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Research article

Integrating suitable habitat dynamics under typical hydrological regimes as guides for the conservation and restoration of different waterbird groups

Pingyang Zhang[a,b], Siqi Zhang[b,c], Yeai Zou[a,b,*], Ting Wu[d], Feng Li[a,b], Zhengmiao Deng[a,b], Hong Zhang[e], Yucheng Song[f], Yonghong Xie[a,b,**]

[a] *Key Laboratory of Agro-ecological Processes in Subtropical Regions, Chinese Academy of Sciences, Changsha, 410125, China*
[b] *Dongting Lake Station for Wetland Ecosystem Research, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha, 410125, China*
[c] *University of Chinese Academy of Sciences, Beijing, 100049, China*
[d] *College of Resources and Environment, Hunan Agricultural University, Changsha, 410128, China*
[e] *Forestry Bureau of Yueyang, Yueyang, 414000, China*
[f] *Administrative Bureau of Hunan East Dongting Lake National Nature Reserve, Yueyang, 414000, China*

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ABSTRACT

The operation of the Three Gorges Project (TGP) has influenced the wetland ecosystems downstream, thereby affecting the distribution of habitats suitable for waterbirds. However, dynamic studies on habitat distribution under different water regimes are lacking. Here, using data from three successive wintering periods representing three typical water regimes, we modelled and mapped the habitat suitability of three waterbird groups in Dongting Lake, which is the first river-connected lake downstream of the TGP, and a crucial wintering ground for waterbirds along the East Asian-Australasian Flyway. The results showed that the spatial pattern of habitat suitability varied among the wintering periods and waterbird groups. The analysis estimated the largest suitable habitat area for the herbivorous/tuber-eating group (HTG) and the insectivorous waterbird group (ING) under a normal water recession pattern, whereas early water recession had a more adverse effect. The suitable habitat area for the piscivorous/omnivorous group (POG) was higher under late water recession than under normal conditions. The ING was the most affected by hydrological changes among the three waterbird groups. Further, we identified the key conservation and potential restoration habitats. The HTG exhibited the largest key conservation habitat area compared to the other two groups, while the ING showed a potential restoration habitat area larger than its key conservation habitat area, indicating its sensitivity to environmental changes. The optimal inundation durations from September 1 to January 20 for HTG, ING and POG were 52 ± 7 d, 68 ± 18 d, and 132 ± 22 d, respectively. Therefore, the water recession starting in mid-October may be favourable for waterbirds in Dongting Lake. Altogether, our results can be used as guidance for prioritising certain management actions for waterbird conservation. Moreover, our study highlighted the importance of considering habitat spatiotemporal variation in highly dynamic wetlands when implementing management practices.

1. Introduction

Habitat degradation and loss have threatened biodiversity maintenance over the past few decades. As one of the three major ecosystems globally, wetlands provide critical habitats for waterbirds; however, they are under severe pressure from water resource development, pollution, land reclamation, etc. (Junk et al., 2013). Freshwater wetlands are usually ephemeral and variable because of their close relationship with water changes (Deil, 2005). For this reason, effective conservation or recovery plans for such habitats require the decision-makers to have a certain macro- and dynamic understanding of the habitat pattern of targeted conservation species. Identifying suitable habitats and their spatiotemporal changes could offer significant support for biodiversity conservation (Diniz et al., 2022). Species Distribution Models (SDMs), a common and popular tool to estimate the habitat suitability of a species and support conservation decisions (Guisan et al., 2013), can be used to study how macro-ecological processes drive species range patterns and to visualise the species response

* Corresponding author. Institute of Subtropical Agriculture, Chinese Academy of Sciences, No. 644, Yuanda Second Road, Changsha, 410125, China.
** Corresponding author. Key Laboratory of Agro-ecological Processes in Subtropical Regions, Chinese Academy of Sciences, Changsha, 410125, China.
E-mail addresses: zouyeai@163.com (Y. Zou), yonghongxie@163.com (Y. Xie).

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to environmental changes, in combination with GIS technologies. Thus, they are widely used in conservation applications (Elith and Leathwick, 2009; Murphy and Smith, 2021).

The freshwater wetlands in the middle and lower reaches of the Yangtze River Floodplain form the largest natural and artificial complex wetland ecosystem, constituting 15% of China's total wetland area. These wetlands form a key region for migratory waterbirds as their stopover and wintering sites along the East Asian-Australasian Flyway (Wang et al., 2016). The operation of the Three Gorges Project (TGP) has had considerable impacts on its downstream water systems and has changed the relationship between the Yangtze River and its connected rivers and lakes (Lai et al., 2014). However, the effect of water regime changes on the habitat suitability of wintering waterbirds has not been effectively evaluated. Although previous studies have assessed the variations in suitable habitats for wintering Anatidae and goose species in different stages (He et al., 2022; Li et al., 2021), the effect of water regime changes on the distribution of suitable habitats was not considered. Studies on how spatial patterns of waterbird habitat suitability vary under different water regimes remain unclear. Studying this topic is important because the water level and its change patterns exhibit significant inter-annual differences, especially in river-connected lakes, under the background of the TGP Project. This may lead to drastic variations in the distribution of habitats suitable for waterbirds. Understanding these variations will provide insight into waterbird habitat conservation and restoration. In addition, because of the differences in their ecological characteristics, waterbirds belonging to different feeding groups may respond differently to the same environmental changes (Li et al., 2022). Exploring the habitat changes of different waterbird groups could help develop more targeted management plans.

