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Optimizing Water Level Management Strategies to Strengthen Reservoir Support for Bird's Migration Network

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Abstract: Migratory waterbirds depend on a complex network of wetlands globally for their life cycles. However, habitat loss and degradation pose risks to these networks' sustainability, potentially impacting wetland habitat availability. This study investigates the impact of water level changes in Beijing's Miyun Reservoir on white-naped cranes' *(Antigone vipio)* habitat use. We utilized satellite imagery from 2000–2021 and monthly data from 2018–2023 to observe changes in the reservoir's water and land areas. Additionally, the study tracked 32 cranes using GSM-GPS loggers, yielding insights into their movement patterns and habitat preferences. Our findings emphasize the significant influence of reservoir water levels on habitat availability for these cranes. Notably, our results indicate that the decrease in suitable migratory bird habitats in the reservoir is primarily attributed to high-water level management strategies. This study highlights the necessity for balanced management of aquatic and terrestrial areas in reservoir ecosystems to preserve migratory waterbird habitats.

Keywords: inundation area; water level; habitat suitability; migratory bird; remote sensing

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1. Introduction

Approximately one-fifth of the over 10,000 existing bird species are migratory, and bird migration is one of the most fascinating natural phenomena [1]. Annually, billions of migratory birds travel between breeding and wintering grounds, with migration routes covering the globe [2,3]. Long-distance migratory birds rely on cyclically using different habitats (breeding grounds, molting sites, stopover sites, and wintering grounds) for climate resources and food [4–9]. The breeding sites, molting sites, multiple stopover sites, and wintering grounds together form the migration network for these long-distance birds [10–12]. Like clockwork, migratory waterbirds not only strongly depend on these fixed points spatially but also rely on them temporally for seasonal climate resources and food. The stability of stopover sites is especially crucial, serving as "refueling stations" and "life support stations" for these long-distance migratory birds. Each node in the bird migration network, the stopover sites, plays a vital role; changes in land use and the loss of ecosystem functions at these nodes can lead to a systemic collapse of the migratory network [13–15]. Therefore, birds, particularly large-bodied (weight > 1 kg) long-distance (migration distance > 1000 km) migrants, are more vulnerable compared to other wildlife [16,17].

In a cycle of departure and return, birds have adapted to the Earth's seasonal changes caused by its orbit, such as ice and snow coverage in high-latitude regions, leading to a loss of food resources [18,19]. Birds ingeniously acquire spatially and temporally matched food resources along their migratory routes. They heavily rely on each node (breeding grounds, stopover sites, wintering grounds, etc.) in the migration network [20,21]. Changes in land use or loss of ecosystem functions at any node in the migration network can cause systemic collapse of the network vital for bird survival, potentially leading to a decline in population numbers or even the extinction of a species [22]. Annually, during the spring and autumn migration periods, an estimated 50 million migratory birds in the East Asian–Australasian Flyway (EAAF) [23], along with numerous other wetland-dependent species, traverse China. Their journey extends between breeding grounds in northern Asia and Alaska and wintering locations in Southeast Asia and Australasia. An extensive network of both coastal and inland wetlands serves as vital rest stops for these species, analogous to how petrol stations facilitate long-distance travel [24,25]. This migratory phenomenon underscores the critical role of wetlands in supporting biodiversity and ecological connectivity [26].

However, approximately 2.7 billion people inhabit the major rivers of the world and their adjoining floodplains, areas that are not only cradles of civilization but also among Earth's most biologically diverse habitats. These vital regions are now facing unprecedented challenges, including large-scale damming, alterations in hydrology, pollution, the introduction of non-native species, and sediment mining, each posing a significant threat to their ecological integrity and future sustainability [27,28]. Historically, natural wetlands were often perceived as unproductive and were frequently encroached upon for agriculture and urbanization, leading to significant habitat loss. The world experienced a net loss of approximately 21% of inland wetlands between 1700 and 2020, primarily due to climate change and human activities [29], highlighting the urgency of wetland conservation.

In response, the international community has adopted the Kunming–Montreal Global Biodiversity Framework, targeting these ecological challenges through global collaborative efforts [30]. Concurrently, the Chinese government has initiated the National Major Project for the Protection and Restoration of Key Ecosystems (2021–2035), a strategy aimed at bolstering ecosystem health and diversity, with a particular focus on conserving and restoring wetlands [31]. The project outlines key objectives, including enhancing wetland protection, rehabilitating degraded wetlands, and improving their functional services, reflecting China's commitment to maintaining wetland integrity and promoting biodiversity [32]. But these ecological projects take many years to see results, and at the moment, there is a particular need to provide alternative habitats for tens of millions of migratory birds in a rapid and targeted manner. What gives hope is that as natural wetlands diminish, waterfowl are increasingly turning to artificial bodies of water, such as reservoirs, for alternative habitats. Recent statistics reveal the existence of approximately 515,149 reservoirs worldwide, each covering more than one hectare. As of 2019, China has established 98,112 reservoirs with a total capacity of 898.3 billion cubic meters. The construction of dams and reservoirs across varied topographies has resulted in reservoirs of diverse shapes and sizes, influencing the spatial distribution and numbers of resident waterfowl. Within these reservoir ecosystems, shallow water areas have been consistently identified as positively influencing waterfowl species diversity. Therefore, understanding the utilization patterns of waterfowl in reservoir ecosystems is critical for effective species conservation and management. The fluctuating water levels in these reservoirs have created a vast inundation area, offering rich foraging opportunities and habitats for migratory birds [33–35].

Although both remote sensing and bird tracking technology have recently experienced major advances they have the potential to facilitate integrated analyses of environmental and bird movement data in unprecedented detail [36]. The complex interplay among reservoir water levels, tidal flats, aquatic vegetation, and avian diversity is not yet fully elucidated. An accurate mapping of these drawdown zones under various water levels for each reservoir is still pending. There is an urgent need for the scientific community to provide reservoir managers with empirical data and theoretical guidance [37]. To bridge this knowledge gap, our focus turns to the Miyun Reservoir in Beijing, with the white-naped crane (*Antigone vipio*) as our focal species. Through top-down methodologies leveraging multi-source satellite data coupled with bird-borne telemetry, we aim to shed light on the hitherto obscured biodiversity implications for migratory waterbirds [38,39]. Here, we report on our use of GPS tracking of white-naped cranes to achieve several objectives. Firstly, we seek to map and qualify the dynamic shifts in hydrological inundation of the Miyun Reservoir over the past four decades. Secondly, we wish to evaluate the ramifications of these inundation dynamics on habitat suitability for long-distance migratory waterbirds. Finally, and most importantly, we combine tracking data and remote sensing data to enhance our understanding of optimizing reservoir management, while balancing both social and ecological goals.

2. Materials and Methods

2.1. Study Area

The Miyun Reservoir is one of the tens of thousands of reservoirs built in recent decades, which is located in the Miyun District on the periphery of Beijing and spans across the confluence of the Chao and Bai Rivers (see Figure 1). Approximately 100 km from central Beijing, it was completed on 1 September 1960. Engineered for a once-in-a-millennium flood, the reservoir has a designed water level of 157.5 m and covers 224 square kilometers, representing 10.1% of the district's area. Its storage capacity is a substantial 4.4 billion cubic meters, allocated as follows: 1.9 billion for water supply, 1.8 billion for flood control, and 0.4 billion for dead storage. From 1960 to 2020, the reservoir has directed 39 billion cubic meters of water to the Beijing–Tianjin–Hebei region, with Beijing receiving approximately 28 billion cubic meters. This equates to an average annual supply of 650 million cubic meters, comparable to refilling Kunming Lake over 320 times each year. Considering Beijing's annual water consumption for industrial and domestic purposes is around 2.8 billion cubic meters, it can be deduced that nearly a quarter of the water used by residents originates from the Miyun Reservoir. Consequently, this reservoir is not only Beijing's most vital water source but also a critical ecological asset and strategic safeguard for the city's water supply.

