

Article

Can Reclaimed Artificial Secondary Wetlands in Mining Areas Serve as Habitats for Waterbirds? A Case Study of Shuoxi Lake in Huaibei, China

Xiaozhou Ye ¹, Bingbing Hu ², Fan Qi ², Jing Chen ³ and Shiyuan Zhou ^{2,*}

¹ School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 221116, China; lb18030003@cumt.edu.cn

² School of Architecture and Design, China University of Mining and Technology, Xuzhou 221116, China; hubingbing@cumt.edu.cn (B.H.); ts24190118a31@cumt.edu.cn (F.Q.)

³ Xuzhou Huacheng Planning and Design Consulting Co., Ltd., Xuzhou 221000, China; 18605168009@163.com

* Correspondence: 6093@cumt.edu.cn; Tel.: +86-0516-83591968

Abstract

Coal mining in areas with high groundwater levels often induces land subsidence and water accumulation, leading to the formation of artificial secondary wetlands. Reclaimed wetlands may provide important opportunities for regional biodiversity recovery. Taking Shuoxi Lake Wetland in Huaibei City as a case study, this research aims to reveal the characteristics of waterbird diversity in artificial wetlands after ecological reclamation in a coal mining subsidence area and to identify their key environmental drivers, thereby providing a scientific basis for optimizing the habitat service functions of such wetlands. Based on habitat identification and classification of the reclaimed wetland, waterbird diversity was surveyed, and redundancy analysis (RDA), Mantel tests, and ridge regression models were used to identify the major environmental factors influencing the distribution of different waterbird groups and to quantify their relative contributions. The results showed that after ecological reclamation, a total of 28 waterbird species belonging to 7 families and 6 orders were recorded in the artificial wetland of the coal mining subsidence area. Redundancy analysis (RDA) indicated that wader assemblages were more sensitive to vegetation cover (VC), distance to water bodies (DTW), and distance to buildings (DTB), whereas waterfowl assemblages were mainly affected by distance to buildings (DTB), area (A), and distance to water bodies (DTW), and showed no significant response to vegetation heterogeneity. Mantel tests further confirmed significant spatial correlations between waterbird assemblages and area (A), distance to major roads (DTR), distance to buildings (DTB), water depth (WD), and distance to water bodies (DTW). Ridge regression analysis showed that, under conditions in which anthropogenic disturbance was minimized, vegetation cover (VC) and water depth (WD) were the main positive drivers of wader diversity, whereas perimeter to area ratio (PAR) was the main negative driver. Waterfowl diversity was mainly negatively affected by perimeter to area ratio (PAR) and distance to water bodies (DTW). These findings suggest that appropriately regulating water depth, increasing vegetation cover, and reducing patch fragmentation and anthropogenic disturbance are key measures for enhancing the habitat service functions of artificial secondary wetlands in mining areas. These management strategies provide an important reference for wetland rehabilitation in other coal mining subsidence areas.

Academic Editors: Pieter Boets and Liudmila S. Shirokova

Received: 17 May 2026

Revised: 7 July 2026

Accepted: 23 July 2026

Published: 25 July 2026

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Keywords: artificial secondary wetlands in mining areas; waterbird diversity; mining-area biodiversity; ecological reclamation

1. Introduction

Wetlands, together with oceans and forests, constitute the three major ecosystems on Earth. Their unique hydrological regimes and vegetation structures provide essential habitats for approximately 40% of the world's species, supporting breeding, foraging, and migratory stopovers. Consequently, the stability of wetland ecosystems plays a pivotal role in maintaining the sustainability of regional and global ecological systems. However, driven by anthropogenic disturbances and climate change, more than two-thirds of natural wetlands worldwide have undergone degradation or have disappeared, posing severe threats to regional hydrological processes and biodiversity conservation [1]. Against this backdrop, constructed wetlands have expanded rapidly in both extent and distribution as an important form of ecological compensation. According to the Global Wetland Outlook, the proportion of constructed wetlands in the global wetland area increased from less than 5% in 1970 to approximately 12% in 2015 [2]. By providing alternative habitats for wildlife and enhancing ecological connectivity, constructed wetlands have become an increasingly important component of the global wetland ecological network and play a significant role in conserving regional biodiversity [3].

Mining subsidence wetlands are a distinctive type of anthropogenic secondary wetland that develops in regions with shallow groundwater tables, where underground coal extraction induces land subsidence and subsequent water accumulation [4]. Ecological reclamation of waterlogged mining subsidence areas into wetlands has become a widely adopted strategy for rehabilitating degraded mining landscapes worldwide, with representative examples including Senftenberger See and Geiseltalsee in Germany [5]. Owing to the extensive exploitation of coal resources, the area of mining subsidence wetlands has expanded rapidly in China. It is estimated that the cumulative land subsidence caused by coal mining will reach 3.18×10^6 ha, of which more than 1.91×10^6 ha will be permanently inundated [6]. Consequently, ecological reclamation of mining subsidence wetlands has become a critical issue for achieving the sustainable development of mining regions. Restoring biodiversity is recognized as one of the primary objectives of ecological reclamation in post-mining landscapes. The Biodiversity Management in Mining guideline series published by the International Union for Conservation of Nature (IUCN) explicitly emphasizes the conservation and reclamation of biodiversity throughout the mining lifecycle [7,8]. As a taxonomic group that responds sensitively to changes in wetland environmental conditions, birds are widely regarded as reliable indicators of biodiversity recovery in constructed wetlands [9,10] and of wetland ecosystem health [11,12]. Therefore, assessing whether reclaimed mining-induced secondary wetlands can function as suitable habitats for waterbirds is of considerable scientific significance for guiding biodiversity conservation and enhancing the overall ecosystem services of waterlogged mining landscapes [13–15].

Field surveys conducted across mining subsidence wetlands in different coal mining regions have shown that even in the absence of active ecological reclamation, these wetlands can provide habitats for a number of bird species, and their waterbird assemblages exhibit pronounced nestedness patterns [16]. However, habitat spatial analyses indicate that the formation of mining subsidence wetlands is primarily controlled by underground coal extraction, resulting in fragmented landscapes with relatively low habitat quality. Studies conducted in the Huaibei mining area recorded only 29 waterbird species in unreclaimed mining subsidence wetlands, compared with 41 species in adjacent natural wet-

lands [17]. Similarly, surveys of six mining subsidence wetlands in Yanzhou, Shandong Province, documented 105 bird species, whereas 294 species were recorded in the nearby natural wetland of Weishan Lake [18]. These findings suggest that although mining subsidence wetlands can partially compensate for habitat loss, their biodiversity conservation capacity remains substantially lower than that of natural wetlands.

Mining activities, urbanization, land reclamation, and ecological reclamation policies have been identified as the primary drivers shaping landscape dynamics and habitat functions in mining subsidence wetlands. Optimizing ecological networks at the watershed scale is therefore considered essential for enhancing habitat connectivity and improving wetland ecological functions [19]. Existing studies have mainly investigated waterbird diversity at two spatial scales. At the landscape-network scale, research has primarily focused on changes in bird community composition before and after ecological reclamation [20]. At the habitat-patch scale, studies have emphasized the effects of habitat spatial structure on waterbird distribution following reclamation [21]. Previous studies have demonstrated that optimizing wetland habitat structure can substantially enhance biodiversity and facilitate the recovery of ecosystem services [22]. These include habitat configuration [23], vegetation patterns [24], hydrological conditions [25], and habitat heterogeneity [26]. Nevertheless, quantitative studies examining the relationships between different waterbird guilds and environmental variables in reclaimed mining subsidence wetlands remain limited. In particular, the mechanisms by which habitat structure and landscape configuration influence waterbird diversity have not been systematically elucidated. Consequently, a comprehensive evaluation of habitat characteristics and ecological functions in reclaimed mining subsidence wetlands is urgently needed to identify key habitat patches within ecological networks and to provide a scientific basis for wetland reclamation, ecological compensation, and biodiversity conservation in post-mining landscapes [27,28].