Dongting Lake is renowned as a crucial wetland ecosystem in the Yangtze River Floodplain and encompasses three Ramsar sites: East Dongting Lake wetland, West Dongting Lake wetland, and South Dongting Lake wetland. With Dongting Lake being the first river-connected large lake downstream of the TGP, its water regime has changed conspicuously (Hu et al., 2015). The frequency of extreme hydrological events has increased in recent years. For most years after the impoundment of the TGP, the dry period of Dongting Lake advanced. However, for several years, the timing of the water recession was delayed owing to water manipulation upstream. These changes may cause unfavourable habitat alterations for the wintering waterbird populations. For example, early water recession may lead to high-quantity/low-quality food, while late water recession may lead to low-quantity/high-quality food for wintering geese (Zhang et al., 2020). However, the impact of these drastic annual water-level changes on waterbird habitat suitability has not been studied.

Here, we carried out the first analysis of multigroup suitable habitat changes and overall conservation and restoration potential of this region. During the past three wintering periods (2019/2020–2021/2022), the wetland water recession pattern differed significantly, which may have led to changes in waterbird occurrences. By combining elaborate waterbird survey data and environmental variable data through SDMs, we determined the distributions of potentially suitable habitats for different wintering waterbird groups in different wintering periods. We aimed to: (1) evaluate the suitable habitat dynamics of the three waterbird groups and identify crucial environmental variables affecting their habitat suitability; (2) investigate the key conservation habitats and potential restoration habitats and clarify the best thresholds of inundation duration as guides for restoration. We hypothesise that the suitable habitat areas will be smaller under anomalous hydrological patterns than under normal conditions and that different waterbird groups will respond differently to changes in hydrological patterns. This study has important scientific relevance for the conservation of waterbird communities and their wintering habitats in the Yangtze River floodplain and along the East Asian-Australasian Flyway.

2. Materials and methods

2.1. Study area

Dongting Lake is the second largest freshwater lake in China, with a surface area of 2625 km^2, and plays a vital role in flood control, water supply, and biodiversity maintenance (Geng et al., 2021). As a seasonally inundated waterbody that is directly affected by the operation of the TGP, its water level fluctuates seasonally and annually, ranging from up to approximately 36 m in summer to below 20 m in winter, thus forming a very dynamic landscape (Xie et al., 2015). The wetland water recession typically occurs in mid-fall, while the non-flooding periods generally last from October to May of the following year but exhibit significant annual differences. Dongting Lake consists of two national nature reserves, namely East and West Dongting Lake, and two provincial nature reserves, namely South Dongting Lake and Hengling Lake (Fig. 1a).

2.2. Data processing and modelling

2.2.1. Bird data collection

The wintering period for waterbirds in Dongting Lake typically lasts from early November to early March. Every mid-January, simultaneous waterbird surveys are conducted covering the entire lake following a standard protocol by multiple groups of investigators. Birds were observed using a 20–60 × spotting scope and 10 × 42 binoculars. The coordinates of waterbird occurrence were recorded with a GPS and diastimeter, combined with calibration on a map by experienced investigators who are familiar with the topography and waterbird habitat use of Dongting Lake after the surveys were completed. In this study, waterbird data were collected for three continuous wintering periods from 2019/2020 to 2021/2022 (Fig. 1b). Based on their feeding habitat use and diet characteristics, waterbird species were divided into three different waterbird groups: herbivorous/tuber-eating waterbird group (HTG), insectivorous waterbird group (ING), and piscivorous/omnivorous waterbird group (POG) (Table S1). Representative species from each group were selected, and their occurrences were thinned and pooled for further analysis (Text S1).

2.2.2. Environmental variable processing

We selected a total of 9 environmental variables (Table S2), including factors related to food and habitat availability, water-related factors, and human disturbance, for species distribution modelling based on our expert knowledge and literature review on waterbird habitats (D'Acunto et al., 2021; Li et al., 2017; Maslo et al., 2016; Wang et al., 2021). The Enhanced Vegetation Index (EVI), an effective indicator of resource availability for herbivorous geese (Li et al., 2017), was extracted based on the data products of Landsat 7 and 8 Surface Reflectance Tier 1. The Normalized Difference Water Index (NDWI) was derived from Sentinel-2 satellite images, can be used to monitor changes in water content and to identify water bodies, and is sensitive to variations in hydrological conditions. Wetness data was obtained through Tasselled Cap Transformation based on the surface reflectance datasets of Landsat-8 and Landsat-9 Level 2 Tier 1. In addition, to incorporate the availability of habitat areas, we developed three new variables, namely meadow area, mudflat area, and water area, within a 1 km radius based on the land cover data in January of each wintering period. These variables may also be ecologically relevant to the distribution of waterbirds in Dongting Lake. Distance to water was found to be a very important variable in SDMs based on a quantitative synthesis study (Bradie and Leung, 2017). To create this layer, the grid layer of the water cover in mid-January was extracted based on Sentinel-1 image and Otsu thresholding (Otsu et al., 1979), which is a widely used method for determining the optimal threshold for water detection from image histograms. Subsequently, the Euclidean distance to the water patch was calculated to create the layer of distance to the water. Euclidean distances to the roads and main channels were calculated to assess the

