

Community Structure of Benthic Macroinvertebrates and its Relationship with Environmental Factors in Wetlands of Jinan City: A Multi-Type Comparative Analysis

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Abstract

Wetlands are biodiversity hotspots that provide essential ecosystem services, yet they are increasingly degraded by anthropogenic pressures. Benthic macroinvertebrates are reliable bioindicators of wetland health, but systematic cross-comparisons of their communities across different wetland types within a specific region remain limited. This study conducted a three-year survey (2020–2022) across 90 sampling sites within 5 national and 10 provincial wetlands in Jinan City, comprehensively assessing water environmental factors and macroinvertebrate assemblages. Using multivariate statistical methods, we identified key environmental drivers and evaluated integrated ecosystem health. Results revealed pronounced spatial heterogeneity in water quality, with suspended solids (SS) emerging as the most pervasive stressor (present in 100% of wetlands' PCA profiles). A total of 116 macroinvertebrate species were recorded, predominantly Mollusca and Insecta. National-level wetlands harbored significantly higher species richness and Shannon-Wiener diversity (mean 20.2 species, $H'=2.01$) than provincial counterparts (14.7 species, $H'=1.28$). Canonical Correspondence Analysis (CCA) demonstrated that SS, total phosphorus (TP), and transparency (SD) were the principal determinants of community structure, although a clear dichotomy was observed: lake-type wetlands were primarily governed by TP and SD, whereas riverine wetlands were driven by SS and total nitrogen (TN). A comprehensive health index (DB 3701/T 33-2022) classified only Shandong Jixi National Wetland Park as "healthy" (score 81.28), while nine wetlands were "sub-healthy" and five, predominantly in the Jiyang region, were "unhealthy." This first systematic, multi-type comparison underscores the primacy of particle pollution as a regional ecological filter and delivers a robust scientific basis for differentiated conservation and targeted restoration strategies for Jinan's wetlands.

Keywords

Jinan wetlands; Benthic macroinvertebrates; Bioindicator; Suspended solids; Eutrophication; Ecological health assessment; CCA

1. Introduction

Wetlands, situated at the interface of terrestrial and aquatic environments, perform critical global functions, including nutrient cycling, hydrological buffering, and the provisioning of habitat for specialized biota. Despite their ecological importance, these systems are disproportionately threatened by ongoing anthropogenic activities and climate change, suffering from widespread degradation manifesting as hydrological alterations, eutrophication, and biodiversity loss [1]. Among the most reliable tools for diagnosing such degradation are benthic macroinvertebrates, whose limited mobility, extended life cycles, and differential species-level tolerances make their community structure a time-integrated reflection of ambient environmental quality [2,3].

A substantial body of research has documented how water temperature, dissolved oxygen, nutrient concentrations, and substrate composition individually shape macroinvertebrate assemblages [4,5]. However, the majority of these investigations have been conducted within a single wetland typology, thereby limiting our understanding of how the relative importance of these drivers shifts across different, adjacent ecosystem types under a common regional climate and management framework. This gap is particularly pronounced in the context of differentiating national-level ecological reserves from provincial-level parks, a distinction critical for tiered conservation planning.

Jinan City, capital of Shandong Province and located in the lower Yellow River basin, presents an ideal natural laboratory to address this gap. Its landscape encompasses a rich mosaic of wetland typologies—including spring-fed lakes, Yellow River riverine corridors, and anthropogenic water bodies—under varying degrees of protection. Yet, prior to this work, no systematic survey had simultaneously characterized the macroinvertebrate biodiversity and the environmental stressors shaping it across these diverse systems. Consequently, the key environmental drivers and ecological health status of Jinan's wetland network remained unquantified, hindering evidence-based management.

To fill this knowledge gap, we conducted a comprehensive, three-year survey across 15 national and provincial wetlands in Jinan, integrating detailed water chemistry profiling with quantitative macroinvertebrate community analysis. Our overarching objectives were to:

Characterize the spatial heterogeneity in water quality and benthic community structure across wetland types and protection levels.

Statistically isolate the primary environmental drivers structuring these communities using multivariate ordination.

Perform a comprehensive ecological health assessment that synergizes abio- and biotic indices.

We hypothesized that (i) suspension solids would be a dominant, cross-cutting regional stressor, and (ii) the principal environmental drivers would diverge between lacustrine and riverine wetlands, yielding distinct bioindicator assemblages.

2. Materials and Methods

2.1. Study Area and Spatial Sampling Design

The investigation was conducted from 2020 to 2022 in 15 state-designated wetland parks within the jurisdiction of Jinan City. The sites comprised five national-level parks and ten provincial-level parks, representing a gradient of protection intensity and hydrological types (Table 1). A total of 90 fixed, geo-referenced sampling stations (six per wetland) were established to represent the habitat heterogeneity within each park.

