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Suitable Habitat Dynamics of Wintering Geese in a Large Floodplain Wetland: Insights from Flood Duration

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Abstract: The relationship between hydrological variation and the habitat use of waterbirds in wetland complexes is a significant field of ecological research. Quantification of the relationships between wetland hydrological attributes and waterbirds distribution is critical for the success of waterbird conservation. In this study, flood duration (FD) derived from synthetic aperture radar (SAR) imagery was combined with geese GPS tracking data to quantify the optimal FD thresholds for identifying geese habitats. Based on the thresholds, we defined the suitable habitats of wintering geese and investigated the difference in the spatial distribution pattern of habitat from 2018 to 2020 in Poyang Lake, China. We also considered the role of sub-lakes in habitat protection. The results showed that the area of suitable habitats for wintering geese decreased in both dry and wet years, and the range of optimal FD threshold was wider in normal years than in both dry and wet years. The proportion of suitable habitats per unit area was greater in the sub-lakes than in the whole Poyang Lake. We concluded that FD indices extracted from SAR data are valuable for reflecting the influence of the pattern of hydrological variation on waterbird distribution and for the protection and rational use of wetland ecosystems.

Keywords: habitat; flood duration; synthetic aperture radar (SAR); GPS satellite tracking; distribution probability; herbivorous goose

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Citation: Teng, J.; Yu, X.; Xia, S.; Liu, Y. Suitable Habitat Dynamics of Wintering Geese in a Large Floodplain Wetland: Insights from Flood Duration. *Remote Sens.* **2022**, *14*, 952. https://doi.org/10.3390/rs14040952

Academic Editors: Li Wen, Guangchun Lei and Deepak R. Mishra

Received: 20 December 2021
Accepted: 14 February 2022
Published: 16 February 2022

1. Introduction

Seasonal hydrological variations are the driving factor of ecosystem structure and function in large floodplain wetlands [1–4], through their influences on vegetation colonization and growth, which ultimately affect the distribution patterns of herbivorous waterbird habitats [5,6]. Hydrological conditions in the wet season will also have an effect on the plant growth process in the dry season by affecting the soil moisture and determining the wet meadow exposure timing [7,8]. These hysteretic effects will finally have an effect on the availability and quality of food for herbivorous waterbirds. The continuing hydrological changes through wet/dry cycling can be characterized by the flood duration [9–13]. Nevertheless, how the flood duration affects the wintering geese habitats and how to quantify the relationship between them are still unclear. An improved understanding is needed for the effective conservation of wintering geese and wise use of wetlands.

Since seasonal hydrological variation is highly dynamic, the lack of high-frequency data hinders the predictive understanding in the study of wetland ecology [1,14]. Although hydrological variations may be derived from gauge records of hydrological stations [6], accurately capturing the spatial distribution of hydrological variation is still a challenge [7,15]. Satellite-based remote-sensing techniques, such as the Landsat-8 OLI (multispectral instrument), are widely used for surface-water identification and mapping [16,17]. However, their potentials in quantifying the flood extent, duration, and frequency are often hampered by the low temporal resolution and irregularity due to weather conditions [18]. In contrast to passive optical systems, the major advantage of active microwave monitoring techniques such as synthetic aperture radar (SAR) is that they are cloud-proof and illumination-independent and can therefore provide reliable information of the surface-water occurrence [19]. In addition, the Google Earth Engine (GEE) platform provides a high computational capacity to process and analyze large-scale and high-resolution SAR images, enabling their wide applications in monitoring the surfaces of the Earth, such as topography, oceanography, glaciology, and geology [20,21].

Waterbirds are fast-moving mobile animals. Accurate occurrence data are the foundation for studying their distribution and habitat-selection mechanisms, and the fine details of their locations in landscape have important management relevance [22]. Although traditional field survey data are still commonly used in studies on animal movement ecology, these data lack spatial accuracy and temporal resolution due to limited manpower and unreachable areas [23]. GPS tracking data can save time and effort to obtain high-frequency and high-precision bird location information compared to traditional field survey data [24], and have dramatically expanded in the recent past decade, resulting in unprecedent insights into avian ecology, especially in understanding how animals interact with and respond to variation in their environmen [21].

Poyang Lake, the largest freshwater lake in China, provides rich food resources and suitable habitats for large numbers of wintering geese along the East Asian–Australian flyway [25]. In recent years, there have been frequent extreme hydrologic events, such as droughts or floods, due to climate change and human activities (such as the Three Gorges Dam) [26–28]. Droughts and floods cause abnormal hydrological conditions, with early or late water-level recession, which has been demonstrated to severely affect the growth of food for herbivorous waterbirds [5,29,30]. Given these circumstances, quantifying the relationships between flood duration and geese distribution appears to be vitally important in species conservation and habitat management.

The alternating wet and dry seasons and topographic heterogeneity caused by many sub-lakes of Poyang Lake, providing suitable habitats for waterbirds [31]. In the past, drying and draining for fishing in the sub-lakes in the dry season had a negative impact on wintering waterbirds [31,32]. The Yangtze River fishing ban was implemented in Poyang Lake in 2020, but the impact on waterfowls after the ban is still unclear. Analyzing the contribution of sub-lakes will provide scientific support for hydrological management.

This study aims to develop a hydrological indicator, flood duration (FD), using SAR data to assess the habitat suitability for wintering geese. The GPS tracking data of wintering geese have been coupled with the FD to obtain the optimal flood-duration threshold. Based on the threshold, we analyzed the response of geese to different flood durations and estimated the distribution of suitable habitats in the Poyang Lake from 2018 to 2020. Finally, we analyzed the proportion of suitable habitat per unit area of sub-lakes and the whole Poyang Lake.

