($PO_4{}^+$-P), and chemical oxygen demand (CODcr)
Biological Factors	Reach scale: Periphyton (Peri) and phytoplankton (Phyto)

Temperature (Temp), pH, oxidation redox potential (ORP), salinity (Sal), electrical conductivity (SpCond), dissolved oxygen (DO), turbidity (TurbSC), photosynthetically active radiation (PAR), total dissolved gasses (TDGs) were analyzed using a multi-functional water quality analyzer (Hach DS5X (Shanghai, China)). At each sampling point, two parallel water samples (each 2 L) were collected and placed in a low-temperature insulated box and then transported to the laboratory within 48 h. The selected water chemistry indicators included total nitrogen (TN), ammonia nitrogen (NH_3-N), nitrate nitrogen ($NO_3{}^-$-N), nitrite nitrogen ($NO_2{}^-$-N), total phosphorus (TP), orthophosphate ($PO_4{}^+$-P), and chemical oxygen demand (CODcr).

The Periphyton samples were collected and identified in accordance with the methods specified in the “Technical specifications for aquatic ecological monitoring—Fresh Water Periphyton” [29]. The species identification of algae was based on the relevant literature [30]. Phytoplankton samples were collected and identified according to the methods specified in Methods of Freshwater Plankton Research. The identification of phytoplankton was made with reference to the classical literature [31].

2.3. Methods of Analysis

In this study, we analyzed the structural characteristics of macrobenthic communities from four indices: Margalef richness index, number of EPT taxon richness, Simpson dominance index, and Shannon diversity index [25,32]. Differences between upstream, midstream, and downstream chemotaxonomic factors were demonstrated by box lines with significance asterisks, and the use of ANOVA or Kruskal–Wallis test was supported to evaluate whether the differences were significant or not.

After performing detrended correspondence analysis (DCA) on the indicators characterizing macrobenthic community structure, we found that the gradient value of the macrobenthic data was 2.093, which was less than 3, so we chose RDA [33]. The total variance of the species data matrix was decomposed into different parts: (i) RDA was used to analyze the main influencing factors of different types of environmental factors on macrobenthic community structure. (ii) The joint effect analysis of different types of environmental factors on macrobenthic community structure characteristics was analyzed by using variance decomposition. (iii) The relative importance of different types of environmental factors was analyzed by the method of VPA (Variance Partitioning Analysis) [34]. RDA and VPA were performed using CANOCO 4.5.

3. Results

3.1. Characterization of Macrobenthic Community Structure

By identifying the macrobenthic faunas of the sampled samples from each sampling site in the Chishui River Basin, macrobenthic faunas in 6 phyla, 7 classes, 12 orders, 40 families, 60 genera, and 97 species were counted in 30 samples. Among them, the aquatic insects mainly consisted of EPT (E: Ephemeroptera; P: Plecoptera; T: Trichoptera) and Diptera. There are 17 species of major aquatic insects belonging to the EPT group, and the most common species are *Ephemerellidae* sp., *Choroterpes* sp., *Baetidae* sp., *Ecdyonurus* sp., and so on. Among the Diptera, Chironomidae contains the largest number of species, amounting to 17 genera and 35 species, and the species of this family are distributed in all the samples except C10. *Isonychiidae*, *Stenopsychidae*, *Limnophilidae*, *Leptoceridae*, *Macromiidae*, *Libellulidae*, and *Lumbriculidae* are rare families and have been detected only in a single sample.

The distribution of species richness within the community is shown in Figure 2. The upper Chishui River Basin sample C30 contained the highest number of macrobenthic species, with 38 species, while the lower Chishui River sample C09 contained the lowest number of species, with 3 species. The Margalef richness index was the highest in the upper Chishui River Basin sample C27 (5.63), and the mean of the upstream sites in the Chishui River was 3.72, the mean of the middle reaches of the Chishui River was 2.62, and the mean of the downstream sites was 2.68 (Table 3).

The sampling sites with a higher number of EPT species were distributed in C27 and C28 in the upper Chishui River Basin, with 11 and 13 EPT species, and the EPTs were mainly Hydropsychidae, Caenidae, Baetidae, Chironomidae, and Tabanidae. The samples with fewer EPT species were distributed in the C04 and C08 in the lower part of the Chishui River Basin, and C09, C10, C13, C17–C19, and C21–C23 in the middle part of the river, with 0 or 1 EPT species (Figure 2, Table 3).

