

Article

Spatial Variation of Zooplankton Diversity and Taxonomic Group Responses in the Nanming River, Guiyang: Coupling Effects of Urbanization Disturbance and Multiple Environmental Factors

Lifen Du ^{1,2,3,4} , Qiuhua Li ^{1,2,3,4,5,*} , Haiquan Yang ⁶  and Long He ⁷

- ¹ Key Laboratory for Information System of Mountainous Area and Protection of Ecological Environment of Guizhou Province, Guizhou Normal University, Guiyang 550001, China; dlf1212@gznu.edu.cn
- ² Guizhou Key Laboratory of Advanced Computing, Guiyang 550001, China
- ³ Guizhou International Cooperative Research Base-International Joint Research Center for Water Ecology, Guiyang 550001, China
- ⁴ Guizhou Province Field Scientific Observation and Research Station of Hongfeng Lake Reservoir Ecosystem, Guiyang 551499, China
- ⁵ School of Cyber Science and Technology, Guizhou Normal University, Guiyang 550001, China
- ⁶ Chinese Acad Sci, State Key Lab Environm Geochem, Inst Geochem, Guiyang 550081, China
- ⁷ Guizhou Zhuxin Water Environmental Industry Co., Ltd., Guiyang 550081, China
- * Correspondence: qiuhua2002@126.com; Tel.: +86-136-08511078

Abstract

This study investigated the effects of urbanization on zooplankton communities in the Nanming River, a typical karst urban river in Southwest China. Thirty-three sampling sites were set along an urbanization gradient: urban, suburban, and exurban areas. We identified 33 zooplankton species, with rotifers dominating (84.62%). Zooplankton abundance and diversity were significantly higher in the exurban area, showing a negative correlation with urbanization intensity. *Lepadella ovalis* and *Monostyla angulata* were dominant, while *Lecane cornuta* was exclusive to the exurban zone. Gradient Boosting Models (GBMs) and Structural Equation Modeling (SEM) indicated that Cu, Zn, TN, and NH₃-N were key drivers, and urbanization acted via heavy metal pollution and nutrient regulation. Rotifers showed strong urbanization adaptability, while copepods were most sensitive. Controlling nitrogen and heavy metals is critical for protecting karst urban river ecosystems.

Keywords: urbanization; Nanming River Basin; zooplankton; aquatic environment; biodiversity



Academic Editor: Mário Gabriel
Santiago dos Santos

Received: 22 April 2026

Revised: 19 June 2026

Accepted: 16 July 2026

Published: 19 July 2026

Copyright: © 2026 by the authors.
Licensee MDPI, Basel, Switzerland.
This article is an open access article
distributed under the terms and
conditions of the [Creative Commons
Attribution \(CC BY\) license](https://creativecommons.org/licenses/by/4.0/).

1. Introduction

As the core water system of Guiyang City, the Nanming River not only serves as a critical source of domestic and industrial water supply for the urban area but also plays an irreplaceable role in landscape shaping, ecological regulation, and biodiversity conservation [1]. With the global acceleration of urbanization [2], urban river ecosystems are increasingly subjected to dual pressures from land-use change and environmental pollution, which profoundly alter the structure and function of aquatic biological communities [3,4]. Rivers in the karst region of Southwest China, characterized by unique hydrological and ecological features driven by karst geology, represent typical examples of such vulnerable urban river systems [5]. In recent decades, the sharp decline in natural vegetation, expansion of construction land, and intensification of human activities within the basin have exacerbated soil erosion. Concurrently, the discharge of industrial wastewater, domestic

sewage, and agricultural non-point source pollution has led to increasingly prominent eutrophication and heavy metal accumulation [6], resulting in persistent water quality deterioration that poses a serious threat to river ecological health and urban sustainable development [7].

Zooplankton, as a key component in aquatic ecosystems, exhibit high sensitivity to water quality changes and occupy a central position in the food web [8,9], making them widely recognized as reliable indicator organisms for assessing aquatic ecosystem health [10]. By grazing on algae and microorganisms, zooplankton regulate algal population dynamics and maintain aquatic ecological balance [11]; they also serve as a primary food source for various fish species, playing a crucial role in energy flow and material cycling processes [12]. Nevertheless, due to their small size and diverse life-history strategies, the mechanisms underlying zooplankton responses to environmental changes remain inadequately understood [13]. This knowledge gap is particularly pronounced in the karst region of Southwest China, where urban rivers exhibit high habitat heterogeneity shaped by unique geological and hydrological conditions. Consequently, studies on the ecological responses of zooplankton to urbanization stress in this specific region remain relatively scarce [14]. Urbanization directly alters the physicochemical properties of water bodies by modifying land-use patterns and introducing exogenous pollutants (e.g., nutrients and heavy metals), thereby significantly impacting zooplankton community structure [15]. Previous studies have demonstrated that eutrophication-induced algal blooms and subsequent fluctuations in dissolved oxygen can trigger zooplankton population collapses [16], while heavy metal pollution can inhibit their reproduction and growth, leading to reduced species richness [17]. Additionally, zooplankton can act as vectors for pollutant transfer within the food web, amplifying ecological risks [18]. To date, most research on the aquatic environment of the Nanming River Basin has focused on physicochemical water quality indicators and microbial communities. Systematic investigations into the zooplankton community—particularly their response mechanisms along urbanization gradients and analyses using coupled models—remain insufficient. Therefore, a systematic analysis of zooplankton structural changes and taxonomic group responses along urbanization gradients is crucial for revealing the evolutionary patterns of aquatic ecosystems under anthropogenic disturbance.

Urbanization is a long-term, cumulative process for which historical ecological data are often limited. The “space-for-time substitution” method has thus emerged as an effective approach to elucidate the ecological effects of urbanization [19]. By establishing sampling sites along a spatial gradient representing different urbanization intensities, this method enables the analysis of community–environment relationships within a relatively short timeframe [20,21]. Based on this rationale, the Nanming River was selected as the study area. A comprehensive analysis was conducted to explore the relationships among water physicochemical properties, land-use types, and the zooplankton community. The specific objectives of this study were to: (1) clarify the variation characteristics of zooplankton species diversity and community structure along the urbanization gradient; (2) analyze the differential regulatory effects of key environmental factors (heavy metals and nutrients) on the density of different taxonomic groups (rotifers, cladocerans, copepods) and identify their ecological thresholds; (3) reveal the direct and indirect pathways through which urbanization—mediated by land use and aquatic environmental factors—influences the structure of zooplankton taxonomic groups. This research aims to provide a theoretical basis and practical guidance for the ecological restoration, biodiversity conservation, and scientific management of the Nanming River and similar plateau urban rivers in the karst region of Southwest China.

2. Materials and Methods

2.1. Study Area and Sampling Site Design

The Nanming River Basin ($26^{\circ}23'–26^{\circ}35' \text{ N}$, $106^{\circ}37'–106^{\circ}52' \text{ E}$) is located in the core area of Guiyang City, Southwest China (Figure 1). With a total length of 118 km and an average annual precipitation of 1000–1200 mm (Guiyang Water Resources Bulletin, 2024), the basin serves as a critical waterbody for urban water supply, flood regulation, and the maintenance of regional ecological balance. As a typical urban river in the karst region of Southwest China, the Nanming River not only undertakes important socio-economic functions but also holds irreplaceable ecological value in sustaining aquatic biodiversity and shaping urban landscape patterns [22].