2. Materials and Methods

2.1. Study Area

Poyang Lake (29°03′N, 116°16′E), located on the south bank of the middle and lower reaches of the Yangtze River, is the largest freshwater lake in China(Figure 1). It is currently one of only two lakes in the middle and lower reaches of the Yangtze River that naturally feed into it. Poyang Lake is characterized by a low gradient of 0.1° and shallow water (with an average water depth of 8.4 m) and low subsidence rate [33]. Poyang Lake is divided geographically into two parts by Songmen mountain: the south is large and shallow, and the north outlet is narrow and deep [34]. The five main tributaries (Ganjiang River, Fuhe River, Xiushui River, Xinjiang, and Rao River) and rainfall are the main water sources of the lake [35]. The local climate is affected by the monsoon, which is warm and humid, and the average annual precipitation is 1450–1550 mm [36]. The highest water levels generally range from approximately 18 to 21 m during the wet season (June to August), and the lowest levels usually range from 9 to 11 m during the dry season (November to January) [37].

The water level of Poyang Lake rises from April, usually peaks in August, and typically recedes from early September, exposing the lakebed to vegetation colonization, and forming sub-lakes (i.e., hydrologically disconnected waterbodies) in late October [38–40]. Sub-lakes are independent lakes under the influence of seasonal hydrological variation during the dry season and are of great significance to wintering waterbirds, which rely on wet meadows and mudflats [41].

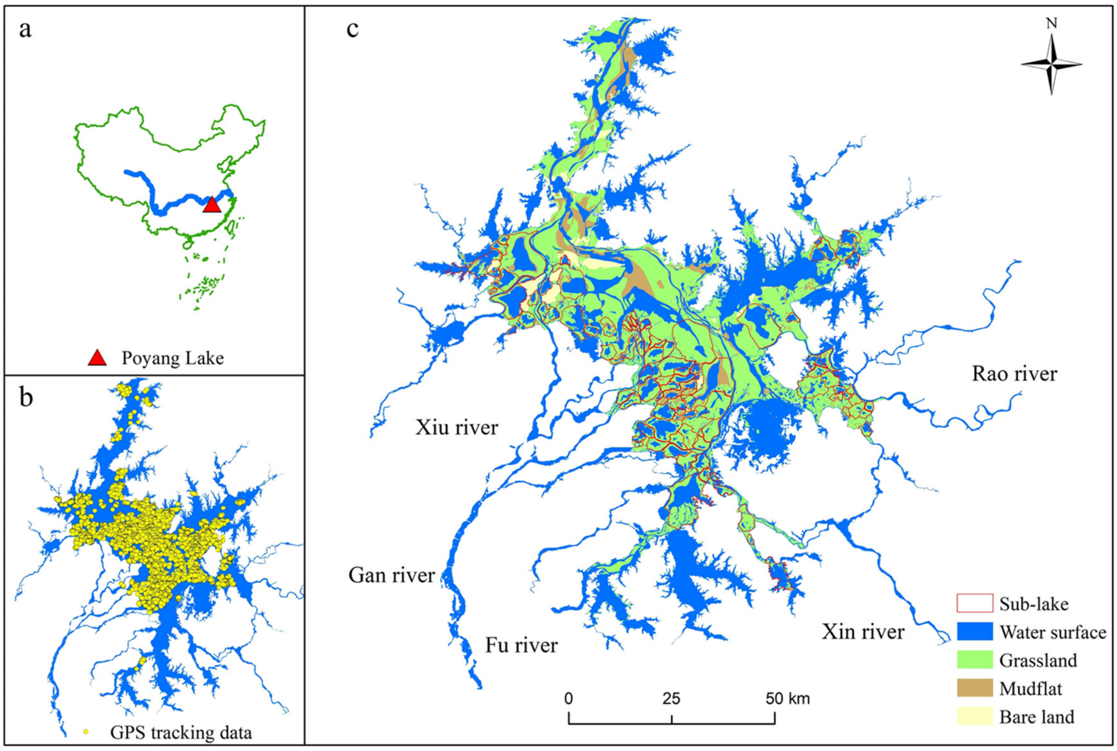

Figure 1. (**a**) Location of the study area. (**b**) GPS tracking data in Poyang Lake. (**c**) The land use/cover was interpreted from Sentinel-2 in the winter of 2019.

2.2. Data

2.2.1. GPS Tracking Data

GPS tracking provides high-frequency and precise monitoring data of goose distribution dynamics. Greater white-fronted geese (Anser albifrons), the dominant anatid species at Poyang Lake, were captured without causing injury or harm from 2018 to 2020. Firstly, the geese were captured without causing injury or harm through the maze tool and fitted with GPS transmitters (produced by Hunan Global Messenger Technology Company, Xiangtan, China). The weight of the transmitters is less than 3% of the body weight of geese, which avoids impacting the normal activities of the geese. Then, the transmitter number and transmitter for geese was installed. The geese were released after confirming that their activities were normal and in good condition (Figure 2).