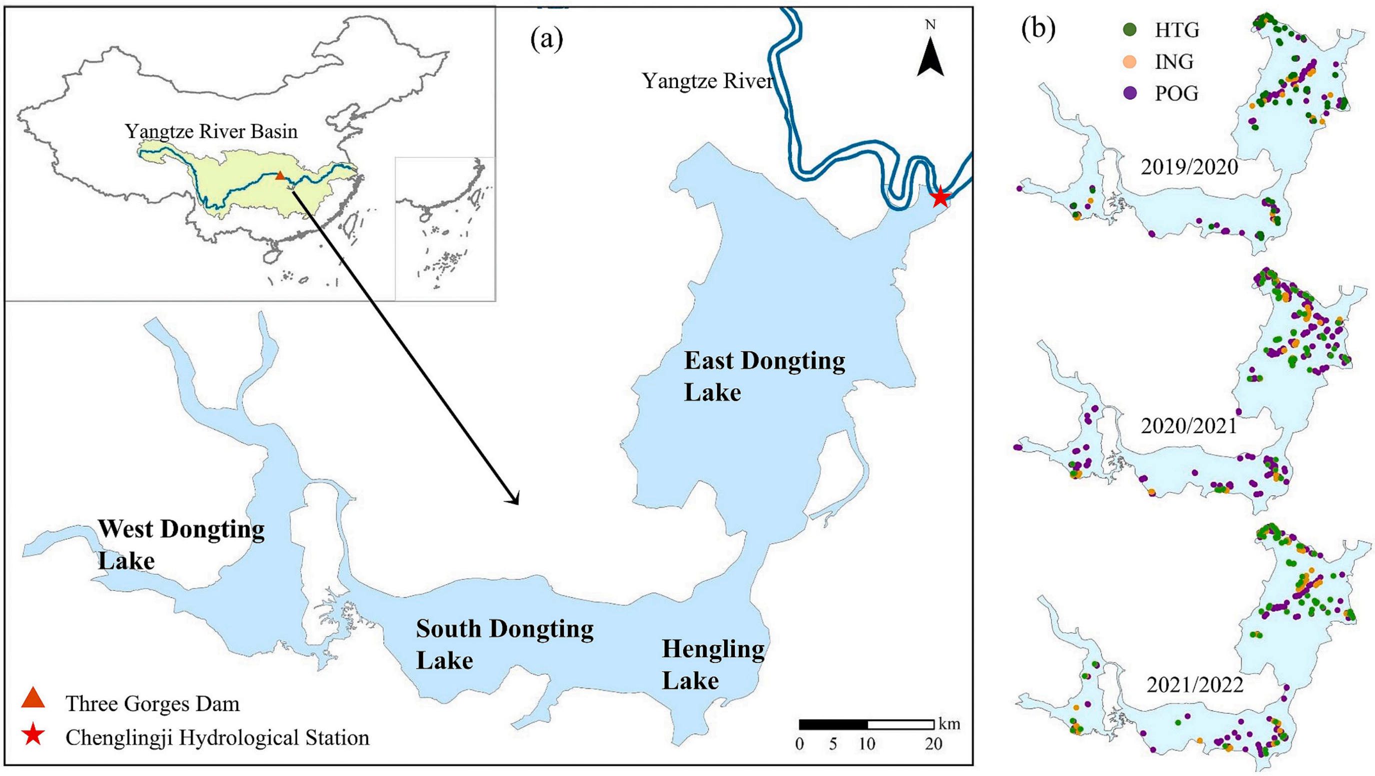

Fig. 1. (a) Map of the study area (Dongting Lake). Chenglingji Hydrological Station is the location where daily water level data shown in the Results section 3.1 were recorded. (b) Species occurrence localities used for the modelling of the three waterbird groups. HTG = herbivorous/tuber-eating waterbird group, ING = insectivorous waterbird group, POG = piscivorous/omnivorous waterbird group (see details in Table S1).

potential influence of human activities on habitat suitability. All environmental variable layers were resampled onto a 90 m × 90 m equal-area grid with the same origin and extent. All geospatial data were processed using ArcMap 10.2 (ESRI, 2014), Google Earth Engine, and the "raster" package in R v4.2.2 (Hijmans, 2022; R Core Team, 2022). The collinearity problem, which may lead to incorrect identification of relevant predictors in SDM (Dormann et al., 2013), was addressed by calculating the Pearson correlation coefficient between each two variables (Fig. S1). The absolute value of the correlation coefficient $R > 0.7$ was defined as the threshold.

2.2.3. *Suitable wintering habitat modelling*

To investigate the dynamics of suitable wintering habitats under different hydrological regimes, we established SDMs for each wintering period and mapped the habitat suitability across Dongting Lake. For each waterbird group, we selected specific environmental variables ecologically relevant to their distributions to build SDMs (Text S1 and Table S2). We considered that more robust forecasts could be achieved if the ensemble models were produced and analysed appropriately (Araújo and New, 2007). Here we used maximum entropy (MAXENT) and random forest (RF) to build ensemble models. MAXENT and RF are two widely used and high-performance machine learning algorithms in SDMs and typically outperform other methods based on predictive accuracy (Effrosynidis et al., 2018; Merow et al., 2013). All models were trained using the above two algorithms available in the R package "biomod2" (Thuiller et al., 2021), which is the most well-known and well-established ensemble tool in the SDM community (Hao et al., 2019). MAXENT requires presence-background data, whereas RF requires pseudo-absences. Thus, 5000 pseudo-absences were randomly selected within the background data. The number of repetitions was set to ten. To evaluate the performance of the model predictions, we used the area under the receiver operating characteristic curve (AUC) statistic, which quantifies how well the model can distinguish the presences from background samples. The dataset was split into training (80%) and testing data (20%) for calibration and evaluation, respectively.