In the Chishui River Basin, there are four dominant species: *Othacladius* sp., *Cricotopus* sp., *Chironomus* sp., and *Planarian*. The dominant species in the upper reaches of the Chishui River are *Baetidae* sp., *Cinygmina* sp., and *Chironomus* sp. The dominant species in the middle reaches of the Chishui River are *Othacladius* sp., *Chironomus* sp., and *Atyridae* sp. *Atyidae* sp., *Lithoglyphopsis hyalinus*, and *Planarian*; in the lower reaches of the Chishui River, they are *Chironomus* sp., *Lithoglyphopsis hyalinus*, *Pseudobythinella liuiui*, and *Pseudobythinella liui*. *Pseudobythinella liui* has three types of dominant species.

Samples with a high Shannon diversity index were mainly located in C27 (2.45) in the upper Chishui River Basin, with a mean value of 1.80 in the upper Chishui River; a mean value of 1.48 in the middle Chishui River; and a mean value of 1.55 in the lower Chishui River (Figure 2, Table 3).

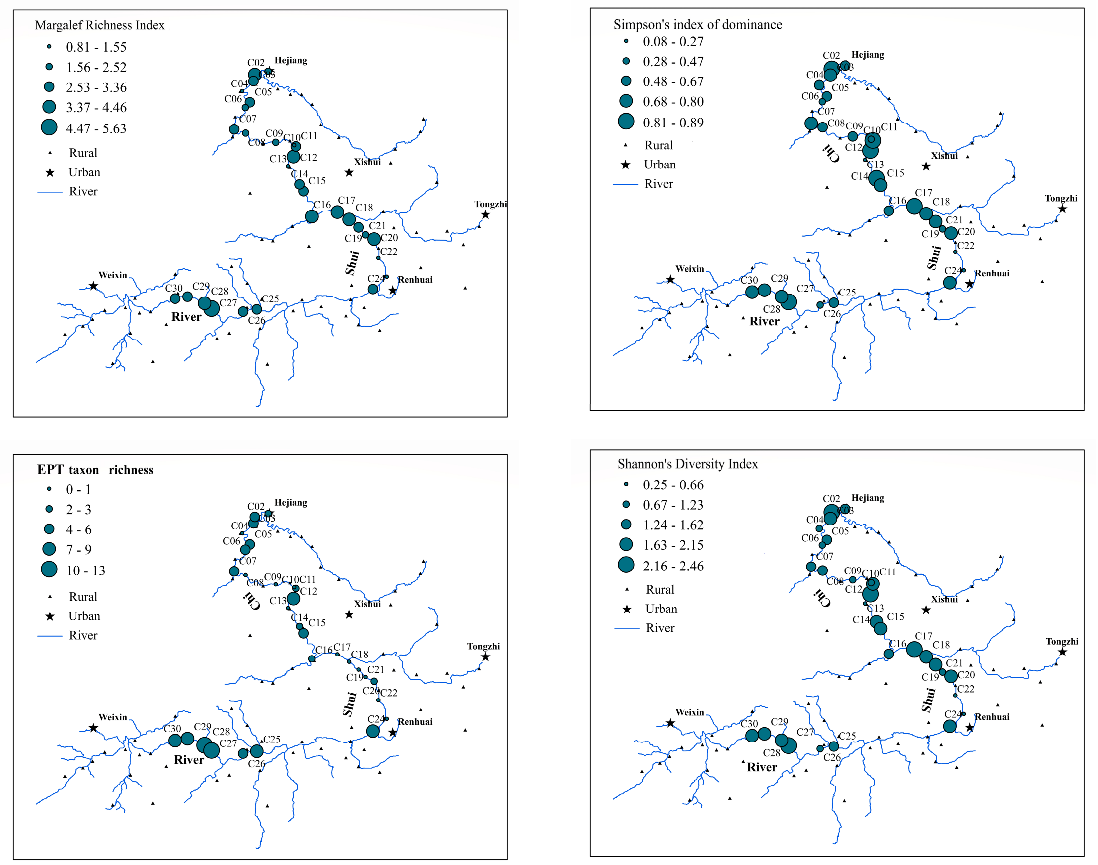


Figure 2. The spatial distribution of macrobenthic community structure indicators in the Chishui River Basin.