The GPS transmitters received the location latitude and longitude, speed, heading, altitude, and other information for the waterbirds every hour. GPS data require a series of pretreatments before analysis [6]. GPS data were collected if the following conditions were met: (1) it is inside the Poyang Lake wetland boundary; (2) the speed is 0; (3) the accuracy level of the satellite data was divided into 5 levels: A (5 m), B (10 m), C (20 m), D (100 m), E (2000 m), and invalid data. The data with an accuracy greater than grade C is selected (Figure 3). Finally, we grouped the GPS data according to "Year" attributes (2018, 2019, and 2020). The research used 42 GPS transmitters in 2018, 30 in 2019, and 16 in 2020.

Figure 2. GPS transmitters installation process.

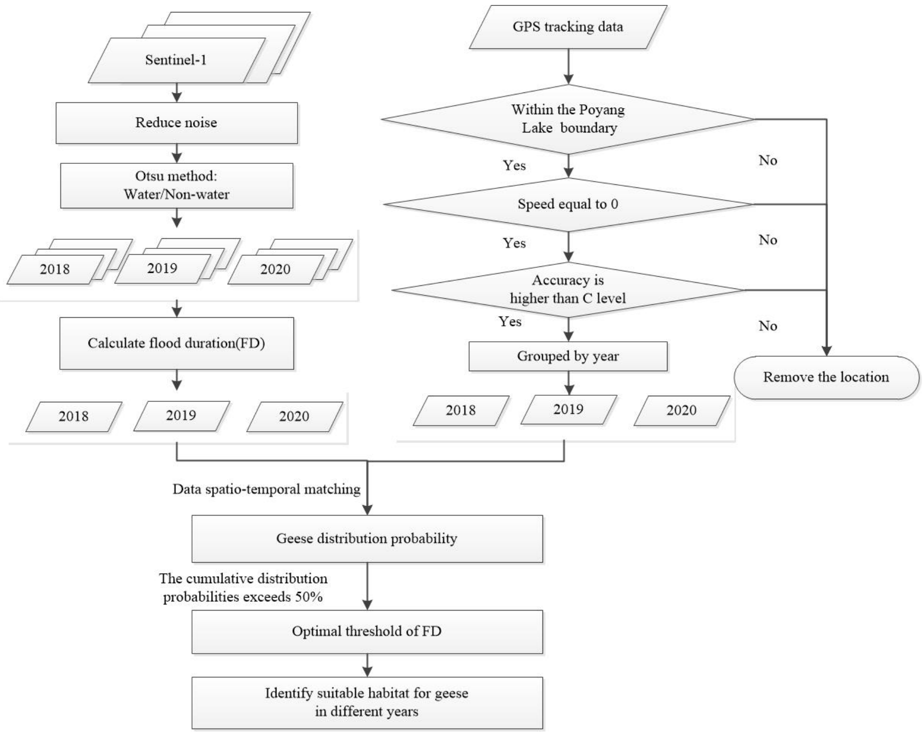

Figure 3. Method workflow.

2.2.2. Synthetic Aperture Radar Data

Synthetic aperture radar (SAR) is an active earth-observation system. SAR can receive microwave signals emitted and reflected by various ground objects [42]. One of its advantages over other systems is that the active transmission signal and the passive reception signal are not dependent on light, which means that it can be observed 24 h a day and is not affected by the weather. Sentinel-1 of the European Space Agency (ESA) consists of two satellites, Sentinel-1A and Sentinel-1B, which have a 6-day repeat orbit cycle. SAR data can effectively detect water bodies through vertical transmission and vertical reception (VV) or vertical transmission and horizontal reception (VH) polarization [43], thereby distinguishing water bodies from land and mapping flooded wetlands [44].

2.3. Method

2.3.1. Flood Duration Index

We used the VV polarization data of Sentinel-1 in GEE from January 2018 to December 2020 for calculation and analysis [45]. The following steps are required to generate FD (Figure 3):

1. Reduce noise. SAR images usually have speckle noise, which reduces the image quality. This study used a median filter to reduce noises, which is a convenient and effective method [18]. This method was applied in each SAR image to view each pixel and its neighbors and took the median value to remove noise at small and medium scales.

2. Water surface extraction. We used the Otsu method to divide the study area into two types (water and non-water). This method separates water and non-water without samples using the image histogram to automatically select the threshold between water and non-water [44,46]. The between-class variance at a certain threshold is calculated, and the optimal threshold is automatically selected to maximize the variance between classes. The equation is as follows:

$$n(k^*) = \max_{1 \le k \le n} \frac{\omega_0(k)\omega_1(k)[\mu_0(k) - \mu_1(k)]^2}{\delta^2}, \quad (1)$$

where k^* is the best threshold to distinguish between water and non-water; $\omega_0(k)$ and $\omega_1(k)$ are the probabilities of being divided into a water body and non-water body, respectively, by the threshold k; $\mu_0(k)$ and $\mu_1(k)$ are the average values of water and non-water bodies at k; and δ^2 is the total variance.

3. FD calculation. The water or non-water pixels were set to 1 or 0, respectively. The annual data is accumulated to obtain total number of waters per pixels. The flood duration was calculated by Equation (2).

$$FD = TNW \times t, \quad (2)$$

where FD is the flood duration per raster; TNW is total number of waters per pixels; t is time interval of Sentinel-1 (6 days). Finally, the distribution of the FD in 2018, 2019, and 2020 was generated. The above calculations were all made on the GEE platform.

2.3.2. Geese Distribution Probability

The sizes of the GPS locations datasets in 2018, 2019, and 2020 are as follows 19,084, 14,700, and 5177 points(95% confidence intervals in Table S1). To clear up trouble from different sizes of datasets, 80% of datasets (4000 GPS points) of the smallest dataset (2020 data set) were randomly selected from the annual data set. The proportion of GPS points corresponding to different FD was counted to obtain the geese distribution probability. This process was repeated 1000 times to avoid sample bias [47,48], and then the average values were taken as the results.