When creating the ensemble models, the quality threshold for the evaluation metric was set to 0.85, meaning that the models with an AUC score lower than 0.85 were not used for further building the ensemble models. The weighted mean of the probabilities, which returns the weighted sum by the AUC value, was used as the ensemble model algorithm. The AUC and true skill statistics (TSS) were used to evaluate the ensemble models. The permutation importance values generated by ensemble models were examined to determine the influence of each environmental variable on wintering habitat suitability.

2.2.4. *Identifying management measures*

First, for each waterbird group during each winter, the presence probabilities were transformed into binary maps, i.e., suitable and unsuitable, by adopting TSS as the binary method. Subsequently, the areas projected as "suitable" (habitat suitability > threshold that maximizes TSS) were calculated. For each waterbird group, we overlapped the suitable/unsuitable output maps of the three wintering periods that corresponded to the three typical water regimes. The areas consistently identified as suitable across all three winters were extracted and considered as key conservation habitats for each group. Additionally, areas suitable under normal water regime but unsuitable under anomalous water regimes were considered potential restoration sites. Patches with areas <0.1 km^2 were excluded from the maps.

To propose feasible management measures, we employed remote sensing inversion to extract the inundation duration (d) between September 1 and January 20. This time frame was selected because the study area is typically flooded before September, and the simultaneous waterbird surveys in this study are usually conducted in mid-January. The inundation duration was determined by multiplying the inundation frequency by the time interval between September 1 and January 20. The value range of inundation duration in the key conservation areas for each groups was extracted and considered an important parameter to guide habitat restoration efforts.

2.3. Statistical analysis

Analysis of variance (ANOVA) was used to examine whether the mean water level in October differed significantly among the different winters. Welch's ANOVA was used because homogeneity of variance held false. A post hoc pairwise comparison test (Games–Howell) followed by ANOVA was used to investigate the differences.

3. Results

3.1. Comparison of water level change under typical water regimes

The daily water level changes showed that generally, the water level of Dongting Lake decreased gradually from September to December (Fig. 2a). The mean water levels in October, which is the key month before waterbird arrival, were significantly different among the three study years and the 30-year mean before the TGP ($p < 0.001$, Fig. 2b). Specifically, the mean water level in October 2021 was not significantly different from that of the 30-year mean before the TGP ($p > 0.05$), whereas those of 2019 and 2020 were significantly lower and higher, respectively, than the 30-year mean ($p < 0.001$). Therefore, we classify the three years into three different typical water recession patterns compared with the water regime before the operation of the TGP. Specifically, 2019 represented a typical early water recession year, followed by the 2019/2020 wintering period; 2020 represented a typical late water recession year, followed by the 2020/2021 wintering period, and 2021 represented normal water recession, followed by the 2021/2022 wintering period.

3.2. Effect of water regime on suitable wintering habitat distributions

All the ensemble models exhibited high predictive accuracy, with all AUC >0.95 and TSS >0.85, based on the testing dataset (see details in Table S3). Variable importance differed among the waterbird groups and water regimes. Overall, based on the 3-year average of variable importance values, the most crucial variables for HTG were meadow area, mudflat area, and EVI; the meadow area was consistently the most important variable across all three winters (Fig. 3a). For ING, water area, mudflat area, and distance to channel were the top three significant predictors of habitat suitability (Fig. 3b). As for POG, distance to water, NDWI, and distance to channel were the most important variables (Fig. 3c). It is important to note that the importance of these variables may differ among different wintering periods. Nevertheless, the distance to road had a relatively minor impact on all three waterbird groups.

For each waterbird group, suitable habitat distributions exhibited spatial variations under different hydrological regimes but were mainly distributed in East Dongting Lake (Fig. 4). The areas of suitable wintering habitats were calculated based on the binary transformation results (Fig. S2). The results indicated that the suitable habitat areas were smaller during both early and late water recession compared to normal water recession. The only exception was the POG, for which suitable habitat area was higher under late water recession than under normal conditions (Table 1). The reduction in suitable habitat area was particularly significant for ING, with early water recession having a more adverse effect compared to late water recession, which was also observed for the HTG.

3.3. Predicted crucial habitat and optimal inundation duration threshold

The HTG had the largest key conservation area (86.3 km^2) which was mainly distributed in East Dongting Lake and Hengling Lake (Fig. 5a & Table S4). The area of potential restoration habitat of the ING was larger than that of its key conservation habitat, indicating less overlap of suitable habitats among different winters. The potential restoration areas for the POG were the smallest (18.0 km^2) among the three waterbird groups and mainly distributed in the interior of East Dongting Lake (Fig. 5b & Table S4). We subsequently extracted the values of inundation duration, a factor directly related to wetland management, for each waterbird group in their respective key conservation habitats. The results showed that the optimal inundation durations from September 1 to January 20 for HTG, ING, and POG were 52 ± 7 d, 68 ± 18 d, and 132 ± 22 d, respectively (Fig. 5c).

