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Habitat Suitability and Enhancement Strategies for Waterbirds in Fishing Withdrawal Zones: An Evidence-Based Assessment

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Abstract: The Yancheng coastal wetlands serve as a crucial stopover site along the East Asian–Australasian Flyway. The rapid expansion of aquaculture has led to a significant decline in natural wetlands, impacting both the distribution and quality of waterbird habitats. Following the designation of the region as a World Natural Heritage site in 2019, the local government has prioritized the protection of waterbird habitats, leading to the large-scale withdrawal of aquaculture from the region. Nevertheless, the impact of the fishing withdrawal on waterbird habitat selection and the ecological benefits it brought remain unknown. In this study, based on the identification of fishing withdrawal zones in the Yancheng coastal area, six waterbird groups, *Anatidae*, *Ardeidae*, *Charadriiformes*, *Laridae*, *Gruidae* and *Ciconiidae*, were selected to construct an evaluation index system for habitat suitability. The Biomod2 ensemble model was employed to analyze the spatial differences of suitable habitats for waterbirds within the fishing withdrawal zones. The result revealed the following: (1) As of 2022, the area of fishing withdrawal zones had reached 2.23×10^4 ha, primarily distributed in Beihuan and Nanhuan. Among these, the area of fishing withdrawal zones in Nanhuan was the largest, reaching 6.78×10^3 ha. (2) Unsuitable area for waterbirds was largest in the fishing withdrawal zones, with a proportion of 60% and 58% for *Gruidae* and *Ciconiidae*, respectively. (3) The rich nutrients, high coverage and tall stature of emergent vegetation in the fishing withdrawal zones led to a reduction in water surface area, resulting in significant adverse effects on the suitable habitats for *Charadriiformes* and *Gruidae*. Therefore, the results suggest that most areas after fishing withdrawal were still not suitable habitats for waterbirds. The implementation of scientific fishing withdrawal practices, along with ecological restoration and management, is crucial for improving the habitat suitability in fishing withdrawal zones. This study provides valuable insights for more purposeful selection of fishing withdrawal sites, and more scientific management and restoration of these areas to enhance their ecological benefits.

Keywords: fishing withdrawal zone; waterbirds; habitat suitability; ensemble model; UNESCO World Natural Heritage sites

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1. Introduction

Biodiversity conservation is a crucial component of global ecological protection [1]. At the 15th meeting of the Conference of the Parties to the Convention on Biological Diversity (COP15) held in 2022, the Kunming–Montreal Global Biodiversity Framework was adopted. During the conference, the "30 by 30" target was established, which aimed to protect at least 30% of global land and sea areas by 2030 [2]. China has made a range of attempts and efforts toward achieving biodiversity protection [3]. Since the 19th CPC Congress called for "strengthening the protection and restoration of wetlands", the National Development and Reform Commission and the Ministry of Natural Resources have issued and implemented the "Master Plan for Major Projects of National Important Ecosystem Protection and Restoration (2021–2035)". Additionally, the "Wetland Protection Law of the People's Republic of China" was introduced in 2021. These governmental actions collectively underscore the urgent need for wetland protection. To protect wetlands and their habitats for wetland organisms, as well as to improve ecological benefits, "fishing withdrawal" has emerged as one of the most important ecological restoration measures and an effective means of preserving the ecological functions of wetlands [4]. Several regions in China have already implemented fishing withdrawal programs. Coastal areas, as transition zones between land and sea, serve as habitats for numerous waterbirds and other species, with significant ecological functions [5]. Therefore, China's coastal areas led the way in implementing "fishing withdrawal to wetlands". In 2015, a large-scale "ponds-to-wetlands" restoration project was carried out in the Liaohe Estuary area [6]. In December 2019, ecological restoration was implemented in the Maiya River wetland area in Haikou, Hainan, with a total planned area of 5.68×10^2 ha [7]. Fishing areas were withdrawn, and fishponds in river channels were demolished to restore the original river system. Yancheng City, Jiangsu Province, is a key node on the East Asian–Australasian Flyway for migratory birds. Each year, millions of waterbirds winter, breed and transit here [8]. Since 2010, large-scale fishing withdrawal programs have been implemented in the Yancheng coastal wetlands to protect waterbirds. According to the "Ecological Restoration Planning for the Buffer Zone of Jiangsu Yancheng Wetland Rare Birds National Nature Reserve" compiled by the Yancheng National Rare Birds Nature Reserve, it is planned to invest CNY 141 million to implement wetland ecological restoration projects including fishing withdrawal in the 327 km^2 of the reserve buffer zone. It is crucial to assess whether these fishing withdrawal zones meet the expected goal of protecting waterbird habitats and whether waterbirds are utilizing these zones as anticipated. This is of great significance to waterbird conservation and wetland ecological restoration. Considering the urgent needs of reality, it is also helpful to help the government to strike a balance between the ecological benefits brought by huge investments and the economic benefits brought by aquaculture. There are many existing studies on waterbird habitat suitability in Yancheng, which primarily focused on the impacts of anthropogenic reclamation [9] and invasive species [10], emphasizing landscape pattern changes at the regional scale [11]. These works aimed to provide regional habitat restoration strategies [12] and ecological corridor optimization approaches [13]. Studies have shown that the quality and range of suitable waterbird habitats in Yancheng coastal wetlands have continued to decline [14], and the negative impact of reclamation activities has become increasingly apparent [15]. As protection-oriented artificial transformation areas, fishing withdrawal zones are a special type of study area that require a comprehensive waterbird habitat suitability assessment to promote targeted habitat restoration and strengthen waterbird biodiversity conservation.

Species distribution modeling is an important method for assessing waterbird habitat suitability and quantifying their various habitat requirements. Therefore, it was commonly used in studies on waterbird habitat protection [16]. Species distribution models (SDM) are mathematical models constructed using known species distribution points and related environmental variables, employing various algorithms. They can quantify species habitat requirements and identify suitable potential habitats. Common species distribution models include the generalized linear model (GLM), generalized additive model (GAM), multiple adaptive regression splines (MARS), classification tree analysis (CTA), artificial neural network (ANN), surface range envelope (SRE), flexible discriminant analysis (FDA), random forest (RF), generalized boosted regression models (GBM), maximum entropy model (MaxEnt) and so on [17,18]. Different species distribution models use various algorithms, leading to different results in evaluating habitat suitability. Each model has its advantages and limitations. For example, the generalized linear model can intuitively determine the role and importance of environmental variables for species distribution. The random forest model and the artificial neural network model are easy to operate and relatively accurate, but their ecological significance during the modeling process is insufficient [18]. Selecting the optimal model for species habitat suitability is challenging.