2.3.3. Identification of Suitable Habitat

The higher the geese distribution probability, the better the habitat. We regard that the optimal threshold of the flood duration index is around the highest distribution probability. The threshold that cumulative distribution probabilities (CDP hereafter) of the geese on both sides of the highest distribution probability exceed 50% (Table 1) was found as the optimal threshold of FD. Poyang wetland was classified into two types based on the optimal threshold: suitable habitats (CDP over 50%) and unsuitable habitats (others) [49].

Table 1. Habitat classifications and cumulative distribution probabilities for wintering geese at Poyang Lake.

Type	The Cumulative Distribution Probabilities (CDP)
Suitable habitats	CDP Exceeds 50%
Unsuitable habitats	Others

3. Results

3.1. Flood Duration Index

Using the GEE platform, the water surface distribution of Poyang Lake was extracted, and the water area of each scene within the Poyang Lake wetland was calculated (Figure 4). From 2018 to 2020, there were 187 scenes of water surface distribution data. In 2018, the maximum water surface area was 3115 km^2. In 2019, the maximum area was 3817 km^2. The maximum area for 2020 was 3941 km^2 (Table 2). For this study, we defined 2018 as a dry year, 2019 as a normal year, and 2020 as a wet year according to their average annual water level and maximum water area.

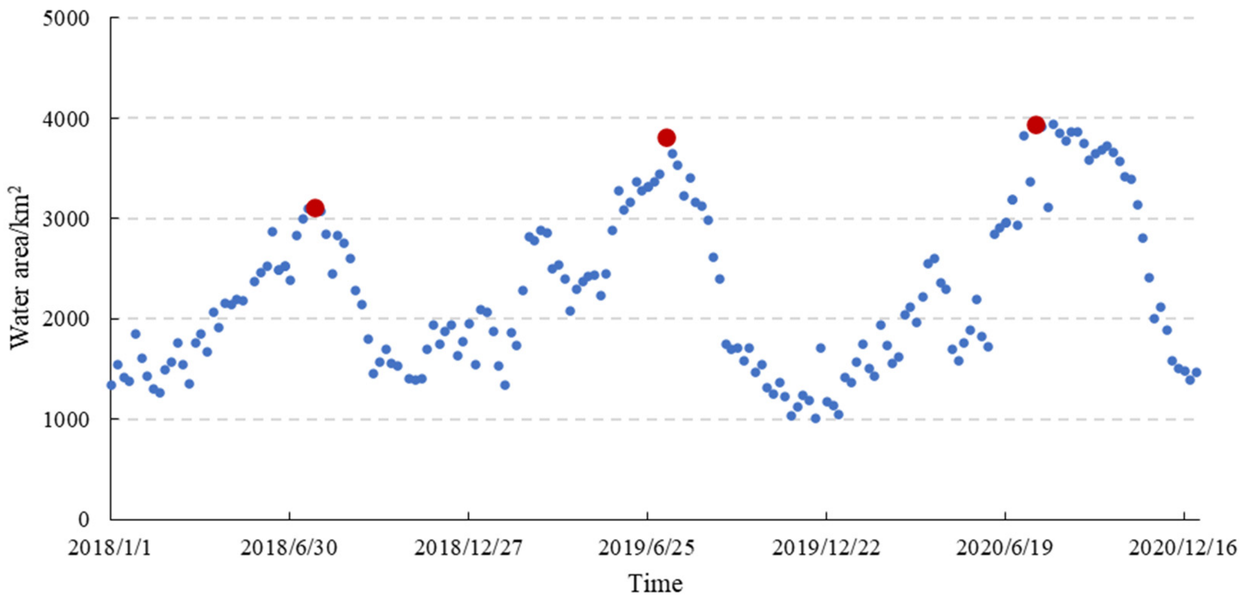

Figure 4. Time series of water surface area for Poyang Lake from 2018 to 2020.

Table 2. Maximum and minimum water body and inundation areas and dates from 2018 to 2020 at Poyang Lake.

Year	Maximum Waterbody Area	Corresponding Date	Minimum Waterbody Area	Corresponding Date	Inundation Areas
2018	3115 km^2	July 25	1266 km^2	February 19	1849 km^2
2019	3817 km^2	July 14	1005 km^2	December 11	2811 km^2
2020	3941 km^2	July 20	1365 km^2	January 16	2576 km^2

Inundation areas were the difference between the maximum and minimum water surface areas. The year 2019 (the normal year) had the largest inundation areas, followed by 2020 (the wet year) and 2018 (the dry year). Therefore, the maximum water area appeared in 2020 (3941 km^2), while the largest inundation areas that may provide potential habitats for geese appeared in 2019.

A comparison of the spatial changes of the FD between 2019 (the normal years) and 2018 (the dry year) indicates that the area for which the FD increased was 2980 km^2 (from 2018 to 2019). For the period of 2019 to 2020, the area for which the FD was reduced by 2153 km^2 (Figure 5).