4. Discussion

In the fall of 2021, for the first time in nine years, Dongting Lake experienced a normal pattern of water level recession (Zhang et al., 2021a). Our previous study showed that the water level in East Dongting Lake in October might be closely related to the spatiotemporal distributions of wintering waterbirds (Zhang et al., 2018). In the present study, we compared the mean water levels in October before the three wintering periods and found that the water level before the 2021/2022 wintering period was very similar to the long-term mean water level before the beginning of TGP operation. Based on this finding, we considered the wetland water recession pattern for 2021/2022 to be

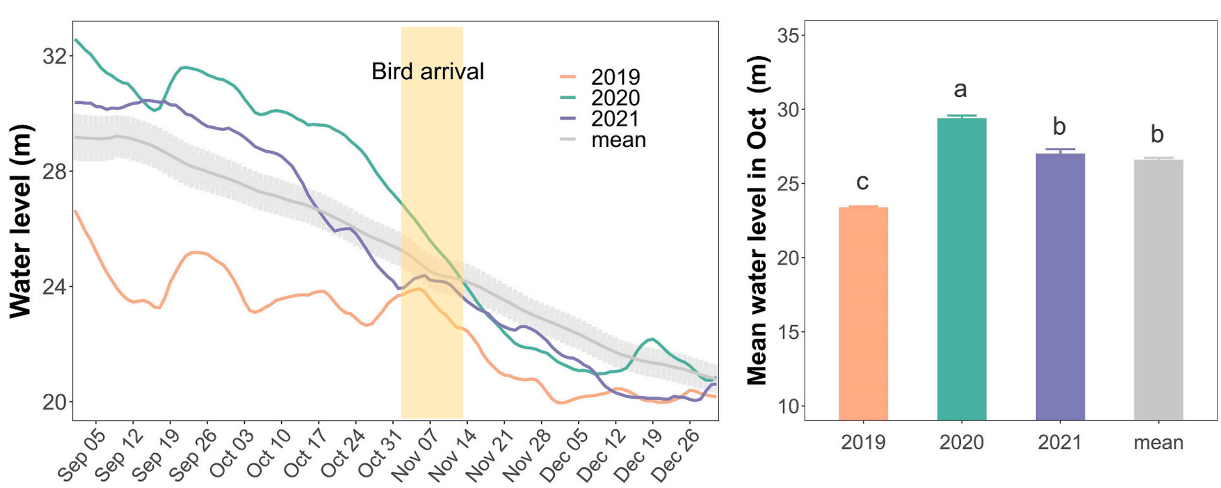

Fig. 2. (a) Daily water level variations from September to December. The grey line indicates the mean water level over 30 years prior to the operation of the TGP (1977–2006), and the grey area indicates its standard error. (b) Comparison of mean water levels in October. Different letters indicate significant differences in mean water levels among the years at the 0.05 significance level.

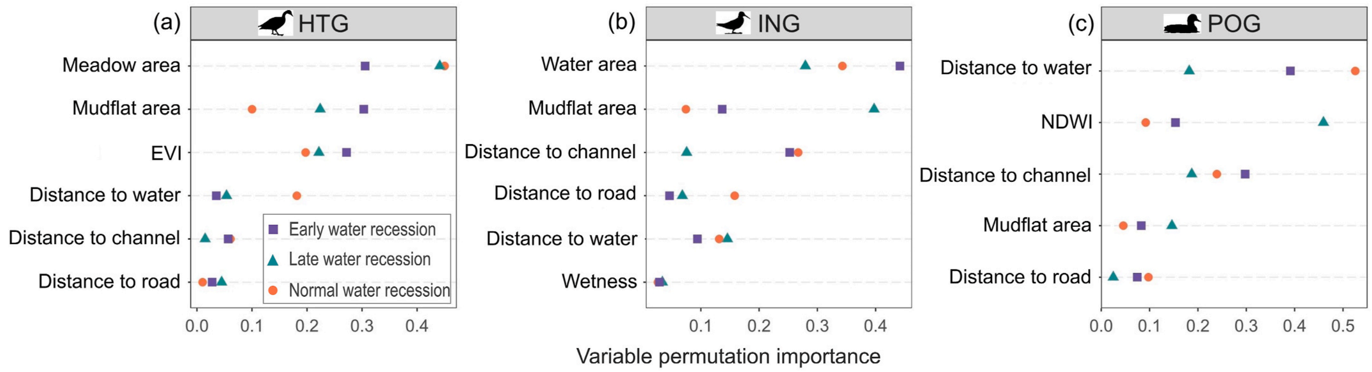

Fig. 3. Importance of all environmental variables involved within each ensemble model. HTG = herbivorous/tuber-eating group, ING = insectivorous group, POG = piscivorous/omnivorous group. For each group, variables are shown from top to bottom in order of average importance over the three winters.