Given the advantages and limitations of the above species distribution models, ensemble models have been applied to the habitat assessment of plants and animals. Ensemble models offer various options which can be combined for species simulation based on research requirements [19]. This approach allows for the selection of models that meet expectations with higher accuracy. Additionally, models with good simulation effects can be integrated. Ensemble models help avoid data overfitting, improve prediction accuracy and provide more precise forecasts [20]. Ensemble models have been widely used in geographic distribution studies of plants, animals and disease spread (such as the spread of *Streptococcus pneumoniae*) [21–24]. Currently, ensemble models are used for plant studies on endangered and invasive species, and for animal studies on insects and other mammals, but are rarely used to analyze potential habitats of waterbirds. Existing studies typically focused on single waterbird species or groups [25], with less emphasis on protecting waterbird diversity or evaluating habitat suitability for multiple waterbird species. Methodologically, existing studies on waterbird habitats in Yancheng have predominantly employed the MaxEnt model [26] and random forest (RF) algorithm [14], while ensemble modeling approaches have been relatively underutilized, presenting certain methodological limitations.

This study used the Biomod2 ensemble model, which provided more accurate predictions of waterbird habitat suitability compared to other species distribution models. The study focused on areas that were transformed from aquaculture ponds with high intensity of human activities to fishing withdrawal zones with low intensity of human activities. It explored the habitat suitability for different waterbird groups in the existing fishing withdrawal zones, and analyzed the importance of habitat suitability evaluation factors for different waterbird groups. The findings can provide a reference for more targeted selection of fishing withdrawal sites and provide guidance for the scientific management and restoration of these fishing withdrawal zones.

2. Materials and Methods

2.1. Study Area

The Yancheng coastal wetland in Jiangsu Province, China, is located between longitudes 119°45′ E–121°30′ E and latitudes 32°30′ N–34°30′ N, covering an area of 4.68×10^3 km^2 (Figure 1), spanning five counties: Xiangshui, Binhai, Sheyang, Dafeng and Dongtai. It possesses the largest muddy coast along the western Pacific Ocean and is a key node on the East Asian–Australasian Flyway for migratory birds. In 2019, it was approved as a UNESCO World Natural Heritage site. With two national nature reserves, wetland restoration in this region is critical for waterbird conservation. The area includes various types of wetlands in natural, semi-natural, artificial and semi-artificial states inside and outside the boundaries of the two reserves as well as on both sides of the old and new sea walls. Over the past 30 years, due to the development of coastal areas and excessive pond farming, the aquaculture area has grown, growing from 8.98×10^2 km^2 in 2010 to 1.04×10^3 km^2 in 2015, which led to great changes in the ecological structure and spatial pattern of Yancheng coastal wetland. It caused severe habitat fragmentation and a decline in habitat quality for waterbirds. To protect the ecological environment of Yancheng coastal wetlands and provide suitable wintering habitats for thousands of migratory birds, the "Fishing Withdrawal Program" was implemented in 2010. By the end of 2022, the area of fishing withdrawal zones reached 2.23×10^4 ha. Based on previous research results [27], the Yancheng coastal zone was divided into six major waterbird habitats in this study: Guandong Habitat, the northern part of the buffer zone, Hexin Area, the southern part of the buffer zone, Dafeng Habitat and Tiaozini Habitat (hereinafter referred to as Guandong, Beihuan, Hexin, Nanhuan, Dafeng and Tiaozini, respectively).

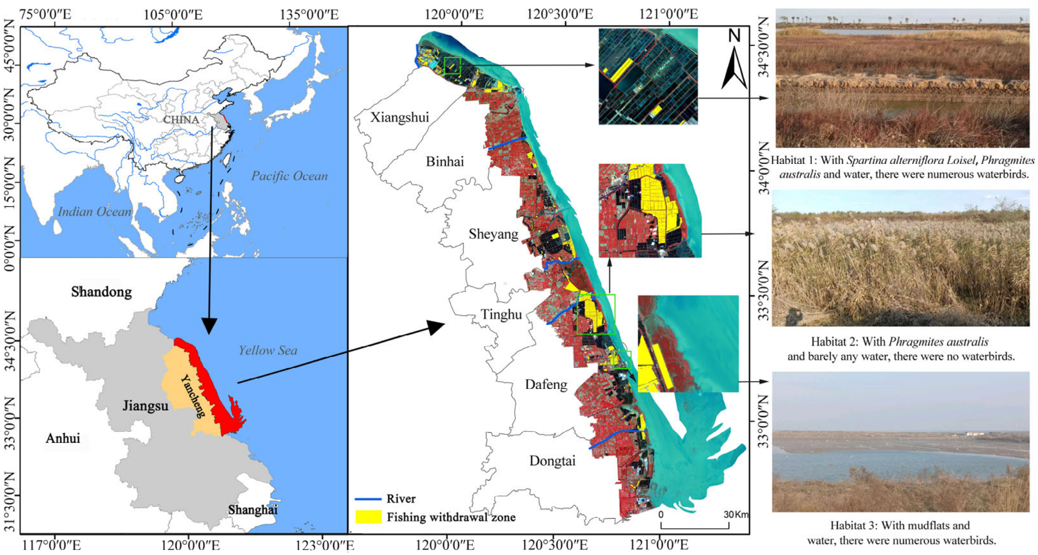

Figure 1. Study area and primary fishing withdrawal zones.

2.2. Data Sources and Processing

The data of this study included two parts: waterbird field survey data and surface information data. The waterbird distribution data for the fishing withdrawal zones were collected from field surveys conducted by the research team in Yancheng coastal wetlands mainly in 2023. The waterbird surveys employed point sampling and line sampling methods under clear-weather and low-wind conditions. Portable GPS (Trimble Juno SA/Trimble Inc., Sunnyvale, CA, USA), a laser rangefinder (LTI-TruPulse 360/Laser Technology, Inc., Centennial, CO, USA) and binoculars (Boshile 7 × 50/Yiwu Suolan Outdoor Camping Supplies Co., Ltd., Jinhua, Zhejiang, China) were used to record the coordinates of waterbirds. Based on the survey data, waterbirds were categorized into 6 groups: *Anatidae*, *Ardeidae*, *Charadriiformes*, *Laridae*, *Gruidae* and *Ciconiidae*. The distribution data for waterbirds in the fishing withdrawal zones included 205 points for *Anatidae*, 157 points for *Ardeidae*, 140 points for *Charadriiformes*, 158 points for *Laridae*, 140 points for *Gruidae* and 152 points for *Ciconiidae*. Landsat (spatial resolution of 30 m) and Sentinel images (spatial resolution of 10 m) from 2010 and 2021 were used. Images with less than 10% cloud cover were selected on the Google Earth Engine (GEE) platform, processed for cloud removal, cropped and mosaicked. The distribution of aquaculture ponds in 2010 and 2022 in remote sensing images was compared, and, combined with field surveys and grassroots visits, the scope of the fishing withdrawal zones along the coast of Yancheng at the end of 2022 was obtained. Based on the remote sensing images from the end of 2022, the surface information data required for the evaluation of waterbird habitat suitability were obtained.