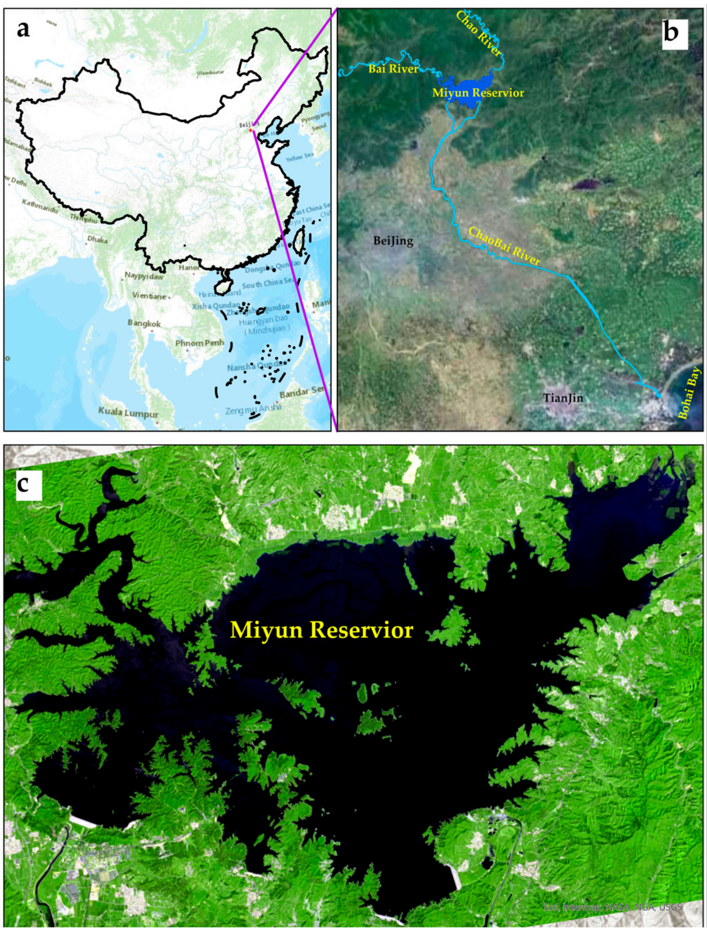

Figure 1. Location of Miyun Reservoir ((**a**) The relative location of the study area in China; (**b**) The relative location of the study area in the Chaobai River basin; (**c**) A Sentinel-2 satellite image of Miyun Reservoir captured on 25 August 2022).

2.2. Remote Sensing Data

Our inundation mapping of the Miyun Reservoir (2018–2023) utilized a composite dataset, detailed in Figure 2, comprising the following: (1) Sentinel-1 SAR GRD: This C-band Synthetic Aperture Radar in Ground Range Detected mode was essential for monthly maximum water extent assessments. (2) JRC Monthly Water History Dataset: Provided annual surface water distribution maps from 2000 to 2021, enabling extensive statistical analysis of water body dynamics. (3) Sentinel-2 MSI: The MultiSpectral Instrument, Level-1C, from the European Space Agency, with a 10 m resolution and 5–6-day revisit cycles, was crucial for cross-validating our findings. (4) ALOS DSM Dataset: Offered by JAXA's Earth Observation Research Center, this 30 m resolution dataset was pivotal in rectifying shadow-induced misclassifications in water identification. These datasets were seamlessly integrated within the Google Earth Engine platform for comprehensive analysis.

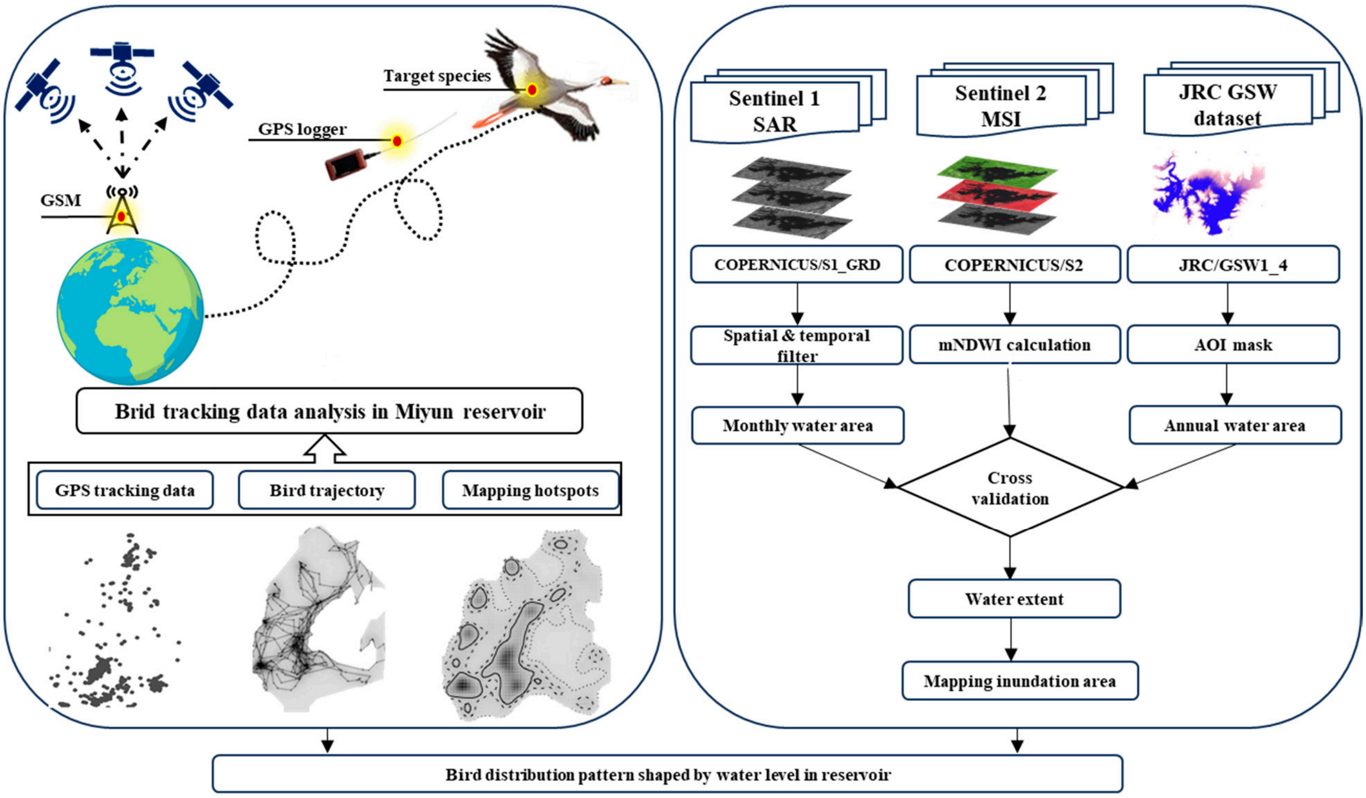

Figure 2. Flowchart to quantify water dynamics and bird distribution patterns.

To characterize the land cover for bird GPS fixes during their staging at Miyun Reservoir, we used the "Esri Land Cover" datasets from 2018 to 2022, produced by Impact Observatory for Esri Inc. The Esri Land Cover map uses Sentinel-2 satellite imagery with a 10 m resolution and a land classification model to classify the Earth's surface into 10 categories, namely, crops, water, trees, grass, flooded vegetation, built area, scrub/shrub, bare ground, snow/ice, and clouds for areas with no data. The scrub category mainly represents open areas covered in homogenous grasses with little to no tall vegetation in the study area, as confirmed by our field survey. This dataset is based on the dataset produced for the Dynamic World Project by the National Geographic Society in partnership with Google and the World Resources Institute. We assessed the habitat usage patterns by identifying land cover types for every single GPS fix.

2.3. Bird Tracking Data

In our research, we implemented a specific methodology to deepen our understanding of the conservation needs of the white-naped crane (*Antigone vipio*), listed as 'Vulnerable' on the IUCN Red List. During the summers of 2017, 2018, and 2019, within their flightless periods, we captured and equipped 39 white-naped cranes at their nesting locations in eastern Mongolia [40]. Out of these, 32 cranes that opted to rest at the Miyun Reservoir during their migratory journeys were analyzed in this study. The capture teams skillfully approached and pursued the flightless cranes and subsequently outfitted them with waterproof, leg-mounted Ornitela L-40 GPS/GSM logging transmitters (hereafter, "loggers"), weighing 35 g. Each logger was affixed in under a minute, ensuring the birds were set free at the capture location within 30–40 min. Before releasing, we meticulously observed each crane to ascertain there were no indications of capture myopathy, trauma, or stress from the capture and instrumentation procedure. These loggers generated an extensive dataset, capturing details such as GPS coordinates, flight altitude, speed, direction, horizontal dilution of precision, and battery voltage. The loggers were used to allow on-board storage of data that can be remotely downloaded via GSM/GPRS/3G networks and later retrieved from Ornitela's website (https://www.ornitela.com/ accessed on 31 July 2023). Devices were programmed to collect GPS fixes at an interval of 10 min.