This study was conducted in Shuoxi Lake Wetland, located in the Huaibei Plain of eastern China, an important stopover site along the East Asian–Australasian Flyway. The wetland provides critical habitats for migratory waterbirds, including shorebirds and Anatidae species, by supporting their stopover, refueling, and wintering activities. The objectives of this study were to investigate the diversity patterns of waterbird communities in a reclaimed mining subsidence wetland and to elucidate the underlying environmental drivers. Specifically, this study aimed to: (1) characterize the community structure and diversity of waterbirds following ecological reclamation; (2) identify the key environmental factors and quantify their relative contributions in shaping waterbird community composition; and (3) propose habitat-unit-based reclamation and management strategies for artificial wetlands in mining areas. The findings are expected to provide scientific support for biodiversity conservation, habitat optimization, and ecological reclamation of mining subsidence wetlands in regions with shallow groundwater tables.

2. Materials and Methods

2.1. Study Area

Huaibei City (116°24′–117°03′ E, 33°16′–34°10′ N) is located in northern Anhui Province and represents a major coal-producing base in East China. As of the end of 2024, the city's permanent resident population stood at 1.932 million, with an urbanization rate of 66.2% [29]. The region has a warm temperate, semi-humid monsoon climate, with a mean annual temperature of 14.5 °C, mean annual precipitation of 802.3 mm, and mean annual evaporation of 908.2 mm. The terrain is dominated by plains, while mountains and hills account for only 4.7% of the total area. After more than half a century of intensive coal mining, the cumulative subsidence area in Huaibei City reaches 362 km², including a total waterlogged area of 100 km².

The study focuses on Shuoxi Lake Wetland Park, a coal mining subsidence wetland located in northeastern Huaibei City. The wetland covers approximately 966.67 hm², with open water accounting for 75.5% (Figure 1). Before the development of coal resources, the Shuoxi Lake area was originally farmland. A survey of birds in the Huaibei Plain showed that 18 bird species were recorded in the farmland area [30]. Through the implementation of measures such as concurrent mining and reclamation, water circulation and water resource regulation, and the reconstruction of aquatic-terrestrial composite ecosystems, Shuoxi Lake successfully addressed the challenges of homogenous habitat types, low vegetation coverage, and poor water quality in the post-flooded wetland. Following ecological restoration, the wetland exhibited a marked expansion in vegetation coverage and a significant increase in landscape diversity, while the water quality improved from worse than Class IV to Class III of surface water standards. At present, the wetland has restored vegetation from 80 plant families, including reeds and calamus, more than 20 waterbird species recorded, such as Swan Goose (*Anser cygnoides*) and Falcated Duck (*Mareca falcata*) [31]. The wetland provides multiple ecological functions, including water conservation, microclimate regulation, and biodiversity conservation. The wetland also records the occurrence of the nationally Class I protected (rare and endangered, under China's highest legal protection) Baer's Pochard (*Aythya baeri*), along with several other rare bird species.

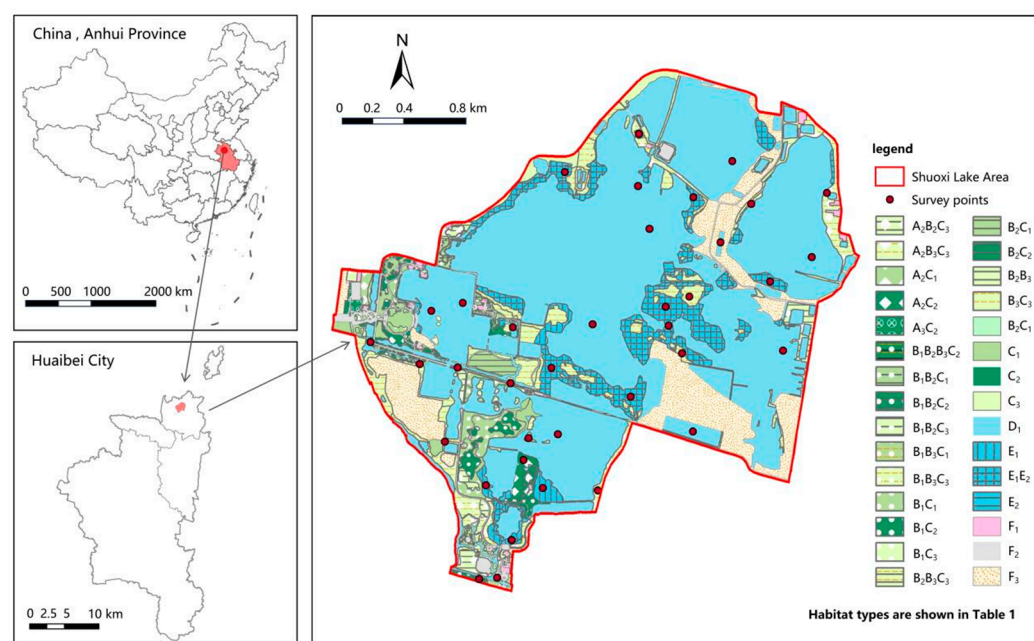


Figure 1. Location of the study area.

2.2. Data Collection

2.2.1. Habitat-Unit Delineation

Baseline surveys of wetland habitats provide an essential prerequisite for examining relationships between avian diversity and habitat environmental factors. This study adopts a three-level hierarchical habitat-unit classification system [32,33] to identify and classify habitat patches within Shuoxi Lake Wetland in detail (Table 1). First, Google Earth Pro high-resolution imagery and Landsat-8 OLI multispectral data are used to conduct a preliminary interpretation of the wetland. Second, unmanned aerial vehicle (UAV) aerial surveys are conducted to obtain orthomosaics, and field verification is performed to revise and refine the interpretation results. Finally, habitat units are delineated in ArcGIS 10.8 to produce a habitat-type distribution map of the wetland.

Table 1. Hierarchical classification of waterbird habitat units in coal mining subsidence wetlands.

Level I Unit	Level II Unit	Level III Unit
Upper-layer vegetation (A)	Coniferous forest (A ₁)	Single-layer structure: C _x Two-layer structure: A _x B _x /B _x C _x /A _x C _x Multi-layer structure: A _x B _x C _x /B _x B _x C _x /A _x B _x B _x /C _x
	Broadleaved forest (A ₂)	
	Complex mixed forest (A ₃)	
Mid-layer vegetation (B)	Low trees (B ₁)	
	Shrubs (B ₂)	
	Graminoid vegetation (B ₃)	
Lower-layer vegetation (C)	Grassland (C ₁)	
	Ground cover (C ₂)	
	Bare land (C ₃)	
Waterbody (D)	Open water surface (D ₁)	–
Aquatic-vegetation cover (E)	Emergent macrophyte cover (E ₁)	Single cover type: E _x
	Floating-leaved macrophyte cover (E ₂)	Mixed cover type: E ₁ E ₂
Artificial surfaces (F)	Buildings (F ₁)	–
	Roads (F ₂)	
	Other land (F ₃)	

The Level I habitat units are classified into six categories based on land-cover types: upper-layer vegetation (A; >5 m), mid-layer vegetation (B; $0.5\text{ m} < h \leq 5\text{ m}$), lower-layer vegetation (C; $h \leq 0.5\text{ m}$), open water (D), aquatic vegetation (E), and artificial surfaces (F). Vegetation is further stratified into multiple layers according to its vertical structure. Aquatic habitats include both open-water areas and zones covered by aquatic vegetation. Artificial surfaces comprise built hardstanding and other land uses. Because cropland within the study area consists primarily of dryland fields that provide limited habitat support for waterbirds, it is classified as “other land” in this study.

The habitats are then further subdivided by vegetation cover type and spatial distribution, and the Level I habitat units are classified into 14 Level II habitat-unit types. Specifically, upper-layer vegetation (A) is divided by species composition into coniferous forest (A₁, such as Chinese arborvitae and pond cypress), broadleaved forest (A₂, such as poplar and willow), and complex mixed forest (A₃, mainly dominated by Chinese arborvitae-poplar mixed stands). Mid-layer vegetation (B) is divided into low trees (B₁, such as crape myrtle and hibiscus), shrubs (B₂, such as sour jujube and bush clover), and graminoid vegetation (B₃, such as reed and Bermuda grass). Lower-layer vegetation (C) is classified into grassland (C₁), ground cover (C₂), and bare land (C₃). Category (D) represents open water. Aquatic vegetation (E) is divided by growth form into emergent macrophyte cover (E₁) and floating-leaved macrophyte cover (E₂). Artificial surfaces (F) are classified by functional use into buildings (F₁), roads (F₂), and other land (F₃). In addition, based on Level II habitat units and incorporating vegetation vertical-structure characteristics, Level III habitat units are delineated by vertical superposition of different Level II units (Figure 2). This Level III delineation enables a finer characterization of habitat spatial structure and ecological functions. To ensure classification accuracy, the boundaries of microhabitat units are defined on the basis of remote-sensing classification results and further constrained using natural boundaries identified through field surveys. Habitat-unit mapping of Shuoxi Lake Wetland Park is completed following the classification scheme described above.