2.3. Methods

2.3.1. Selection of Evaluation Factors and Construction of Indicator System for Waterbird Habitat Suitability in Fishing Withdrawal Zones

Considering the habitat requirements of waterbirds and data availability, 9 evaluation factors from 4 aspects were selected (Table 1). These aspects were food abundance, water resources, concealment conditions and human disturbance. Among all factors, habitat types in the fishing withdrawal zones were categorized based on field surveys, due to the limited vegetation types along the Yancheng coast. The fishing withdrawal zones consisted of patches of varying sizes, with larger patches supporting more diverse ecosystems and having different impacts on waterbirds. These patches were divided into five grades according to the distribution and features of different patch areas in fishing withdrawal zones.

Table 1. Selection of evaluation factors for waterbird habitat suitability in fishing withdrawal zones.

Aspects	Evaluation Factor	Abbreviation	Interpretation
Food abundance	Habitat types	T_hab	*Phragmites australis*, *Spartina alterniflora*, *Suaeda salsa* habitats
	Habitat patch size	A_hab	Calculation of various fishing withdrawal patches, categorized into 5 levels: 2×10^2~4×10^2 ha; 4×10^2~7×10^2 ha; 7×10^2~1.5×10^3 ha; >1.5×10^3 ha
	Vegetation coverage	FVC	Use pixel dichotomy model of vegetation coverage and Normalized Difference Vegetation Index (NDVI)
Water resources	Surface area	A_wat	Extract water bodies using Normalized Difference Water Index (NDWI)
	Distance to river/sea	D_wat	Euclidean distance
Concealment conditions	Vegetation height	H_pla	*Phragmites australis*: 1–2.5 m; *Suaeda salsa*: 0.5–1 m; *Spartina alterniflora*: 1–1.5 m (based on the field surveys)
Human disturbance	Distance to farmland	D_far	Euclidean distance
	Distance to roads	D_roa	Euclidean distance
	Distance to residential/industrial areas	D_res	Euclidean distance

Considering the high activity ability and wide activity range of waterbirds, and based on the characteristics of patch size in fishing withdrawal zones and the features of species distribution models, a 30 m resolution was selected for nine environmental factor layers, through multiple simulation attempts at different spatial resolutions. To prevent model overfitting due to high collinearity among environmental variables, Pearson correlation analysis was conducted to examine the correlation coefficients among the nine factors, all of which were found to be less than 0.7.

2.3.2. Construction of Individual Model

The waterbird distribution data in the fishing withdrawal zones were randomly divided into a training dataset (75%) and test dataset (25%). Due to the absence of missing samples, two sets of pseudo-missing data were randomly generated during the model construction process. A total of nine individual models were used: GLM, GBM, GAM, CTA, ANN, FDA, SRE, RF, MARS and MaxEnt. During the construction of individual models, parameter tuning was performed, and each model was run 10 times. These individual models were run for the six different waterbird groups, respectively. The final results provided the spatial distribution of habitat suitability for different waterbird groups under the operation of various individual models.

2.3.3. Construction of Biomod2 Ensemble Model

The Biomod2 ensemble model was run in R (version 4.3.2), with nine layers of environmental factors imported for model simulation. High-accuracy, well-performing individual models were selected and combined to form the ensemble model. Common methods for model integration include Committee Averaging (CA) and the Weighted Mean of Probabilities (WM). The CA method converts the predicted probabilities of individual models to be integrated into votes of presence or absence according to the optimal threshold and then calculates the average value. It can be used to test the consistency of models. When the committee average value is close to 0, it indicates that all single models involved in the ensemble can be predicted as non-existent; if it is close to 1, the opposite is true. If it is close to 0.5, then it means the models predicting existence and non-existence each account for half, indicating poor consistency [28]. The WM method assigns different weights to evaluation results from individual models involved in the ensemble, then averages the predicted probabilities. The CA method is typically used when the individual models involved in the ensemble show good consistency, while the WM method has a broader application range. In specific studies, the two integration methods should be compared based on the evaluation indicators TSS and AUC and the more suitable method chosen.

2.3.4. Habitat Suitability Estimation and Classification

Model accuracy was assessed using True Skill Statistics (TSS) and the Area Under the Curve (AUC) of the Receiver Operator Characteristic Curve (ROC). TSS inherit the advantages of the Kappa statistic and overcome the limitation of the Kappa statistic's unimodal curve response form to species occurrence rate [19]. The closer the value of TSS is to 1, the better the simulation performance is. The AUC, commonly used as an indicator to evaluate niche prediction results, compares the accuracy of two diagnostic tests. The AUC value, which ranges from 0 to 1, indicates the model fit and prediction accuracy, with values closer to 1 representing better performance [29]. The habitat suitability of different waterbird groups was classified into four levels using the natural breaks method: unsuitable, low suitability, sub-suitable, and most suitable.

3. Results

3.1. Distribution of the Fishing Withdrawal Zones in Yancheng Coastal Wetlands

Based on the distribution features of fishing withdrawal zones and six major habitats in Yancheng coastal wetlands, the study area was divided into District A, B, C and D. District C (Figure 2), with the largest fishing withdrawal area (1.19×10^4 ha), had a relatively concentrated distribution of fishing withdrawal zones. It included three main waterbird habitats: Beihuan, Hexin and Nanhuan. The three habitats were closely connected, forming the largest waterbird habitat block in Yancheng coastal wetlands. Among them, the area of the fishing withdrawal zone in Nanhuan was the largest. The area of fishing withdrawal zones in District B was the smallest, only 1.35×10^3 ha. The largest fishing withdrawal patch inside District B was near the road, and the main vegetation was *Phragmites australis*. A small portion of fishing withdrawal zones along the coast was due to coastal erosion. District A and District D had similar fishing withdrawal areas, with District A covering 4.37×10^3 ha and District D covering 4.72×10^3 ha. The fishing withdrawal zones in District D were mainly distributed on the south part of Dafeng Habitat, while the fishing withdrawal zones in District A were more dispersed and had smaller individual patches, with the largest patch being 6.74×10^2 ha.

