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Landscape Pattern Changes of Aquatic Vegetation Communities and Their Response to Hydrological Processes in Poyang Lake, China

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Abstract: Hydrology is an important environmental factor for the evolution of wetland landscape patterns. In the past 20 years, Poyang Lake, the largest freshwater lake in China, has experienced significant inundation shrinkage and water level decrease, posing a significant threat to the local vegetation community. To explore the potential relationship between aquatic vegetation and hydrological processes in the recent hydrological situation, in this study, the landscape patterns of aquatic vegetation communities in Poyang Lake were studied using time-series Landsat remote sensing images and a support vector machine classifier. The stepwise regression analysis method was adopted to analyze the relationship between the vegetation area and hydrological factors. The results indicated that the area of submerged and emergent vegetation in the entire lake decreased significantly from 2001 to 2017, whereas the area of moist vegetation showed a remarkably increasing trend. The average distribution elevation of the submerged vegetation increased by 0.06 m per year. The corresponding landscape patterns showed that the degree of fragmentation of aquatic vegetation communities in Poyang Lake increased. Several hydrological factors were selected to quantify the potential impact of water level fluctuations. The correlation analysis results indicated that hydrological conditions during the rising- and high-water periods may be the key factors affecting the area of aquatic vegetation. This study systematically investigated the evolution of vegetation communities in Poyang Lake wetlands over the past two decades, which contributes to the protection and management of this unique ecosystem.

Keywords: wetland vegetation; remote sensing; supervised classification; landscape pattern; hydrological factors

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1. Introduction

Wetland vegetation is an important part of wetland ecosystems and has rich ecological functions such as reducing flow erosion, preserving species diversity, maintaining ecological corridors, and purifying water [1–5]. Wetland vegetation is also an excellent indicator of habitat quality [6,7]. Even the smallest wetland vegetation communities reflect changes in the quantity and composition of the wetland environment [8–10].

The hydrological processes in the wetland play an important role in the distribution and structure of aquatic vegetation communities, as water could provide the basic elements required for vegetation growth. However, both excessive and insufficient water could both inhibit vegetation growth [11,12], and there exist complex interactions between vegetation and water flow [13,14]. Different types of vegetation have different water demands, leading to significant differences in their adaptability to hydrological conditions, which are usually reflected in the spatial distribution of vegetation [15]. Water level, water depth, and inundation time are hydrological indicators commonly used in wetland research [16,17]. David [18] suggested that even minor changes in water depth and inundation time may affect the existence of certain vegetation communities.

Poyang Lake is located in a subtropical monsoon climatic region of China. The lake area is dominated by non-zonal wetland vegetation, including 60 formations, most of which are distributed worldwide. The most common formations in the lake area are the Carex, Phalaris, Polygonum, and Phragmites formations [19–21]. Meanwhile, there is an obvious water gradient in the spatial distribution of wetland vegetation, and the distribution shows irregular zonal differentiation along the elevation [22]. The aquatic vegetation communities in Poyang Lake are mainly distributed at elevations below 16 m according to two large-scale scientific investigations in 1983 and 2013 [19,21].

Considering the huge cost of labor and material resources required for large-scale field investigations in the past 50 years, remote sensing technology has been widely used to study changes in wetland land-cover types [23–25]. Han et al. [26] divided the Poyang Lake wetland into sand, vegetation, mudflats, and water based on Landsat remote sensing images and analyzed the multi-year trends of different land-cover types from 1973 to 2013. The vegetation area showed an increasing trend, whereas the mudflat area has decreased significantly since 1984. Chen et al. [27] extracted NDVI time-series data of lake pixels using MODIS images and established a decision tree model for land classification based on flooding time. The lake area was classified into four types: water, mudflats, emergent vegetation, and submerged vegetation. However, the submerged vegetation in their study included both moist and submerged vegetation. Wan et al. [28] employed Landsat images to identify dominant vegetation communities in Poyang Lake and established a biomass estimation model using the random forest method. Unfortunately, most existing studies have focused on land-cover types or vegetation biomass of Poyang Lake during a specific year. Although some studies have considered multi-year changes in vegetation in the lake area, vegetation is usually regarded as a single type, which does not reflect the long-term changes in different aquatic vegetation communities (such as submerged, moist, and emergent vegetation) in Poyang Lake, and previous studies often neglected the long-term spatiotemporal differences in vegetation landscape patterns.