Table 3. The statistical values of macrobenthic community structure indicators in the Chishui River Basin.

Data	Position in the Basin	Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation
EPT taxon richness	Upstream	4.00	13.00	8.71	1.08	12.45%
	Midstream	0.00	8.00	1.87	0.59	31.74%
	Downstream	0.00	5.00	3.13	0.72	22.98%
	Whole river	0.00	13.00	3.80	3.62	95.36%
Margalef richness index	Upstream	2.91	5.63	3.72	0.37	9.93%
	Midstream	0.81	4.06	2.62	0.30	11.41%
	Downstream	1.55	3.51	2.68	0.21	7.91%
	Whole river	0.81	5.63	2.89	1.07	37.04%
Simpson dominance index	Upstream	0.43	0.85	0.71	0.05	7.48%
	Midstream	0.08	0.89	0.60	0.07	11.64%
	Downstream	0.44	0.87	0.65	0.05	7.45%
	Whole river	0.08	0.89	0.64	0.21	33.51%
Shannon diversity index	Upstream	1.05	2.45	1.80	0.18	9.87%
	Midstream	0.25	2.46	1.48	0.19	12.69%
	Downstream	1.14	2.39	1.55	0.14	9.23%
	Whole river	0.25	2.46	1.58	0.60	38.02%

3.2. Characterization of Environmental Factors

The results of conventional statistical analysis of mean, variance, and coefficient of variation in physical, chemical, and biological factors at 30 sampling sites is shown in Table 4. Water temperature, pH, ORP, Sal, SpCond, DO, TDG, Cc, Alt, Lat, and Sin showed less spatial variability relative to other water quality indicators with coefficients of variation of 7.00%, 2.73%, 7.23%, 9.39%, 8.97%, 16.91%, 2.55%, 17.42%, 1.29%, 0.26%, and 6.50%. The spatial variability of PAR, NO_2-N, TP, PO_4-P, and Slo was greater than 100%, with coefficients of variation of 116.66%, 151.89%, 251.09%, 298.93%, and 105.69%. The points with higher PAR concentrations were mainly concentrated in the midstream (C10, C11, C14, C18) and upstream (C25, C26, C30). Points with higher concentrations of NO_2-N, TP and PO_4-P were mainly concentrated in the midstream points.

As seen in Figure 3, the physical factors Slo, Sin, H, Lon, Lat, and Alt, the chemical factors NH_4-N, TDG, PAR, TurbSC, SpCond, Sal, pH, and Temp, and the biological factor Phyto were significantly different in the upper, middle, and lower reaches of the Chishui River.