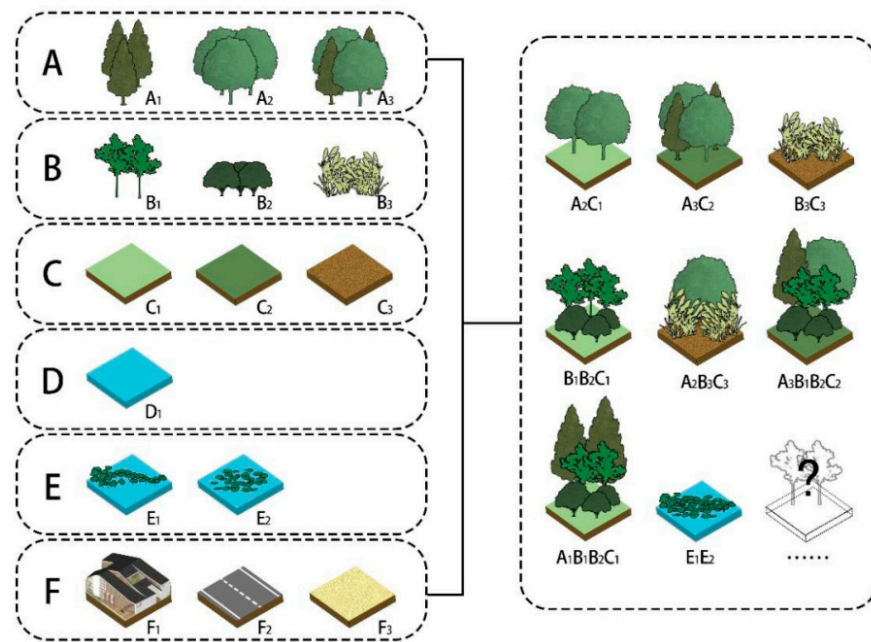


Figure 2. Schematic diagram of habitat-unit overlay. A (upper-layer vegetation); B (mid-layer vegetation); C (lower-layer vegetation); D (open water); E (aquatic vegetation); F (artificial surfaces).

2.2.2. Waterbird Data Collection

During the period from December 2023 to November 2024, the research team conducted a preliminary survey of waterbirds in the Shuoxi Lake coal mining subsidence wetland, recording species identity, abundance, and habitat locations. Through statistical analysis, the utilization patterns and distribution characteristics of each species across different habitat types were derived to identify areas with the highest concentrations of waterbird activity in the wetland. Based on the preliminary survey, 12 major waterbird habitat types are identified, including A₂C₁ (broadleaved forest–grassland), A₂C₂ (broadleaved forest–ground cover), B₁B₂B₃C₂ (low trees–shrubs–graminoid vegetation–ground cover), B₁B₂C₂ (low trees–shrubs–ground cover), B₁B₃C₁ (low trees–graminoid vegetation–grassland), B₁B₃C₃ (low trees–graminoid vegetation–bare land), B₁C₂ (low trees–ground cover), B₃C₃ (graminoid vegetation–bare land), D₁ (open water), E₁ (emergent macrophytes), E₁E₂ (emergent macrophytes–floating-leaved macrophytes), and E₂ (floating-leaved macrophytes) (Figure 3). Stratified random sampling is then implemented in ArcGIS, with full consideration of vegetation types, water body distribution, and proportional representation of habitat types, in order to minimize subjective bias and ensure the representativeness of sampling points. To reduce the influence of edge effects on observations, each sampling point is placed at least 15–25 m from habitat boundaries. Sampling locations are further adjusted based on the pre-survey, resulting in a total of 47 sampling points.

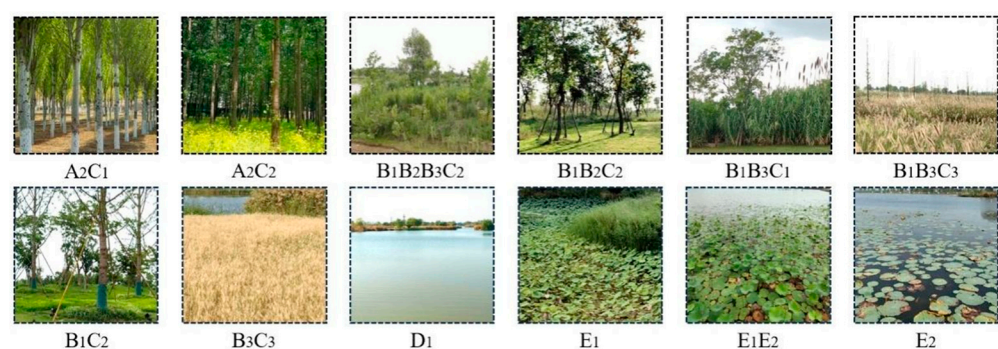


Figure 3. Major waterbird habitat types in Shuoxi Lake Wetland Park.

During the investigation, eight field surveys were conducted at the 47 sampling sites using the point-count method. Two surveys were performed in each season to ensure balanced data representation across different seasons. Each point is surveyed for a fixed duration of 15 min, and the effective sampling radius is adjusted according to habitat visibility (typically 25 m; expanded to 50 m in open mudflat areas and reduced to 10 m in dense woodland) [34]. During each survey, a spotting scope (20–60 × 80 ED) is used to record, within the sampling radius, the species, abundance, behavioral patterns, and habitat-use types of perched or foraging individuals [35]. Fly-over individuals merely passing through are excluded to avoid double counting. Observations are carried out during peak activity periods (08:30–10:00 and 15:00–18:00), when waterbird activity is frequent and individual visibility is high, while avoiding disruptive conditions such as precipitation, strong winds, and low visibility. Species identification follows the “China Birdwatching Handbook” [36] and “A Field Guide to the Birds of China” [37], and the taxonomic framework strictly adheres to “A Checklist on the Classification and Distribution of the Birds of China” (3rd ed.) [38].

2.2.3. Environmental Variables

To elucidate relationships between waterbird assemblage patterns and landscape environmental characteristics, this study draws on relevant literature from comparable urban and regional contexts [39–41] and, in combination with site-specific conditions of the Shuoxi Lake coal mining subsidence wetland in Huaibei City, selects nine environmental variables across four dimensions: habitat-patch configuration, vegetation community structure and richness, water conditions, and anthropogenic disturbance (Table 2). Variables describing habitat-patch configuration characterize patch form and spatial structure, including patch area (A), perimeter to area ratio (PAR), and Euclidean nearest-neighbor distance (ENN), which are used to reflect habitat integrity, edge complexity, and connectivity [42]. Vegetation community structure and richness capture wetland vegetation conditions [43]; plant species richness (PSR) and vegetation cover (VC) are selected to represent habitat quality. Water bodies constitute a core component of wetland ecosystems, and in particular, continued subsidence in coal mining areas induces dynamic changes in water depth, thereby exerting important influences on bird habitat use [44]. For water-condition variables, water depth (WD) and distance to water bodies (DTW) are selected to represent hydrological effects on avian assemblages. For anthropogenic disturbance, given the dual influence of urban construction and road traffic in the study area, distance to buildings (DTB) and distance to major roads (DTR) are used as indicator variables to characterize the intensity of human activities and their spatial gradients [45,46].

Table 2. Selection of environmental variables.