Plenty of studies have discussed the relationship between vegetation communities and hydrological conditions in Poyang Lake. Ye et al. [29] found that the main factor affecting the wetland vegetation area was the lake water level, whereas temperature and water level had a greater impact on vegetation biomass. Zhou et al. [30] found that the area of Carex in Poyang Lake was affected by water level and recession processes, and its spatial pattern was closely related to water level. In low water years, the landscape of Carex was more fragmented. Tan et al. [31] interpreted the vegetation community of Poyang Lake in 2013 based on Landsat8 imagery and explored the relationship between hydrological conditions and wetland vegetation. The results showed that the Carex community preferred the hydrological environment with longer inundation time and larger water depth than the Phragmites community. However, the quantitative effects of hydrological processes on various aquatic vegetation communities remain largely unknown.

The research objectives of this study were as follows: (1) to explore a reasonable method for dividing the wetland vegetation into emergent, moist, and submerged vegetation; (2) to analyze changes in the distribution of aquatic vegetation in Poyang Lake and two national reserves over a long period; and (3) to reveal the relationship between vegetation areas and hydrological factors. An enhanced understanding of the relationships between vegetation communities and hydrological processes can provide a reference for the rational regulation of water levels. It could also be beneficial to quantify the impacts of related projects on wetland vegetation communities, thereby providing a scientific basis for wetland management. Figure 1 shows the flowchart of the study.

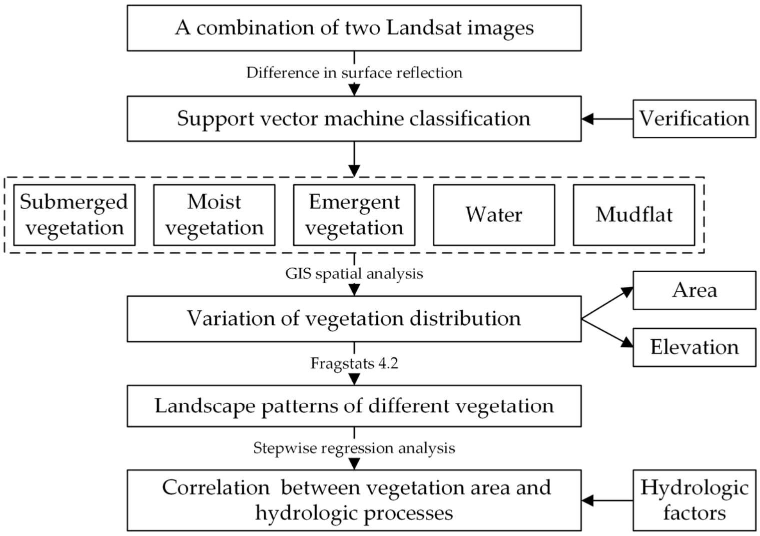


Figure 1. Flowchart of the study.

2. Study Area and Data Sources

2.1. Study Area

Poyang Lake is located on the south bank of the middle and lower reaches of the Yangtze River, and the entire lake is in Jiangxi Province (Figure 2). As the largest freshwater lake in China, Poyang Lake is internationally renowned. The water system of the Poyang Lake Basin is radially distributed and contains five main tributaries: the Ganjiang, Fuhe, Xinjiang, Xiuhe, and Raohe rivers. The upstream runoff flows through Poyang Lake for regulation and storage and finally enters the Yangtze River through the northern waterway.