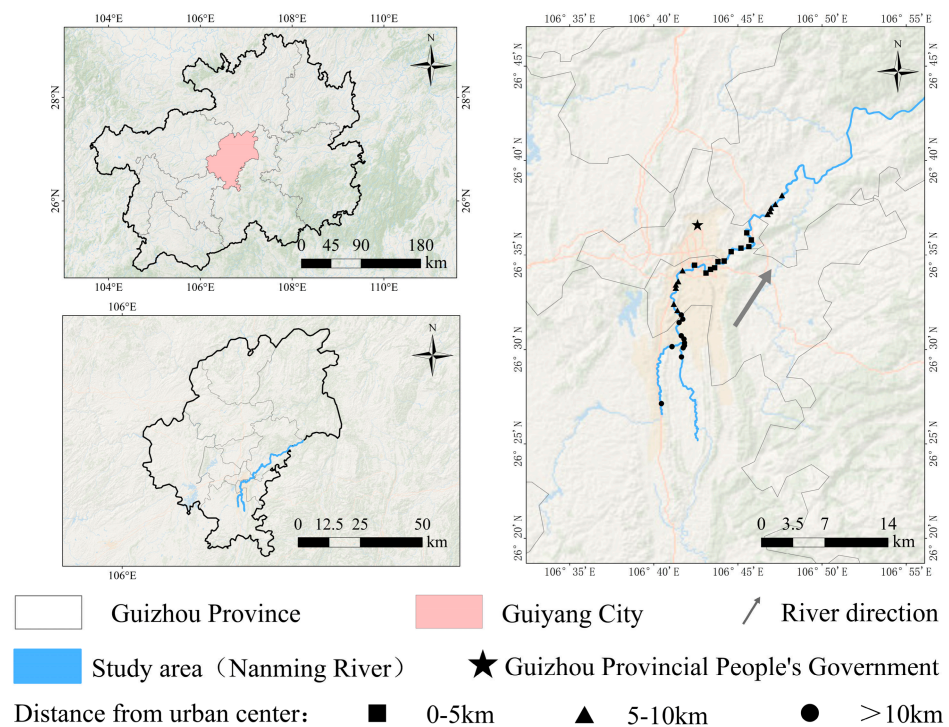


Figure 1. Sampling area map of Nanming River in Guiyang City.

In October 2018, 33 sampling sites were established along the river course of the Nanming River Basin, forming an urbanization gradient from upstream exurban areas to downstream urban areas. Site classification was based on two key criteria: (1) the shortest geographical distance from the city center (Guizhou Provincial People's Government (106.71° E , 26.61° N), located in Yunyan District—the political and geographical center of Guiyang City—was selected as the reference point for calculating the shortest geographical distance), which was calculated using the Euclidean distance tool in ArcGIS 10.8 software; and (2) the characteristics of riparian land use types (predominantly built-up land in urban areas, with increasing proportions of cropland and forestland in suburban and exurban areas) and the distribution of major pollution sources. The two criteria were used in combination. Sites were first assigned to three zones according to distance thresholds from the city center. This preliminary classification was then checked against riparian land use composition and the distribution of major pollution sources. Where the distance-based classification did not fully match the local land use and pollution-source context, the site was assigned to the zone that best represented its actual urbanization intensity. All sites were categorized into three groups: urban area (0–5 km from the city center, $n = 11$), suburban area (5–10 km from the city center, $n = 11$), and exurban area (>10 km from the city center, $n = 11$) (Figure 2).

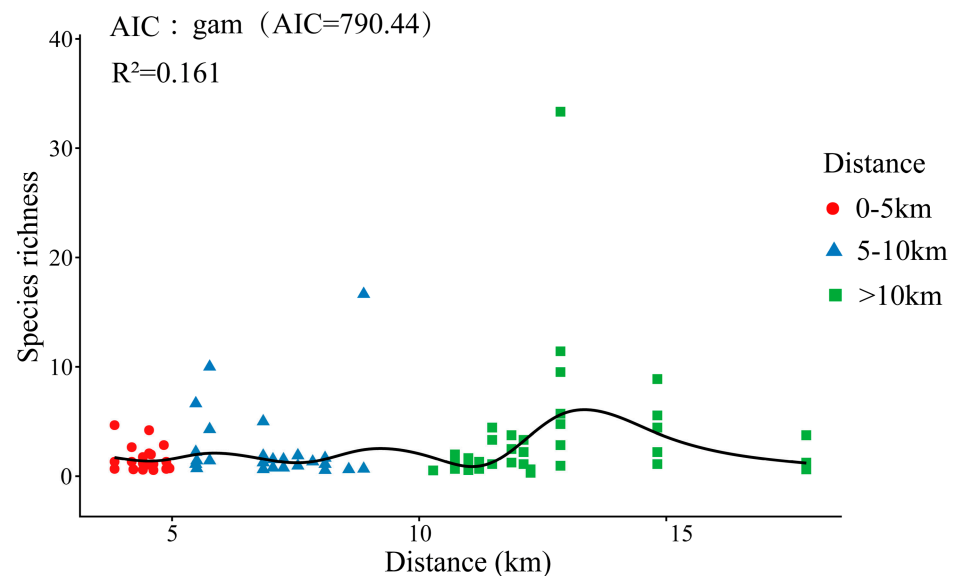


Figure 2. Relationship between zooplankton species richness and distance from the city center.

2.2. Water Sample Collection and Physicochemical Analysis

2.2.1. Water Sample Collection and In-Situ Measurement

At each sampling site, in-situ measurements of water temperature (WT), pH, dissolved oxygen (DO), electrical conductivity (EC), and turbidity (NTU) were performed using a portable water quality analyzer (HI98194, Hanna Instruments, Woonsocket, RI, USA). Integrated water samples were collected by mixing surface water (0.5 m below the water surface) and bottom water (0.5 m above the riverbed) at a 1:1 volume ratio using a 2.5 L plexiglass vertical water sampler (model PWS-2.5, Beijing Purkinje General Instrument Co., Ltd., Beijing, China). The sampler was slowly lowered to the target depth, opened to allow water to fill completely, then sealed and lifted to the surface to avoid sample disturbance. Two types of mixed water samples were collected: one 1 L aliquot for nutrient analysis and another 1 L aliquot for heavy metal analysis. Immediately after collection, all water samples were stored in a 4 °C refrigerated container and transported to the laboratory for processing within 24 h to ensure sample integrity.

2.2.2. Laboratory Analysis

Nutrient indicators, including total nitrogen (TN), total phosphorus (TP), and ammonia nitrogen (NH₃-N), were determined following the protocols described in the HACH Water Analysis Handbook using a HACH DR 2800 spectrophotometer [23]. Heavy metals, including copper (Cu), lead (Pb), mercury (Hg), arsenic (As), and zinc (Zn), were analyzed using a WFX-210 atomic absorption spectrophotometer (Beijing Beifen-Ruili Analytical Instrument [Group] Co., Ltd., Beijing, China). To ensure data reliability, strict quality-control procedures were implemented throughout the analyses. One procedural blank and one certified reference material, GBW08607, were analyzed with every batch of 10 samples. GBW08607 was used to verify the analytical recoveries of Cu, Pb, and Zn, which ranged from 92% to 108% [24]. All heavy-metal and nutrient analyses were performed in duplicate, and the relative standard deviations (RSDs) of duplicate measurements were below 5%.

2.3. Zooplankton Sampling and Identification

Qualitative zooplankton samples were collected using a 13-μm mesh plankton net. At each site, the net was held at approximately 0.5 m below the water surface and towed within an approximately 5 m sampling reach. During each tow, the net was moved laterally from one side of the sampling point toward the channel center, then to the opposite side,

and finally back through the center, so that both sides of the local channel and the central flow were covered. The towing speed was maintained at approximately 0.5 m/s, and this lateral sweeping procedure was repeated three times at each site to improve sampling representativeness. Collected samples were preserved in a 4% formaldehyde solution [25]. For quantitative sampling, a 25- μ m mesh plankton net was used to filter 15 L of water from both the surface (0.5 m) and bottom (0.5 m) layers, resulting in a total integrated water volume of 30 L per site. The filtered samples were concentrated via the plankton net, and the concentrates were fixed and preserved in 4% formalin [26] before transportation to the laboratory for taxonomic identification and enumeration.