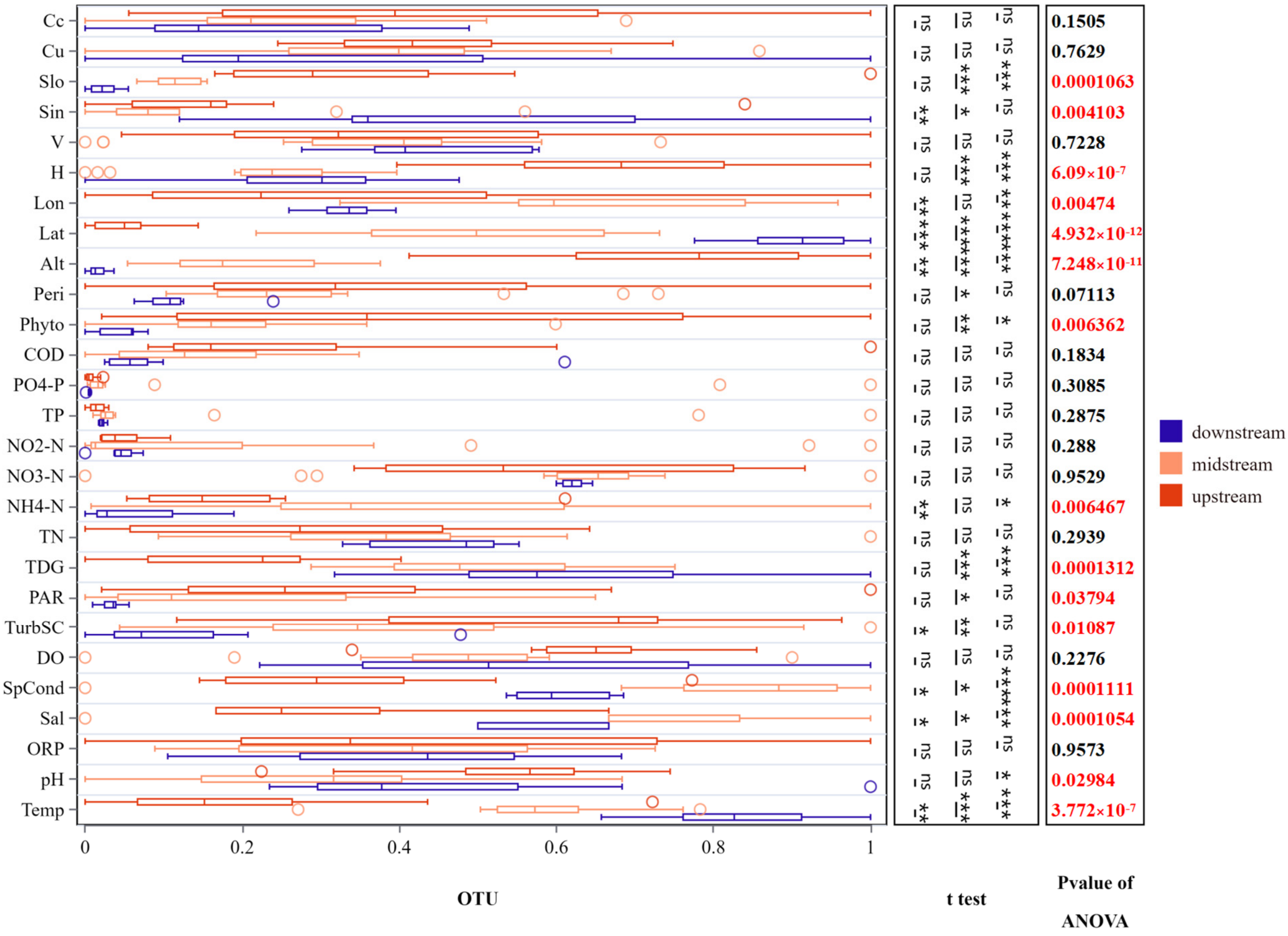


Figure 3. The characterization of different types of environmental factors in the upper, middle, and lower reaches of the Chishui River Basin (left panel: data distribution or mean values, OTU (operational taxonomic units: sampling points); middle panel: post hoc test results ($p < 0.05$, *; $p < 0.01$, **; $p < 0.001$, ***); right panel: p-values of global test results between groups; the smaller the p-value, the more significant the difference, and p-values less than 0.05 are marked in red).

Table 4. Statistical values of water quality factors.

Data	Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation
pH	7.78	8.76	8.17	0.22	2.73%
ORP	351.76	465.84	398.44	28.81	7.23%
Sal	0.14	0.20	0.18	0.02	9.39%
SpCond	284.70	396.00	356.02	31.92	8.97%
DO	4.95	11.16	8.27	1.40	16.91%
TurbSC	9.06	42.59	22.29	9.98	44.77%
PAR	39.36	2977.41	617.00	719.81	116.66%
TDG	683.90	764.20	719.87	18.35	2.55%
TN	1.97	4.90	3.07	0.63	20.38%
NH_4-N	0.10	0.89	0.33	0.22	68.04%
NO_3-N	0.18	3.41	2.12	0.66	31.03%
NO_2-N	0.02	0.48	0.08	0.12	151.89%
TP	0.00	0.70	0.06	0.16	251.09%
PO_4-P	0.00	0.65	0.05	0.15	298.93%
COD	0.56	7.01	1.73	1.41	81.42%
Phyto	0.53	9.41	2.51	2.30	91.38%
Peri	8.52	217.41	67.80	51.43	75.86%
Cu	1.00	4.18	2.26	0.74	32.61%
Cc	1.00	1.90	1.27	0.22	17.42%
Temp	15.45	20.06	17.96	1.26	7.00%
Alt	207.00	670.00	348.33	143.07	41.07%
Lat	27.71	28.81	28.23	0.36	1.29%
Lon	105.44	106.34	105.92	0.27	0.26%
H	0.10	0.73	0.32	0.16	48.22%
V	0.03	1.33	0.54	0.29	54.20%
Sin	1.01	1.26	1.067	0.07	6.50%
Slo	1.9×10^{-4}	0.01	0.002	0.002	105.69%