Level I Category	Level II Variable	Rationale for Selection	Data Source
Habitat-patch configuration	Area (A)	Represents patch size	Calculated in Fragstats 4.2
	Perimeter to area ratio (PAR)	Quantifies patch-shape irregularity	Calculated in Fragstats 4.2
	Euclidean nearest-neighbor distance (ENN)	Indicates inter-patch connectivity	Calculated in Fragstats 4.2
Vegetation community structure and richness	Plant species richness (PSR)	Indicates diversity of plant species	Field quadrat survey (October–November 2023; tree 20 × 20 m, shrub 10 × 10 m, herb 1 × 1 m)

	Vegetation cover (VC)	Represents vegetation cover density	Field quadrat survey (October–November 2023; tree 20 × 20 m, shrub 10 × 10 m, herb 1 × 1 m; percentage of canopy vertical projection area recorded)
	Water depth (WD)	Describes wetland water depth	On-site measurement (October–November 2023; Using a measuring vessel to measure water depth)
	Distance to water bodies (DTW)	Euclidean distance from each sampling point to the nearest water body	Euclidean Distance tool in ArcGIS
Anthropogenic disturbance	Distance to major roads (DTR)	Euclidean distance from each sampling point to the nearest major road; indicates intensity of human activities	Euclidean Distance tool in ArcGIS
	Distance to buildings (DTB)	Euclidean distance from each sampling point to the nearest building; indicates intensity of human activities	Euclidean Distance tool in ArcGIS

2.3. Statistical Analysis

2.3.1. Indices of Waterbird Diversity Attributes

The Patrick richness index is used to quantify the number of waterbird species recorded within a single sampling site, reflecting the level of species richness at that site. The index is calculated as follows [47]:

$$R = S \quad (1)$$

where R denotes waterbird species richness and S denotes the number of waterbird species recorded within a sampling site. By directly counting the number of species, the Patrick richness index provides an intuitive measure for evaluating the diversity level of birds in a given habitat. A higher species count generally indicates that the habitat conditions can support a relatively diverse bird assemblage.

The Shannon–Wiener index is used to measure the diversity of waterbird communities within a given sampling plot. By comprehensively considering both species richness and relative abundance, this index reflects the evenness of species distribution within the community, as well as its structural complexity. The index is calculated as follows [48]:

$$H' = - \left(\sum P_i \times \ln P_i \right) \quad (2)$$

where H' denotes the diversity index, and P_i is the relative abundance of species i (i.e., the ratio of the number of individuals of species i to the total number of individuals). The Shannon–Wiener index is commonly used to describe community evenness and the distribution of individuals among species. A higher Shannon–Wiener value indicates greater species diversity and a more even distribution of individuals within the habitat.

2.3.2. Redundancy Analysis

This study uses the Pearson correlation coefficient to quantify linear relationships between pairs of variables and removes environmental variables that are highly correlated with others to reduce the influence of multicollinearity on subsequent models [49]. To further investigate the relationships between the distributions of different ecological

groups of birds and environmental variables, detrended correspondence analysis (DCA) was first conducted to assess the gradient length of the species data. When the gradient length of the first axis is less than 3, species responses to environmental gradients are considered to be better represented by linear models; therefore, a linear constrained ordination method is appropriate [50]. Based on this criterion, redundancy analysis (RDA) was employed. Within a multiple linear regression framework, RDA quantifies the explanatory power of environmental variables for the distributions of waders and waterfowl and visually illustrates the relationships between species distributions and environmental factors through biplots. The calculation is as follows:

$$Y = X\beta + \epsilon \quad (3)$$

where Y is an $n \times m$ matrix representing the richness or cover of m species across n sampling sites; X is an $n \times p$ matrix representing the measured values of p environmental variables at the n sampling sites; β is a $p \times m$ coefficient matrix indicating the effect strength of the environmental variables on the species; and ϵ is an $n \times m$ error matrix representing the unexplained variation not accounted for by the model.

2.3.3. Mantel Test

Chiplot software (<https://www.chiplot.online/>, accessed on 10 October 2025) is further used to conduct Mantel tests to evaluate associations between the bird-assemblage structure matrix and matrices of individual environmental variables [51], thereby testing whether community dissimilarity exhibits concordant trends along environmental gradients or spatial structure. The calculation is as follows:

$$r = \frac{\sum_{i < j} (X_{ij} - \bar{X})(Y_{ij} - \bar{Y})}{\sqrt{\sum_{i < j} (X_{ij} - \bar{X})^2 \sum_{i < j} (Y_{ij} - \bar{Y})^2}} \quad (4)$$

where r is the Mantel correlation coefficient, and X_{ij} and Y_{ij} are elements of the first and second distance matrices, respectively, corresponding to the distance between sampling sites i and j . $\bar{X}$ and $\bar{Y}$ denote the mean values of all elements in the two matrices, respectively.

2.3.4. Regression Analysis

Ridge regression is conducted in SPSSPRO (<https://www.spsspro.com/>, accessed on 13 October 2025) [52], with waterbird diversity indices as the dependent variables and habitat factors as the independent variables. The optimal ridge parameter (K) is selected via cross-validation to quantify the effects of key environmental variables on waterbird diversity, and the model fit and explanatory power are jointly evaluated based on statistical tests and cross-validation results. When multicollinearity exists among predictors—that is, when the eigenvalues of $X^T X$ approach 0—a positive regularization term $K > 0$ is introduced on the diagonal to reduce the near-singularity of $X^T X + KI$, thereby decreasing the root mean square error. The calculation is as follows:

$$\hat{\beta}(K) = (X^T X + KI)^{-1} X^T Y \quad (5)$$

where $\hat{\beta}(K)$ denotes the ridge-adjusted least-squares regression coefficients, K is the ridge parameter, X^T is the transpose matrix of the predictor matrix X , I is the identity matrix, and Y is the response vector (matrix). The regression equation for the dependent variable Y is:

$$Y = \hat{\beta}_0 + \hat{\beta}_1 X_1 + \hat{\beta}_2 X_2 + \dots + \hat{\beta}_K X_K \quad (6)$$

where Y represents the evaluated waterbird diversity outcome, $\hat{\beta}_0$ is the constant term (intercept), and $\hat{\beta}_K$ is the standardized regression coefficient of the K th independent variable.

3. Results

3.1. Structure of the Wetland Waterbird Assemblage

Across 8 field surveys (2 per season), 28 waterbird species (Table 3) were recorded, with a total of over 1500 individuals. Following the taxonomic system of “A Checklist on the Classification and Distribution of the Birds of China” (3rd ed.) [38], the 28 species belong to 6 orders and 7 families (Table 4). Anseriformes and Pelecaniformes show clear dominance in species richness, comprising 9 and 8 species and accounting for 32.14% and 28.57% of the total, respectively. Based on habitat preference and adaptive capacity, birds are commonly categorized into 6 ecological groups (passerines, waders, waterfowl, scan-sorial birds, raptors, and terrestrial birds). The waterbirds recorded in this survey mainly fall into the waterfowl and waders taxonomic groups. Specifically, waterbirds comprised 13 species of swimming birds (46.43%) and 15 species of waders (53.57%). According to the survey data, winter visitors accounted for the highest proportion of the assemblage, with 14 species (50.00%). Based on conservation status, 3 species recorded in the study area are listed on the IUCN (International Union for Conservation of Nature) Red List. These include 1 species classified as Critically Endangered (CR), the Baer’s Pochard (*Aythya baeri*), and 2 species classified as Vulnerable (VU), namely the Swan Goose (*Anser cygnoides*) and the Common Pochard (*Aythya ferina*). In addition, 13 species are classified as Class II protected animals in Anhui Province.

Table 3. Summary statistics of waterbird ecological taxa in Shuoxi Lake Wetland Park.

Ecological Groups	Order		Family		Species	
	Number	Percentage	Number	Percentage	Number	Percentage
Waterfowl	4	57.14%	4	50.00%	13	46.43%
Waders	3	42.86%	4	50.00%	15	53.57%

Table 4. Taxonomic composition and ecological characteristics of waterbirds in Shuoxi Lake Wetland Park.