For quantitative enumeration, each sample was thoroughly homogenized, and a 1 mL subsample was transferred to a Sedgwick–Rafter counting chamber. Species identification and individual counting were conducted under an optical microscope (BX53, Olympus, Japan). Species were identified to the lowest possible taxonomic level using standard taxonomic keys [27]. Each subsample was counted three times, and the average value was used to calculate zooplankton abundance. The abundance (N , ind./L) was computed using the following formula:

$$N = \frac{N_s \times V_t}{V_s \times V_a} \quad (1)$$

where:

N = zooplankton abundance (ind./L);

V_s = average number of individuals counted in 1 mL subsample;

V_t = total volume of the concentrated sample (mL);

V_s = volume of the counted subsample (1 mL);

V_a = volume of the original water sample (L).

2.4. Data Processing and Analysis

All statistical analyses were performed using R software (version 4.3.1). One-way analysis of variance (ANOVA) followed by the Least Significant Difference (LSD) post-hoc test was used to compare differences in environmental factors and biological indicators among the three urbanization zones, with statistical significance set at $p < 0.05$. In the figures and tables, “ns” denotes non-significant differences ($p \geq 0.05$), whereas different lowercase letters indicate statistically significant differences among groups at $p < 0.05$. The Shannon–Wiener diversity index was calculated following Shannon (1948) [28]. Non-metric Multidimensional Scaling (NMDS) and ANOSIM analyses were performed using the R package *vegan*. The exact package version used in the analysis was recorded and reported to ensure reproducibility; in the present analysis, *vegan* version 2.7–3 was used [29]. Gradient Boosting Models (GBM) were constructed using the “gbm” package [30] to evaluate the influence of key environmental factors on the densities of rotifers, cladocerans, and copepods, and to quantify the relative importance of each factor. The key parameters for GBM were set as follows: learning rate = 0.01, number of trees ($n.trees$) = 1000, and interaction depth = 3. The optimal parameter combination was determined through 5-fold cross-validation to avoid overfitting.

Structural Equation Modeling (SEM) was conducted using the “lavaan” package [31,32] to clarify the causal relationships among urbanization, environmental factors, and zooplankton taxonomic groups. Urbanization was represented by two complementary variables in the SEM: (1) “Urb” (urban land proportion), a continuous variable reflecting the intensity of built-up land within the riparian zone, which directly captures the degree of urban land expansion; (2) “DsN” (distance from city center), a continuous variable quantifying the spatial gradient of urbanization from the city center outward. Hg was selected as a representative heavy metal due to its significant positive correlations with other heavy

metals (Cu, Zn, Pb; $r > 0.7$, $p < 0.001$). TN was chosen as a representative nutrient because it exhibited a significant correlation with TP ($r = 0.68$, $p < 0.01$) and a larger coefficient of variation, indicating its sensitivity to urbanization gradients. The model was iteratively modified to optimize fit, and the final model exhibited good fit statistics: $X^2/df = 1.32$, Root Mean Square Error of Approximation (RMSEA) = 0.06, and Comparative Fit Index (CFI) = 0.95. All path coefficients were estimated using the maximum likelihood method, with standard errors reported.

We acknowledge that the sample size of 33 sites is relatively small for SEM, which may limit the statistical power of the model. However, the final model exhibited good fit statistics, and all path coefficients were statistically significant ($p < 0.05$), suggesting that the results are reliable for exploratory purposes. Future studies with larger sample sizes are needed to confirm these findings.

3. Results

3.1. Zooplankton Community Composition and Spatial Patterns of Diversity

In this study, a total of 33 zooplankton species were identified across the 33 sampling sites, belonging to 13 families and 25 genera. Rotifers were the dominant taxon, comprising 22 species and accounting for 84.62% of the total species count. This was followed by cladocerans with 3 species (11.54%) and copepods with 1 species (*Mesocyclops leuckarti*, 3.84%), which ranked second in total abundance among all taxonomic groups.

The individual abundance per unit volume (ind./L) showed an overall increasing trend with decreasing urbanization intensity, although the linear regression relationship between abundance and distance from the city center was not statistically significant ($R^2 = 0.161$, $p = 0.052$) (Figure 2). However, one-way ANOVA revealed significant differences in mean abundance among the three zones: the exurban area exhibited the highest individual abundance (128 ± 32 ind./L), which was significantly higher than that in the suburban (86 ± 24 ind./L) and urban (65 ± 18 ind./L) areas ($p < 0.05$ for both comparisons). No significant difference was observed between the urban and suburban areas ($p = 0.21$).

The Shannon–Wiener diversity index followed a similar trend, increasing significantly from the urban (3.82 ± 2.05) to suburban (4.73 ± 2.08) and exurban (5.18 ± 2.56) areas ($p < 0.05$). NMDS analysis (stress value = 0.12) combined with ANOSIM test results ($R = 0.42$, $p < 0.01$) indicated significant spatial differentiation in zooplankton community structure (Figure 3). The exurban community formed a distinct cluster, significantly separated from the urban and suburban communities. In contrast, the urban and suburban communities showed partial overlap, suggesting a degree homogenization [33]. *Lepadella ovalis* and *Monostyla angulata* were common dominant species across all gradients. *Lecane cornuta* showed a significantly higher relative abundance in the exurban area, making it a characteristic indicator species for that region. The variation in species richness reflects subtle differentiation in zooplankton community structure under different environmental pressures [34].

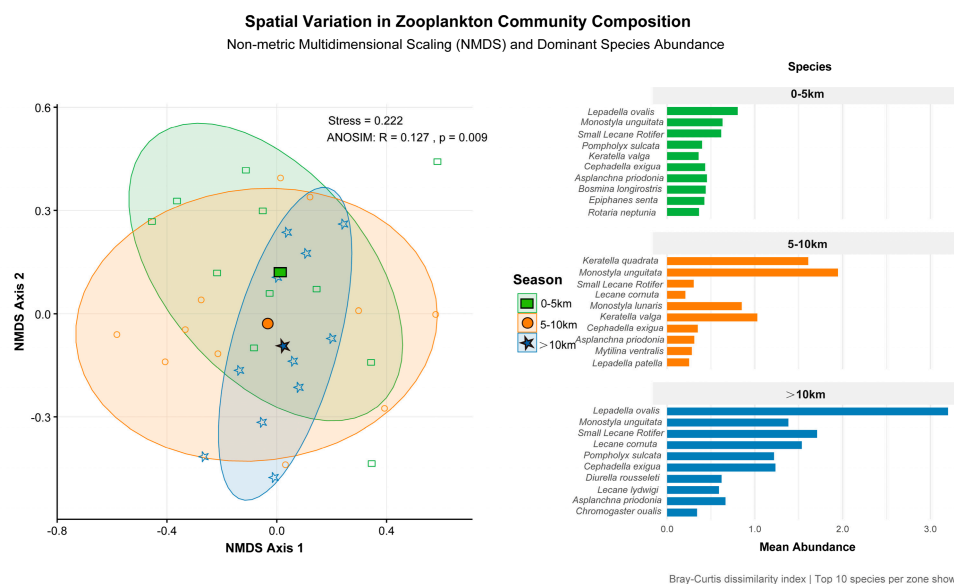


Figure 3. Spatial distribution characteristics and dominant species of the zooplankton community in Nanming River based on Non-metric Multidimensional Scaling (NMDS).