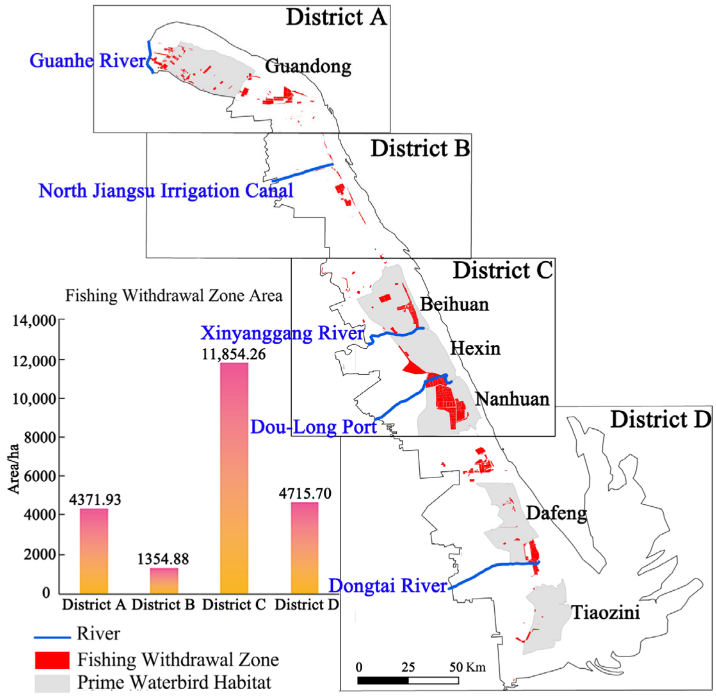

Figure 2. Distribution of the fishing withdrawal zones.

Habitats within the different fishing withdrawal zone varied, mainly in terms of water distribution, habitat type, vegetation coverage and vegetation height (Figure 3). In zones that had been retired for a short period or were in riparian areas, water distribution was more extensive. Variations in water distribution and water salinity influenced the growth of different plant species within these zones. The vegetation in the coastal zone of Yancheng was relatively homogeneous, primarily consisting of *Phragmites australis*, *Spartina alterniflora* and *Suaeda salsa*. These vegetation types formed distinct waterbird habitats, including *Phragmites australis* marsh habitats, *Spartina alterniflora* marsh habitats and *Suaeda salsa* marsh habitats.

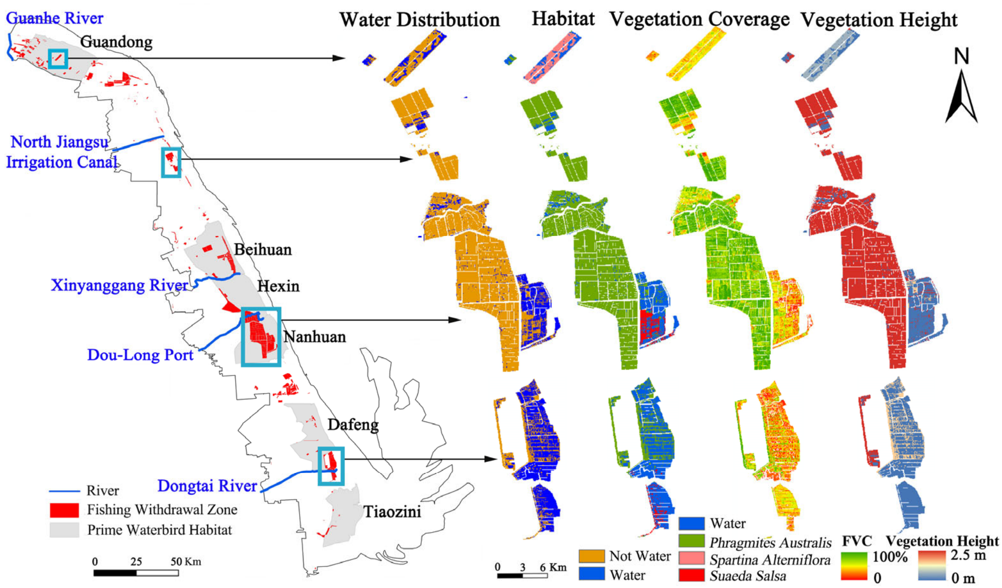

Figure 3. Internal habitats of the fishing withdrawal zones.

The different biological characteristics of *Phragmites australis*, *Spartina alterniflora* and *Suaeda salsa* resulted in varying vegetation heights (Figure 3), with *Phragmites australis* being taller than both *Spartina alterniflora* and *Suaeda salsa*. In addition, water distribution and salinity influenced vegetation density and height. These factors, in turn, affected the overall vegetation coverage within different fishing withdrawal zones, leading to variations in coverage.

3.2. Habitat Suitability Evaluation for Waterbirds in Fishing Withdrawal Zones Based on the Biomod2 Ensemble Model

3.2.1. Model Simulation and Accuracy Assessment of Habitat Suitability for Different Waterbird Groups

Utilizing the distribution data of waterbirds surveyed in the fishing withdrawal zones, waterbirds were categorized into six groups of waterbirds, namely, *Anatidae*, *Ardeidae*, *Charadriiformes*, *Laridae*, *Gruidae* and *Ciconiidae*, based on their species information and habitat preferences. The waterbirds data of each group were divided into a 75% training set and 25% test set. The species distribution models were simulated on the Biomod2 platform for each of these six waterbird groups, running ANN, CTA, FDA, GBM, GLM, MARS, MAXENT, MAXNET, RF, SRE and XGBOOST models for a total of 10 datasets and repeating the runs 10 times, and finally 110 single models.

The distribution of different waterbird groups responded differently to environmental factors, leading to varying results in the independent model evaluations (Figure 4). For *Anatidae*, individual models with TSS values at [0.63, 0.99] and AUC values at [0.88, 1] were selected, excluding low-accuracy, poorly simulated and overfitting models. The RF, MAXENT, GBM and CTA models showed higher accuracy than the others. For *Ardeidae*, the RF, GBM, GLM and CTA models achieved the highest accuracy. For *Charadriiformes*, the RF and GBM models performed best, followed by the FDA and MAXNET models. For *Gruidae*, the GBM model had the highest accuracy, with the RF, MAXNET and MARS models following closely. For *Laridae*, the RF, GBM, GLM and MARS models demonstrated the highest accuracy. Although there were variations in the models with the best accuracy and simulation for different waterbird groups, similarities were observed. Based on the accuracy and occurrence frequency of the independent screenings for six waterbird groups, the RF, GBM, MAXENT, CTA and MARS models outperformed the other models in terms of accuracy and applicability.