Order	Family		Species				Ecological Guild	Residency Status	Threat Category
	Name	Number	Percentage	Name	Number	Percentage			
Podicipediformes	Podicipedidae	1	14.29%	<i>Tachybaptus ruficollis</i>	2	7.41%	Waterfowl	resident	-
				<i>Podiceps cristatus</i>			Waterfowl	winter visitor	-
				<i>Gallinula chloropus</i>	5	17.86%	Waders	resident	-
Gruiformes	Rallidae	1	14.29%	<i>Fulica atra</i>			Waterfowl	winter visitor	-
				<i>Rallus indicus</i>			Waders	passage migrant	-
				<i>Amauornis phoenicurus</i>			Waders	summer visitor	-
				<i>Zapornia pusilla</i>			Waders	resident	-
Anseriformes	Anatidae	1	14.29%	<i>Mareca falcata</i>	9	32.14%	Waterfowl	winter visitor	Anhui Province Class II protected species/NT
				<i>Tadorna ferruginea</i>			Waterfowl	winter visitor	Anhui Province Class II protected species
				<i>Anas platyrhynchos</i>			Waterfowl	winter visitor	Anhui Province Class II protected species

									<i>Anas crecca</i>	Waterfowl	winter visitor	Anhui Province Class II protected species
									<i>Aythya baeri</i>	Waterfowl	winter visitor	Anhui Province Class II protected species/CR
									<i>Aythya ferina</i>	Waterfowl	winter visitor	Anhui Province Class II protected species/VU
									<i>Aythya fuligula</i>	Waterfowl	winter visitor	Anhui Province Class II protected species
									<i>Anser anser</i>	Waterfowl	winter visitor	Anhui Province Class II protected species
									<i>Anser cygnoides</i>	Waterfowl	winter visitor	Anhui Province Class II protected species/VU
Charadriiformes	Charadriidae	2	28.57%	<i>Vanellus vanellus</i>	3	10.71%				Waders	winter visitor	Anhui Province Class II protected species/NT
	Scolopacidae			<i>Tringa glareola</i>						Waders	passage migrant	-
				<i>Scolopax rusticola</i>						Waders	passage migrant	-
Pelecaniformes	Ardeidae	1	14.29%	<i>Botaurus stellaris</i>	8	28.57%				Waders	summer visitor	-
				<i>Ixobrychus sinensis</i>						Waders	summer visitor	-
				<i>Nycticorax nycticorax</i>						Waders	resident	-
				<i>Ardea cinerea</i>						Waders	passage migrant	-
				<i>Egretta garzetta</i>						Waders	summer visitor	Anhui Province Class II protected species
				<i>Ardea alba</i>						Waders	winter visitor	Anhui Province Class II protected species
				<i>Ardea intermedia</i>						Waders	passage migrant	Anhui Province Class II protected species
				<i>Ardeola bacchus</i>						Waders	summer visitor	-
Suliformes	Phalacrocoracidae	1	14.29%	<i>Phalacrocorax carbo</i>	1	3.57%				Waterfowl	winter visitor	-
Total		7			28							

Note: Critically Endangered (CR), Vulnerable (VU), and Near Threatened (NT).

3.2. Correlations Between Waterbird Species in Different Ecological Groups and Environmental Variables

RDA indicates that waders assemblages show clear differentiation along environmental gradients (Figure 4a). The first two axes explain 79.05% of the variation in community composition (RDA1 = 62.35%, RDA2 = 16.70%), and the overall model is significant ($p = 0.001$). Among the environmental variables, distance to buildings (DTB), distance to water bodies (DTW), and vegetation cover (VC) show significant positive associations with multiple waders species. The distributions of the Brown-cheeked Rail (*Rallus indicus*), Eurasian Woodcock (*Scolopax rusticola*), and Baillon's Crane (*Zapornia pusilla*) are closely related to distance to buildings (DTB), indicating a preference for aquatic habitats farther from building-related disturbance. Most Heron species (*Ardeidae*), including the Grey Heron (*Ardea cinerea*), Little Egret (*Egretta garzetta*), and Black-crowned Night Heron (*Nycticorax nycticorax*), are positively associated with distance to water bodies (DTW) and vegetation cover (VC), suggesting that these species tend to occur near open water and show a degree of dependence on vegetated riparian margins. In contrast, water depth (WD) and Euclidean nearest-neighbor distance (ENN) exhibit generally weak correlations with waders, implying that waders primarily use shallow-water or littoral habitats and respond weakly to deep-water conditions and wetland connectivity. Perimeter to area ratio (PAR)

shows negative associations with most waders species, indicating that excessive fragmentation of patch edges at the local scale may constrain species distributions.

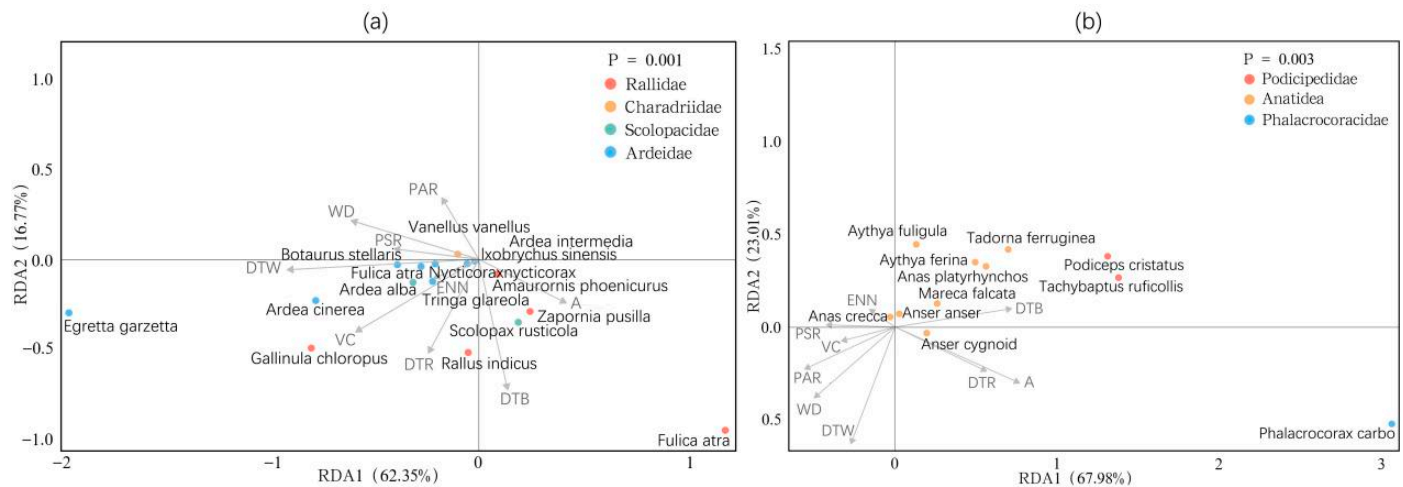


Figure 4. Redundancy analysis (RDA) of waterbird species and environmental variables: (a) RDA results for waders; (b) RDA results for waterfowl. A (patch area); PAR (perimeter to area ratio); ENN (Euclidean nearest-neighbor distance); DTR (distance to major roads); DTB (distance to buildings); WD (water depth); DTW (distance to water bodies); PSR (plant species richness); VC (vegetation cover).

Waterfowl species exhibit a pronounced environmental-response gradient along the RDA1 and RDA2 ordination axes (Figure 4b). The first two axes cumulatively explain 91.29% of the constrained variation (RDA1 = 67.98%, RDA2 = 23.01%), and the overall model is significant ($p = 0.003$), indicating strong explanatory power of the environmental variables for waterfowl. Distance to buildings (DTB) and area (A) are significantly positively associated with the distribution of waterfowl, whereas distance to water bodies (DTW), water depth (WD), and perimeter to area ratio (PAR) show significant negative associations. Most Ducks and Geese (*Anatidae*), including the Mallard (*Anas platyrhynchos*), Common Pochard (*Aythya ferina*), and Ruddy Shelduck (*Tadorna ferruginea*), preferentially occur in habitats farther from buildings and characterized by extensive open-water areas. Similarly, Grebes (*Podicipedidae*), such as the Great Crested Grebe (*Podiceps cristatus*) and Little Grebe (*Tachybaptus ruficollis*), show strong associations with distance to buildings (DTB) and occur in large water bodies away from high-disturbance zones. In contrast, vegetation-related variables, including plant species richness (PSR) and vegetation cover (VC), show no significant responses, suggesting that waterfowl are generally less sensitive to vegetation heterogeneity and instead depend more strongly on the spatial distribution of water bodies and disturbance intensity.