3.2. Characteristics of Environmental Factors Along the Urbanization Gradient

Water quality was assessed according to the Environmental Quality Standards for Surface Water (GB 3838-2002) [24]. The assessment indicated severe water pollution in the Nanming River. Overall, 63.6% of all sampling sites were classified as inferior to Grade V, the lowest water quality class. Urban sites had the poorest water quality, with 63.6% classified as inferior to Grade V and 27.3% as Grade IV. Suburban sites showed even higher proportions of inferior Grade V water (72.7%), while exurban sites exhibited moderate improvement, with 54.5% inferior to Grade V and 18.2% meeting Grade III standards.

Analysis of environmental factors revealed that heavy metal pollution was closely associated with urbanization intensity (Table 1) [35]. Concentrations of Hg, Cu, and Pb were highest in urban areas and generally decreased with increasing distance from the city center. Pb and Zn concentrations showed significant differences among the three zones ($p < 0.05$). For nutrients, TN concentrations differed significantly between exurban areas and both urban and suburban areas ($p < 0.05$), while TP concentrations showed significant differences only between urban and exurban areas ($p < 0.05$). Urban areas had high average TN (3.45 mg/L) and TP (0.272 mg/L) concentrations, indicating severe eutrophication. Suburban areas had the highest mean TN concentration (3.72 ± 0.13 mg/L), slightly exceeding that of urban areas.

Table 1. Water quality indicators at different distance scales.

Environmental Factor	0–5 km	Distance Scale 5–10 km	>10 km
Hg ($\mu\text{g/L}$)	0.222 ± 0.234 a	0.104 ± 0.062 a	0.049 ± 0.018 a
As ($\mu\text{g/L}$)	1.260 ± 1.943 a	1.028 ± 0.148 a	0.975 ± 0.036 a
Cu ($\mu\text{g/L}$)	2.501 ± 0.354 a	1.927 ± 0.435 a	2.149 ± 0.631 a
Pb ($\mu\text{g/L}$)	25.5 ± 1.8 a	22.4 ± 1.7 ab	15.4 ± 5.9 b
Zn ($\mu\text{g/L}$)	19.0 ± 2.4 a	21.5 ± 3.4 b	12.8 ± 2.0 b
TN (mg/L)	3.45 ± 0.43 a	3.72 ± 0.13 b	1.93 ± 1.10 b
TP (mg/L)	0.272 ± 0.033 a	0.40 ± 0.38 ab	0.126 ± 0.087 b
NH ₃ -N (mg/L)	0.40 ± 0.38 a	0.19 ± 0.21 a	0.69 ± 0.21 a

Note: letters indicate statistically significant differences at $p < 0.05$ level; different letters denote significant differences between groups.

3.3. Driving Effects of Environmental Factors on the Zooplankton Community

Pearson correlation analysis was used to examine pairwise linear associations between environmental factors and total zooplankton abundance across different spatial scales and land use types (Figure 4). On the distance scale, abundance in the urban area was primarily inhibited by $\text{NH}_3\text{-N}$ and As. In the suburban area, it showed positive correlations with Pb and As, but significant negative correlations with TN and Zn. In exurban areas, abundance was negatively correlated with Hg and Zn. Regarding land use types, zooplankton abundance in built-up land was suppressed by heavy metals such as Hg and Pb. In cropland, abundance showed a strong positive correlation with nutrient inputs, while being inhibited by pollutants like As and Zn. In contrast, zooplankton in forestland and grassland exhibited greater tolerance to heavy metals. These differences reflect how the intensity and patterns of human activities collectively shape zooplankton habitats [36].

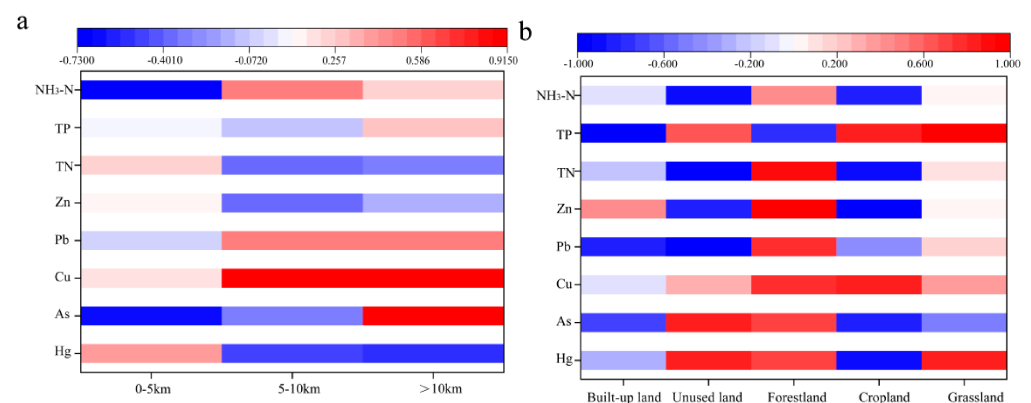


Figure 4. Pearson correlation between environmental factors and zooplankton abundance under different urbanization gradients (a) and land use types (b).

We examined the spatial distribution of zooplankton densities across three major taxonomic groups (rotifers, cladocerans, and copepods), and found significant spatial heterogeneity among them within the urbanization context. The occurrence frequency of the different groups was in the order of rotifers > copepods > cladocerans (Figure 5). However, all three groups shared a common characteristic: they tended to have higher densities in waters with lower pollution and less disturbance. The GBM was further employed to analyze the influence of key environmental factors on the density of each group (Figure 6). The results revealed significant differences in how the groups responded to environmental stress. Cu was the most influential factor affecting rotifer density, with its relative importance considerably higher than that of other factors. Zn and Cu were the primary drivers influencing copepod density. For cladocerans, $\text{NH}_3\text{-N}$ and TN had the most prominent effects. These findings indicate that heavy metals (Cu and Zn) and nutrients (TN and $\text{NH}_3\text{-N}$) exert taxon-specific effects on the densities of different zooplankton taxonomic groups, reflecting differences in ecological niches and physiological sensitivity among rotifers, cladocerans, and copepods.

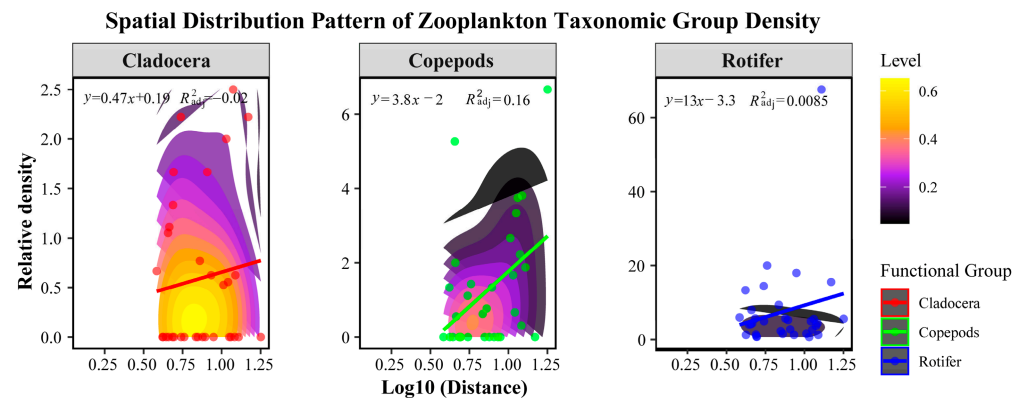


Figure 5. Spatial distribution patterns of the densities of different zooplankton taxonomic groups.