3.3. Relationship Between Macrobenthic Community Structure and Environmental Factors

3.3.1. Key Environmental Factors Influencing Significant Macrobenthic Community Structure

The RDA of physical factors and macrobenthic community structure indicators (Figure 4) showed that the explanatory variables explained 69.0% of the variance. The eigenvalues of the first two axes were 0.6693 and 0.0178, respectively, and the two axes explained 68.71% of the variance information. The correlation coefficients between species and physical factor ordering axes reached 0.8441 and 0.5774, indicating that the ordering diagram could better reflect the relationship between physical factors and macrobenthic community structure indicators. In the RDA, the independent effects of each physical factors were detected, and the significance and significance of each factor were tested by Monte Carlo hypothesis test, and $p < 0.05$ was used as the significance criterion to exclude the factors with smaller contributions. A total of five variables, i.e., Lat, Slo, H, Lon, and Cu, were the main physical factors affecting macrobenthic community structure.

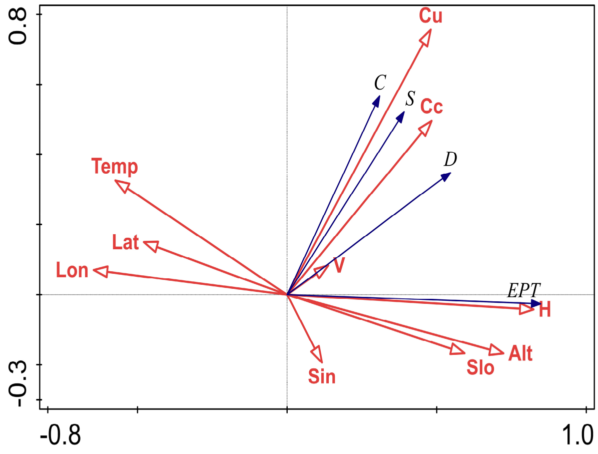


Figure 4. RDA of physical factors with macrobenthic community structure (C: Simpson dominance index; D: Shannon diversity index; S: Margalef richness index; EPT: EPT taxon richness).

The RDA of chemical factors and macrobenthic community structure indicators (Figure 5) showed that the explanatory variables explained 79.0% of the variance. The eigenvalues of the first two axes were 0.7446 and 0.0426, respectively, and the two axes explained 78.72% of the variance information. The correlation coefficients between species and chemical factors sorting axes reached 0.8901 and 0.8881, and the sorting results were reliable. A total of four variables, TDG, Sal, pH and DO, with $p < 0.05$, were the main chemical factors affecting macrobenthic community structure.

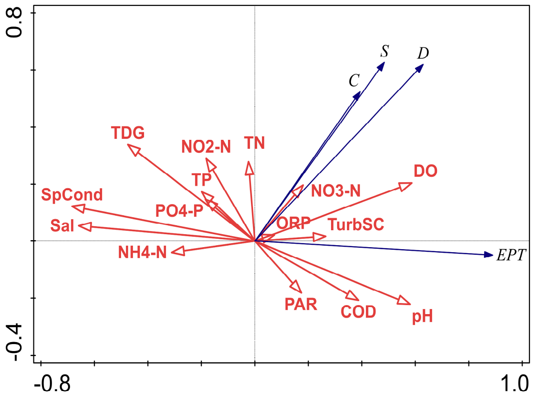


Figure 5. RDA of chemical factors with macrobenthic community structure (C: Simpson dominance index; D: Shannon diversity index; S: Margalef richness index; EPT: EPT taxon richness).

Biological factors were analyzed by RDA with indicators of macrobenthic community structure (Figure 6), and the explanatory variables explained 36.2% of the variance. The eigenvalues of the first two axes were 0.3617 and 0.0005, respectively, and the two axes explained 36.22% of the variance information. The correlation coefficients of species and biological factor sorting axes reached 0.6217 and 0.113. Phyton ($p < 0.05$) was the main biological factor affecting macrobenthic community structure.