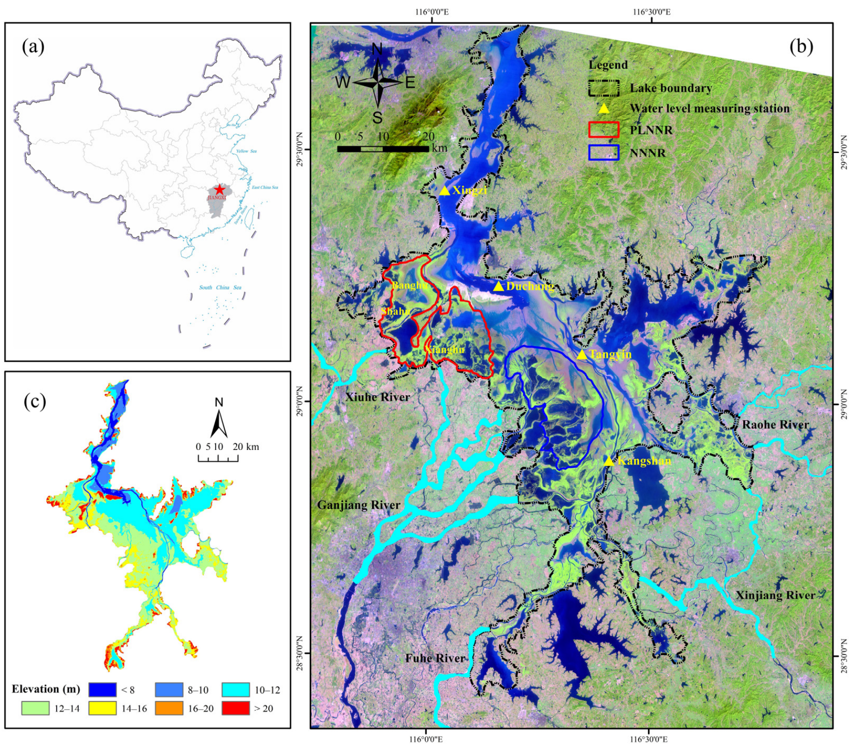


Figure 2. Geographic location and topography of Poyang Lake. (**a**) The location of Poyang Lake on the map of China. (**b**) Overview of the water system in Poyang Lake and the location of two national nature reserves: the Poyang Lake National Nature Reserve (PLNNR) and the Nanjishan National Nature Reserve (NNNR). (**c**) Measured topography of Poyang Lake in 2010.

To better protect this unique wetland ecosystem, the Chinese government established two national nature reserves: the Poyang Lake National Nature Reserve (PLNNR) and the Nanjishan National Nature Reserve (NNNR). The PLNNR is located at the northwestern corner of Poyang Lake (Figure 2b). It was established in 1983 and comprises nine main lakes, including the Banghu and Shahu lakes, with a total area of 224 km^2. The NNNR is situated southwest of Poyang Lake. It was established in 1997 and covers a total area of 333 km^2.

2.2. Lake Morphology

There exist significant morphological differences between the northern and southern parts of Poyang Lake. The southern lake area is the main lake area of Poyang Lake, with flat terrain and shallow water depth. The northern waterway is narrow and long with large topographic changes and deep waters. The overall terrain of the lake basin inclines from south to north. Many beaches are distributed in the southern lake area, with a terrain elevation of 10–16 m, whereas the topographic elevation of the northern waterway is mainly lower than 10 m. During the flood season, the beaches in the main lake area are submerged, and Poyang Lake has a significant lake shape. In the dry season, the water surface area is reduced, beaches are exposed, and water flows downstream through the channel, similar to the characteristics of natural rivers [6].

2.3. Data Sources

In some years, remote sensing images from the dry season were not available for interpreting aquatic vegetation communities in the entire lake area because of high cloud coverage. Therefore, 13 years were selected to study the distribution of different vegetation communities. Table 1 shows the details of the selected images, including the date and the measured water level at Tangyin Station of the later image. Except for in 2001, the water level at Tangyin Station was mostly between 8 and 10 m. The transition zone (bare land) between the moist vegetation community and the water body is visible in these images, which means that the classification results for the dry seasons of different years are comparable. The remote sensing images used for distinguishing different vegetation communities were downloaded from the Geospatial Data Cloud site (Geospatial Data Cloud site. http://www.gscloud.cn, assessed on 10 January 2024) and the United States Geological Survey site (United States Geological Survey site. https://www.usgs.gov/, assessed on 10 January 2024) with a spatial resolution of 30 m.