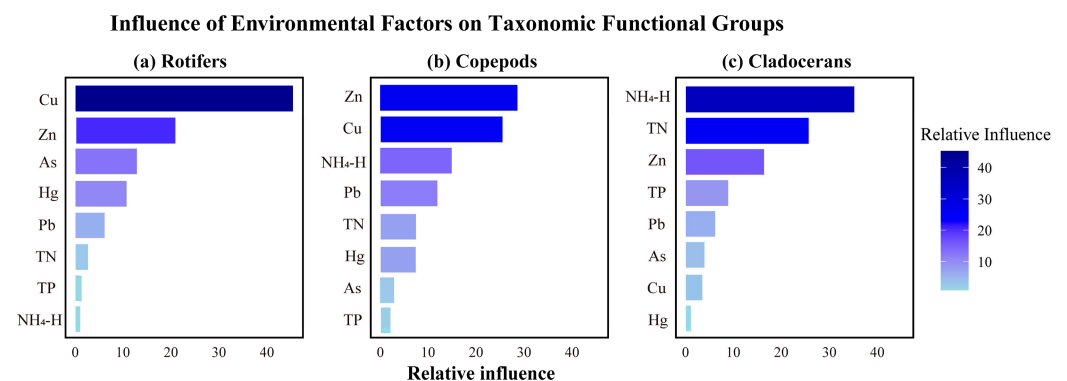


Figure 6. The influence of environmental factors on the densities of different taxonomic groups. (a) Rotifers; (b) Radulids; (c) Branchiopods.

3.4. Path Analysis of Urbanization Effects on Zooplankton Taxonomic Groups

To systematically elucidate the causal relationships among various driving factors, we constructed a SEM (Figure 7). The model demonstrated a good fit ($X^2/df = 1.32$, $RMSEA = 0.06$, $CFI = 0.95$), revealing the pathways through which urbanization affects zooplankton taxonomic groups both directly and indirectly. Cladocerans were not included in the final SEM because their abundance was extremely low across all sampling sites (average density < 2 ind./L), and preliminary path analysis showed that all path coefficients related to cladocerans were not statistically significant ($p > 0.05$), indicating that cladoceran communities were not strongly driven by the environmental factors measured in this study.

The model identified two main pathways for urbanization effects. The direct pathway primarily involved urban land expansion (Urban), which had a strong direct positive driving effect on heavy metals (represented by Hg) (path coefficient, $e = 0.82$). The accumulation of heavy metals, in turn, directly suppressed the density of copepods ($e = -0.33$). This indicates that urban construction is a major source of heavy metal pollution and directly exerts toxic effects on sensitive copepods. The indirect pathway showed that the distance gradient indirectly influenced zooplankton by regulating nutrients. Specifically, as the distance from the city center increased and urbanization pressure decreased [37], the TN content in the water declined significantly ($e = -0.51$). This created a more suitable habitat for rotifers, leading to an increase in their density ($e = 0.37$). Furthermore, the model revealed a significant positive correlation between rotifers and copepods ($e = 0.75$), suggesting potential similarities in resource requirements or niche overlap between the two groups [38]. In summary, the SEM clearly delineates how urbanization shapes the structure of zooplankton taxonomic groups through dual pathways: the direct inhibitory path of

“urban land → heavy metals → copepods” and the indirect regulatory path of “distance gradient → nutrients → rotifers”.

Urbanization Effects on Zooplankton Taxonomic Groups.

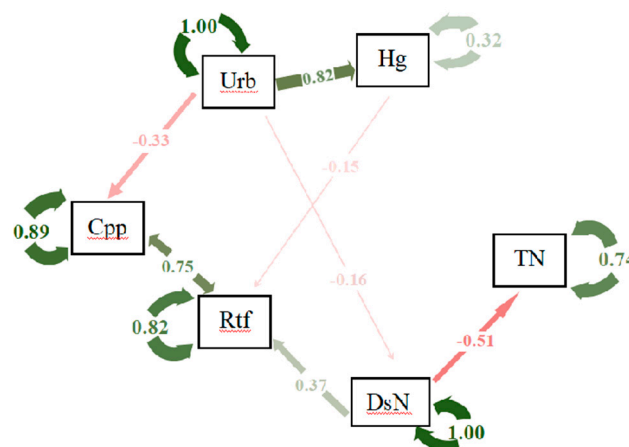


Figure 7. The structural equation model (SEM) illustrating the direct and indirect pathways among urbanization, zooplankton taxonomic groups, and environmental factors. Bold lines and numbers indicate statistically significant path coefficients ($p < 0.05$). ‘Urb’ and ‘Hg’ represent urban land and heavy metals (represented by mercury), respectively; ‘TN’ represents nutrients (represented by total nitrogen); ‘DsN’ represents the distance numeric value (a quantification of the urbanization gradient); ‘Rtf’ and ‘Cpp’ represent rotifers and copepods, respectively.

4. Discussion

4.1. Structural Succession and Habitat Homogenization of Zooplankton Communities Along the Urbanization Gradient

This study clearly reveals a regular pattern of zooplankton community succession along the urbanization gradient in the Nanming River. Both species richness and the Shannon–Wiener diversity index increased significantly with decreasing urbanization intensity and were markedly higher in the exurban area than in the urban area. This pattern is consistent with the widely reported negative relationship between urbanization intensity and biodiversity, whereby increasing urbanization is generally associated with biodiversity loss [39]. Rotifers, as the dominant taxon constituting 84.62%, possess ecological traits characteristic of an “r-strategy”—such as short reproductive cycles and high tolerance—granting them a strong competitive advantage in the heavily polluted waters [40]. NMDS analysis further corroborates the homogenizing effect of urbanization at the community composition level: the exurban community formed a distinct cluster, while the urban and suburban communities exhibited high overlap. This indicates that intensive human activities such as channelization and point-source pollution erase the natural heterogeneity of habitats, leading to simplification and convergence of biological communities [41].

As a lotic ecosystem, the Nanming River has a longitudinal flow regime that transports pollutants, nutrients, and planktonic individuals from upstream reaches to downstream reaches. Zooplankton communities in rivers may also be supplemented by inputs from adjacent water bodies, such as tributaries, lakes, and reservoirs, which makes it difficult to distinguish resident individuals from transient individuals transported downstream. Therefore, the spatial patterns observed in this study may reflect both the direct effects of local environmental conditions and the downstream propagation of organisms and pollutants originating from upstream and connected water bodies. Future studies should incorporate hydrological parameters, such as flow velocity and discharge, and sample

adjacent water bodies to better evaluate source–sink dynamics of zooplankton communities in urban rivers.

Notably, the karst region where the Nanming River is located features a developed network of subterranean rivers. This geological characteristic may provide additional pathways for pollutant migration, accelerating the dispersal of urban pollutants to suburban areas and thereby exacerbating habitat similarity between these two zones [42]. This phenomenon could be a crucial reason for the lack of significant differences in their community structures.

The observed differences in correlation patterns across land use types reflect how different intensities and patterns of human activities shape zooplankton habitats. Built-up land areas are characterized by high levels of industrial and domestic pollution, which suppress zooplankton abundance. Cropland areas receive nutrient inputs from agricultural runoff, which can promote zooplankton growth. Forestland and grassland areas have minimal human disturbance, resulting in more stable environmental conditions.

4.2. Differential Regulation and Ecological Thresholds of Key Environmental Factors on Zooplankton Taxonomic Groups

This study identified heavy metals Cu and Zn and nutrients TN and NH₃-N as key environmental factors regulating the zooplankton community, with their impacts demonstrating significant taxonomic group specificity. Results from the GBM indicated that rotifers were most sensitive to Cu, copepods were jointly constrained by Zn and Cu, and cladocerans were most sensitive to changes in NH₃-N and TN. This difference in response is closely linked to the physiological and ecological characteristics of each taxonomic group. As filter feeders, cladocerans, with their relatively larger body size and longer turnover cycles, are generally more sensitive to toxic substances in water [43]. In contrast, many rotifer species, leveraging their high reproductive efficiency and physiological resilience to harsh conditions, gain a survival advantage in eutrophic and heavy metal-polluted waters [44,45]. This explains why rotifer density was highest in the most polluted urban area, while cladocerans and copepods, which have higher environmental quality requirements, exhibited higher densities in the exurban area with relatively better water quality.