For different waterbird groups, individual models with high accuracy were selected for integration, resulting in ensemble models generated using both Committee Averaging (CA) and Weighted Mean of Probabilities (WM) methods. Based on the accuracy of the ensemble models, the WM method outperformed the CA method for five waterbird groups (Figure 5). Therefore, the WM method was consistently chosen for integration and visualization.

3.2.2. Distribution of Habitat Suitability for Different Waterbird Groups

The Biomod2 ensemble model was used to assess habitat suitability for six different waterbird groups in fishing withdrawal zones of Yancheng coastal wetlands. Habitat suitability was classified into four categories: most suitable, sub-suitable, low suitability and unsuitable. The evaluation results of six waterbird groups indicated that the total area of low-suitability and unsuitable areas was the largest (Figure 6). Overall, *Ardeidae* and *Anatidae* had larger suitable areas, while *Gruidae* and *Laridae* had smaller. The groups with large total areas of unsuitable and low-suitability areas were *Gruidae*, *Laridae* and *Ciconiidae*, with areas of 1.76×10^4 ha, 1.74×10^4 ha and 1.73×10^4 ha, respectively, accounting for 82.03%, 81.14% and 80.66%. This suggested that the fishing withdrawal zones in Yancheng coastal wetlands were not suitable habitats for most waterbirds, especially for *Gruidae*, *Laridae* and *Ciconiidae*.

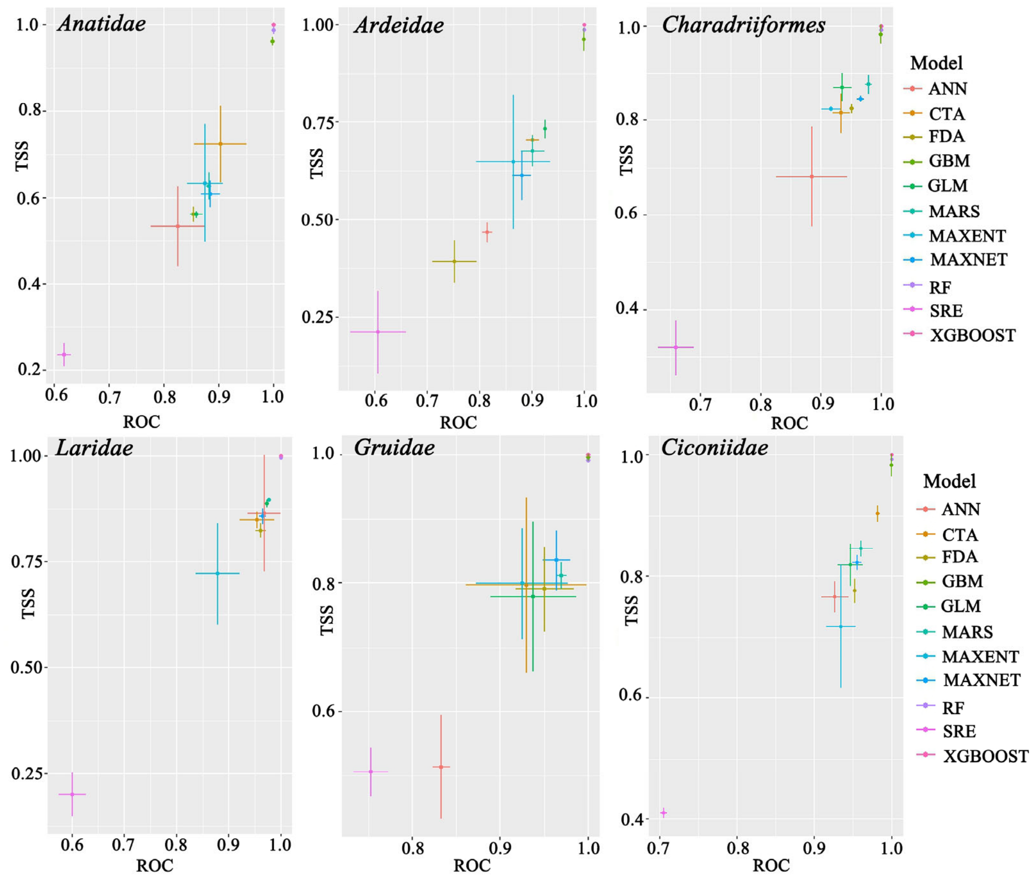

Figure 4. Evaluation of the accuracy of individual models for different waterbird groups.

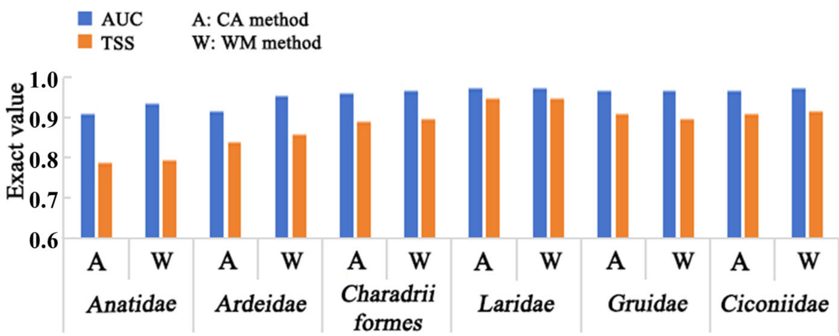

Figure 5. Accuracy of different integration methods.