2.4. Data Processing

The geoprocessing work was mostly conducted using ArcGIS Pro 3.1 software. Our tracking data collection spanned from 1 August 2017 to 30 July 2023. To maintain the dataset's accuracy, any positional anomalies exceeding specified boundaries (longitudes > 180° or latitudes > 90°) were excluded. All time values recorded in original date fields from other time zones (mostly UTC time) were converted to UTC + 8 Beijing standard time using the "Convert Time Zone" tool to conduct an hourly scale analysis. We applied the tracking analyst toolbox of ArcGIS pro 3.1 software to calculate bird movements computed from the distance between successive time-stamped positions along a track, using the "Points To Track Segments" function to generate bird trajectories. We estimated the bivariate density at a given grid point x as follows:

$$\hat{P}(x) = \frac{1}{nh^2}\sum_{i=1}^{n} k\left(\frac{d_i(x)}{h}\right) \quad (1)$$

where $K(\cdot)$ is a kernel, h is the bandwidth or smoothing parameter, and $d_i(x)$ is the distance between the grid point x and the *i-th* visited location Xi = $(x_i, y_i) \in$ X. The most common choice for $K(\cdot)$ is a radially symmetric unimodal probability density function, such as bivariate normal density. The kernel density estimation (KDE) was applied to describe the density of cumulative bird use in two-dimensional space. The density map was made to indicate where the highly preferred zones are for cranes and where hostile habitats are not utilized by cranes in the reservoir.

3. Results

3.1. Range and Spatiotemporal Distribution of Inundation Area

The Miyun Reservoir experiences significant annual fluctuations in water levels, influenced by upstream water inflow, evaporation, and management strategies. These variations result in changes in water coverage and storage capacity. Our remote sensing analysis has meticulously mapped these spatial alterations in water coverage under varying water level conditions (Figure 3).

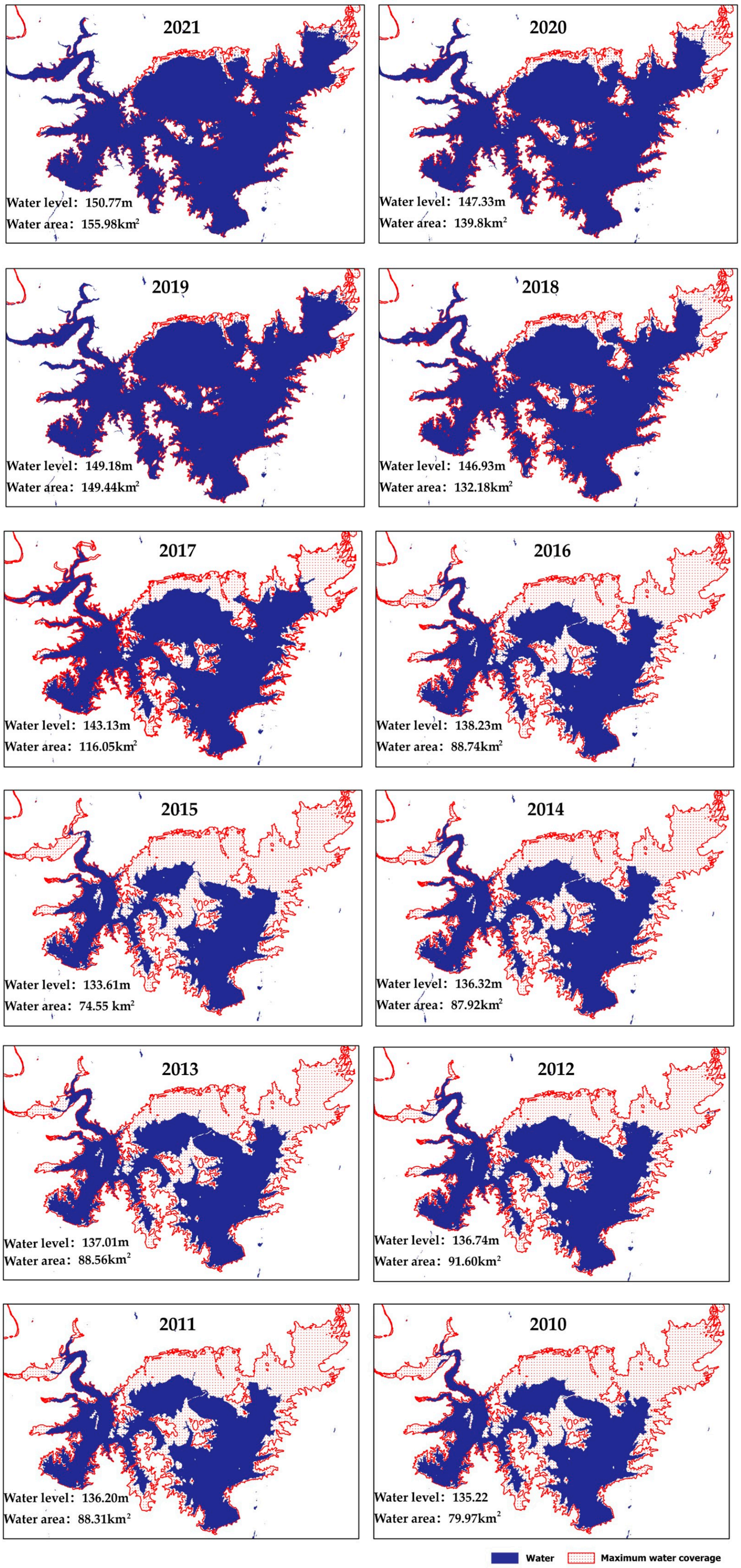

Figure 3. Map of annual water surface distribution from 2010 to 2021.

From 2010 to 2016, the reservoir predominantly operated at lower levels, maintaining an average below 140 m, resulting in extensive drawdown zones, averaging 72 square kilometers, primarily along the elevated regions between the Bai and Chao River sections (Figure 3). In 2017, a notable change occurred with rising water levels, leading to an increase in water-covered areas and a decrease in exposed drawdown zones. The water-covered space expanded to approximately 115 square kilometers, reducing the drawdown zone to about 42 square kilometers. From 2018 to 2021, the reservoir maintained higher levels, frequently exceeding 145 m and reaching a peak of 155.3 m, enlarging the water coverage to approximately 157.3 square kilometers. The drawdown zones were significantly reduced, primarily visible near the Chao River mouth and the northern shorelines. Over the two decades from 2000 to 2021, the reservoir's annual water coverage displayed a fluctuating pattern with notable yearly variations. Since 2018, the reservoir has consistently maintained higher water levels, with a coverage area exceeding 130 square kilometers. By 2021, this expanded to 156 square kilometers. Comparing the average water levels of 133.61 m in 2015 to 150.77 m in 2021, there is a significant increase of 13%. Concurrently, the water coverage expanded from 75 square kilometers in 2015 to 156 square kilometers in 2021, more than doubling. This growth was mirrored in the storage capacity, which surged from 868.9 million cubic meters in 2015 to an impressive 2.8 billion cubic meters by 2021, as depicted in Figures 3 and 4.