Table 1. Summary characteristics of the 15 investigated wetlands in Jinan City.

Wetland Name (Abbrev.)	Level	Area (km ²)	Dominant Wetland Type	Sampling Year
Jixi (JX)	National	33.4	Riverine/Palustrine	2020
Baiyun Lake (BY)	National	17.4	Lacustrine	2020
Meigui Lake (MG)	National	6.85	Riverine/Lacustrine	2020
Xueye Lake (XY)	National	180	Lacustrine	2020
Dawen River (DW)	National	68	Riverine	2020
Huashan Lake (HS)	Provincial	6.25	Lacustrine	2021
Tumu River (TM)	Provincial	2.5	Riverine	2021
Chengbo Lake (CB)	Provincial	2.47	Lacustrine	2021
Yanzi Bay (YZ)	Provincial	1.29	Lacustrine/Palustrine	2021
Dasha River (DS)	Provincial	1.75	Riverine	2021
Jinshui River (JS)	Provincial	0.31	Riverine	2022
Langxi River (LX)	Provincial	2.94	Riverine	2022
Longshan Lake (LS)	Provincial	3.33	Lacustrine	2022
Xiuyuan River (XYR)	Provincial	6.63	Riverine	2022
Wangjiafang (WJ)	Provincial	1.57	Riverine/Palustrine	2022

2.2. Water Quality Sampling and Laboratory Analysis

At each site, 17 physicochemical parameters were measured or analyzed. Field parameters—including water temperature (TEMP), dissolved oxygen (DO), pH, and turbidity (NTU)—were recorded in situ using a calibrated YSI multiparameter probe (eXplorist 200). Transparency (SD) was determined with a Secchi disk. Concurrently,

duplicate water samples were collected in acid-washed containers for laboratory analysis. Concentrations of total nitrogen (TN), ammonia nitrogen ($\text{NH}_3\text{-N}/\text{NH}_4^+\text{-N}$), nitrite nitrogen ($\text{NO}_2^-\text{-N}$), nitrate nitrogen ($\text{NO}_3^-\text{-N}$), total phosphorus (TP), orthophosphate (PO_4^{3-}), and permanganate index (CODMn) were determined spectrophotometrically following standard national protocols. Suspended solids (SS) were quantified gravimetrically by filtering a known volume of water through pre-weighed 0.45 μm filters.

2.3. Benthic Macroinvertebrate Collection and Identification

Quantitative benthic samples were collected using a Surber net (0.09 m^2 , 40-mesh) at wadeable sites by disturbing the substrate upstream. At non-wadeable sites, a 1/16 m Wetland Name (Abbrev.) Level Area (km^2) Dominant Wetland Type

Sampling	Year							
Jixi (JX)	National	33.4	Riverine/Palustrine	2020				
Baiyun Lake (BY)	National	17.4	Lacustrine	2020				
Meigui Lake (MG)	National	6.85	Riverine/Lacustrine	2020				
Xueye Lake (XY)	National	180.0	Lacustrine	2020				
Dawen River (DW)	National	68.0	Riverine	2020				
Huashan Lake (HS)	Provincial	6.25	Lacustrine	2021				
Tumu River (TM)	Provincial	2.50	Riverine	2021				
Chengbo Lake (CB)	Provincial	2.47	Lacustrine	2021				
Yanzi Bay (YZ)	Provincial	1.29	Lacustrine/Palustrine	2021				
Dasha River (DS)	Provincial	1.75	Riverine	2021				
Jinshui River (JS)	Provincial	0.31	Riverine	2022				
Langxi River (LX)	Provincial	2.94	Riverine	2022				
Longshan Lake (LS)	Provincial	3.33	Lacustrine	2022				
Xiuyuan River (XYR)	Provincial	6.63	Riverine	2022				
Wangjiafang (WJ)	Provincial	1.57	Riverine/Palustrine	2022	weighted			

Peterson grab was deployed, with 4-6 replicate grabs composited per station. Samples were elutriated in situ to remove fine sediment, sieved through a 40-mesh screen, and preserved in 75% ethanol. In the laboratory, all organisms were hand-sorted under a dissecting stereoscope and identified to the lowest feasible taxonomic level (typically species or genus) using authoritative morphological keys [6,7]. Following enumeration, the wet biomass of each taxon was determined to 0.0001 g precision, and density (ind/m^2) and biomass (g/m^2) were calculated.

2.4. Statistical and Multivariate Analyses

Community structure was assessed using the Shannon-Wiener diversity index (H'), Margalef's richness index (dM), and Pielou's evenness (J'). The Berger-Parker dominance index (Y) was calculated to identify dominant species ($Y > 0.02$) [8].