Table 1. Details of the selected remote sensing image for vegetation classification.

Year	Date from Remote Sensing Images	Water Level at Tangyin Station (m)
2001	2001293 [1] (L5 [2]), 2001325 (L5)	10.91 [3]
2003	2003299 (L5), 2003339 (L7)	8.65
2004	2004286 (L5), 2004334 (L5)	9.95
2006	2006267 (L7), 2006315 (L7)	9.46
2007	2007278 (L5), 2007334 (L7)	8.13
2008	2008289 (L7), 2008345 (L5)	9.98
2009	2009275 (L7), 2009331 (L5)	10.12
2010	2010278 (L7), 2010342 (L7)	9.45
2011	2011281 (L7), 2011329 (L7)	9.98
2013	2013278 (L8), 2013326 (L8)	9.40
2014	2014297 (L8), 2014345 (L8)	9.71
2016	2016271 (L8), 2016351 (L8)	10.03
2017	2017281 (L7), 2017345 (L7)	9.71

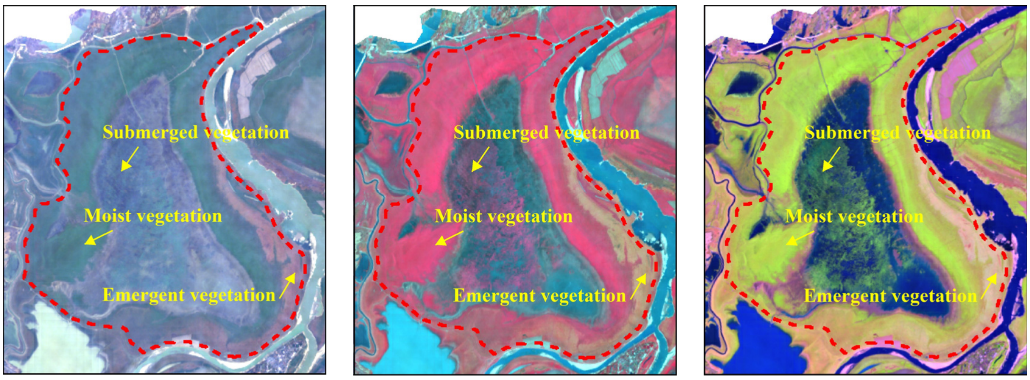
Notes: [1] The first four digits of the number refer to the year, and the last three digits refer to the number of days in the corresponding year. [2] L5 represents Landsat5 TM remote sensing image, L7 represents Landsat7 ETM+ remote sensing image, and L8 represents Landsat8 OLI remote sensing image. [3] The value is the measured water level of the second Landsat image.