In terms of zones, the most suitable habitats for *Charadriiformes* were primarily distributed in District A, with the ratio of most suitable and sub-suitable habitats amounting to 43.68%. The most suitable area was mainly located in the former Guandong Salt Farm (Figure 7), where the fishing withdrawal zones had a larger water surface area, deeper water levels and vegetation dominated by *Phragmites australis* and *Suaeda salsa*, with limited distribution of *Spartina alterniflora*. The growth of *Phragmites australis* was stressed by high water salinity, leading to lower vegetation coverage. For *Gruidae* and *Ciconiidae*, they had mainly low-suitability and unsuitable areas in District A, with 99.31% of the low-suitability and unsuitable area for *Gruidae* and 93.46% for *Ciconiidae*. This indicated that most fishing withdrawal zones in District A were not suitable for *Gruidae* and *Ciconiidae*. In District B, unsuitable areas dominated for all six waterbird groups, suggesting that the fishing withdrawal zones there did not meet the habitat requirements of these groups. The most suitable habitats for *Ardeidae* and *Anatidae* were distributed in District C, with the area of most suitable and sub-suitable areas accounting for 58.43% for *Ardeidae*, followed by *Anatidae* with 43.53%. The most suitable habitats for *Ardeidae* were primarily located in Nanhuan, followed by Hexin. For *Anatidae*, the most suitable habitats were mainly distributed in Hexin, followed by Nanhuan and Beihuan. Additionally, the most suitable and sub-suitable habitats for *Laridae*, *Gruidae* and *Ciconiidae* were primarily distributed in District C (Figure 7). The large area of fishing withdrawal zones in District C, their concentrated spatial distribution and their positioning primarily within key waterbird habitats contributed to habitat diversity, meeting the needs of various waterbird species. Compared to other waterbird groups, *Anatidae* in District D had a larger extent of most suitable and sub-suitable habitats, primarily located in the fishing withdrawal zones on the southern side of Dafeng Habitat. However, the fishing withdrawal zones in District D were predominantly low-suitability and unsuitable areas for all six waterbird groups.

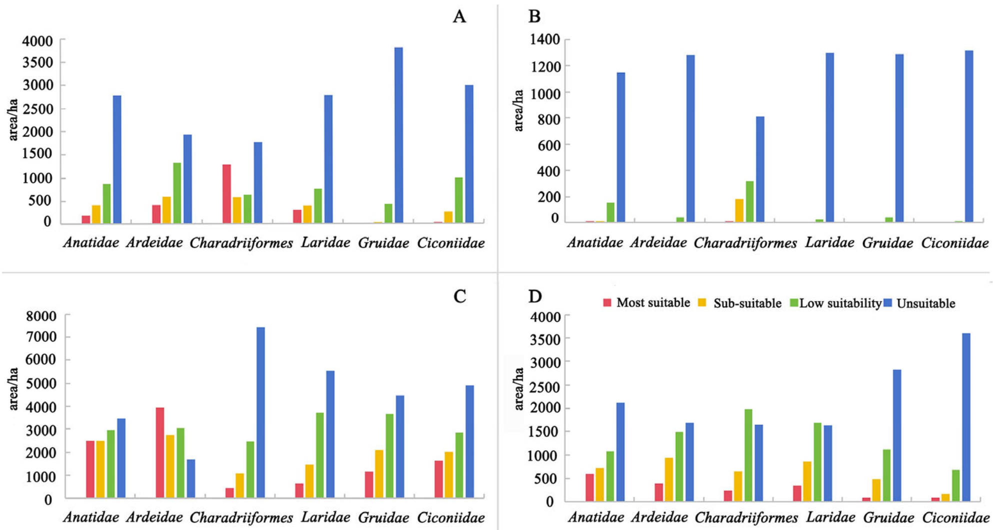

Figure 6. Area of habitat suitability at different levels for various waterbird groups in each district. (**A**) District A; (**B**) District B; (**C**) District C; (**D**) District D.

3.2.3. Importance Analysis of Waterbirds Suitability Evaluation Factors

Based on the simulation results with high accuracy across different waterbird groups, the factors affecting their habitat suitability were further analyzed. The main factors affecting all six waterbird groups included distance to roads, distance to residential areas, distance to water sources and distance to farmland. This indicated that human disturbance, shelter conditions and water resources were key factors influencing waterbird habitat selection. The habitat suitability of *Anatidae* was primarily influenced by distance to residential areas, followed by distance to farmland, and lastly distance to rivers/sea areas. For *Ardeidae*, distance to residential areas was the most influential factor, followed by distance to roads, distance to rivers/sea areas and distance to farmland, all of which played significant roles. *Charadriiformes* differed from other groups, with the area of water surface being the most crucial factor, followed by distance to farmland, distance to rivers/sea areas and vegetation coverage. *Laridae* relied more heavily on distance to farmland, followed by distance to roads, distance to residential areas and distance to water sources. *Gruidae* exhibited notable differences, with vegetation height being the most critical factor, followed by distance to rivers/sea areas, distance to farmland and distance to residential areas. For *Ciconiidae*, the factors were ranked as follows, from most to least influential: distance to farmland, distance to roads, distance to rivers/sea areas and habitat patch area (Figure 8). Therefore, different waterbird groups exhibited distinct differences, with *Charadriiformes* emphasizing water distribution, *Gruidae* focusing on vegetation height and *Ciconiidae* considering habitat patch size.

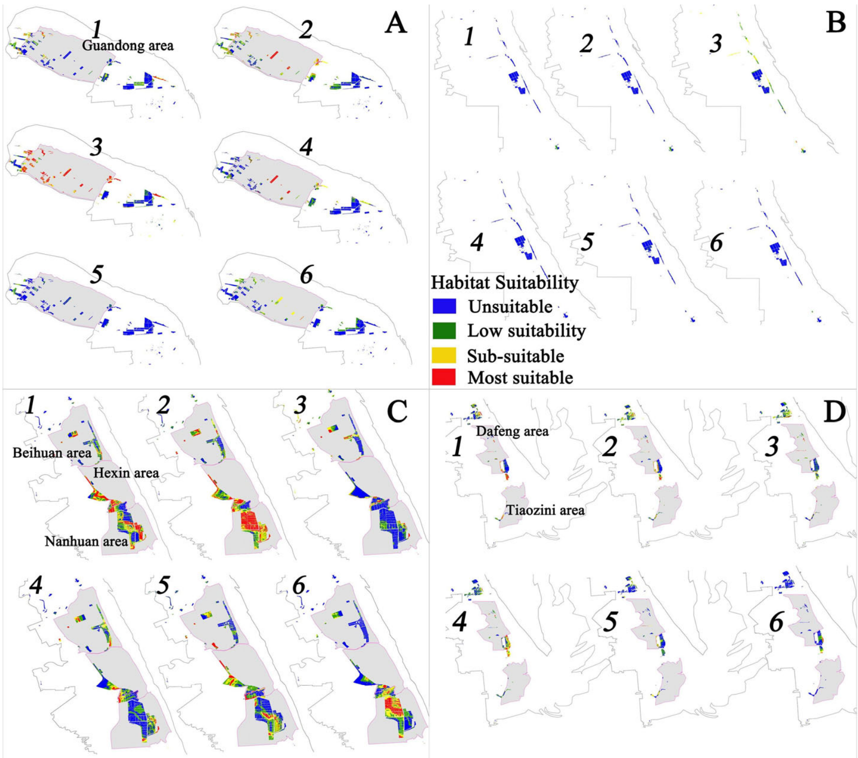

Figure 7. Distribution of habitat suitability at different levels for different waterbird groups (1: *Anatidae*, 2: *Ardeidae*, 3: *Charadriiformes*, 4: *Laridae*, 5: *Gruidae*, 6: *Ciconiidae*). (**A**) District A; (**B**) District B; (**C**) District C; (**D**) District D.