The higher TN concentration in suburban areas compared to urban areas can be attributed to extensive agricultural non-point source pollution in this zone. Suburban areas have large areas of cropland ($35.8 \pm 6.9\%$), where nitrogen fertilizers are widely used. In contrast, exurban areas have less intensive agriculture and more forestland, which acts as a natural buffer for nutrient runoff, resulting in lower TN concentrations.

The lack of significant negative correlations between zooplankton abundance and heavy metals in forestland and grassland areas may reflect lower pollution levels in these regions rather than greater tolerance of the zooplankton communities. Further experimental studies are needed to directly assess physiological tolerance.

Rotifers showed the strongest adaptability to urban pollution, being present at all sampling sites. Copepods had a wider distribution range than cladocerans but were more sensitive to heavy metal pollution than rotifers, as indicated by the significant negative path coefficient in the SEM ($e = -0.33$). Cladocerans were the most sensitive group, being absent from many heavily polluted sites.

More importantly, based on breakpoint analysis derived from the GBM, we identified ecological thresholds for the key environmental factors. For instance, the critical concentration of Cu affecting rotifer density was approximately 1.8 µg/L, while the critical concentration of TN affecting cladoceran density was approximately 2.0 mg/L. When environmental factor concentrations exceed these thresholds, the densities of the corresponding taxonomic groups may decline sharply, potentially leading to community structure collapse.

This finding provides direct scientific evidence for formulating water quality standards based on ecosystem health.

4.3. Driving Pathways of Urbanization Effects on Zooplankton Communities and Management Implications

This study employed SEM to disentangle the complex pathways through which urbanization affects zooplankton communities, distinguishing between direct and indirect effects [46]. The SEM results confirmed that urbanization operates through two core pathways: first, the direct toxicity pathway of “land use → heavy metals,” whereby urban land expansion directly leads to heavy metal pollution such as Hg, thereby suppressing pollution-sensitive copepods [47]; second, the indirect habitat alteration pathway of “distance gradient → nutrients,” whereby increasing distance from the city center (and the concomitant decrease in urbanization pressure) results in lower levels of nutrients such as TN, thereby favoring the proliferation of specific taxa like rotifers [48,49]. This finding moves beyond traditional simple correlation analyses, revealing the hierarchical nature of the driving mechanisms.

These results carry clear implications for the management of karst urban rivers, suggesting the need for zoned and targeted precision strategies. In urban areas, management should focus on stringent control of heavy metal emissions, particularly Hg and Cu from construction and industrial activities. For suburban zones, simultaneous attention to industrial point sources, such as Zn, and agricultural non-point sources, including total nitrogen and total phosphorus, is essential. In exurban areas, the priority shifts to preserving existing low-pollution water bodies and maintaining habitat integrity. For example, the ecological threshold of 1.8 µg/L for Cu identified in this study can directly inform the revision of industrial wastewater discharge standards in urban settings. Additionally, the dominant species like *Lecane cornuta* and community parameters such as a rotifer proportion exceeding 90% can serve as bioindicators for rapid water quality assessment. These indicators support the development of a zooplankton-based rapid evaluation framework, facilitating long-term ecological monitoring and adaptive management.

5. Conclusions

This study systematically elucidates the integrated impact mechanisms of urbanization on zooplankton communities in the Nanming River, a representative karst urban river in Southwest China. The key findings are threefold. First, zooplankton diversity exhibited a significant increasing trend with decreasing urbanization intensity, reflecting a negative response to anthropogenic disturbance. Rotifers, characterized by strong pollution tolerance and rapid reproduction, emerged as the dominant taxon across the study area, accounting for 84.62% of total species. Community structure analysis revealed that the exurban area harbored a significantly distinct zooplankton assemblage compared to urban and suburban areas, whereas the latter two exhibited evident habitat homogenization resulting from intensive human activities such as land-use conversion and pollutant discharge.

Second, heavy metals, particularly Cu and Zn, together with nutrients including TN and NH₃-N, were identified as the key environmental drivers shaping zooplankton community structure. These factors exerted significant differential effects on the three major taxonomic groups: Cu was the most critical factor affecting rotifer density; copepod distribution and abundance were jointly regulated by Zn and Cu; and cladoceran communities were primarily driven by TN and NH₃-N. This taxonomic group-specific response highlights the importance of considering taxonomic differences when assessing the ecological effects of urbanization on aquatic biota.

Third, structural equation modeling revealed two distinct pathways through which urbanization impacts zooplankton communities: a direct toxicity pathway, i.e., urban land expansion leading to heavy metal accumulation and subsequent copepod community degradation, and an indirect habitat alteration pathway, i.e., urbanization gradient driving nutrient enrichment and promoting rotifer dominance. Among taxonomic groups, copepods exhibited high sensitivity to urbanization-related stressors such as heavy metal pollution, whereas rotifers demonstrated stronger environmental adaptability, likely attributable to their r-selected life-history strategies, including short generation time and high fecundity, as well as broad ecological niches.

These findings provide a clear scientific basis and actionable recommendations for the ecological management and restoration of karst urban rivers during the autumn season. Specifically, we propose three key strategies: implement zoned management based on urbanization gradients, adopting differentiated pollution control and ecological protection measures for urban, suburban, and exurban areas, such as strengthening riparian buffer zones in urban areas and promoting ecological agriculture in suburban areas to reduce non-point source pollution; enforce strict source control focusing on reducing industrial heavy metal emissions in urban areas and agricultural non-point source pollution, particularly nitrogen and phosphorus runoff, in suburban areas; and establish a biological monitoring system integrating key indicator species, e.g., copepods as sensitive indicators and *Lecane cornuta* as a candidate indicator species for low-disturbance river reaches, along with taxonomic group characteristics such as rotifer dominance as a pollution indicator, to support rapid and accurate water quality assessment. Further validation across multiple river systems and temporal scales is required to verify the universality of these candidate bioindicators.

Despite its contributions, this study has certain limitations. The space-for-time substitution method, while effective for revealing spatial differentiation patterns, cannot fully capture temporal dynamics. Second, this study was conducted only in October 2018, representing a single season. Zooplankton communities exhibit strong seasonal variation, so future studies should include sampling across multiple seasons to capture temporal dynamics. Third, this study did not explicitly consider the effects of river flow and upstream–downstream connectivity on zooplankton communities. Future research should incorporate long-term time series data, including seasonal and interannual variations, to clarify the temporal stability of zooplankton community responses to urbanization. Additionally, expanding the scope of environmental factors to include emerging contaminants such as microplastics and pharmaceuticals, hydrological conditions including flow velocity and water depth, and riparian vegetation cover will enable a more comprehensive understanding of the complex mechanisms underlying the evolution of karst urban river ecosystems. Such research will provide deeper scientific support for regional ecological restoration, biodiversity conservation, and sustainable urban development in karst regions.

We acknowledge that the low species richness of cladocerans (3 species) and copepods (1 species) limits the generalizability of our findings regarding these taxonomic groups. This low diversity is likely a result of the severe pollution in the Nanming River, which has eliminated more sensitive species. Future studies should include less polluted reference rivers to provide a more comprehensive understanding of zooplankton community responses to urbanization.