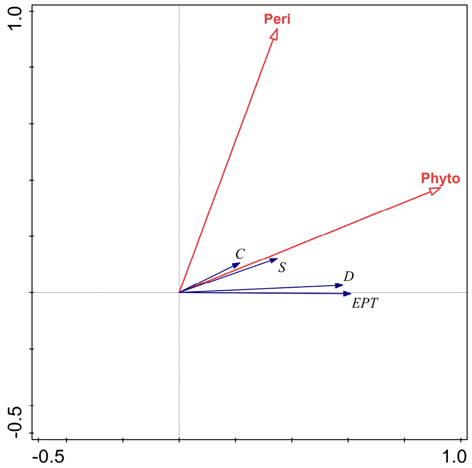


Figure 6. RDA of biological factors with macrobenthic community structure (C: Simpson dominance index; D: Shannon diversity index; S: Margalef richness index; EPT: EPT taxon richness).

3.3.2. Analysis of Joint Effects of Different Types of Environmental Factors

The correlation of different types of environmental factors on macrobenthic community structure characteristics was analyzed by the method of variance decomposition (Figure 7). In the Chishui River Basin, chemical, biological, and physical factors alone revealed 11.8%, 2.1% and 1.4% of the variation in macrobenthic community structure characteristics, respectively, and chemical factors had the most significant effect on the spatial differentiation of macrobenthic community structure. The interactions of chemical factors, biological factors, and physical factors were the most important explanatory variables, accounting for 41.7% of the changes in macrobenthic community structure characteristics. This indicates that there is a covariation phenomenon in the effects of different types of environmental factors on macrobenthic community structure characteristics.

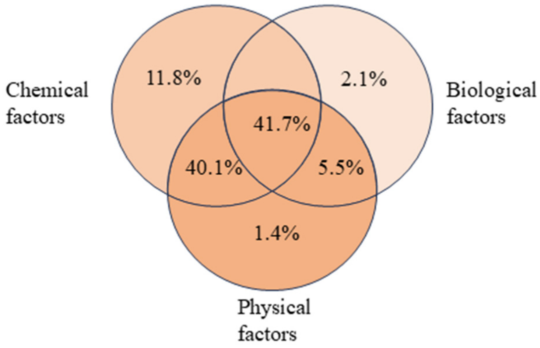
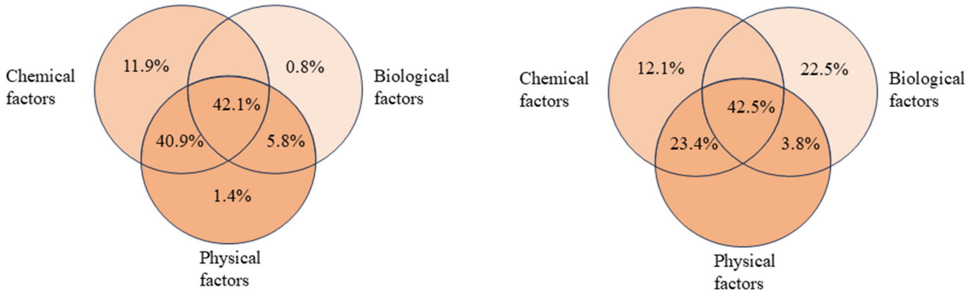


Figure 7. Plot of RDA of bioenvironmental factors and macrobenthic community structure (values < 0 not shown).

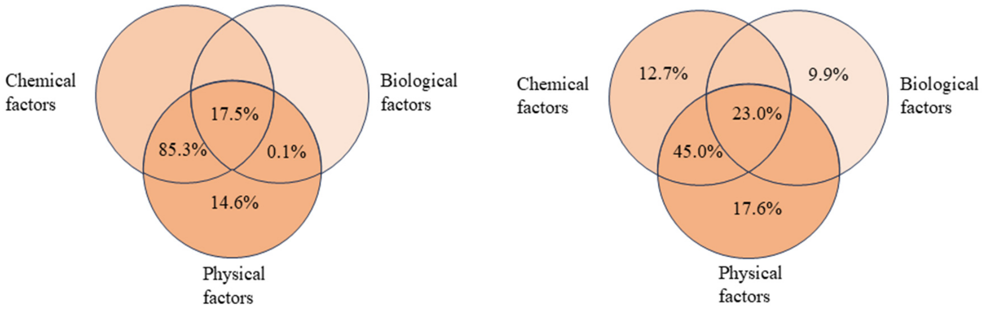
3.3.3. Relative Importance of Different Types of Environmental Factors

The analysis of variance decomposition is shown in Figure 8. For the number of EPT taxonomic units and Shannon diversity index, the interaction of chemical, biological, and physical factors in the Chishui River Basin was the most important explanatory variable, accounting for 42.1% and 42.5% of the changes in the structural characteristics of the macrobenthic community. For Margalef richness index and Simpson dominance index, the interactions of chemical and physical factors were the most important explanatory variables, accounting for 45.0% and 85.3% of the changes in the structural characteristics of macrobenthic community.