3. Method

3.1. Classification of Land-Cover Types

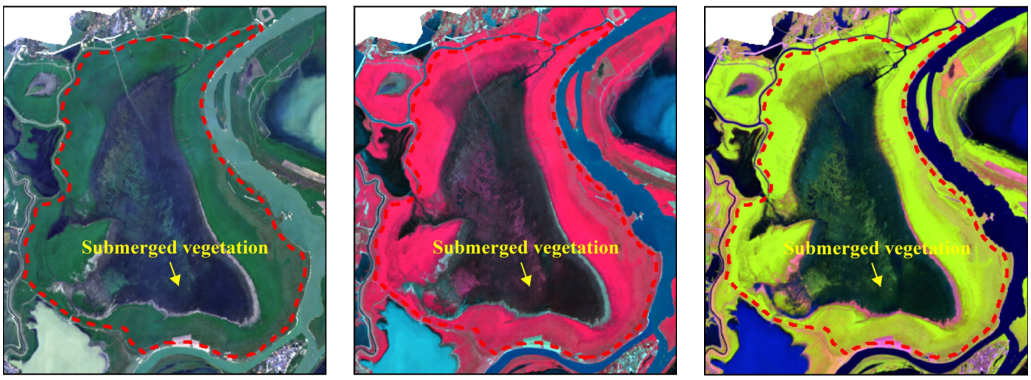
3.1.1. Difference in Surface Reflection

Figure 3 shows the synthesis maps of the different bands based on the Landsat image captured on 22 November 2013. In Figure 3a, the emergent vegetation entered the wilting period, and the entire area was brown. The emergent vegetation in Figure 3a and Figure 3b is yellow or faint yellow, respectively. Moist vegetation is located at the lower edge of the emergent vegetation, and its withering period is generally later than that of the emergent vegetation. It is brownish-green, red, or bright green in the three figures. Submerged vegetation is often located in flooded areas, and its color is dark green, dark red, or blackish green. The differences in growth rhythms and phenological characteristics can be used to identify different aquatic vegetation communities. However, considering that the coverage of submerged vegetation generally reaches a maximum from September to October, the remote sensing images in this period were supplemented to interpret the submerged vegetation and modify the previous classification results. Figure 4 shows the synthesis maps for 5 October 2013. The coverage of submerged vegetation was higher in October. Therefore, submerged vegetation during the dry season could be better identified under the combination of two remote sensing images.



(**a**) B321 (**b**) B432 (**c**) B543

Figure 3. Synthesis maps of different bands based on the Landsat image on 22 November 2013. The red dashed line represents the range of Banghu Lake. (**a**) B321 indicates that the color map is composed of B3, B2, and B1, and it is known as the synthesis map with true color for its consistency between the image color and the actual color of the surface scenery. (**b**,**c**) B432 and B543 are synthesis maps with false colors, which are used to enhance the distinguishability of various vegetation communities. (B1–B5 are blue, green, red, near-infrared, and short-wave-infrared 1 bands, respectively).



(**a**) B321 (**b**) B432 (**c**) B543

Figure 4. Synthesis maps of different bands based on the Landsat image on 5 October 2013. The red dashed line represents the range of Banghu Lake.

3.1.2. Image Processing

The emergent vegetation community is mainly distributed in the 14–16 m elevation area of the lake, and its distribution elevation is usually higher than that of the moist and submerged vegetation communities [20,21]. Considering that the area above 16 m is dominated by mesophytic meadows and lakeside highland coniferous forests, only the area below 16 m in Poyang Lake was studied, and an elevation mask was generated based on the terrain measured in 2010 (Figure 2c). The support vector machine classifier in the supervised classification was adopted to classify land-cover types in this study [26,32]. Visual interpretation combined with Google Earth was used to extract training samples [28]. The land-cover types were classified into five types: water, bare land, submerged vegetation, moist vegetation, and emergent vegetation. Land-cover types were obtained from a combination of two Landsat images: the first (from September to October) and the second (from November to December). When the grid was submerged vegetation in the second image, two situations were considered: (1) when the grid was water or bare land in the first Landsat image, it was modified to submerged vegetation, and (2) when the grid was moist vegetation or emergent vegetation, it remained unchanged.

Once the land-cover types were obtained, a combination of GIS spatial analysis and mathematical statistics was used to calculate the areas of different vegetation. Then, the land-cover map and measured topography were registered to the same geographic and projection coordinate system, meaning that each vegetation grid has corresponding elevation information.

3.1.3. Accuracy Evaluation

A vegetation distribution map from the second Poyang Lake comprehensive scientific survey in 2013, combined with Google Earth and Landsat images, was used to extract 1000 grids of different types as verification samples. The user precision, producer precision, overall classification precision, and kappa coefficients of the classification results were calculated by establishing a confusion matrix for the validation samples. The calculation results showed that the overall accuracy was 93.5%, and the kappa coefficient was 0.92, proving that this classification method is feasible.

3.2. Landscape Pattern Analysis

To analyze the landscape patterns of various vegetation communities, several landscape pattern metrics were selected to reflect the structural composition and spatial configuration of different land-cover types [32–35]. The details of each landscape index are listed in Table 2, and the software package FRAGSTATS 4.2 was adopted to calculate these metrics.

Table 2. Details of the selected landscape pattern metrics.