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

Funding: This work was supported by the National Natural Science Foundation of China (No. 42463007) and the Guizhou Provincial Science and Technology Program (QKHPT-ZSYS[2025]004; QKHPT-YWZ[2024]006; QKHFQ[2024]016; QKHFQ[2023]010; QKHPT-JSZX[2025]011).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: Author Long He was employed by the company Guizhou Zhuxin Water Environmental Industry Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Mostofa, K.M.G.; Wu, F.; Liu, C.Q.; Fang, W.L.; Yuan, J.; Ying, W.L.; Wen, L.; Yi, M. Characterization of Nanming River (southwestern China) sewerage-impacted pollution using an excitation-emission matrix and PARAFAC. *Limnology* **2010**, *11*, 217–231. [\[CrossRef\]](#)
- Timon, M.P.; Pickett, S.T.A.; Grimm, N.B.; Niemelä, J.; Alberti, M.; Elmqvist, T.; Weber, C.; Haase, D.; Breuste, J.; Qureshi, S. Advancing Urban Ecology toward a Science of Cities. *Bioscience* **2016**, *66*, 198–212. [\[CrossRef\]](#)
- Gao, X.; Han, G.; Zhang, S.; Zeng, J. Sources, Water Quality, and Potential Risk Assessment of Heavy Metal Contamination in Typical Megacity River: Insights from Monte Carlo Simulation. *Water* **2025**, *17*, 224. [\[CrossRef\]](#)
- Hu, X.; Zuo, D.; Xu, Z.; Huang, Z.; Liu, B.; Han, Y.; Bi, Y. Response of macroinvertebrate community to water quality factors and aquatic ecosystem health assessment in a typical river in Beijing, China. *Environ. Res.* **2022**, *212*, 113474. [\[CrossRef\]](#) [\[PubMed\]](#)
- Wang, W.; Li, S.L.; Zhong, J.; Slowinski, S.; Li, S.; Li, C.; Su, J.; Yi, Y.; Dong, K.; Xu, S.; et al. Carbonate mineral dissolution and photosynthesis-induced precipitation regulate inorganic carbon cycling along the karst river-reservoir continuum, SW China. *J. Hydrol.* **2022**, *615*, 9. [\[CrossRef\]](#)
- Yang, J.L.; Li, Z.F.; Jeppesen, E.; Moi, D.A.; Liu, Y.; Mo, Y.; Bai, X.; Wang, F.; Xie, Z.; Zhang, J. Urbanization alters river multifunctionality by reducing macroinvertebrate diversity in highly human-impacted plain river networks. *Limnol. Oceanogr.* **2025**, *70*, 3447–3461. [\[CrossRef\]](#)
- Tao, X.Z.; Tang, C.Y.; Wu, P.; Han, Z.; Zhang, C.; Zhang, Y. Occurrence and behaviour of nonylphenol and octylphenol in Nanming River, Guiyang City, China. *J. Environ. Monit.* **2011**, *13*, 3269–3276. [\[CrossRef\]](#) [\[PubMed\]](#)
- Basu, B.K.; Pick, F.R. Factors regulating phytoplankton and zooplankton biomass in temperate rivers. *Limnol. Oceanogr.* **1996**, *41*, 1572–1577. [\[CrossRef\]](#)
- Heneghan, R.F.; Everett, J.D.; Blanchard, J.L.; Sykes, P.; Richardson, A.J. Climate-driven zooplankton shifts cause large-scale declines in food quality for fish. *Nat. Clim. Change* **2023**, *13*, 470–477. [\[CrossRef\]](#)
- Long, S.; Hamilton, P.B.; Wang, C.; Li, C.; Zhao, Z.; Wu, P.; Hua, L.; Wang, X.; Uddin, M.M.; Xu, F. Key role of plankton species and nutrients on biomagnification of PAHs in the micro-food chain: A case study in plateau reservoirs of Guizhou, China. *J. Hazard. Mater.* **2024**, *475*, 14. [\[CrossRef\]](#) [\[PubMed\]](#)
- Kovalenko, K.E.; Reavie, E.D.; Figary, S.; Rudstam, L.G.; Watkins, J.M.; Scofield, A.; Filstrup, C.T. Zooplankton-phytoplankton biomass and diversity relationships in the Great Lakes. *PLoS ONE* **2023**, *18*, 14. [\[CrossRef\]](#) [\[PubMed\]](#)
- He, R.; Hu, R.; Xiao, B.; ang, H.; Wei, J.; Wu, P. Niche and interspecific association of dominant zooplankton species near the Taishan coastal area in the South China Sea. *Mar. Environ. Res.* **2025**, *204*, 106929. [\[CrossRef\]](#) [\[PubMed\]](#)
- Castilho-Noll, M.S.M.; Perbiche-Neves, G.; Dos Santos, N.G.; Schwind, L.T.F.; Lansac-Tôha, F.M.; da Silva, A.C.S.; de Meira, B.R.; Joko, C.Y.; de Moraes-Júnior, C.S.; Silva, E.E.C.; et al. A review of 121 years of studies on the freshwater zooplankton of Brazil. *Limnology* **2023**, *100*, 126057. [\[CrossRef\]](#)
- Li, W.; Zou, J.; Yu, C.; Qiu, F.; Tan, H.; Du, Y.; Shi, J. Characterization of soil bacterial pathogens in peri-urban zones across population density gradients and land use patterns: Insights into pathogen diversity, composition, interactions, and community assembly processes. *Environ. Res.* **2025**, *285*, 122273. [\[CrossRef\]](#) [\[PubMed\]](#)