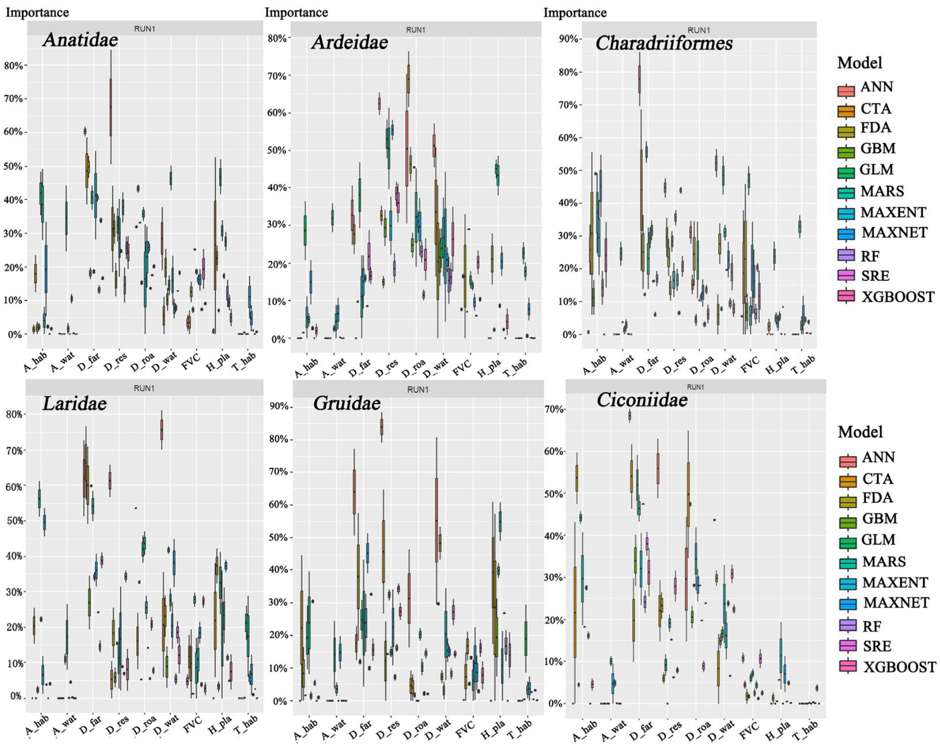

Figure 8. Importance of habitat evaluation factors for different waterbird groups determined by the "Jackknife" test.

4. Discussion

4.1. Differences of Habitat Suitability Among Waterbird Groups in Fishing Withdrawal Zones

Within the fishing withdrawal zones, *Ardeidae* (e.g., *Ardea cinerea*, *Egretta garzetta*) and *Anatidae* (e.g., *Anas platyrhynchos*, *Anser fabalis*) exhibited significantly larger suitable habitat areas compared to *Ciconiidae* (e.g., *Ciconia boyciana*) and *Gruidae* (e.g., *Grus japonensis*). This disparity fundamentally stemmed from the divergence in ecological adaptation strategies among these taxonomic groups. Most species of *Ardeidae* and *Anatidae* observed in field surveys are ecological generalists with relatively broader tolerance thresholds for habitat conditions [30], enabling them to effectively utilize various habitat types formed in withdrawal zones, including areas with different water depths and vegetation coverage. This pattern was consistently reflected in both field observations and model predictions. In contrast, *Ciconiidae* and *Gruidae* demonstrated strict habitat requirements that fundamentally mismatched the current landscape configuration of withdrawal zones, which were characterized by limited water distribution and homogeneous vegetation structure (with *Phragmites australis* under 2 m tall in the majority). Although vegetation coverage and height increased within the withdrawal zones, they still failed to meet the habitat needs of *Ciconiidae*. For instance, they rely on extensive tall woodlands for breeding [31] and low grasslands for foraging [32], yet most withdrawal zones lacked vegetation of these height classes. Moreover, species with narrower ecological niches are more susceptible to habitat fluctuations [33]. The reduction in water surface area within withdrawal zones has particularly constrained the available habitat for *Gruidae*, as they require high-density water distribution [34].

The ecological transition from active aquaculture ponds to withdrawal zones is characterized by four fundamental habitat modifications: substantial reduction in food resources, increased vegetation coverage and height and significantly decreased water depth and aquatic surface area. The distinct habitat preferences exhibited by different waterbird functional groups demonstrated that the establishment of fishing withdrawal zones did not uniformly benefit population growth across all groups. As evidenced in Section 3.2.3, *Anatidae*, *Laridae* and *Ciconiidae* exhibited strongest sensitivity to distance to farmlands, suggesting that agricultural lands served as critical supplemental foraging grounds that partially compensated for the diminished food availability in withdrawal zones [35]. However, *Charadriidae*, whose utilization of active aquaculture ponds was historically limited primarily to drained ponds [36], showed water distribution dependence that could be enhanced by maintaining shallow water areas (3–10 cm depth [37]). *Gruidae* benefited most from post-withdrawal vegetation changes through improved concealment conditions [38]. The above evidence revealed guild-specific responses where *Anatidae*/*Laridae*/*Ciconiidae* experienced the strongest nutritional constraints from aquaculture cessation, *Charadriidae* responses depended primarily on water resource characteristics and *Gruidae* benefited most from successional vegetation changes.

4.2. How to Increase the Area of Suitable Habitats for Waterbirds in Fishing Withdrawal Zones

Based on the above analysis, human disturbance and food abundance had the greatest impact on waterbirds. Therefore, factors such as distance to rivers, roads and residential/industrial areas should be considered when selecting the geographic location of fishing withdrawal zones. Additionally, the size of the fishing withdrawal zone directly affected the stability of its internal habitat. Smaller and more dispersed fishing withdrawal zones were more prone to habitat fragmentation and had a weak resistance to human disturbance.