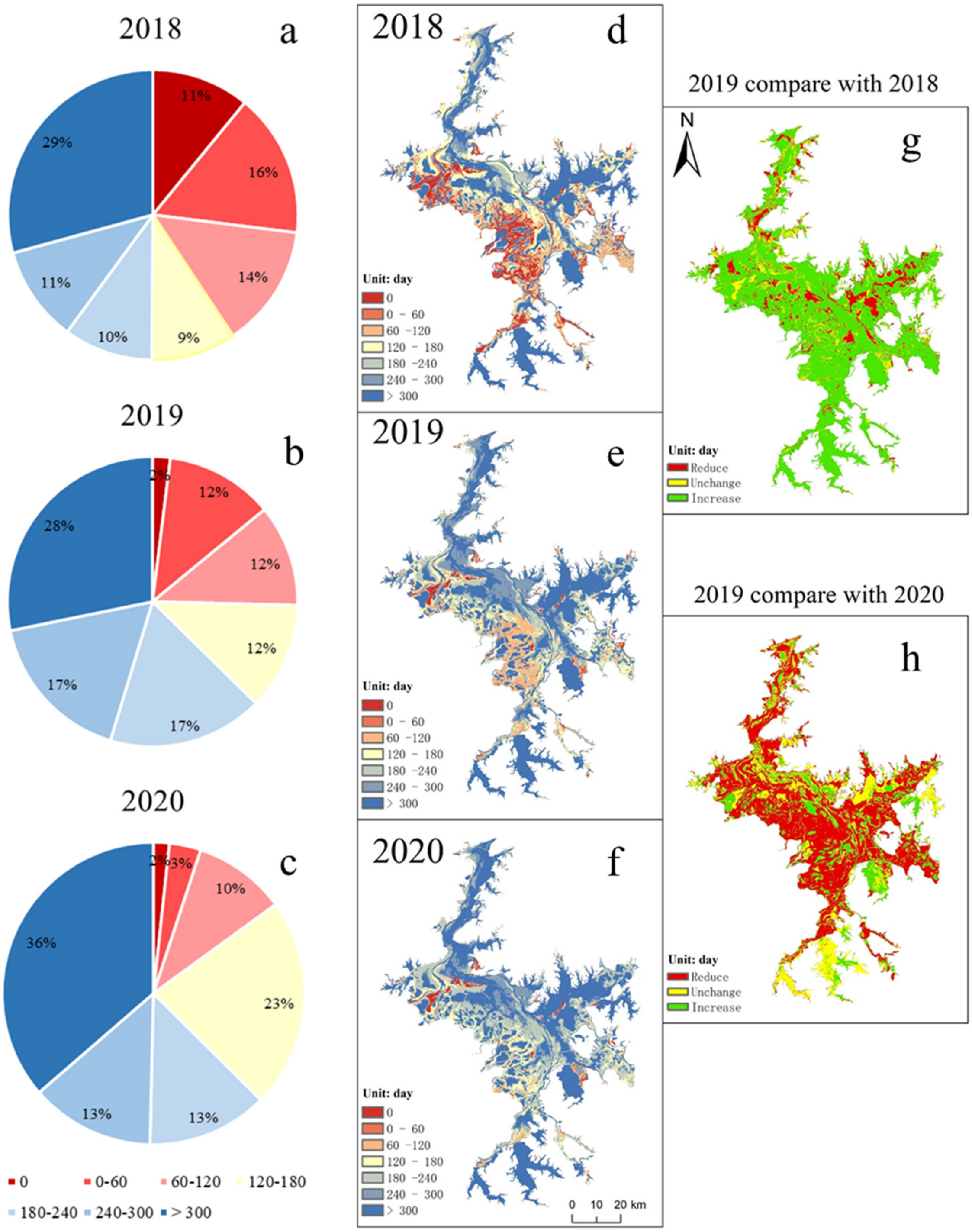

Figure 5. (**a**–**c**) Areas of different flood duration (FD) values (percentage) for 2018 to 2020. (**d**–**f**) Spatiotemporal distribution of the FD from 2018 to 2020. (**g**) FD spatiotemporal pattern changes from 2018 to 2019. (**h**) FD spatiotemporal pattern changes from 2019 to 2020.

3.2. Response of Geese to Flood Duration Changes

The FD corresponding to the highest goose distribution probability and CDP of more than 50% is shown in Figure 6 for 2018, 2019, and 2020.