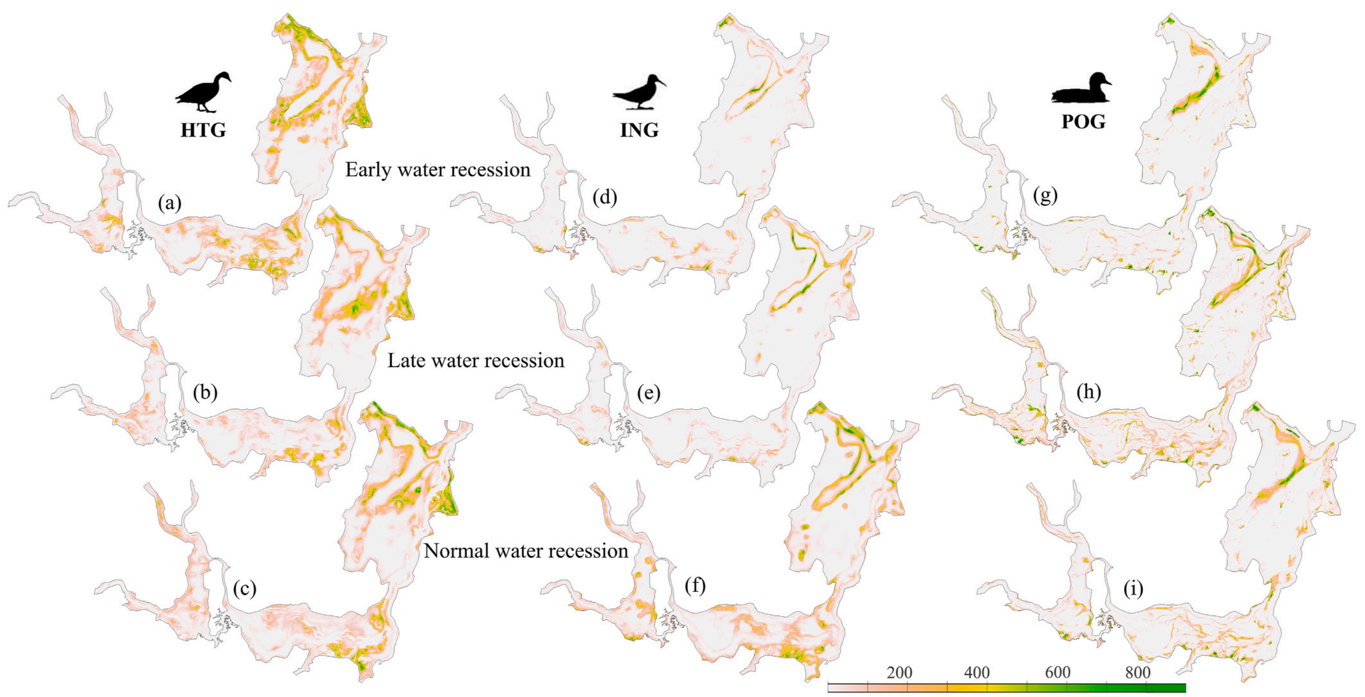

Fig. 4. Wintering habitat suitability distribution for (a–c) herbivorous/tuber-eating group (HTG), (d–f) insectivorous group (ING), and (g–i) piscivorous/omnivorous group (POG) under different water regimes. The values were converted into a 0–1000 integer scale.

Table 1
Potentially suitable habitat areas and percentage changes for different waterbird groups in Dongting Lake during the three wintering periods. 2019/2020 indicates early water recession, 2020/2021 indicates late water recession, and 2021/2022 indicates normal water recession. HTG = herbivorous/tuber-eating group, ING = insectivorous group, POG = piscivorous/omnivorous group.

Wintering period	HTG		ING		POG	
	Area (km^2)	% change vs 2021/2022	Area (km^2)	% change vs 2021/2022	Area (km^2)	% change vs 2021/2022
2019/2020	287.6	−19.8%	92.0	−65.8%	160.1	−30.4%
2020/2021	343.9	−4.2%	98.6	−63.3%	263.1	14.3%
2021/2022	358.8		268.7		230.1	

normal. We found that the suitable habitat distributions of the three different waterbird groups changed according to the contrasting hydrological conditions in the three wintering periods. Overall, these changes in habitat area are in line with our hypothesis that an anomalous water regime would have an adverse effect on waterbird habitat suitability.

Floodplains are highly complex and dynamic ecosystems. The role of wetlands as waterbird habitats in floodplains is also dynamic, especially in wetlands that are greatly influenced by dam operations (Khatun et al., 2021; Kingsford and Thomas, 2004). The impoundment of the TGP has led to significant alterations in hydrological conditions, which was likely the primary factor contributing to the observed changes in wetland cover types, including vegetation, mudflats, and water areas, within Dongting Lake (Yang et al., 2020). These alterations directly impact the main habitats of various waterbird groups. In another typical Yangtze-connected freshwater lake, it was found that water level fluctuations strongly correlated with land cover patterns and affected habitat availability for wintering waterbirds of different functional groups (Li et al., 2019). For herbivorous geese, which mainly feed on wet meadows, excessive drought or flood was related to prolonged or inadequate meadow exposure duration, which may lead to less suitable and less available habitats (Zhang et al., 2021a; Teng et al., 2023). These habitat conditions are closely related to EVI and meadow area, which