Landscape Pattern Metrics [1]	Introduction	Ecological Significance
NP	Total number of patches of a certain land type ($NP \geq 1$).	NP describes the heterogeneity of the overall landscape.
PD	Number of patches per unit area ($PD > 0$, number/km^2).	PD generally has a good correlation with landscape fragmentation.
MPS	Area of a certain land type divided by the number of the patches ($MPS > 0$, hm^2).	MPS reflects the fragmentation degree of different landscapes and indicates the differences among different types of landscapes.
LPI	Proportion of the largest patch of a certain land type in the whole landscape ($0 < LPI \leq 100$, %).	LPI reflects the dominance of patches.

Table 2. *Cont.*

Landscape Pattern Metrics [1]	Introduction	Ecological Significance
LSI	Deviation degree of a certain land type patch from the square of the same area (LSI $\geq$ 1).	LSI reflects the complexity of landscape shape.
AI	Number of like adjacencies involving the corresponding class, divided by the maximum possible number of like adjacencies involving the corresponding class (0 < AI $\leq$ 100, %).	AI reflects the connectivity and aggregation degree between landscape patches. A larger AI value means a higher aggregation degree.

Note: [1] patch number (PD), patch density (PD), mean patch size (MPS), largest patch index (LPI), landscape shape index (LSI), and aggregation index (AI).

3.3. Correlation Analysis Method

Stepwise regression analysis is a statistical method that uses regression models to predict and explain the relationship between variables. The principle is to establish an optimal regression model by gradually introducing and excluding variables through the form of a sequence of *F*-test. A significance level of 5% was used to filter core variables. For more details on the method, one can refer to Heuvelmans et al. [36]. The form of the stepwise regression model is as follows:

$$y = \beta_0 + \beta_i x_i + \varepsilon, \quad i = 1, 2, \ldots p \tag{1}$$

where y is the dependent variable, and in this paper y represents vegetation area; x_i is the independent variable and represents hydrological factors; β_i is the regression coefficient, which is often solved using the least squares method; and ε is a residual and follows a normal distribution.

4. Results

4.1. Annual Variation of Vegetation Communities in Poyang Lake

The land-cover types of Poyang Lake from 2001 to 2017 were detected by time-series Landsat remote sensing images. Figure 5 shows the spatiotemporal distribution of different aquatic vegetation communities in the dry season. From the center to the boundary of the lake area, the land-cover type is generally water → submerged vegetation → bare land → moist vegetation → emergent vegetation, indicating a gradual increase of the distribution elevation, which corresponds to previous studies [20,21]. Meanwhile, there exist great differences in the spatial distribution of different types of aquatic vegetation. In the northern channel, the local vegetation is mainly moist, but all types of vegetation communities are widely distributed in the main region of the lake.

The area of submerged vegetation ranges from 26.5 km^2 to 585.7 km^2, with an average of 287.6 km^2. The area of moist vegetation ranges from 656.8 km^2 to 1114.4 km^2, with an average of 907.7 km^2, and the area of emergent vegetation ranges from 152.1 km^2 to 506.7 km^2, with an average of 375.2 km^2. The submerged vegetation was mainly distributed in the two national nature reserves and northeast of the main lake area before 2010, and there was an obvious aggregation of submerged vegetation in the northeast of Poyang Lake from 2006 to 2009. After 2010, the submerged vegetation was still present in the two national nature reserves, but its distribution area decreased. Meanwhile, the submerged vegetation in the northeast disappeared completely. The moist vegetation always maintained a stable community and dominant position in the entire lake. The emergent vegetation was mainly distributed in the high beach area of Poyang Lake, with an average elevation of 14 m, and its distribution area in the south of PLNNR decreased significantly.