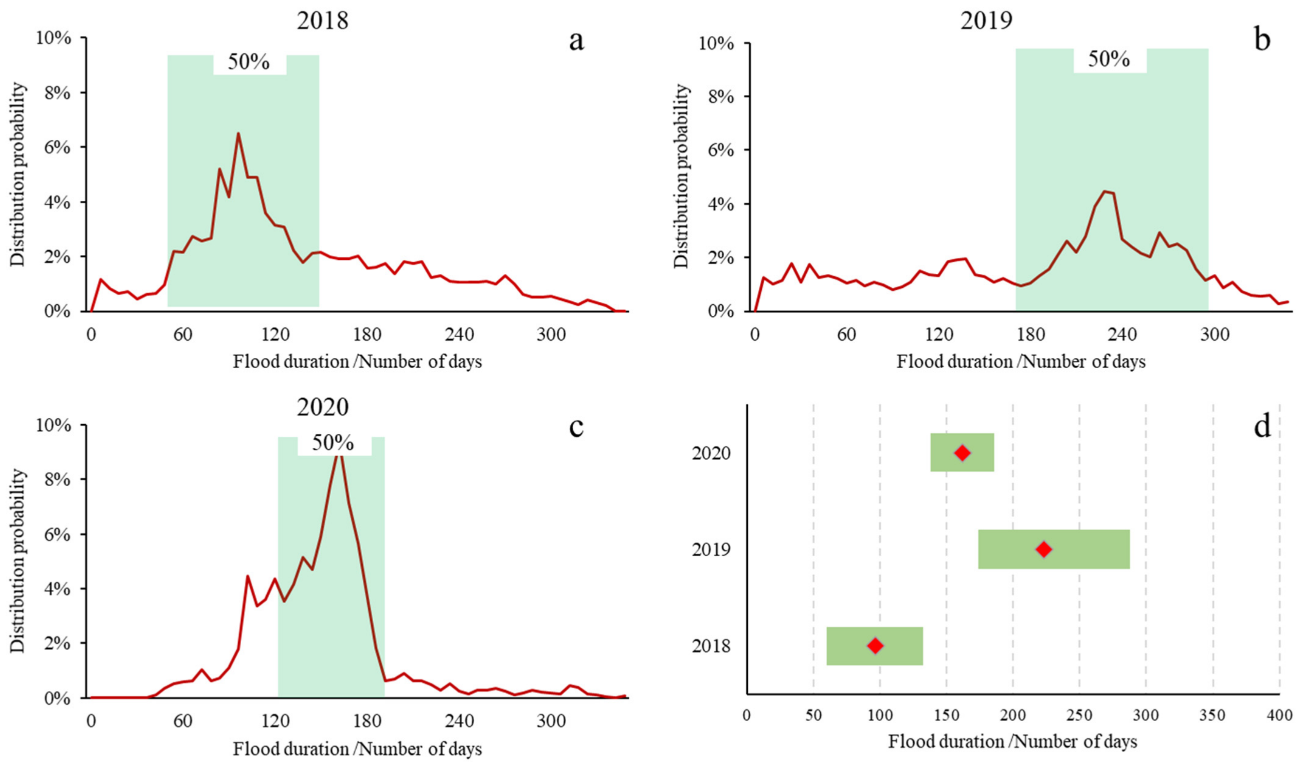

Figure 6. (**a**–**c**) The goose distribution probability and their corresponding flood duration at Poyang Lake from 2018 to 2020. (**d**) The optimal threshold of flood duration and the highest distribution probability for 2018, 2019, and 2020 (Green colored part: the optimal threshold of the flood duration index. Red square symbol: the highest distribution probability).

According to the analysis (Table 3), the highest distribution probability of geese in 2020 (Figure 6c) is 9.36%; in 2018 (Figure 6a) and 2019 (Figure 6b), it is 6.52% and 4.45%, respectively. In 2019, the variation in CDP of more than 50% was the highest, followed by 2018 and 2020. This means that wintering geese are more flexible in a normal year, while their flood duration threshold may shrink in dry or wet years. Compared to the dry year, flood durations will become narrower in wet years.

Table 3. Response threshold of geese to flood duration (FD) in different hydrological years.

Year	The Highest Distribution Probability		CDP > 50%	
	The Highest Probability	**Flood Duration Range**	**Variation**	**Flood Duration Range**
2018	6.52%	96	60–132	72
2019	4.45%	223	174–288	114
2020	9.36%	162	138–186	48

CDP = cumulative distribution probability.

3.3. Temporal and Spatial Pattern Changes of Habitats

Based on the optimal threshold of FD, the suitable habitats (CDP > 50%) from 2018 to 2020 were mapped (Figure 7). The largest area of suitable habitats, 1331 km^2, occurred in 2019. In 2020 and 2018, the corresponding values were 764 km^2 and 714 km^2, respectively. From the spatial distribution presented in 2019 (Figure 7e), it is clear that the suitable habitats were distributed not only in sub-lake but also in other areas. In 2018 or 2020 (Figure 7d,f), suitable habitats were more concentrated in the sub-lakes. From 2018 to 2019, the area by which the goose distribution probability increased was the largest (Figure 7g), 1971 km^2. From 2019 to 2020, the area by which the distribution probability of geese decreased was the largest at 1441 km^2.