All multivariate analyses were conducted in Canoco 5.0. To identify the primary axes

of variation in the physicochemical environment, a Principal Component Analysis (PCA) was performed on $\log(x+1)$ transformed and normalized water quality data for each wetland. A preliminary Detrended Correspondence Analysis (DCA) on the species abundance matrix indicated gradient lengths consistently exceeding 4.0 SD units, justifying the use of a unimodal model. Thus, Canonical Correspondence Analysis (CCA) was employed to relate community composition to environmental predictors. The significance of individual environmental factors was tested using forward selection with a Monte Carlo permutation test (999 permutations, $P < 0.05$). Cluster analysis (Bray-Curtis similarity) was used to group wetlands by both water quality and community composition.

A comprehensive trophic level index (TLI), integrating Chl^*a^* , TP, TN, SD, and CODMn, was calculated to assess eutrophication status. The final integrated ecological health assessment was performed according to the local standard DB 3701/T 33-2022, which combines normalized scores from both water quality and biological indices into a composite health index, classifying ecosystems as "Healthy" (score ≥ 80), "Sub-healthy" (60 – 80), or "Unhealthy" (< 60).

3. Results

3.1. Spatial Heterogeneity and Drivers of Water Quality

The water environment across Jinan's wetlands exhibited pronounced spatial variability. Parameters related to particle load and optical characteristics were particularly heterogeneous, with CVs for SS (146.3%), SD (61.5%), and NTU (56.7%) all exceeding 50%. PCA applied separately to each of the 15 wetlands consistently extracted four principal components explaining over 75% of the total variance in water chemistry. A subsequent meta-analysis of the 60 extracted top-loading factors (four per wetland) identified SS as the singularly most pervasive driver, accounting for 31% of all factor occurrences and appearing as a principal axis in all 15 wetlands. Transparency (SD, 22%), NTU (20%), and TN (18%) formed the second tier of prevalent regional stressors.

Hierarchical cluster analysis of the 15 wetlands based on their 17 water quality metrics generated three distinct statistical clusters that corresponded to a clear water quality gradient. Cluster A (Good Quality) comprised five wetlands characterized by high transparency (>150 cm) and low nutrient/SS loads, exemplified by the northern lakes (XY, LS). Cluster B (Moderate Quality) represented the largest group, including JX and MG, exhibiting intermediate conditions. Cluster C (Poor Quality) was composed of the provincial wetlands in the Jiyang district (YZ, CB, TM), marked by critically high SS (averaging >100 mg/L) and reduced SD..

3.2. Macroinvertebrate Community Composition and Biodiversity Patterns

A total of 116 benthic macroinvertebrate taxa were identified across the 15 wetlands. Gastropoda and Insecta were the predominant classes, with the balance between them shifting predictably along the lake-river continuum. Mollusks dominated lacustrine systems, whereas aquatic insects, particularly Chironomidae, prevailed in riverine wetlands.

A clear protection-level effect was observed: national wetlands supported a significantly higher mean species richness (20.2 ± 4.5) compared to provincial wetlands (14.7 ± 7.1) (**-test, $P < 0.05$). Similarly, the average H' was substantially greater in national parks (2.01 ± 0.94) than in provincial ones (1.28 ± 0.56). This was extreme in the degraded Jiyang cluster, where H' values fell below 1.0, indicating a heavily stressed community. In contrast, Laiwu Xueye Lake National Park (XY) achieved the highest H' of 3.99, the sole site to reach a "good" biological quality threshold ($H' > 3.0$). The analysis of dominant species revealed that the pollution-tolerant gastropod *Bellamya purificata* was a core community component across 10 wetlands. Conversely, *Parafossarulus striatulus*, which has a known affinity for well-oxygenated waters, was exclusively dominant in four cleaner, circum-neutral wetlands in the southern mountainous region, indicating its potential as a regional bioindicator of high integrity.

3.3. Identification of Key Environmental Drivers for Community Structure

CCA was performed for each wetland to resolve the specific environmental filters acting on its community. Across all 15 site-specific analyses, the frequency of statistically significant drivers ($P < 0.05$) again highlighted SS (40% of sites) as the most common, followed jointly by TP (33.3%) and SD (33.3%). This demonstrates a consistent regional pattern where particle pollution and associated light-limitation are the principal selective forces.

Importantly, a marked divergence in driving mechanisms emerged when wetlands were categorized by type. In lacustrine wetlands, the CCA ordinations showed that TP and SD exerted a dominant influence on species distribution, suggesting that internal nutrient cycling and subsequent algal turbidity are the primary constraints. In contrast, for riverine wetlands, the significant axes were heavily weighted by SS and TN, implicating external, watershed-derived inputs from erosion and agricultural runoff as the main structuring forces. Indicator species derived from the CCA validated this dichotomy. For example, caddisflies and mayflies were more closely aligned with the SS-TN gradient in rivers, whereas pulmonate snails appeared sensitive to the TP-SD axis in lakes.