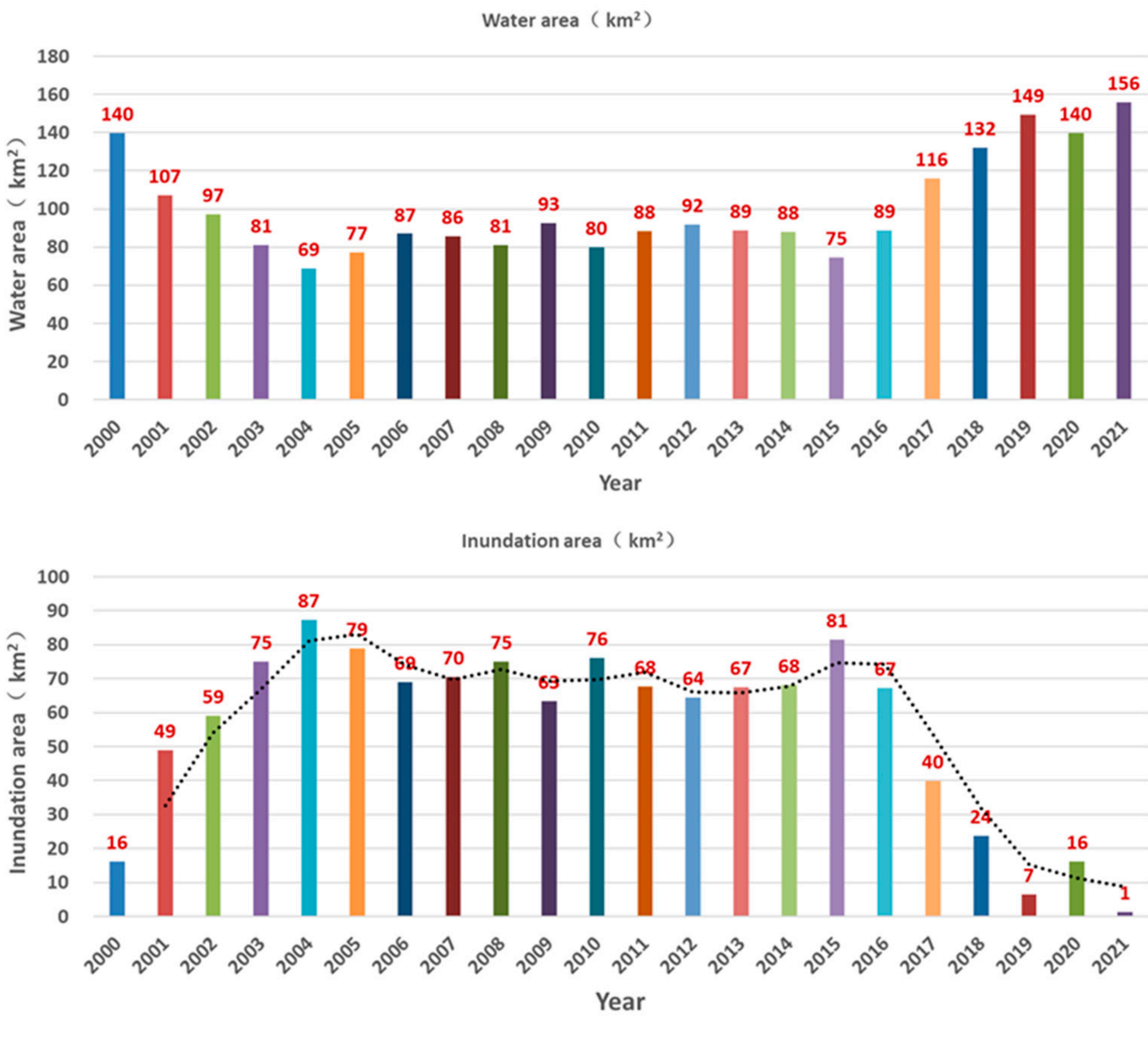

Figure 4. Interannual dynamics of the surface area of Miyun Reservoir from 2000 to 2021.

The water levels of the Miyun Reservoir are intricately governed by a triad of primary factors: inflow from upstream sources, contributions from the South-to-North Water Diversion Project, and strategic human interventions. The Chao and Bai Rivers, which feed the reservoir, experience their peak rainy seasons in July and August, coinciding with the flood season of the Miyun Reservoir. This seasonal alignment results in a significant increase in upstream water input. In anticipation of these floods, reservoir storage is strategically reduced in May and June, facilitating the accommodation of the incoming surge. Therefore, the observed fluctuation in water coverage, characterized as the "expansion and recession" cycle, emerges not solely from natural causes but is a product of an intricate interplay between natural dynamics and calculated human management.

The integration of the South-to-North Water Diversion Project has transformed the Miyun Reservoir into a critical component of this national initiative, serving as a "regulation and storage reservoir." This project channels "Southern Water" from Tuancheng Lake, transported through a series of nine pump stations along the Jingmi Canal. This elaborate infrastructure elevates the water by 133 m to facilitate its entry into the Miyun Reservoir. The augmentation of the reservoir's capacity by this project not only enhances Beijing's strategic water reserves but also significantly contributes to the city's overall water supply rate. In 2022, the project delivered a substantial 38 million cubic meters of water to the reservoir, highlighting its crucial role in modulating the reservoir's water expanse.

In October 2021, the Miyun Reservoir experienced a historic zenith in its water level, reaching 155.3 m. This peak resulted in an extensive water coverage area of 156 square kilometers. Over the course of that year, the reservoir's water level rose from an initial measurement of 148.23 m to this record high. This increase was mirrored in the expansion of the water coverage area, growing from 138 square kilometers to 156 square kilometers, as detailed in Figures 5 and 6. Analysis of data from 2018 onward, as depicted in Figure 7, reveals the monthly variations in the reservoir's water coverage. Despite intermittent fluctuations, a clear upward trajectory in water coverage expansion is discernible.

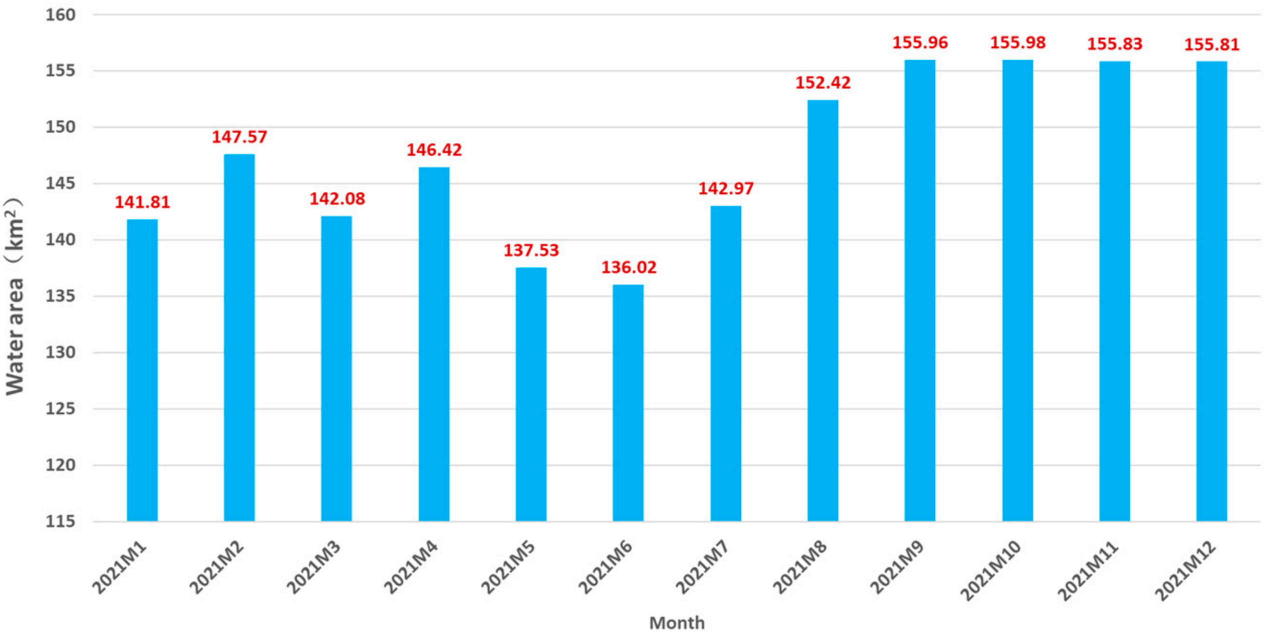

Figure 5. Monthly dynamics of the surface area of Miyun Reservoir in 2021.