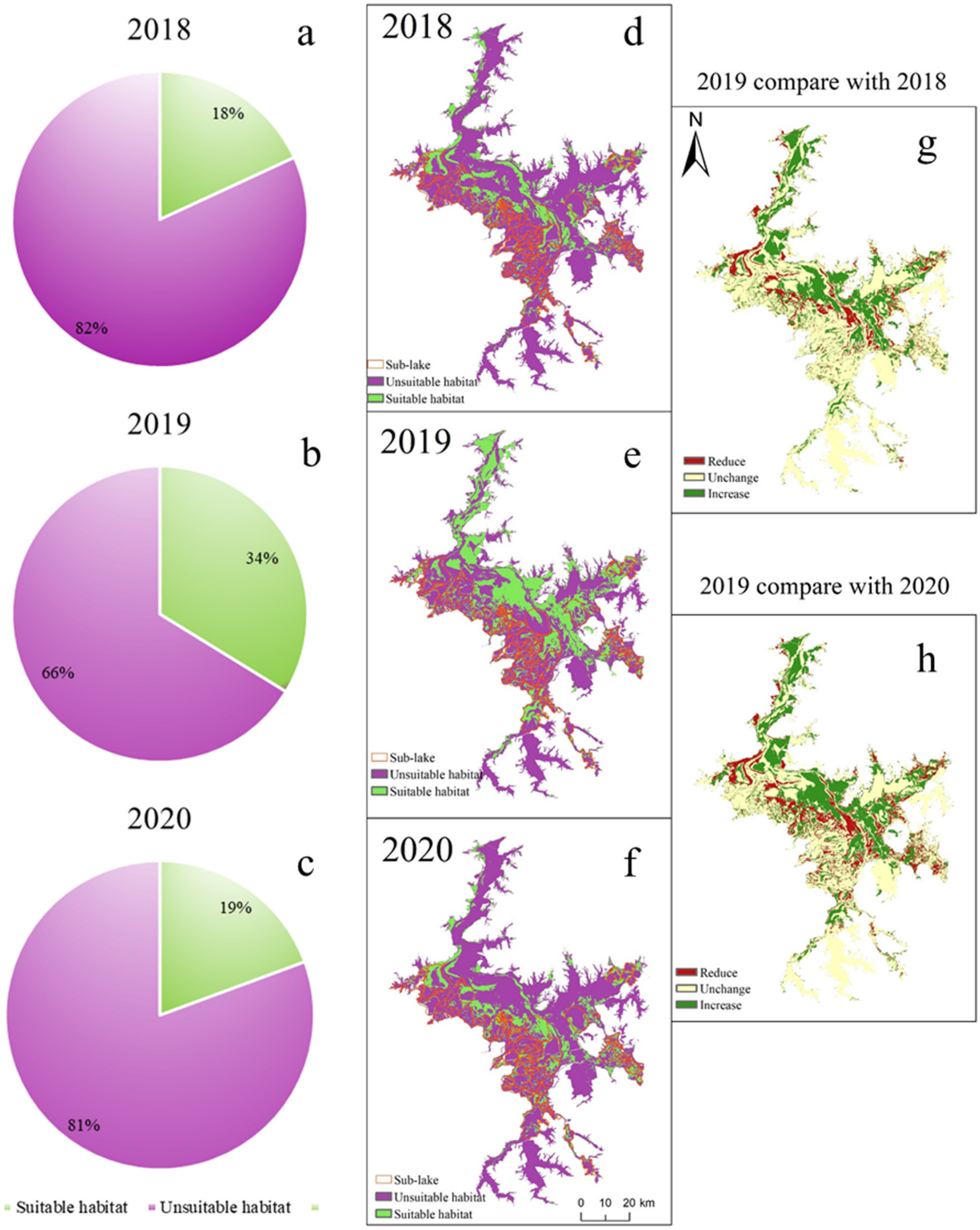

Figure 7. (**a**–**c**) Percentage of suitable habitat area for 2018 to 2020. (**d**–**f**) Spatiotemporal distribution of the suitable habitat from 2018 to 2020. (**g**) Suitable habitat spatiotemporal pattern changes from 2018 to 2019. (**h**) Suitable habitat spatiotemporal pattern changes from 2019 to 2020.

3.4. Importance of Sub-Lakes under Different Hydrological Conditions

The suitable habitats of the sub-lakes were the largest in 2019, with an area of 320 km^2. In 2020, these habitats had an area of 298 km^2. The area of suitable habitat was the smallest in 2018, when the area was only 225 km^2.

There were 110 sub-lake boundary areas with an area of 1140 km^2, and the whole lake (Poyang Lake) area was 3941 km^2. This research counted the proportion of suitable habitats per unit area to avoid the impact of differences in areas. Although the maximum suitable area of sub-lake was distributed in 2019 (Figure 8a), the proportion of suitable habitats per unit area was smaller than that of the whole lake. The proportion of suitable habitats per unit area was greater in the sub-lakes than in the whole lake in 2018 and 2020 (Figure 8b).

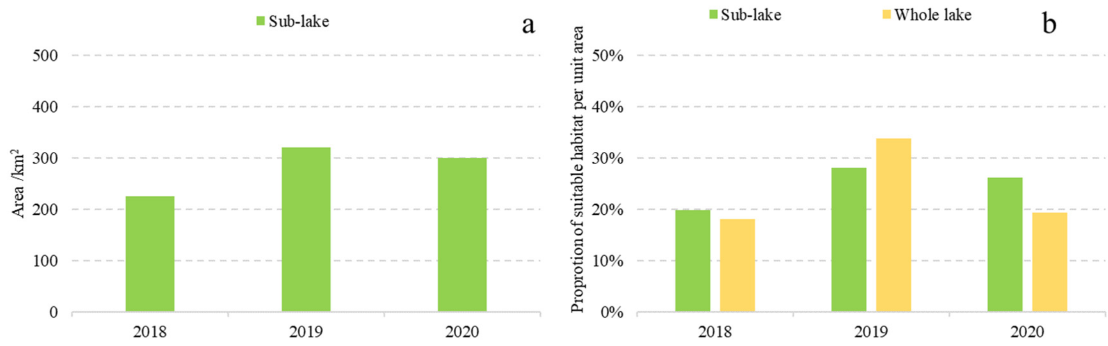

Figure 8. (**a**) Area of suitable sub-lakes habitat in 2018–2020 at Poyang Lake. (**b**) The proportion of suitable habitats per unit area of the sub-lakes and the whole lake in 2018–2020.

4. Discussion

4.1. Characteristics and Application of the Flood Duration

The habitat use of wetland waterbirds is affected by hydrological variation [14], especially the flood duration, the requirements of waterbirds for specific resources, or their different life-history stages [50]. Using the hydrological model [7] or mapping the spatial pattern of the inundation area [51,52] has been proposed to predict the distribution of suitable habitats in the study area.

The estimation FD used here is based on the GEE platform and calculated using SAR data (6 days/scene, 10 m resolution) [19,43]. The calculation efficiency and the analysis of the hydrological condition data in Poyang Lake can be completed in an efficient and convenient manner [53]. During the period of low water levels, the analysis of the sub-lakes was limited by the site-based hydrological data [31]. SAR remote-sensing monitoring can reflect the actual water surface distribution of sub-lakes, providing a significant method for studying changes in the temporal and spatial hydrological patterns of Poyang Lake.