3.3. Associations Between Waterbird Assemblages and Environmental Variables

Mantel test results indicate significant spatial associations between different waterbird assemblages and environmental gradients (Figure 5). Rails (*Rallidae*) show positive correlations with water depth (WD), plant species richness (PSR), distance to water bodies (DTW), and vegetation cover (VC) ($p < 0.05$). Plovers (*Charadriidae*) are significantly positively correlated with distance to major roads (DTR) ($p < 0.01$). Herons (*Ardeidae*) exhibit significant positive correlations with distance to water bodies (DTW) and water depth (WD) ($p < 0.05$). Grebes (*Podicipedidae*) show the strongest positive correlations with patch area (A), perimeter to area ratio (PAR), and water depth (WD) ($p < 0.001$). Ducks and geese (*Anatidae*) are positively correlated with distance to major roads (DTR), distance to buildings (DTB), and water depth (WD) ($p < 0.05$). Cormorants (*Phalacrocoracidae*) show positive

correlations with patch area (A) and distance to major roads (DTR) ($p < 0.05$). Notably, Sandpipers (*Scolopacidae*) show no significant correlations with any of the nine environmental variables.

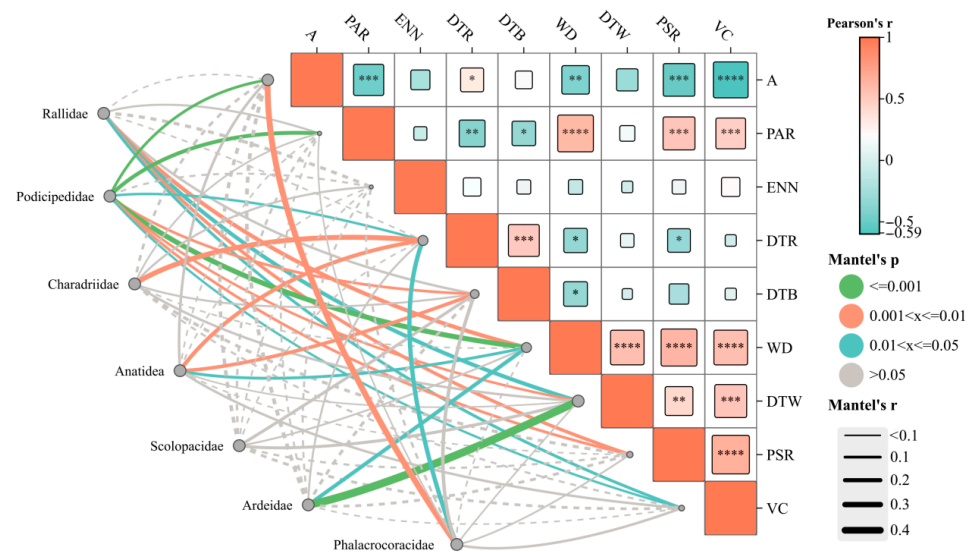


Figure 5. Mantel-test analysis of correlations between waterbird assemblages and environmental variables. A (patch area); PAR (perimeter to area ratio); ENN (Euclidean nearest-neighbor distance); DTR (distance to major roads); DTB (distance to buildings); WD (water depth); DTW (distance to water bodies); PSR (plant species richness); VC (vegetation cover); * ($p < 0.05$); ** ($p < 0.01$); *** ($p < 0.001$); **** ($p < 0.0001$).

3.4. Responses of Waterbird Diversity to Environmental Variables

Regression results indicate that waders richness responds to multiple environmental variables to varying degrees (Table 5). The model showed good overall fit (adjusted $R^2 = 0.444$) and is significant at the model level ($F = 5.085$, $p < 0.001$), suggesting that the selected variables explain a substantial proportion of the spatial variation in waders richness. Among the predictors, vegetation cover (VC) exerts the strongest positive effect on waders richness; higher vegetation cover provides shelter and stable food resources, thereby markedly enhancing habitat suitability. In addition, distance to buildings (DTB) and water depth (WD) both show relatively strong positive associations, indicating that waders preferentially use areas with lower human disturbance and suitable water depth. In contrast, perimeter to area ratio (PAR) shows a negative trend with waders richness, indicating that overly complex and fragmented patch edges may be unfavorable for waders activities. This pattern also suggests that excessive edge fragmentation occurs along parts of the Shuoxi Lake wetland, potentially reducing habitat suitability for waders.

Table 5. Regression model results for wader species richness.

K = 0.19	Unstandardized Coefficients		Standardized Coef-	t	p	F	Adjusted R ²
	B	Standard Error	ficients Beta				
Constant	2.173	0.205	-	10.586	0.000 ***	5.085 (0.000 ***)	0.444
A	−0.109	0.171	−0.068	−0.639	0.526		
PAR	−0.401	0.219	−0.195	−1.833	0.075 *		
ENN	−0.123	0.533	−0.022	−0.232	0.818		
DTR	0.173	0.165	0.108	1.047	0.302		
DTB	0.349	0.18	0.194	1.941	0.060 *		

WD	0.347	0.178	0.215	1.943	0.060 *
DTW	0.229	0.188	0.125	1.221	0.230
PSR	0.112	0.198	0.062	0.565	0.575
VC	0.623	0.178	0.387	3.5	0.001 ***

Notes: *** and * indicate significance at the 1% and 10% levels, respectively. A (patch area); PAR (perimeter to area ratio); ENN (euclidean nearest-neighbor distance); DTR (distance to major roads); DTB (distance to buildings); WD (water depth); DTW (distance to water bodies); PSR (plant species richness); VC (vegetation cover); B (unstandardized coefficient); Beta (standardized coefficient); t (t-statistic); F (model F-statistic); R² (coefficient of determination); K (ridge parameter).

Regression results further show (Table 6) that the Shannon–Wiener index (H') of waders exhibits multidimensional responses to landscape variables. The overall model fits the data well (adjusted R² = 0.412) and is significant (F = 4.575, $p < 0.001$). In this model, vegetation cover (VC) has the strongest positive effect, followed by a negative effect of perimeter to area ratio (PAR), which is consistent with the waders richness model. Unlike the richness model, distance to buildings (DTB) and water depth (WD) show stronger positive associations in the Shannon–Wiener model, indicating that waders diversity is more sensitive to disturbance intensity and water-level conditions. In addition, distance to major roads (DTR) shows no significant effect in either model, suggesting that the influence of road-related disturbance on waders is limited, potentially due to the spatial configuration of roads or the relatively constrained disturbance intensity. Plant species richness (PSR) likewise did not exhibit a significant effect, implying that plant species richness is not a primary determinant of waders diversity. By contrast, vegetation cover (VC) remains consistently significant, indicating that vegetation structural attributes (e.g., cover and concealment) exert stronger ecological regulation on waders assemblages than plant species counts.

Overall, the results of the wader richness model and the Shannon–Wiener model show a relatively high degree of consistency. Both models indicate that vegetation cover (VC) and distance from buildings (DTB) are key positive factors influencing wading bird communities, whereas the perimeter-to-area ratio (PAR) consistently exerts a negative influence, suggesting that the degree of habitat patch fragmentation is a significant limiting factor for wading bird distribution. Furthermore, water depth (WD) exhibits a positive correlation in both models, indicating that wading birds prefer habitats characterized by shallow water, low disturbance levels, and favorable vegetation conditions.

Table 6. Regression model results for the Shannon–Wiener index (H') of wader.

K = 0.19	Unstandardized Coefficients		Standardized Coefficients	t	p	F	Adjusted R ²
	B	Standard Error	Beta				
Constant	0.585	0.077	-	7.582	0.000 ***		
A	−0.028	0.064	−0.048	−0.442	0.661		
PAR	−0.163	0.082	−0.217	−1.983	0.055 *		
ENN	−0.117	0.2	−0.058	−0.584	0.562		
DTR	0.032	0.062	0.054	0.516	0.609	4.575 (0.000 ***)	0.412
DTB	0.157	0.068	0.239	2.319	0.026 **		
WD	0.138	0.067	0.234	2.051	0.047 **		
DTW	0.097	0.071	0.145	1.371	0.179		
PSR	0.026	0.075	0.039	0.344	0.733		
VC	0.211	0.067	0.358	3.148	0.003 ***		

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively—A (patch area); PAR (perimeter to area ratio); ENN (euclidean nearest-neighbor distance); DTR (distance to major roads); DTB (distance to buildings); WD (water depth); DTW (distance to water bodies); PSR (plant species richness); VC (vegetation cover); B (unstandardized coefficient); Beta (standardized coefficient); t (t-statistic); F (model F-statistic); R² (coefficient of determination); K (ridge parameter).