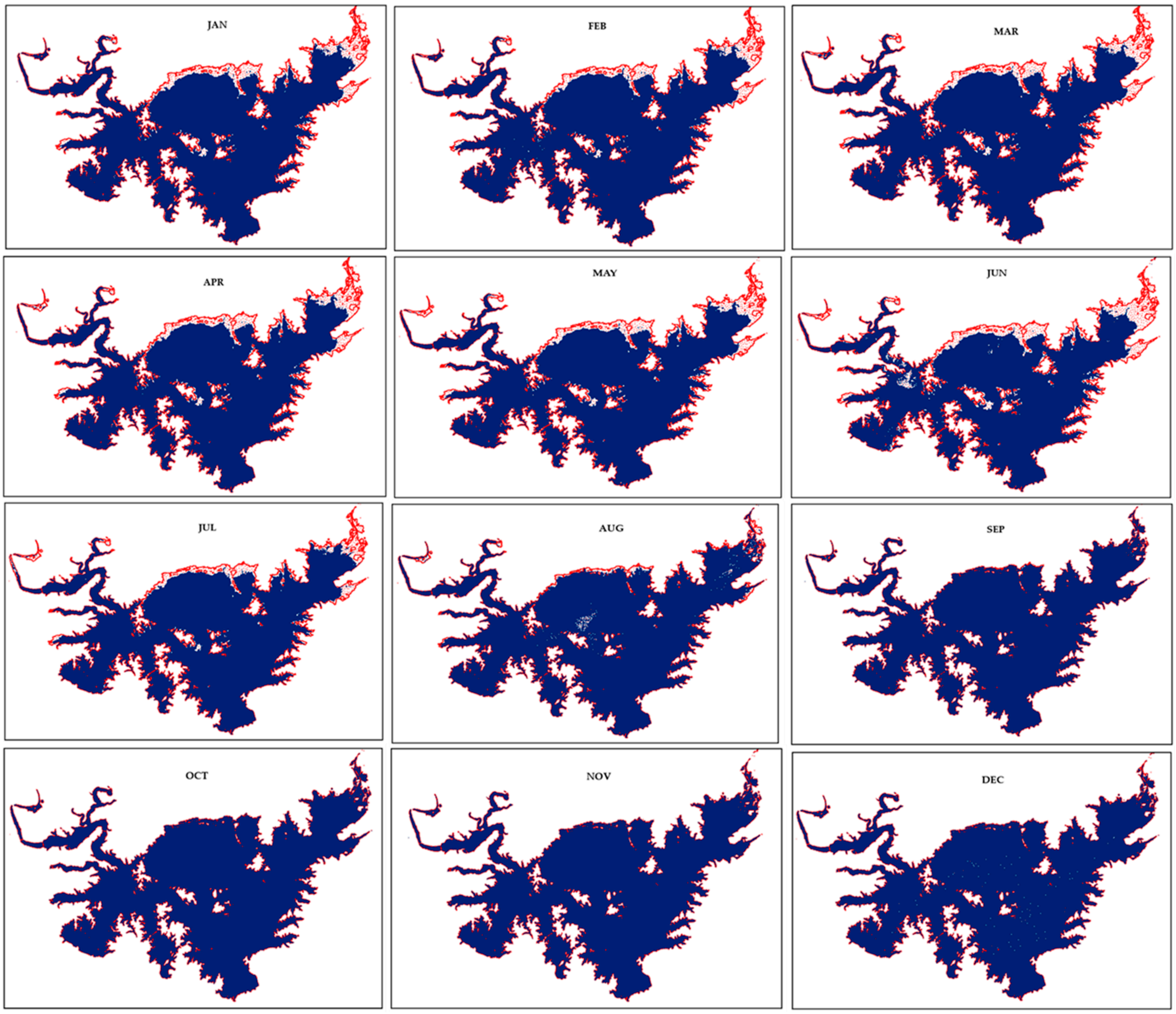

Figure 6. Monthly map of the surface area of Miyun Reservoir in 2021.

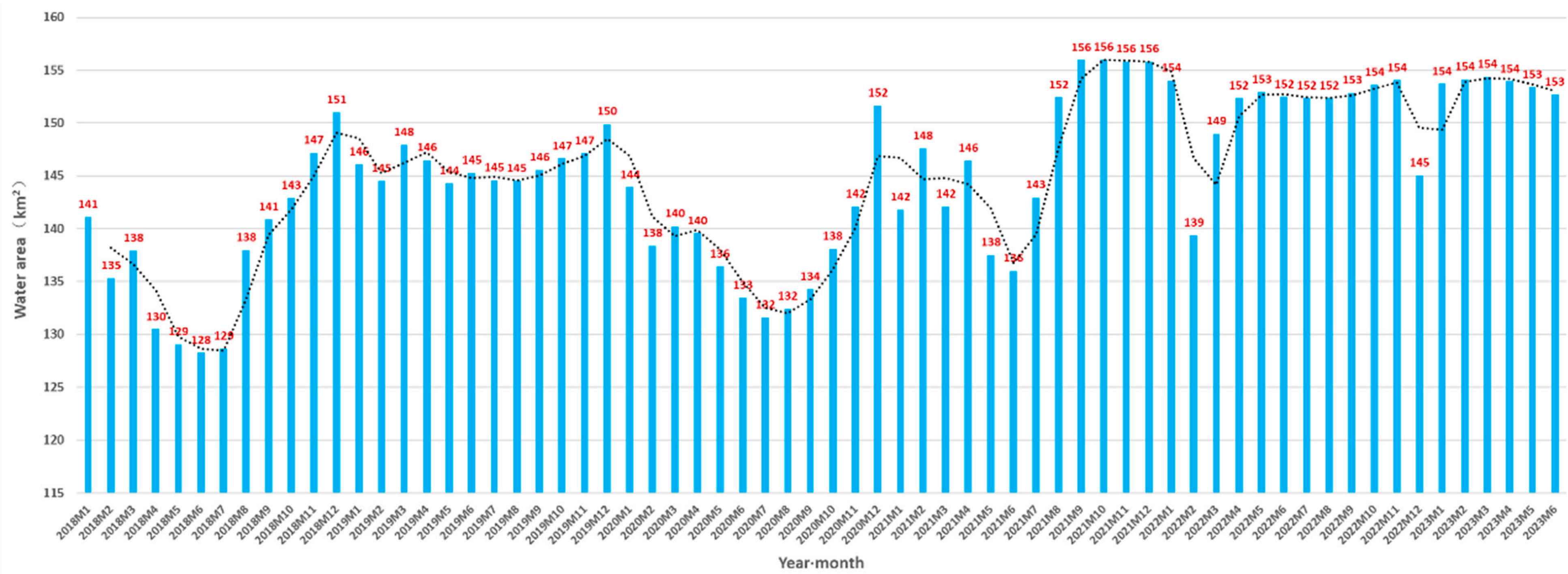

Figure 7. Monthly water area dynamics of Miyun Reservoir from 2018 to 2023.

3.2. Patterns of Bird Habitat Utilization in Miyun Reservoir

We deployed loggers on 19 HY (hatching year) birds in 2017, 3 adults in 2018, and 17 birds in 2019 during the molt of their plumages before regaining the power of flight [40]. The survival rate of the 39 tracked cranes for all years is listed in Table 1. Comprehensive data obtained from the loggers, encompassing entire migratory cycles, revealed that all 39 monitored white-naped cranes traversed between their breeding grounds in Mongolia and their designated wintering habitats in China's Yangtze River Basin [40]. Among these, the migratory routes of 32 cranes, represented by 18,937 location points, intersected with the Miyun Reservoir. These cranes collectively accumulated 196 days within the Miyun Reservoir environment from autumn 2017 to spring 2023. We defined the birds that transmit data back in the given year as living birds, and the survival rates are listed in Table 1. The sharp drop in tracked bird survival rates occurred in the year of 2021, when the reservoir operated a high water level strategy. For years with data coverage throughout the year, the reservoir supported 15 birds out of 19 birds during their flyway in 2018, while it supported 9 birds out of 16 birds in 2022; the ratio of birds that visited Miyun Reservoir dropped from 79% in 2018 to 56% in 2022.

Table 1. Number of tracked birds and survival rate.

Year	Number of Tracked Birds	Number of Birds Alive	Survival Rate	Number of Birds that Visited Miyun Reservoir	The Ratio of Birds that Visited Miyun Reservoir
2017	19	19	100%	14	74%
2018	3	19	86%	15	79%
2019	17	32	82%	24	75%
2020	-	26	67%	23	88%
2021	-	19	49%	13	68%
2022	-	16	41%	9	56%
2023	-	12	31%	7	58%
Total	39			32	82%

The recorded data indicate distinct migratory stopover patterns for these tagged white-naped cranes; they utilized the reservoir for 144 days during spring migration and 52 days in the autumn migration phase. During their spring migration, these cranes typically arrived at the Miyun Reservoir around 9 March (±3 days), staying for an average of 19 days (±17 days) before proceeding northward around March 27th (±15 days). In contrast, their autumn migration saw them arriving at the reservoir around 18 October (±9 days), with an average residency of 19 days (±12 days), before resuming their southward journey around 6 November (±4 days), as depicted in Figure 8.