Relationship between EPT taxon richness and environmental factors

Relationship between Shannon diversity index and environmental factors



Relationship between Simpson index of dominance and environmental factors

Relationship between Margalef richness index and environmental factors

Figure 8. Interrelationships and contributions between macrobenthic community structure indicators and environmental factors (values < 0 not shown).

4. Discussion

4.1. Relationships Between Different Types of Environmental Factors and Macrobenthic Community Structure

The community structure of macrobenthos is closely linked to environmental factors, and there is obvious variability in species composition, abundance, biomass, superiority, and diversity in different habitats [35]. The effects of environmental factors on macrobenthos are very complex; there are not only numerous environmental factors but also different environmental factors that have incompletely consistent effects on different macrobenthic taxa [26]. This study analyzes the effects of different types of environmental factors, i.e., physical, chemical, and biological, on the community structure of riverine macrobenthos. Physical factors included in the analysis explained 68.7% of the spatial variation in macrobenthic community structure and 1.4% of the variation in macrobenthic community structural features revealed individually. A total of five variables, i.e., Lat, Slo, H, Lon and Cu, were the main physical environmental factors affecting macrobenthic community structure. Alt, Lat, and Lon factors do not directly affect riverine organisms per se, but generally act indirectly on riverine ecosystems through factors such as temperature and precipitation [36,37]. There are significant differences in the Alt, Lat, and Lon factors in above, middle, and lower reaches, which leads to one of the reasons for changes in the structure of the upstream, middle, and lower reaches of the chinensis. The macrobenthic invertebrate community structure clearly varies with water depth [38]. Slo affects macrobenthic community structure by altering river velocity and flow; waters with steep slopes are generally saturated with oxygen and suitable for oxygen-loving macrobenthic invertebrates; conversely, waters with gentle or parallel slopes have lower oxygen content and are suitable for macrobenthic invertebrates with low oxygen demand [39]. The heterogeneity and stability of the substrate determine the characteristics of macrobenthic community to a certain extent. Mud, fine sand, and gravel are less stable, with low heterogeneity and lower biomass and diversity of macrobenthic invertebrates; pebbles, rounded stones, and drifted stones have a complex surface structure, are more stable, and have higher biomass and diversity [26].

The chemical factors included in the analysis explained 78.3% of the spatial variation in macrobenthic community structure and 11.8% of the variation in macrobenthic community structural features revealed individually. A total of four variables, i.e., TDG, Sal, pH, and DO, with $p < 0.05$, were the main chemical factors affecting the community structure of macrobenthic fauna. A reduction in mean salinity below the threshold may positively affect macrobenthic abundance and persistence of sensitive taxa in the river [40]. The pH value has a great influence on the reproductive capacity of macrobenthic invertebrates, and the biomass of macrobenthic invertebrates is significantly reduced, and their reproductive capacity is significantly weakened when the pH value is below 5.0 [41]. DO is one of the important factors affecting the structure of macrobenthic invertebrate communities in water bodies, and different taxa have different dissolved oxygen requirements [42].

The biological factors included in the analysis explained 36.2% of the spatial variation in macrobenthic community structure and 2.1% of the variation in macrobenthic community structure characteristics revealed individually. Phyton ($p < 0.05$) was the main biological factor affecting macrobenthic community structure. Compared with other aquatic organisms, phytoplanktons have a simple structure, shorter life cycle, faster growth rate, easy sample collection, and higher sensitivity to environmental fluctuations, and can quickly and sensitively reflect changes in water quality. They have unique advantages and important applications in evaluating water quality and aquatic ecosystem health [43].