In the waterfowl richness model (Table 7), the overall model is significant ($F = 7.627$, $p < 0.001$) with a relatively high explanatory power (adjusted $R^2 = 0.565$). Perimeter to area ratio (PAR) has a significant negative effect on waterfowl richness, further confirming that increasingly complex patch shapes intensify edge effects, reduce effective habitat area, and thereby increase disturbance experienced by waterbirds [53]. Distance to water bodies (DTW) also shows a significant negative association, indicating that waterfowl preferentially use habitats close to open-water bodies. In addition, distance to buildings (DTB) has a significant positive effect on waterfowl richness, whereas the effect of distance to major roads (DTR) does not reach significance, which is consistent with the results of the waders regression models.

Table 7. Regression model results for waterfowl species richness.

K = 0.19	Unstandardized Coefficients		Standardized Coefficients	t	p	F	Adjusted R ²
	B	Standard Error	Beta				
Constant	2.683	0.265	-	10.14	0.000 ***		
A	0.302	0.22	0.129	1.374	0.178		
PAR	−1.039	0.282	−0.347	−3.686	0.001 ***		
ENN	−1.022	0.687	−0.127	−1.488	0.145		
DTR	0.344	0.213	0.147	1.616	0.115	7.627 (0.000 ***)	0.565
DTB	0.656	0.232	0.251	2.829	0.008 ***		
WD	−0.246	0.23	−0.105	−1.069	0.292		
DTW	−0.908	0.242	−0.34	−3.753	0.001 ***		
PSR	0.349	0.256	0.133	1.367	0.180		
VC	0.283	0.229	0.121	1.233	0.225		

Notes: *** indicates significance at the 1%. A (patch area); PAR (perimeter to area ratio); ENN (euclidean nearest-neighbor distance); DTR (distance to major roads); DTB (distance to buildings); WD (water depth); DTW (distance to water bodies); PSR (plant species richness); VC (vegetation cover); B (unstandardized coefficient); Beta (standardized coefficient); t (t-statistic); F (model F-statistic); R² (coefficient of determination); K (ridge parameter).

In the waterfowl Shannon–Wiener index model (Table 8), the model is also significant with strong explanatory power ($F = 6.549$, $p < 0.001$), with an (adjusted $R^2 = 0.521$). Consistent with the richness model, perimeter to area ratio (PAR) remains the strongest negative predictor, highlighting the dominant role of patch configuration in shaping the composition of waterfowl assemblages. Distance to water bodies (DTW) also shows a significant negative association, indicating that diversity likewise depends on proximity to water. Unlike the richness model, distance to buildings (DTB) is only marginally significant ($p = 0.085$), suggesting that waterfowl diversity is less sensitive to building-related disturbance than abundance-based responses; this pattern may be related to increases in disturbance-tolerant species, such as Mallard (*Anas platyrhynchos*) and Coot (*Fulica atra*), that can adapt to human-modified environments. Vegetation variables, including plant species richness (PSR) and vegetation cover (VC), show no significant effects, consistent with the richness model.

Overall, the results from both the waterfowl richness model and the Shannon – Wiener model indicate that the perimeter-area ratio (PAR) and distance to water (DTW) are the primary negative influencing factors, whereas distance to buildings (DTB) exerts a positive effect. This suggests that waterfowl rely more heavily on habitat conditions characterized by open water and remoteness from disturbance. Compared with waders, waterfowl exhibit insignificant responses to vegetation variables (VC, PSR), indicating that their dependence on habitat structure is more strongly associated with the spatial patterns of water bodies than with vegetation characteristics.

Table 8. Regression model results for the Shannon–Wiener index (H') of waterfowl.

K = 0.19	Unstandardized Coefficients		Standardized Coefficients	t	p	F	Adjusted R ²
	B	Standard Error	Beta				
Constant	0.749	0.08	-	9.348	0.000 ***		
A	0.065	0.067	0.096	0.974	0.336		
PAR	−0.383	0.085	−0.444	−4.488	0.000 ***		
ENN	−0.229	0.208	−0.098	−1.101	0.278		
DTR	0.08	0.065	0.118	1.242	0.222	6.549 (0.000 ***)	0.521
DTB	0.124	0.07	0.165	1.77	0.085 *		
WD	−0.041	0.07	−0.06	−0.587	0.561		
DTW	−0.25	0.073	−0.325	−3.412	0.002 ***		
PSR	0.037	0.077	0.048	0.473	0.639		
VC	0.109	0.07	0.16	1.563	0.127		

Notes: *** and * indicate significance at the 1% and 10% levels, respectively. A (patch area); PAR (perimeter to area ratio); ENN (euclidean nearest-neighbor distance); DTR (distance to major roads); DTB (distance to buildings); WD (water depth); DTW (distance to water bodies); PSR (plant species richness); VC (vegetation cover); B (unstandardized coefficient); Beta (standardized coefficient); t (t-statistic); F (model F-statistic); R² (coefficient of determination); K (ridge parameter).

4. Discussion

4.1. Ecological Reclamation Strategies for Constructed Wetlands Based on Optimization of Waterbird Habitat Units

Long-term exploitation of natural wetlands has accelerated wetland loss and functional degradation; therefore, constructing artificial wetlands, while strengthening the protection of remaining natural wetlands, has become an important approach for wetland ecological compensation. After reclamation, habitat heterogeneity in Shuoxi Lake increased markedly, and waterbird richness reached 28 species across 6 orders and 7 families, higher than the number of terrestrial bird species in the surrounding non-subsidence agricultural areas. During the same period, surrounding unreclaimed coal mining subsidence wetlands showed low vegetation cover and plant species diversity, with only 13 waterbird species recorded. The formation of coal mining subsidence wetlands has led to the loss of original farmland, while simultaneously increasing landscape heterogeneity in traditional agricultural areas. In the mining regions of Illinois, USA, post-mining agricultural land that could not be restored in the short term was transformed into permanent ecological land, including woodlands and wetlands, thereby enriching landscape diversity and expanding habitat areas [54]. Even unreclaimed coal mining subsidence wetlands still provide new habitats for a limited number of waterbirds. However, unreclaimed coal mining subsidence wetlands are characterized by a single type of aquatic vegetation and low variability in water depth, and their habitat service functions require rehabilitation and improvement. Based on the results of environmental factor analysis, ecological reclamation

of coal mining subsidence wetlands should incorporate the behavioral and ecological characteristics of birds into wetland functional zoning, surrounding land-use development control, dynamic water-level regulation, vegetation structural optimization, and shoreline morphology improvement. Waders and waterfowl are the dominant waterbird groups in the study area and differ markedly in their life-history traits and habitat use. Waders typically forage in shallow water or mudflats and are more sensitive to changes in shoreline habitat structure, whereas waterfowl mainly utilize open-water habitats and obtain food by swimming or diving. The RDA results show that both groups exhibit significant negative associations with anthropogenic disturbances, particularly distance to buildings (DTB). Potential pathways include noise, light pollution, and microclimatic alterations. Accordingly, wetland landscape design can mitigate external disturbance by increasing peripheral topographic relief or establishing buffer woodland belts along wetland margins to reduce the effects of noise and artificial lighting from nearby buildings and traffic corridors. Establishing independent bird islands and implementing isolation measures can further limit the intensity of development and recreational use in adjacent waters. Waders primarily use the aquatic–terrestrial ecotone and typically occur in shallow water (water depth < 20 cm), and they show higher sensitivity to human disturbance. Wetland bathymetric design should therefore increase the proportion of shallow-water zones and designate protected areas to reduce overlap between human activity spaces and key bird-use areas. In addition, vegetation cover and vegetation types exert stronger effects on the distribution and diversity of waders. Vegetation community construction should emphasize vertical structural complexity by creating high–mid–low vegetation strata to provide more resting and concealment sites. The results further suggest that waterbirds are more sensitive to shrub cover and shrub types; thus, ecological design should align vegetation types, locations, and combinations with the habitat preferences of different bird groups to improve habitat suitability.