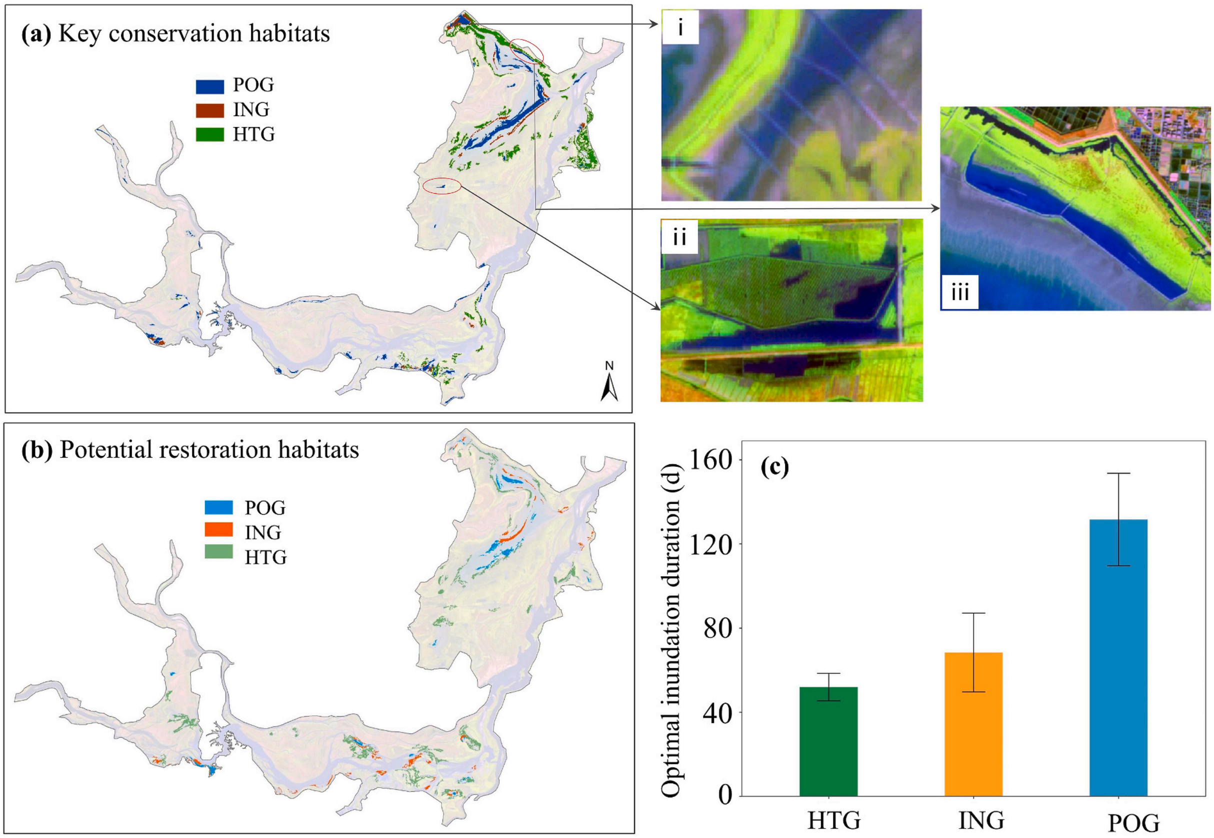

Fig. 5. (a) Key conservation habitats and (b) potential restoration habitats for the three waterbird groups based on the overlap of suitable and unsuitable habitats among the different wintering periods. (c) The optimal thresholds of the inundation duration (from September 1 to January 20) based on the average values (mean ± sd) in the key conservation areas. The satellite images shows three representative wetland restoration projects, namely (i) Daxi Lake, (ii) Zhengbo Lake, and (iii) Dingzidi (Zhang et al., 2021b) in Dongting Lake.

are crucial factors affecting the habitat suitability of HTG. Insectivorous waterbirds mainly utilise mudflats and shallow water and prey on benthic macroinvertebrates (Schaffer-Smith et al., 2018; Studds et al., 2017). Their habitat and food availability are also closely related to hydrological factors such as water depth variations (Collazo et al., 2002; Iwamura et al., 2013). We concluded that the water regime has driven the changes in habitat distribution of waterbirds in Dongting Lake. Changes in the water regime can impact the area of various habitat types, the distribution and extent of water patches, EVI, and other variables (Fig. S3), consequently influencing waterbird habitat suitability.

Our results also confirmed our expectation that the three waterbird groups would respond differently to the same hydrological changes. Specifically, the suitable habitat distribution of ING was the most affected by hydrological changes. In Dongting Lake, the mudflat area is much smaller than the vegetation and water areas, and the mudflat distribution range is relatively confined (Wu et al., 2017). Shallow water bodies and mudflat areas are sensitive to changes in water levels (Shi et al., 2017; van der Wegen et al., 2017); therefore, the differences in suitable wintering habitat area between different hydrological patterns were significant for ING. The increase in suitable habitat area for POG during the 2020/2021 wintering period (late water recession) may be attributed to the largest water area during this period compared with the other winters (Fig. S3). What is common among all three waterbird groups is that they were more impacted by early water recession, indicating unfavourable wintering conditions if the water level recedes early. Therefore, proactive management measures should be considered in advance to mitigate the adverse effects on their habitats. However, we are aware of the limitations of this study, as the three wintering periods may not fully reflect the response of waterbird habitat suitability to water regime change. Future studies should investigate the variations in more wintering periods under different water regimes.