The flood duration is mainly affected by the hydrology and topography [7] and can reflect the temporal and spatial hydrological conditions of wetlands throughout the whole year. Thus, the quantification of this indicator is very useful in floodplain areas such as Poyang Lake, where wetland functions and processes are very complicated [38]. Furthermore, the data for the final year of this study may reflect the effects of the Poyang Lake fishing ban policy implemented in 2020, which increased the flood duration of sub-lakes [32].

4.2. Responses of Geese to Hydrological Variation

Hydrological variation is the main driving force of wetland vegetation colonization [54]. In particular, *Carex* spp. [55], the main food source for wintering geese [56], is very sensitive to hydrological conditions. This study analyzed the response characteristics of wintering geese to wet, dry, and normal years. Analysis of the relationship between the distribution probability of geese and the FD shows that the threshold range of the index was larger in normal years and was smaller in dry and wet years.

Based on the threshold of the FD, the habitat patterns of geese in different hydrological years were predicted. In 2019 (a normal year), the FD threshold range and the area of suitable habitat was the largest. This finding is supported by previous studies [7,57]. They simulated the suitability of migratory bird habitat in Poyang Lake and found that the proportion of suitable habitat was higher in normal years. This is likely because the hydrological conditions were suitable, allowing the geese to inhabit a larger space [57,58]. Geese can choose to feed on vegetation in its early growth stages with high palatability [47].

In 2018 and 2020, the area of suitable habitat was smaller than that in 2019. Some scholars also demonstrated that the abundance of waterbirds is influenced by the occurrence of floods and droughts by constructing the categories vulnerability index [59]. Unsuitable hydrological features (dry, wet) can result in great variations in vegetation quantity and quality. At the same time, there are phenological mismatches in the research findings caused by unsuitable hydrological conditions which can explain the population variation of the goose [60]. This study also verifies the result from the side. In 2018, which was a dry year, there was early water recession due to early exposure of the meadow lakebed, with high food quantity and low food quality for geese [2,5]. The high water level in 2020 may indicate an insufficient food supply [2]. The above factors will limit the habitat of wintering geese, as only specific flooded areas can meet the habitat requirements of the geese. Finally, the threshold range of the FD decreases smaller and declines in the area of suitable habitat.

The average water level of Xingzi station in Poyang Lake from 1990 to 2020 is 13.17 m, while those in 2018, 2019, and 2020 are 11.91 m, 12.84 m, and 13.91 m, respectively, which shows that they are certainly representative in wet, normal, and dry years. However, GPS data are difficult to obtain in long time-series due to a technical bottleneck; only three years of data were obtained. It is also mentioned that the dry/wet years are relatively defined in this study and it is not typically a “dry and wet year” in term of hydrological concept. Methodological innovations, adequate field study, and more systematic research and model simulation are needed in the future.

4.3. Conservation Implication

The hydrological conditions of the normal year were optimal, while they were the opposite in the dry and wet years. The extent of seasonal inundation areas will decrease at both low and high water levels, which may lead to a decrease in available habitats [61]. The shrinking range of geese in dry and wet years implied that geese may face more challenges of food shortages. Due to the terrain and human activities, sub-lakes provide higher landscape heterogeneity in the dry season, which plays a positive role in the habitat maintenance of wintering migratory birds [39,61]. The results also showed that the proportion of suitable habitats per unit area was greater in the sub-lakes than that in the other areas both in dry and wet year. This means the sub lakes have greater regulation flexibility for wintering waterbirds in Poyang Lake in extreme climates, such as less precipitation and a high rate of evaporation in dry years. Therefore, managers in protected areas can jointly regulate the water level of different sub-lakes according to the requirements of wintering geese, for example, making water level management plans for different sub-lakes, and controlling the water discharge of each sub-lake according to the carrying capacity requirements of wintering waterbirds to ensure more effective foraging habitats for overwintering waterbirds in dry years.

5. Conclusions

The flood duration, derived from SAR data, was used to analyze the suitable habitats for wintering geese in China’s largest freshwater lake. The results showed that the distribution of geese in normal years was more flexible, which may be related to the larger inundation areas in normal years, while their distribution in dry years and wet years was more concentrated. Suitable habitats were more abundant in a normal year, with an area of 1331 km^2, and smaller in dry and wet years, with areas of 714 km^2 and 764 km^2, respectively. The sub-lakes played a more important role in wet and dry years, with the proportion of suitable habitats per unit area being higher than that of the whole lake. The results of this study indicate that FD based on remote sensing data is a valuable tool for investigating the role of spatial and temporal changes in hydrology in waterbirds, and for the wise use and protection of wetlands.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs14040952/s1, Table S1: 95% confidence intervals for FDs extracted from GPS data in 2018, 2019, and 2020.

Author Contributions: Conceptualization, J.T.; Investigation, J.T. and S.X.; Writing—original draft, J.T. and S.X.; Writing—review & editing, X.Y., S.X. and Y.L.; Funding acquisition, X.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (Grant Nos. 4217011443; 41971133), Strategic Priority Research Program of the Chinese Academy of Science, China (Grant No. XDA23040203) and Department of Water Resources of Jiangxi Province, PRC.

Data Availability Statement: Not available.

Conflicts of Interest: The authors declare no conflict of interest.

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