To further illustrate the spatial distribution pattern of tracked birds in the reservoir, we employed a fishnet measuring 100 m by 100 m. Based on this fishnet, we counted the number of bird gps fixes within each grid to show hotspots of bird distribution in each year (Figure 9). Red grids represent hotspots that are highly used by cranes, blue grids represent low bird density, and yellow ones represent regions that are moderately used by cranes. The results indicate that cranes primarily utilize the region within Miyun Reservoir, but they also visit farmlands within 2 km north of the reservoir to seek food resources. Cranes utilized the Miyun Reservoir the most in 2018, a year with low water levels. Hotspots are mainly distributed in the northern nearshore roosting area and shallow water regions. Subsequently, as the water level gradually increased in 2019, 2020, and 2021, the roosting areas on the northern shore of the reservoir were submerged. The suitable habitat range for cranes shrunk significantly in the small region in the estuarine area on the northeast where the Chao River enters the reservoir.

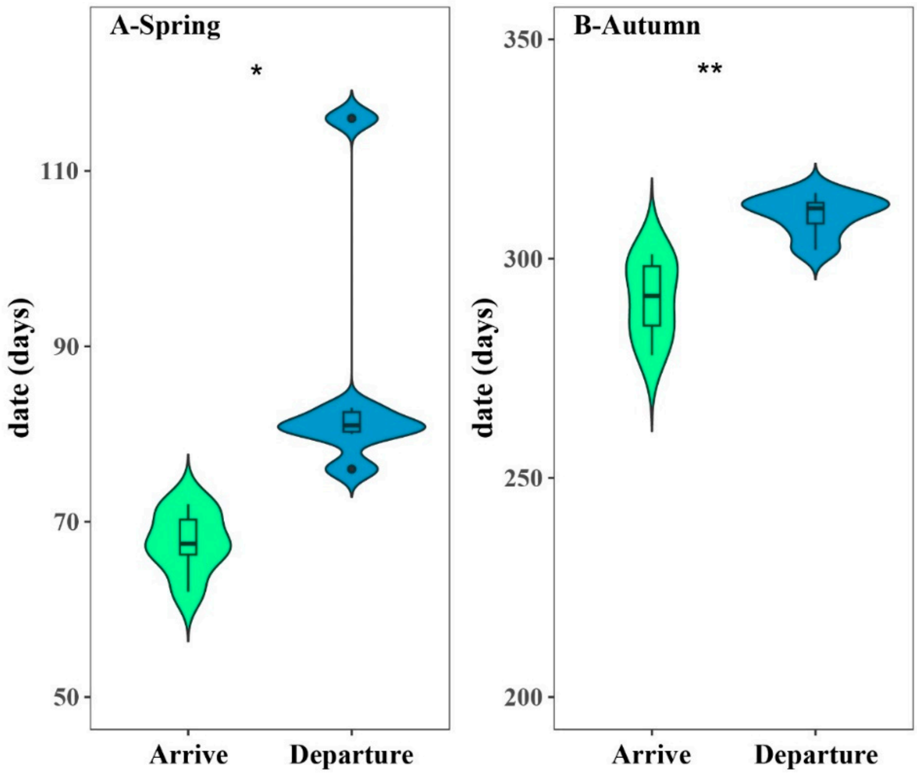

Figure 8. Arrival and departure dates of white-naped cranes at Miyun Reservoir(* $p < 0.05$, ** $p < 0.01$).

In terms of spatial preferences, the cranes predominantly selected areas along the northern exposed shorelines of the reservoir and at the confluences of tidal rivers flowing into the reservoir, particularly in zones with extensive inundation. During a year of low water levels, such as 2018, the cranes cumulatively spent 51 bird days at the Miyun Reservoir. However, in a year with higher water levels like 2021, there was a notable decrease in crane presence, with a total of only 33 bird days recorded at the reservoir. Significantly, there were profound shifts in the spatial distribution of crane habitats. In 2018, white-naped cranes could be found dispersed widely along the exposed northern shorelines of the reservoir, as illustrated in Figure 10a. In stark contrast, by 2021, the habitat range of these cranes had dramatically contracted, primarily confined to the river mouths influenced by tides that flowed into the reservoirs. When we compared the spatial layout of exposed zones with the distribution patterns of white-naped cranes, we observed a remarkable consistency between the two (see Figures 10 and 11).

All 32 birds generated a total of 18,937 GPS fixes within the rectangular area defined by the four corners of the reservoir. Those GPS fixes were used to overlay a land cover data layer with a 10 m resolution to identify their traits of habitat use. Figure 12 shows a pattern map of the land cover used for the white-naped crane. The landcover was validated using high-resolution images from Google Earth and reclassified into five types. The cranes predominantly used the inundation area as a habitat. Still, there were high levels of grass and crops during their staging season in the Miyun Reservoir (Figure 12).

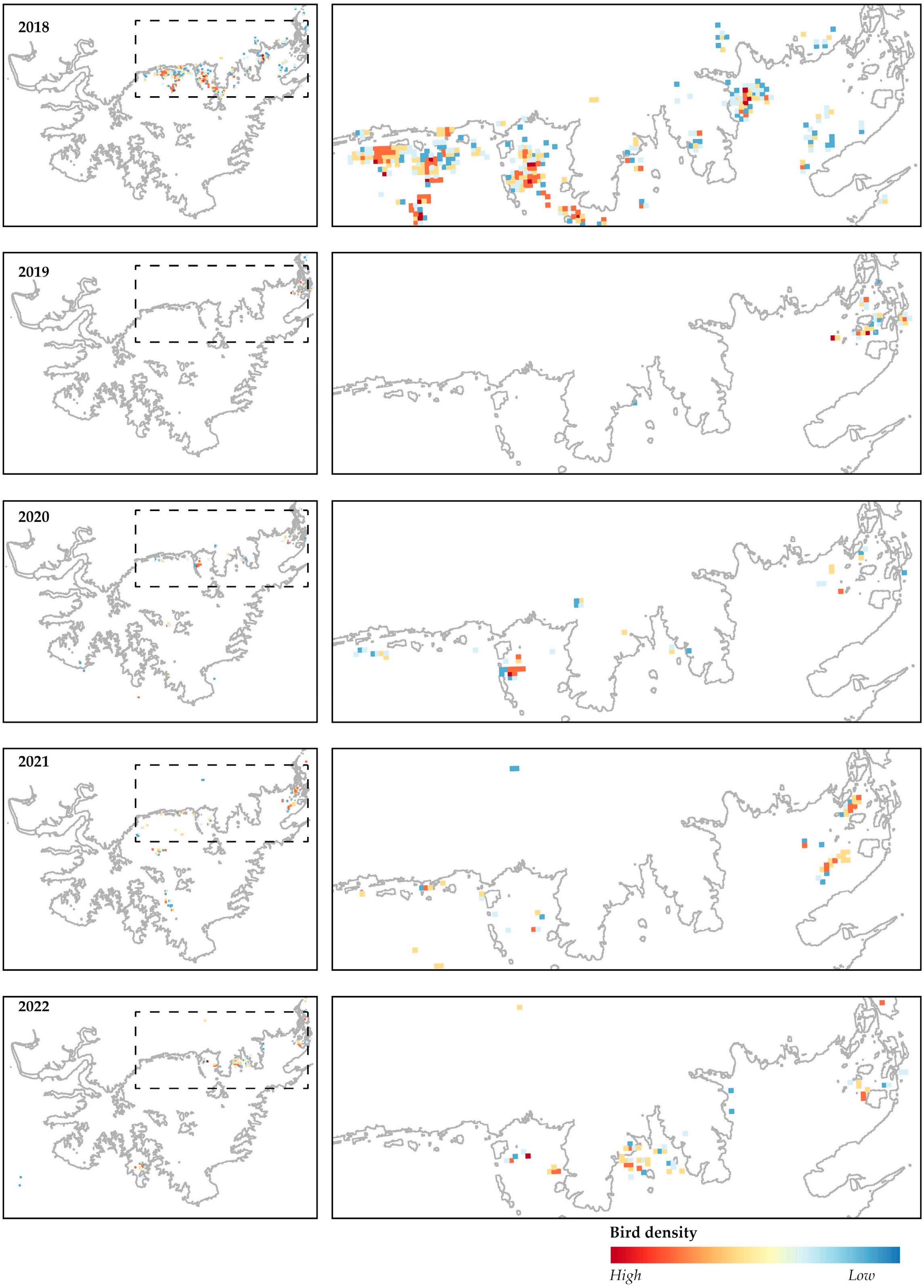

Figure 9. Distribution maps of tracked birds in Miyun Reservoir from 2018 to 2022.