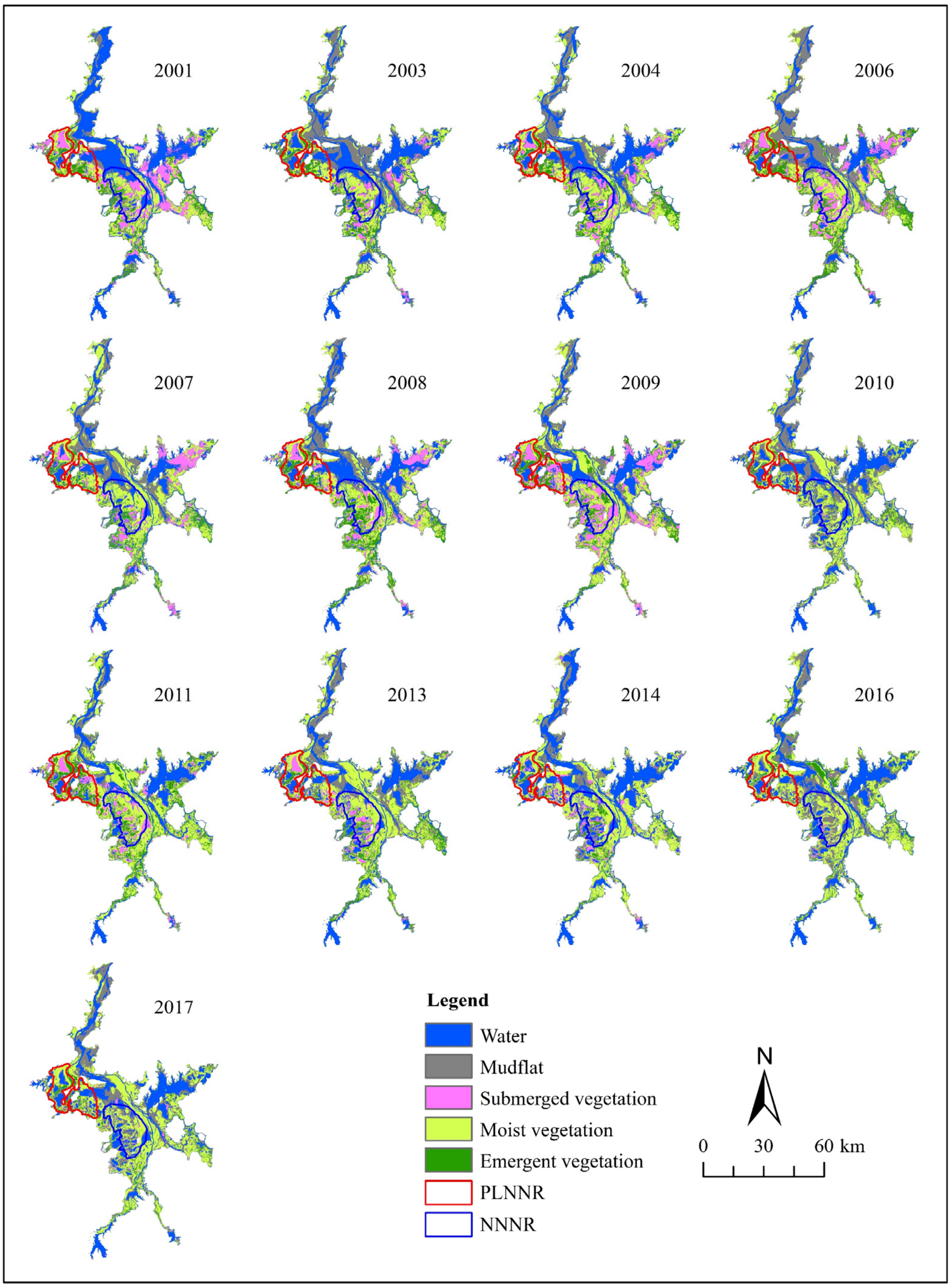
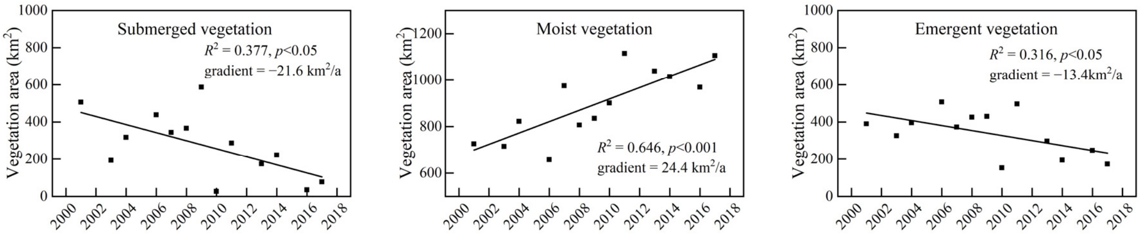


Figure 5. Spatial distribution results of different land-cover types in the dry season of Poyang Lake from 2001 to 2017.