3.4. Integrated Ecological Health Assessment

The TLI-based evaluation revealed a landscape dominated by nutrient enrichment, with half of the wetlands classified as lightly to moderately eutrophic. Yet, the final

comprehensive health index (DB3701/T 33-2022), which balances chemical status with biotic integrity, painted a more nuanced picture. Only Shandong Jixi National Wetland Park (JX) achieved a score placing it in the "Healthy" category (81.28). A majority of systems (9 out of 15) fell into the "Sub-healthy" range (scores 62–79), suggesting that while ecosystem function persists, resilience is compromised.

Critically, five provincial wetlands in the Jiyang region and Shanghe were designated as "Unhealthy" (score < 60), with Jiyang Yanzi Bay recording the lowest score (53.12). These "Unhealthy" sites were universally characterized by a triad of high SS (>50 mg/L), elevated TN and TP, and a Shannon-Wiener diversity index below 1.0, a combination indicative of severe environmental decoupling of their biotic communities.

4. Discussion

Our systematic survey confirms that water quality and macroinvertebrate communities in Jinan's wetlands are highly heterogeneous, shaped by a clear hierarchy of environmental stressors. The most impactful finding is the identification of suspended solids as the dominant regional environmental filter. The ubiquity of SS as a primary driver, both in PCA of water quality (31% of all factors) and in CCA of communities (40% frequency), points to a landscape-level issue of soil erosion and particulate runoff. This aligns with research demonstrating that high suspended sediment can exert multiple, synergistic pressures on benthic fauna, including physical abrasion of respiratory surfaces, burial of interstitial habitats necessary for insect larvae, and reduction of food quality for filter-feeders [9]. The extreme case of Yanzi Bay, where SS loads were an order of magnitude higher than in healthy reference systems and macroinvertebrate diversity nearly collapsed ($H' = 0.71$), represents an acute manifestation of this pressure.

The disparity in ecological condition between national and provincial wetlands was statistically significant and biologically meaningful. National parks supported richer, more diverse communities. This is not merely a function of a larger protected area but is likely a cumulative result of enforced conservation regulations, restricted anthropogenic activities, and more active management interventions, such as the restoration initiatives undertaken at Jixi, the only "Healthy" wetland.

The distinction in key drivers between lake and river systems provides a high-resolution understanding that directly translates to policy. Our data show that lake wetlands are principally TP- and SD-mediated, making them particularly vulnerable to internal phosphorus loading and the onset of algal blooms that reduce light availability. Management for these shallow lakes should prioritize controlling not just external but also internal nutrient recycling, perhaps through biomanipulation or sediment capping. In contrast, riverine wetlands are driven by SS and TN, a chemical fingerprint of non-point source agricultural pollution and bank erosion. This finding strongly advocates for riparian buffer zone restoration

and catchment-wide best management practices as the most effective restoration levers for these linear systems.

The comprehensive health assessment, which combined a trophic state index with a biodiversity index, proved more sensitive than either metric in isolation. Several wetlands, such as Jiyang Chengbo Lake, were classified as merely "mesotrophic" by chemical TLI, which might suggest an acceptable state. However, its biological signal was one of collapse, with a highly degraded H' of 0.89. This bio-chemical decoupling, where physical habitat and chronic toxicity due to sediment-bound pollutants have eliminated sensitive species even when dissolved nutrients are not extremely elevated, is a warning sign of a system at a tipping point. Our identification of contrasting indicator species—the tolerant, ubiquitous *Bellamyia purificata* versus the sensitive, clean-water *Parafossarulus striatulus*—offers a cost-effective biological monitoring tool that managers can deploy to rapidly track ecological recovery following the implementation of these restorative measures.

5. Conclusions

This study presents the first comprehensive, cross-typological assessment of wetland health in Jinan City, uncovering a pervasive regional stressor (suspended solids) and a clear hierarchical degradation pattern. While national wetlands generally maintain a sub-healthy-to-healthy status, provincial wetlands in agricultural landscapes are critically unhealthy. The environmental mechanisms are type-specific: TP and transparency govern lake communities, whereas SS and TN structure riverine assemblages. The integration of chemical and biological metrics into a composite health index identified that more than half of the wetlands are in a degraded state. These findings provide an actionable framework for targeted management, emphasizing that a uniform approach is inadequate. Future conservation efforts must be differentiated, focusing on riparian erosion control for river systems, internal nutrient management for lakes, and urgent remediation of the critically unhealthy wetlands in the Jiyang region.

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