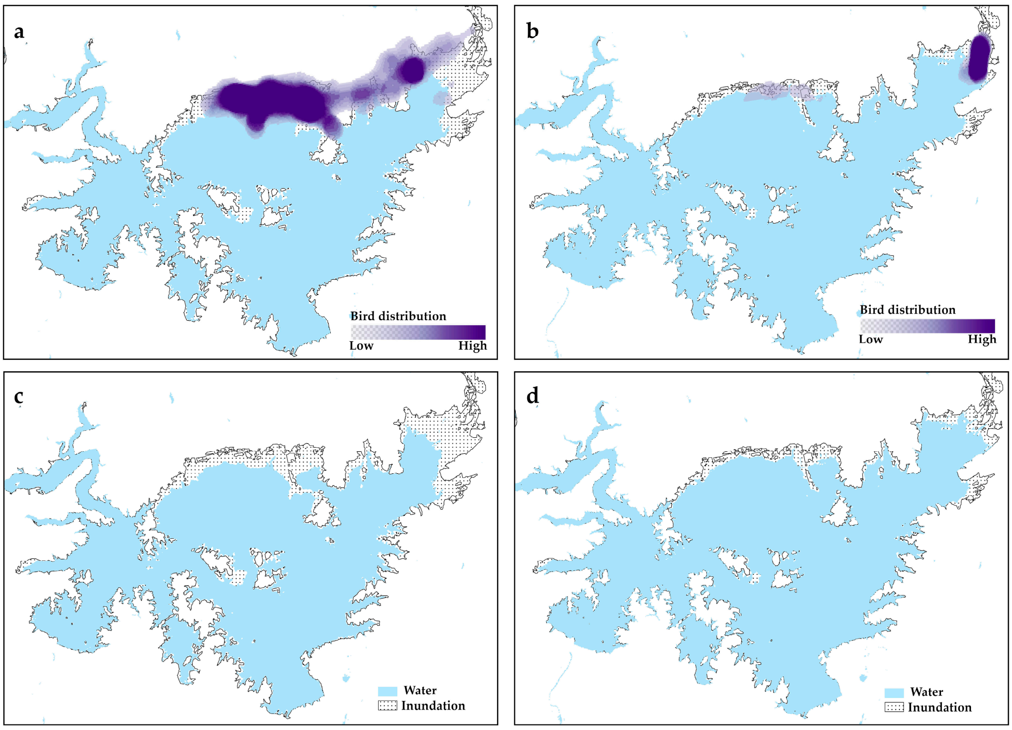

Figure 10. Comparison bird distribution in Miyun Reservoir between 2018 and 2021.((**a**) Map of birds distribution in 2018; (**b**) Map of birds distribution in 2021; (**c**) Map of inundation area distribution in 2018; (**d**) Map of inundation area distribution in 2021).

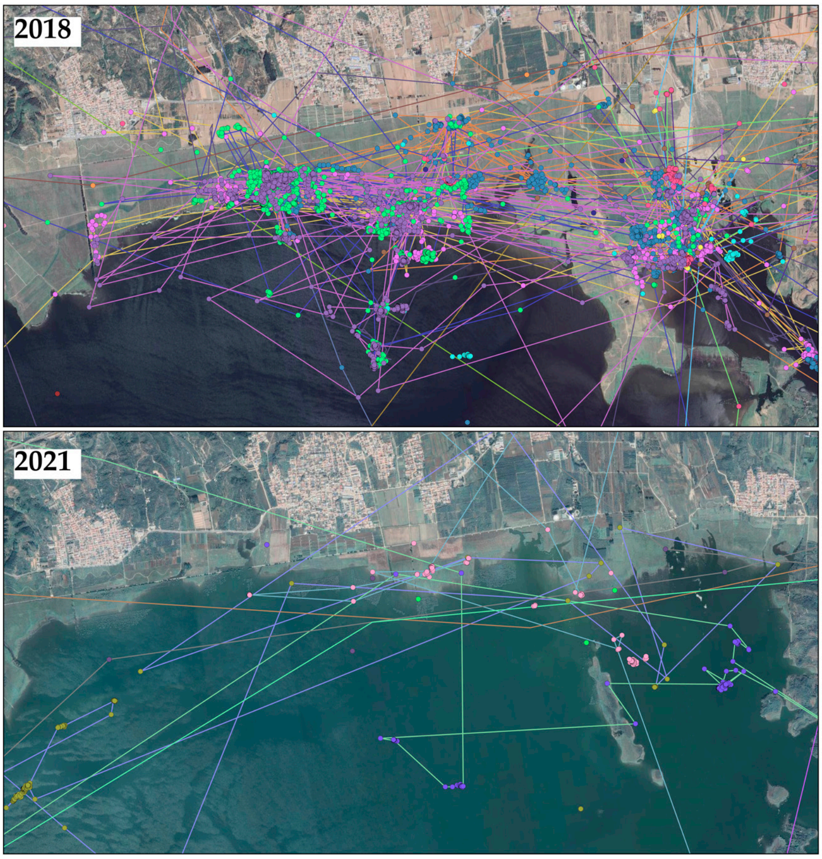

Figure 11. Spatial variation in bird distribution between 2018 and 2021.(The dots of each colour represent the locations of a bird, and the lines represent the movement trajectories of each bird).

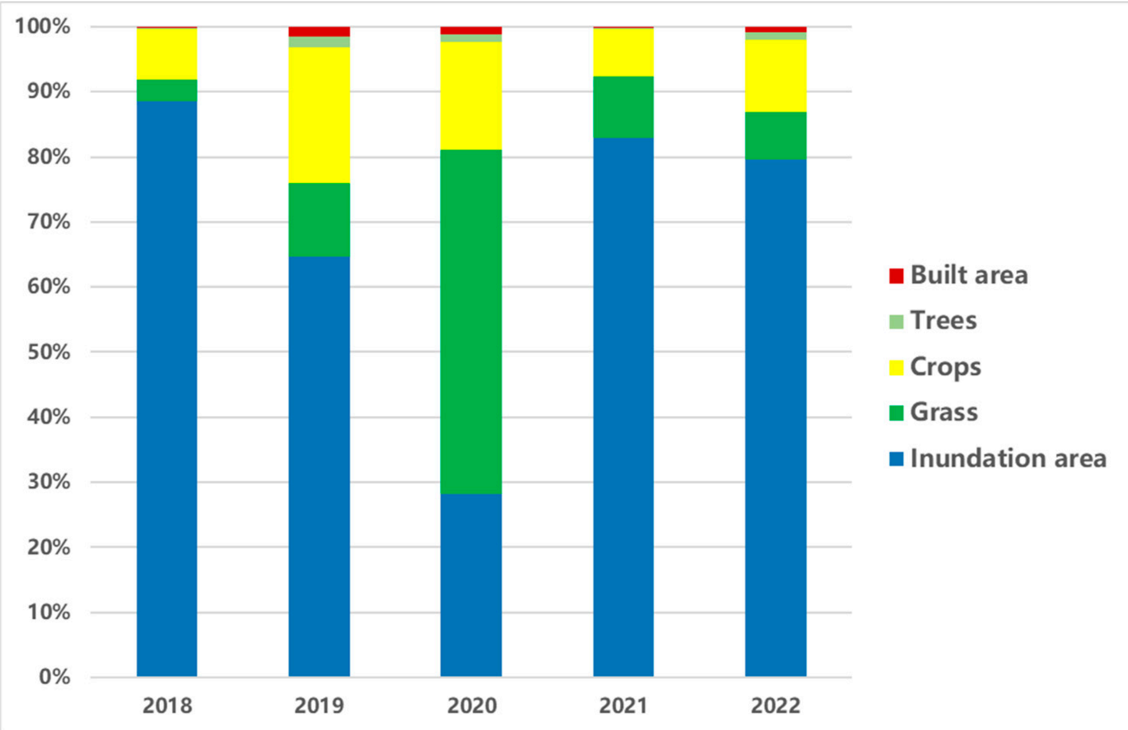

Figure 12. Patterns of land cover used derived from the bird GPS fixes in Miyun Reservoir and neighboring areas.