4.2. Analysis of Joint Effects of Different Scales and Types of Environmental Factors

In riverine ecosystems, different spatial-scale environmental factors, such as key watershed-scale environmental variables: latitude, elevation, watershed size where the sample sites are located, percentage of forested land, etc.; key reach-scale environmental variables: sinuosity, longitudinal drop of the channel, water depth and flow velocity, total nitrogen, total phosphorus, silica concentration, etc.; and key microhabitat-scale environmental variables: substrate particle size, heterogeneity, stability, etc., have an impact on the benthic faunal community [44,45]. Small, poorly mobile organisms such as macrobenthos are more sensitive to small-scale environmental factors. Moreover, each environmental factor does not act independently, but always acts in combination with other environmental factors on macrobenthic community structure [16,46]. In this study, we found that the interactions of different types of environmental factors, including physical, chemical, and biological factors, were the most important explanatory variables at different spatial scales in the Chishui River Basin at the watershed, reach, and microhabitat scales, which accounted for 41.7% of the changes in the structural characteristics of the macrobenthic community. This indicates that there are covariations in the effects of different scales and types of environmental factors on the structural characteristics of macrobenthic communities.

4.3. Relationship Between Macrobenthic Community Structure Indices and Different Types of Environmental Factors

The Margalef richness index, EPT taxon richness, the Simpson dominance index, and the Shannon diversity index of macrobenthos can reflect the species composition, structural characteristics, and functions of macrobenthic communities. In this study, we study that macrobenthic community structure indices are affected by different types of environmental factors to different degrees, and in the Chishui River Basin, the interactions among chemical, biological, and physical factors in the Chishui River Basin are the most important explanatory variables for the number of taxonomic units in the EPT taxon richness and Shannon diversity index. EPT taxon richness, as a sensitive group, usually has abundant sensitive groups in river sections with better habitats [47]. In the Chishui River Basin, the interaction of both chemical and physical factors is the most important explanatory variable for Margalef richness index and Simpson dominance index. Among them, the main factors affecting Margalef richness index and Simpson dominance index are physical factors. In rivers with natural features, reaches with changing characteristics such as open valleys, poorly incised channels, and low gradients usually have lower taxa richness and biological quality indices [48].

5. Conclusions

1. There are significant differences in different types of environmental factors in the upper, middle, and lower reaches of the Chishui River Basin. Among them, the physical factors Slo, Sin, H, Lon, Lat, and Alt, the chemical factors NH_4-N, TDG, PAR, TurbSC, SpCond, Sal, pH, and Temp, and the biological factor Phyto were significantly different in the upper, middle, and lower reaches of the Chishui River.
2. Macrobenthic community structure is comprehensively affected by different types of environmental factors in the Chishui River Basin. The interaction of chemical, biological, and physical factors was the most important explanatory variable, accounting for 41.7% of the variation in the structural characteristics of macrobenthic communities. Lat, Slo, H, Lon, and Cu were the main physical factors affecting macrobenthic community structure. TDG, Sal, pH, and DO were the main chemical factors affecting macrobenthic community structure. Phyton ($p < 0.05$) was the main biological factor affecting macrobenthic community structure.

3. Indices of macrobenthic community structure are subject to different types of environmental factors in the Chishui River Basin. The interactions of chemical, biological, and physical factors in the Chishui River Basin were the most important explanatory variables in terms of EPT taxon richness and the Shannon diversity index. For Margalef richness index and Simpson dominance index, the interaction of both chemical and physical factors is the most important explanatory variable.

Author Contributions: S.F.: investigation, writing—original draft, analyzing, validation, methodology, and data curation; H.W.: methodology, investigation, and data curation; J.Z. (Jing Zhang): methodology, investigation, data curation, and validation; J.Z. (Jinyong Zhao): formal analysis, project administration, and funding acquisition; X.Z.: investigation, data curation, and validation; F.M.: conceptualization and formal analysis; W.P.: project administration and funding acquisition; Q.C.: writing—original draft and validation. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the China Institute of Water Resources and Hydropower Research (grant no. WE0145B042021) and Central Sector Budget Project "Research on Multi-scenario and Strongly Disturbed River Ecology Methods and Key Technologies for the Recovery of River and Lake Ecology in the Operation and Management of the Three Gorges Project" (WE0161A042024).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated or analyzed during this study are included in this published article.

Conflicts of Interest: The authors declare that they have no conflicts of interest that influenced the work reported in this study.

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