Water bodies provide the primary food base for most waterbirds; consequently, water-surface area, configuration, depth, and aquatic vegetation conditions are closely associated with waterbird habitat quality. Both the RDA and Mantel analyses indicate that waterfowl are more sensitive to open-water area, water depth, and waterbody configuration. Constructed wetlands in coal mining subsidence areas are often characterized by closed water systems with limited water exchange and weak hydrological regulation. Reclamation should therefore simulate ecohydrological processes of natural wetlands by using dikes and sluices to enable zonal control and dynamic adjustment of water levels. Based on the bird community survey in the study area, spring and summer correspond to the breeding season for most resident birds, during which relatively higher water levels should be maintained to support concealment and nesting [55]. In autumn, when large numbers of migratory birds arrive, water levels can be moderately lowered to increase shallow water and mudflat areas, thereby providing suitable foraging habitats during migratory stopovers. In winter, which is also the dry season in the study area, external water sources may be required to maintain a basic ecological water level and prevent extensive surface icing that could restrict water-surface activity by wintering birds. Waterbody design should additionally emphasize diversified shoreline forms and optimized underwater microtopography; creating sufficiently open water surfaces is particularly important for expanding suitable habitat space for waterfowl. In addition, three IUCN threatened species were recorded in the study area, primarily occurring in the lake's core areas and near-natural shoreline zones away from urban disturbance, and were less frequently observed in sites close to urban built-up areas. Baer's Pochard prefers deeper open-water habitats and feeds mainly on aquatic plants and benthic invertebrates [56]. Swan Goose forages mainly in shallow waters and vegetated shoals [57]. Common Pochard prefers deeper waters and feeds by diving [58]. Therefore, maintaining diverse water-depth gra-

dients, open water areas, and low levels of human disturbance is of particular importance for enhancing habitat suitability for these threatened species.

4.2. Community Characteristics of Waterbirds in Coal Mining Subsidence Wetlands

As a distinctive type of artificial wetland, the ecologically reclaimed Shuoxi Lake Wetland has become an important supplementary habitat for regional waterbirds, particularly by providing essential habitat services for wintering waterbirds. In terms of dominant species, the Eurasian coot, mallard, Eurasian teal, and little grebe constituted the overwhelmingly dominant assemblage, with their combined abundance accounting for more than 65% of the total waterbird abundance. Among them, the Eurasian coot often formed single-species flocks of several hundred individuals during winter, reflecting the relatively high resource carrying capacity of the wetland during the overwintering period. In terms of species composition, a total of 28 waterbird species were recorded, among which winter visitors accounted for a relatively high proportion (14 species). A total of 37 wintering waterbird species have been recorded in Huaibei City [59], indicating that Shuoxi Lake, as an artificial wetland, has become an important node in the regional avian habitat network. In terms of residency status, resident species were the least represented, with only four species recorded, while summer visitors and passage migrants each accounted for five species, indicating that the community is primarily driven by migratory and seasonally dynamic utilization. Threatened species such as the Baer's pochard and Swan goose were all winter visitors, further highlighting the ecological importance of this wetland for the conservation of threatened waterbirds. In terms of ecological groups, 13 species were classified as waterfowl, including grebes, ducks, the Eurasian coot, and cormorants, which mainly used open-water habitats. Fifteen species were classified as waders, including some rallid species, plovers and sandpipers, and herons, which were primarily active in shallow-water areas and vegetated zones. These two functional groups exhibited complementary spatial niches. Seasonally, species richness was highest in winter, when 18 species, including winter visitors and resident birds, were recorded, accounting for more than 60% of the total species richness. During the spring and autumn migration periods, five passage migrant species were recorded, and community turnover increased markedly. In the summer breeding season, the community was mainly composed of four resident species and five summer visitors, totaling nine species, thereby forming a relatively stable breeding assemblage.

The Huaibei Plain is located within a key section of the East Asian-Australasian Flyway, and its lacustrine and marsh wetlands serve as important wintering grounds for waterbirds such as geese, ducks, and cranes [60]. Over the past three decades, continuous pressures from intensive development activities, including agricultural reclamation, urban expansion, and water conservancy construction, have led to a decline in the area of natural wetlands in the Huaibei Plain [61]. Natural wetland patches have become increasingly fragmented and isolated, resulting in a substantial reduction in suitable habitats for wintering waterbirds and significant declines in both population abundance and species richness. Artificial secondary wetlands formed in coal mining subsidence areas can improve the connectivity of habitat networks. The analysis of the waterbird community indicates that Shuoxi Lake plays an important role in enhancing the habitat network for wintering waterbirds. Given that waterbird species richness is highest in winter and that the wintering assemblage represents the core component of the community, ecological conservation zones should be designated in Shuoxi Lake during winter. Seasonal closure management should also be implemented to minimize the negative impacts of human activities on energy replenishment and flock stability during the wintering period.

4.3. Limitations and Future Perspectives

Using Shuoxi Lake in Huaibei City as a case study, this study delineates habitat units and surveys avian diversity in a reclaimed coal mining subsidence wetland, and identifies the environmental factors influencing major bird populations, thereby providing support for ecological reclamation of coal mining subsidence wetlands. However, given the formation characteristics of subsidence wetlands, reclamation effectiveness needs to be further evaluated at broader landscape scales, with explicit consideration of regional ecological network construction and watershed hydrological connectivity, in order to achieve systematic recovery of habitat functions in these wetlands. On this basis, future research could focus on threatened bird species and propose corresponding conservation measures. Long-term monitoring could also be used to evaluate waterbird responses to ecological reclamation measures and assess their effectiveness.

5. Conclusions

This study investigated the composition, diversity, and environmental drivers of waterbird assemblages in Shuoxi Lake Coal Mining Subsidence Wetland Park, and the following conclusions were drawn:

1. A total of 28 waterbird species were recorded, with winter visitors constituting the dominant group. Three species recorded in the study area are listed on the IUCN Red List, and 13 species are identified as Anhui Province Class II protected species, indicating that artificial wetlands in coal mining subsidence areas possess high habitat service value.
2. RDA revealed clear differentiation between wader and waterfowl assemblages along environmental gradients. The distribution of waders was mainly influenced by vegetation cover (VC), distance to water bodies (DTW), and distance to buildings (DTB), whereas waterfowl assemblages were primarily sensitive to distance to buildings (DTB), patch area (A), and distance to water bodies (DTW). Mantel tests further confirmed significant spatial correlations between different assemblages and patch area (A), distance to major roads (DTR), distance to buildings (DTB), water depth (WD), and DTW.
3. Ridge regression analysis indicated that, after controlling for anthropogenic disturbance (DTB), wader assemblages preferred habitats with higher vegetation cover and suitable water depth. Waterfowl were more sensitive to the perimeter-area ratio (PAR) and DTW. In addition, PAR showed negative effects across all models, indicating that excessively fragmented patch shapes are unfavorable for waterbird habitat use.

Overall, the structure of the waterbird assemblage in Shuoxi Lake Wetland is jointly regulated by multiple interacting factors. Future management should follow the principles of “ecological priority, gradient-based protection, and human-bird coexistence”. Strategies such as zoned management, spatial separation, optimization of vegetation stratification, and dynamic water-level regulation should be implemented to meet the ecological requirements of different bird groups. The findings of this study can provide a scientific reference for promoting harmonious coexistence between humans and nature in wetlands of coal mining subsidence areas.

Author Contributions: Conceptualization, X.Y., S.Z. and B.H.; methodology, X.Y., S.Z. and B.H.; software, X.Y. and B.H.; validation, X.Y., S.Z. and B.H.; formal analysis, X.Y., S.Z. and B.H.; investigation, X.Y., F.Q. and J.C.; resources, S.Z.; data curation, X.Y. and B.H.; writing—original draft preparation, X.Y.; writing—review and editing, X.Y., S.Z. and B.H.; visualization, X.Y.; supervision, S.Z.,

B.H., F.Q. and J.C.; funding acquisition, S.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundations of China, grant number 52378082, 52208091.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to express their gratitude to the reviewers and editor for their insightful comments and suggestions.

Conflicts of Interest: Author Jing Chen was employed by the company Xuzhou Huacheng Planning and Design Consulting 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.

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