The importance of distance to road was low for all three groups. A similar finding was reported by Yuan et al. (2014), where the distance to road had no significant correlation with waterbird abundance. A possible reason is that the entire study area is located in nature reserves where no traffic roads are constructed internally. The boundaries are mainly dikes that have been built for decades. The influence of roads on and outside the boundary may not interfere with the distribution of waterbirds. In contrast, distance to channel had a stronger influence on waterbirds, especially for ING and POG, as there are channels distributed within the study area, and ING and POG are usually distributed in habitats such as water bodies and areas close to water. We suggested that human activities such as fishing and transportation within and adjacent to the occupied habitat should be controlled during the wintering period.

Under the strategy of "Great Protection of the Yangtze River" implemented by the Chinese government, local administrations have made great efforts to invest capital in the conservation and restoration of wetland habitats in Dongting Lake in recent years. However, a lack of understanding of the biodiversity-environment relationship may result in a potential science-practice gap (Hughes et al., 2018). Therefore, it is necessary to incorporate scientific guidance into habitat restoration practices. Identification of conservation and restoration priorities has been promoted by several studies on habitat evaluation based on SDMs (Cotrina Sánchez et al., 2021; Zhong et al., 2021). In this study, based on the spatiotemporal changes in suitable habitat distribution, we considered the prospects for habitat conservation and restoration of wintering waterbirds in our study area. HTG had the largest key conservation habitat area, emphasising the importance of Dongting Lake as an irreplaceable wintering ground for herbivorous geese. The potential habitat restoration area for ING was larger than its key restoration area, indicating that this group was sensitive to habitat change. We indicated that reserve administrations need to focus on strengthening management and protection, including strict prohibition of human activities and improving waterbird and habitat monitoring, in the key conservation areas. On the other hand, the design and practice of habitat restoration could be carried out in potential restoration areas according to the actual situation and needs, followed by an assessment of waterbird community responses to restoration efforts, to enhance the wetland's biodiversity conservation function. Our results also proved the effectiveness of several existing representative wetland restoration projects in Daxi Lake (implemented in 2017), Dingzidi (implemented in 2006), and Zhengbo Lake (implemented in 2020) within Dongting Lake (satellite images in Fig. 5). All the three restored areas are located within the key conservation habitats, indicating high habitat suitability under different hydrological regimes.

Inundation is a typical characteristic of wetlands and a significant factor affecting wetland ecological patterns and processes (Keddy, 2010). Inundation duration is an applicable factor in habitat restoration and management, as it can be controlled by local water level manipulation, which is one of the most important management strategies for waterbird conservation. In Yangtze River floodplain lakes, the inundation area is the key determinant of waterbird abundance and diversity (Jia et al., 2018); however, few studies have included inundation duration as a guide for management efforts. In the present study, we determined the optimal threshold of inundation duration for each waterbird group based on the values within the key conservation habitat (Fig. 5c). Based on the result, we suggest that the recession of water level from mid-to late October would be favourable for HTG, while areas exposed between late October and mid-November would be favourable for ING. An appropriate timing of water recession and recession rate potentially results in a more dynamic habitat and, thus, more abundant food resources for waterbirds over longer periods throughout the wintering season (Aharon-Rotman et al., 2017). For POG, enough water body area should be ensured during January. Adaptive water level management in sub-lakes is a common measure of habitat restoration projects in Dongting Lake. By constructing earthen dikes and regulating sluice, and setting appropriate timing and rate of water recession, it is possible to create favourable and continuously available habitats for wintering waterbirds (Guan et al., 2016;Zhang et al., 2021b; Zhu et al., 2022). Therefore, the results of the present study could be incorporated into habitat restoration efforts in Dongting Lake.

5. Conclusions

In this study, we investigated how spatial patterns of waterbird habitat suitability varied under different water regimes in Dongting Lake, using species distribution models combining multisource environmental data and field survey data of three waterbird groups, namely herbivorous/tuber-eating waterbird, insectivorous waterbird, and piscivorous/omnivorous waterbird groups. We concluded that the water regime change had driven the changes in the suitable habitat distribution of waterbirds in Dongting Lake. In most cases, a normal water recession pattern was associated with larger suitable habitat area, whereas anomalous water regime resulted in more confined suitable habitat areas for the wintering waterbirds. The insectivorous waterbird group exhibited the highest sensitivity to hydrological changes. All three groups were more affected by early water recession compared to late water recession. We identified the key conservation habitats as well as potential restoration habitats for each waterbird group as guidance for wetland management and extracted the optimal threshold of inundation duration. This study has important scientific relevance for the conservation of waterbird wintering habitats in the Yangtze River floodplain and along the East Asian-Australasian Flyway, and will help to guide future management and conservation practices.

Credit author statement

Pingyang Zhang: Conceptualization, Methodology, Formal analysis, Visualization, Writing - original draft, Writing – review & editing. Siqi Zhang: Conceptualization, Investigation, Methodology, Writing – review & editing. Yeai Zou: Conceptualization, Supervision, Writing - review & editing, Funding acquisition. Ting Wu: Investigation, Methodology. Feng Li: Formal analysis, Funding acquisition. Zhengmiao Deng: Conceptualization, Methodology. Hong Zhang: Investigation, Data curation, Writing – review & editing. Yucheng Song: Investigation, Data curation. Yonghong Xie: Funding acquisition, Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118451.

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