With the goal of protecting waterbird diversity, improving the utilization of waterbirds in the fishing withdrawal zones and maximizing ecological benefits, this study proposed a "waterbird-friendly" conservation structure of "ecological protective slope—water, *Phragmites australis* marshes and mudflat interspersed zone—ecological protective slope" (Figure 9). Based on the analysis of environmental factors, distance to roads and distance to residential/industrial areas significantly impacted the distribution of six waterbird groups, indicating that waterbirds were greatly disturbed by human activities. Constructing an ecological protective slope within the fishing withdrawal zones could strengthen resistance to disturbances and enhance habitat suitability for waterbirds. Additionally, distance from the river/sea areas and the size of the water surface had considerable effects, reflecting the role of water and food abundance for waterbirds. The proposed "water, *Phragmites australis* marshes and mudflat interspersed zones" structure could not only reduce the distance between waterbirds and water sources, but also increase the area of water in the fishing withdrawal zones. At the same time, the interspersed distribution of shallow-water ponds, deep-water ponds, mudflats and *Phragmites australis* marshes could diversify the internal habitats of the fishing withdrawal zones, helping waterbirds with different ecological requirements find suitable habitats, thereby increasing their utilization of the entire fishing withdrawal zone and maximizing the ecological benefits.

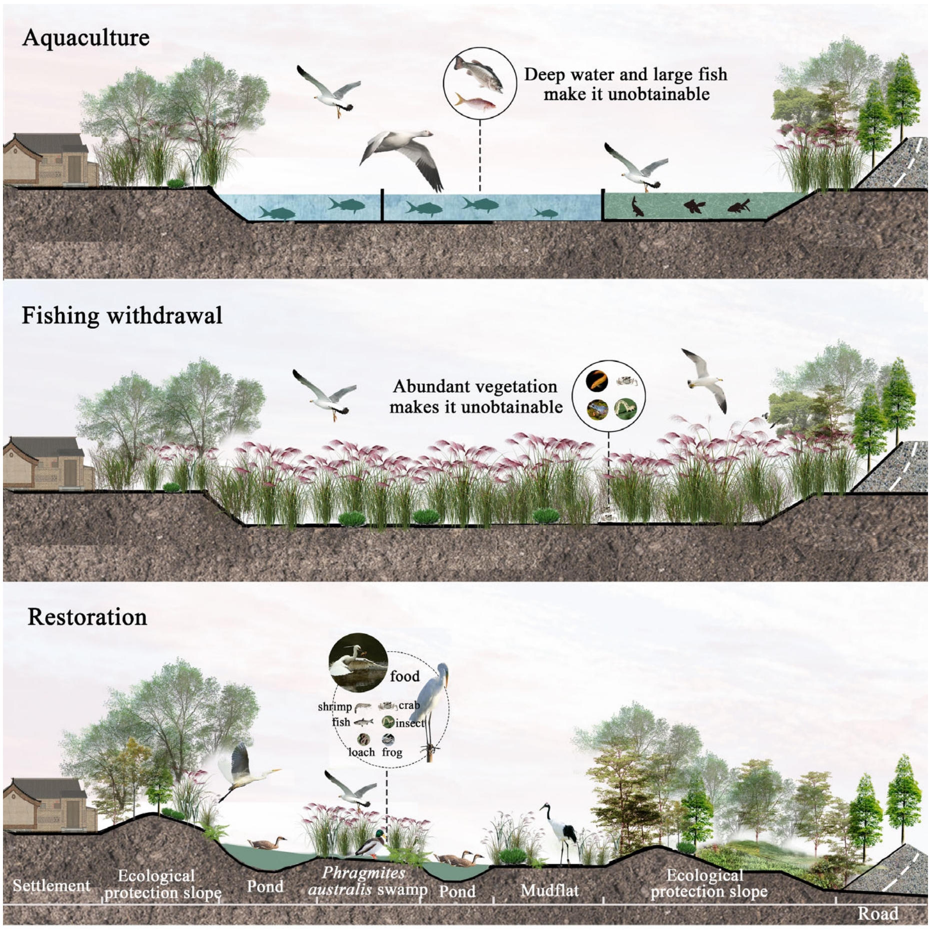

Figure 9. Ecological restoration of fishing withdrawal zones.

5. Conclusions

Through the interpretation and identification of remote sensing images of Yancheng coastal wetlands, it was found that the fishing withdrawal zones were primarily concentrated in Beihuan, Hexin and Nanhuan, with the largest area located in Nanhuan. The Biomod2 ensemble model was applied to evaluate the habitat suitability for six waterbird groups, namely, *Anatidae*, *Ardeidae*, *Charadriiformes*, *Laridae*, *Gruidae* and *Ciconiidae*, in the identified fishing withdrawal zones. Among these six waterbird groups, *Anatidae* and

Ardeidae had the largest area of most suitable and sub-suitable areas, while the areas for *Laridae*, *Gruidae* and *Ciconiidae* were comparatively smaller. Additionally, the proportion of low-suitability and unsuitable areas was high for all six groups: 58.15% for *Ardeidae*; 67.87% for *Anatidae*; 79.10% for *Charadriiformes*; and exceeding 80% for *Laridae*, *Gruidae* and *Ciconiidae*. This suggests that the existing fishing withdrawal zones in Yancheng coastal wetlands are not suitable habitats for the majority of waterbirds. Based on this, the evaluation factors affecting the habitat suitability of different waterbird groups showed both commonalities and significant differences. The commonalities lay in the fact that distance to roads, distance to residential/industrial areas, distance to water sources and distance to farmland were important influencing factors for all six waterbird groups. The differences were reflected in the varying rankings of the importance of evaluation factors for different groups. For *Charadriiformes*, the area of water surface was the most important influence; for *Gruidae*, vegetation height had the greatest impact; and, for *Ciconiidae*, habitat patch area played a significant role. Therefore, when determining the geographic location of fishing withdrawal zones, it is crucial to consider the distance to roads, residential/industrial areas and rivers. To avoid fragmentation of the fishing withdrawal zones, their area should not be too small, and they should be distributed as concentrically as possible. Their linkage with the original waterbird habitats should be taken into account. For the management of existing fishing withdrawal zones, the "waterbird-friendly" ecological restoration structure proposed in this study, which consists of "ecological protective slope—water, *Phragmites australis* marshes, mudflats interspersed zone—ecological protective slope", can be applied.

This study has several limitations. In the future, the status of waterbird colonies in the fishing withdrawal zones at different periods will be investigated. At the same time, sub-meter remote sensing images will be used to further analyze the internal structure of the habitat, and explore the changes in waterbirds' utilization and adaptability to the withdrawal zones in different withdrawal years.

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