4. Discussion

4.1. Optimizing Water Level Management Strategies in Reservoirs

Over recent centuries, a marked diminution of natural wetlands has been observed at local, national, and global levels. Natural wetlands are indispensable, providing essential habitats for a multitude of migratory waterbirds globally across their annual life cycles. The deterioration and loss of wetlands not only affects the hydrological cycle but also has significant implications for the carbon cycle and the global migratory pathways of waterbirds [41,42]. In light of this situation, our research proposes that reservoirs, especially those in eastern and northern China, where they are prevalent, could serve as feasible alternative habitats for waterbirds. The Miyun Reservoir, in particular, is notable as a vast natural terrestrial freshwater ecosystem within its geographical latitude in East Asia.

Our investigation focuses on how recent variations in water levels at the Miyun Reservoir have affected water and inundation area patterns over the past two decades. From 2000 to 2021, these areas, monitored annually, exhibited a significant range in the water areas that fluctuated between 69 and 156 km^2, while the inundation areas varied from 87 to 1 km^2. Notably, in 2021, monthly changes in water areas were observed from 136 to 156 km^2. This change in water level dynamics led to the formation of extensive floodplain wetlands along the reservoir's periphery. Seasonal diversity in water level changes has resulted in a diverse landscape in the inundation zones, comprising both aquatic and non-aquatic environments. These inundation zones are characterized by a diverse array of microhabitats, including floodplains, sandbars, depressions, channels, ponds, islands, and gravel bars. This varied habitat supports a wide range of avian species, including carnivorous birds such as cranes, geese, storks, and herons. With a recorded presence of 228 bird species, the Miyun Reservoir has become an integral stopover and breeding site on the East Asia–Australasia migratory flyway.

Understanding where, when, and why target species move, can be used to develop conservation strategies that are flexible in time and space and may improve the effective of reservoir management actions [37]. Our analysis utilized GSM-GPS loggers to track the movements of 32 cranes, providing data at 10 min intervals. This enabled us to identify key habitat utilization hotspots within the Miyun Reservoir. The findings highlight the critical role of inundation levels in defining habitat niches for white-naped cranes, as determined through a comparative analysis of crane movement patterns and water distribution maps. Contrary to expectations, the reduction in suitable habitats for these migratory birds was not primarily due to human encroachment but was linked to the reservoir's high water level management practices. The water level rise also caused a rapid decrease in shallow water areas and a decline in the number of shallow-water-preferring avian group, such as waders, geese, and dabbling ducks [43,44]. Our results indicate a decline in the role and ecosystem service capacity of Miyun Reservoir as a crucial stopover site for bird migration following its operation at high water levels (Table 1).

While acknowledging the primary functions of the reservoir in flood control, water supply, and power generation, we advocate for a balanced approach to reservoir management that equally considers aquatic and non-aquatic zones. We suggest management strategies to improve the importance of water-level-controlled reservoirs as breeding areas for resident species and migratory birds. Particularly during peak migratory periods in March and October, maintaining a water level at least 5 m below the annual peak is recommended for this study case at Miyun Reservoir. This practice would ensure that a substantial area (>20 km^2) of the riparian floodplain becomes accessible, thereby providing essential feeding and nesting areas for migratory birds. Reservoir and wetland managers should use a mix of full drawdowns and passive wetlands to provide habitat for the greatest diversity and number of birds throughout the year [45].

4.2. Restoration of Waterbird Habitats: Evidence and Strategies

In 2018, tagged cranes demonstrated a marked preference for the exposed shorelines of the northern reservoirs, as delineated in Figure 10. By 2021, however, there was a notable absence of cranes in this area. This change is attributed primarily to two factors: the elevated water levels in 2021, which submerged a large portion of the region, and the post-2019 extensive tree planting, resulting in tall tree habitats unsuitable for most migratory waterfowl.

The establishment of alternative habitats is a critical strategy to mitigate biodiversity loss and bolster waterbird populations. Such measures can offset the negative impacts of natural wetland habitat degradation and loss, thereby facilitating the revival of waterbird populations. Waterbirds, owing to their mobility, social behavior, and visible presence, are effective bioindicators for reservoir ecosystems. The presence or absence of specific waterbird species can provide insights into the ecological health and food resource availability of a reservoir. Consequently, we advocate for replicating habitat prerequisites of key avian species at the Miyun Reservoir, including habitat restoration and micro-landscape modifications to enhance food availability and establish avian migration corridors.

Recent studies indicate a preference among various waterfowl species, such as geese, ducks, and cranes, for nesting and foraging in shoreline areas where water depths are less than 2 m [33]. Field surveys at Poyang Lake identified shallow waters and minor lake-like depressions as crucial bird-congregation areas. Drawing on nature-oriented habitat restoration principles, we propose creating additional shallow water ponds along the reservoir's shoreline, maintaining water depths below 1 m. This approach involves allowing these areas to be submerged during high water events and subsequently isolated from the main reservoir as water levels recede, forming natural, shallow water habitats. These environments are ideal foraging sites for various waterbirds, such as wagtails, tattlers, stilts, egrets, and sandpipers, due to the abundance of invertebrates like flies, caterpillars, worms, snails, and crustaceans in the soft mud. These organisms promote aquatic vegetation growth, attracting more invertebrates and small prey, which are crucial for the diet of waterbirds. Additionally, we recommend the removal of recently planted trees on the northern fringes of the Miyun Reservoir to enhance accessibility for a broader range of waterbirds.

4.3. Implications of Reservoir Management for Global Bird Conservation

Reservoirs are large wetlands around cities. Managers of reservoirs should balance water management and wetland management. The ecological function of wetlands in reservoirs should be enhanced while ensuring the safety of water resources. In particular, species protection of the reservoir's rare and endangered representative species should be incorporated into the management objectives. Our study advocates for an integrated approach in which reservoir water level management is optimized to expose larger areas of drawdown zones during migration seasons. We anticipate that this management strategy will increase the availability of wetlands and food resources, thus better catering to the needs of migratory bird species [46]. This method aligns with the objectives of biodiversity conservation and wetland restoration and presents a practical, scalable solution using existing infrastructure [47]. The broader implication of this research is the potential role of coordinated reservoir management as a crucial intervention in habitat provision, significantly contributing to global bird conservation efforts. This strategy goes beyond mere habitat protection for migratory birds. It aims to enhance the overall health and functionality of wetland ecosystems, resulting in widespread environmental and socioeconomic benefits [48]. This holistic approach emphasizes the interdependence of ecosystem management and biodiversity conservation, calling for integrated, evidence-based policymaking in ecological stewardship [49].

5. Conclusions

This research focused on the white-naped cranes (*Antigone vipio*) inhabiting the Miyun Reservoir in Beijing as a model species to assess the impact of reservoir water level fluctuations on migratory waterfowl habitat utilization. We conducted a detailed analysis of the water area from 2000 to 2021, utilizing annual measurements and extending this observation monthly from 2018 to 2023 through satellite data. Additionally, we tracked the movement and habitat preferences of 32 cranes outfitted with GSM-GPS loggers, providing position data at 10 min intervals. Our findings underline the significant influence of inundation areas in the reservoir on the habitat selection of white-naped cranes. Notably, the observed decrease in suitable habitats for migratory birds within the reservoir is not predominantly due to conventional human activities, such as land reclamation. Instead, it is primarily associated with the high-water level management strategies employed within the reservoir. These insights suggest a potential need for reservoir management to reconsider and adapt their water level control strategies to better accommodate the habitat requirements of migratory waterbirds. Such adaptations may involve creating and maintaining areas that are more conducive to supporting waterbird populations. The results of this study highlight the intricate relationship between changes in reservoir water levels and the sustainability of habitats critical for waterbirds and their migratory patterns. Crucially, our research underscores the broader ecological value of reservoir ecosystems. It suggests that, beyond their primary function in water storage and provision, reservoirs can be strategically utilized as alternative habitats for a variety of migratory waterfowl species. A critical component of this initiative involves the strategic use of reservoirs. The strategic management of water levels in these reservoirs offers an opportunity to create temporary habitats and food sources for migratory birds, particularly during essential migration periods. This approach could significantly contribute to the conservation of avian biodiversity on a global scale.

Author Contributions: K.Y. conceived the ideas and designed the framework of the study. F.M. and D.G. collected the bird tracking data. K.Y. performed analysis with contributions from Q.M., F.M., D.G. and K.Y. wrote the initial draft of the paper, with substantial editorial input from all authors. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The raw/processed data required to reproduce the above findings cannot be shared at this time as the data also forms part of an ongoing study.

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