15. Shen, J.; Qin, G.; Yu, R.; Zhao, Y.; Yang, J.; An, S.; Liu, R.; Leng, X.; Wan, Y. Urbanization has changed the distribution pattern of zooplankton species diversity and the structure of functional groups. *Ecol. Indic.* **2021**, *120*, 106944. [\[CrossRef\]](#)
16. Liu, Z.; Yang, A.; Liu, J.; Xing, C.; Huang, S.; Huo, Y.; Yang, Z.; Huang, J.; Liu, W. Turnover of phytoplankton and zooplankton communities driven by human-induced disturbances and climate changes in a small urban coastal wetland. *Ecol. Indic.* **2023**, *157*, 111271. [\[CrossRef\]](#)
17. Gagneten, A.; Paggi, J. Effects of heavy metal contamination (Cr, Cu, Pb, Cd) and eutrophication on zooplankton in the lower basin of the Salado River (Argentina). *Water Air Soil Pollut.* **2009**, *198*, 317–334. [\[CrossRef\]](#)
18. Foster, K.L.; Stern, G.A.; Pazerniuk, M.A.; Hickie, B.; Walkusz, W.; Wang, F.; Macdonald, R.W. Mercury biomagnification in marine zooplankton food webs in Hudson Bay. *Environ. Sci. Technol.* **2012**, *46*, 12952–12959. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Lin, Y.M.; Cui, P.; Ge, Y.G. The succession characteristics of soil erosion during different vegetation succession stages in dry-hot river valley of Jinsha River, upper reaches of Yangtze River. *Ecol. Eng. J. Ecotechnol.* **2014**, *62*, 13–26. [\[CrossRef\]](#)
20. Shen, J.; Zhang, Z.; Liu, R.; Wang, Z.H. Ecological restoration of eroded karst utilizing pioneer moss and vascular plant species with selection based on vegetation diversity and underlying soil chemistry. *Int. J. Phytoremediat.* **2018**, *20*, 1369–1379. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Wang, J.; Fu, Z.; Qiao, H.; Liu, F. Assessment of eutrophication and water quality in the estuarine area of Lake Wuli, Lake Taihu, China. *Sci. Total Environ.* **2019**, *650*, 1392–1402. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Yuan, Z.; Li, Q.; Ma, X.; Han, M. Assessment of heavy metals contamination and water quality characterization in the Nanming River, Guizhou Province. *Environ. Geochem. Health* **2021**, *43*, 1273–1286. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Nollet, L.M.L.; Stocks, H.B. *Handbook of Water Analysis*; M. Dekker: New York, NY, USA, 2000. [\[CrossRef\]](#)
24. GB 3838-2002; Environmental Quality Standards for Surface Water. State Environmental Protection Administration of China and General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China: Beijing, China, 2002.
25. Zhao, Z.; Li, H.; Sun, Y.; Yang, Q.; Fan, J. Contrasting the assembly of phytoplankton and zooplankton communities in a polluted semi-closed sea: Effects of marine compartments and environmental selection. *Environ. Pollut.* **2021**, *285*, 117256. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Li, B.; Li, Q.; Wang, P.; Song, X.; Li, J.; Han, M.; Zhou, S. From River to Reservoir: The Impact of Environmental Variables on Zooplankton Assemblages in Karst Ecosystems. *Sustainability* **2025**, *17*, 4240. [\[CrossRef\]](#)
27. Chiang, S.C.; Du, N.S. *Fauna Sinica: Crustacea: Freshwater Cladocera*; Science Press: Beijing, China, 1979; 297p. (In Chinese)
28. Shannon, C.E. A Mathematical Theory of Communications. *Bell Syst. Tech. J.* **1948**, *27*, 379–423. [\[CrossRef\]](#)
29. Oksanen, J.; Simpson, G.L.; Blanchet, F.G.; Kindt, R.; Legendre, P.; Minchin, P.R.; O'Hara, R.B.; Solymos, P.; Stevens, M.H.H.; Szoecs, E.; et al. *vegan: Community Ecology Package*; R package version 2.7-3; R Foundation for Statistical Computing: Vienna, Austria, 2026. [\[CrossRef\]](#)
30. Friedman, J.H. Greedy Function Approximation: A Gradient Boosting Machine. *Ann. Stat.* **2000**, *29*, 1189–1232. [\[CrossRef\]](#)
31. Alnsour, M.; Alnsour, E. Application of structural equation modelling (SEM) and fuzzy analytic hierarchy process (FAHP) based approach toward a hybrid urban sustainability assessment system (USAS) of Jordan. *Sustain. Cities Soc.* **2025**, *130*, 106590. [\[CrossRef\]](#)
32. Rosseel, Y. Lavaan: An R Package for Structural Equation Modeling. *J. Stat. Softw.* **2012**, *48*, 1–36. [\[CrossRef\]](#)
33. Zhang, S.; Han, G.; Gao, X.; Liu, J.; Qiao, N. Megacity river as a critical anthropogenic source of strontium release in global Sr cycle: Insights from Bayesian mixing model and Sr isotope. *Water Res.* **2025**, *278*, 123402. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Brans, K.I.; Govaert, L.; Engelen, J.M.; Gianuca, A.T.; Souffreau, C.; De Meester, L. Eco-evolutionary dynamics in urbanized landscapes: Evolution, species sorting and the change in zooplankton body size along urbanization gradients. *Philos. Trans. R Soc. Lond. B Biol. Sci.* **2017**, *372*, 20160030. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Zhang, H.; Zhou, C.; Buttino, I.; Jinpei, Y.; Xinjian, Y.; Mengyuan, L.; Yueze, Z. Environmental DNA reveals how the absolute dominant zooplankton species affects the community. *Mar. Environ. Res.* **2025**, *209*, 107191. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Guo, Y.; Liu, Y.; Li, W.; Cai, X.; Liu, X.; Liao, H. Multi-Scale Impacts of Land Use Change on River Water Quality in the Xinxian River, Yangtze River Basin. *Water* **2025**, *17*, 1541. [\[CrossRef\]](#)
37. Zong, M.; Hu, Y.; Liu, M.; Li, C.; Wang, C.; Liu, J. Quantifying the Contribution of Agricultural and Urban Non-Point Source Pollutant Loads in Watershed with Urban Agglomeration. *Water* **2021**, *13*, 1385. [\[CrossRef\]](#)
38. Singaram, P.; Retnamma, J.; Cheruparambil, R.; Nagarathinam, A.; Loganathan, J.; Thangaraj, J.R.; Radhakrishnan, S.S. Heavy metals concentration in zooplankton (copepods) in the western Bay of Bengal. *Environ. Sci. Pollut. Res.* **2023**, *30*, 101565–101584. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Perkins, D.M.; Bailey, R.A.; Dossena, M.; Gamfeldt, L.; Reiss, J.; Trimmer, M.; Woodward, G. Higher biodiversity is required to sustain multiple ecosystem processes across temperature regimes. *Glob. Change Biol.* **2015**, *21*, 396–406. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Gilbert, J.J. Food niches of planktonic rotifers: Diversification and implications. *Limnol. Oceanogr.* **2022**, *67*, 2218–2251. [\[CrossRef\]](#)

41. Oliveira, A.G.; Baumgartner, M.T.; Gomes, L.C.; Dias, R.M.; Agostinho, A.A. Long term effects of flow regulation by dams simplify fish functional diversity. *Freshw. Biol.* **2018**, *63*, 293–305. [[CrossRef](#)]
42. Li, K.; Cao, X.; Zhou, S.; Li, L. Spatial and temporal distribution characteristics of pCO₂ and CO₂ evasion in karst rivers under the influence of urbanization. *Environ. Sci. Pollut. Res.* **2023**, *30*, 53920–53937. [[CrossRef](#)] [[PubMed](#)]
43. Ju, Y.; Lo, W.T.; Chen, C.; Chen, C.-W.; Huang, Z.-L.; Dong, C.-D. Effect of metals on zooplankton abundance and distribution in the coast of southwestern Taiwan. *Environ. Sci. Pollut. Res.* **2019**, *26*, 33722–33731. [[CrossRef](#)] [[PubMed](#)]
44. Jeppesen, E.; Peder Jensen, J.; Søndergaard, M.; Lauridsen, T.; Landkildehus, F. Trophic structure, species richness and biodiversity in Danish lakes: Changes along a phosphorus gradient. *Freshw. Biol.* **2000**, *45*, 201–218. [[CrossRef](#)]
45. Oh, H.J.; Jeong, H.G.; Nam, G.S.; Oda, Y.; Dai, W.; Lee, E.-H.; Kong, D.; Hwang, S.-J.; Chang, K.-H. Comparison of taxon-based and trophi-based response patterns of rotifer community to water quality: Applicability of the rotifer functional group as an indicator of water quality. *Anim. Cells Syst.* **2017**, *21*, 133–140. [[CrossRef](#)] [[PubMed](#)]
46. Li, Z.; Bai, M.; Yao, L.; Ma, J.; He, F.; Bian, G.; Li, W. Phytoplankton and Zooplankton Community Dynamics in an Alpine Reservoir: Environmental Drivers and Ecological Implications in Daqing Reservoir, China. *Water* **2025**, *17*, 1202. [[CrossRef](#)]
47. Żurek, R. Upper Vistula River: Response of Aquatic Communities to Pollution and Impoundment. VIII. Zooseston. *Pol. J. Ecol.* **2002**, *50*, 201–221.
48. Gianuca, A.; Engelen, J.; Brans, K.; Hanashiro, F.T.T.; Vanhamel, M.; Berg, E.M.v.D.; Souffreau, C.; De Meester, L. Taxonomic, functional and phylogenetic metacommunity ecology of cladoceran zooplankton along urbanization gradients. *Ecography* **2018**, *41*, 183–194. [[CrossRef](#)]
49. Hoffmann, M.D.; Dodson, S.I. Land use, primary productivity, and lake area as descriptors of zooplankton diversity. *Ecology* **2005**, *86*, 255–261. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.