Figure 6 shows the calculated values and linear fitting results for vegetation areas in different years. The areas of submerged and emergent vegetation both showed a decreasing trend every year, with rates of -21.6 km^2/a (R^2 = 0.377, p < 0.05) and -13.4 km^2/a (R^2 = 0.377, p < 0.05), respectively. The linear fitting result of the moist vegetation showed that the moist vegetation expanded significantly over the entire lake at a rate of 24.4 km^2/a (R^2 = 0.646), and the variation trend was extremely significant (p < 0.001), indicating that the dominance of moist vegetation was continuously increasing.



(**a**) Submerged vegetation (**b**) Moist vegetation (**c**) Emergent vegetation

Figure 6. Area changes of aquatic vegetation communities in the dry season of Poyang Lake. The dots represent the vegetation area interpreted in Figure 5, and they are fitted using linear equations.

Figure 7 shows the change in the average distribution elevation of aquatic vegetation during the dry season. Only the average distribution elevation of the submerged vegetation was increasing at the rate of 0.06 m/a, and it had a significant variation trend. The distribution elevation of moist and emergent vegetation both showed no significant variation trend ($p > 0.05$).

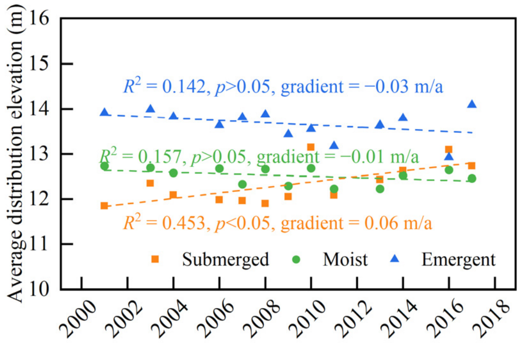


Figure 7. Changes of average distribution elevation of aquatic vegetation communities.

The maximum area of aquatic vegetation during the dry season was 2001.0 km^2, which occurred in 2011. The corresponding average water level at Xingzi Station was only 8.97 m, which was the lowest value from 2001 to 2017. Meanwhile, the top three annual average water levels at Xingzi Station occurred in 2016 (11.93 m), 2010 (11.84 m), and 2003 (11.54 m), whereas the three years with the smallest area of aquatic vegetation were 2010 (1156.6 km^2), 2003 (1261.2 km^2), and 2016 (1357.0 km^2), respectively. The above data support the view that the distribution of aquatic vegetation during the dry season is greatly affected by hydrological processes throughout the year. Specifically, the area of aquatic vegetation was usually larger in the dry years and smaller in the wet years.

4.2. Annual Variation of Vegetation Communities in National Nature Reserves

Figure 8 shows the enlarged results of different vegetation communities in the PLNNR and NNNR during the dry season from 2001 to 2017. In the PLNNR, the submerged vegetation was mainly distributed in Banghu Lake and Shahu Lake, but its community was unstable and varied greatly between different years. The area of submerged vegetation in the PLNNR ranged from 1.5 km^2 (2010) to 99.3 km^2 (2009), with an average of 39.9 km^2, which was the minimum of the three types. The moist vegetation in the PLNNR was mainly located near Banghu Lake and the eastern beach, and its area ranged from 70.0 km^2 (2009) to 144.0 km^2 (2016), with an average of 107.4 km^2. The emergent vegetation was mostly distributed south of Banghu Lake and on the beach near Xianghu Lake; however, the emergent vegetation near Xianghu Lake gradually disappeared after 2011. The average area of emergent vegetation was 66.2 km^2, ranging from 105.2 km^2 (2011) to 27.8 km^2 (2014).

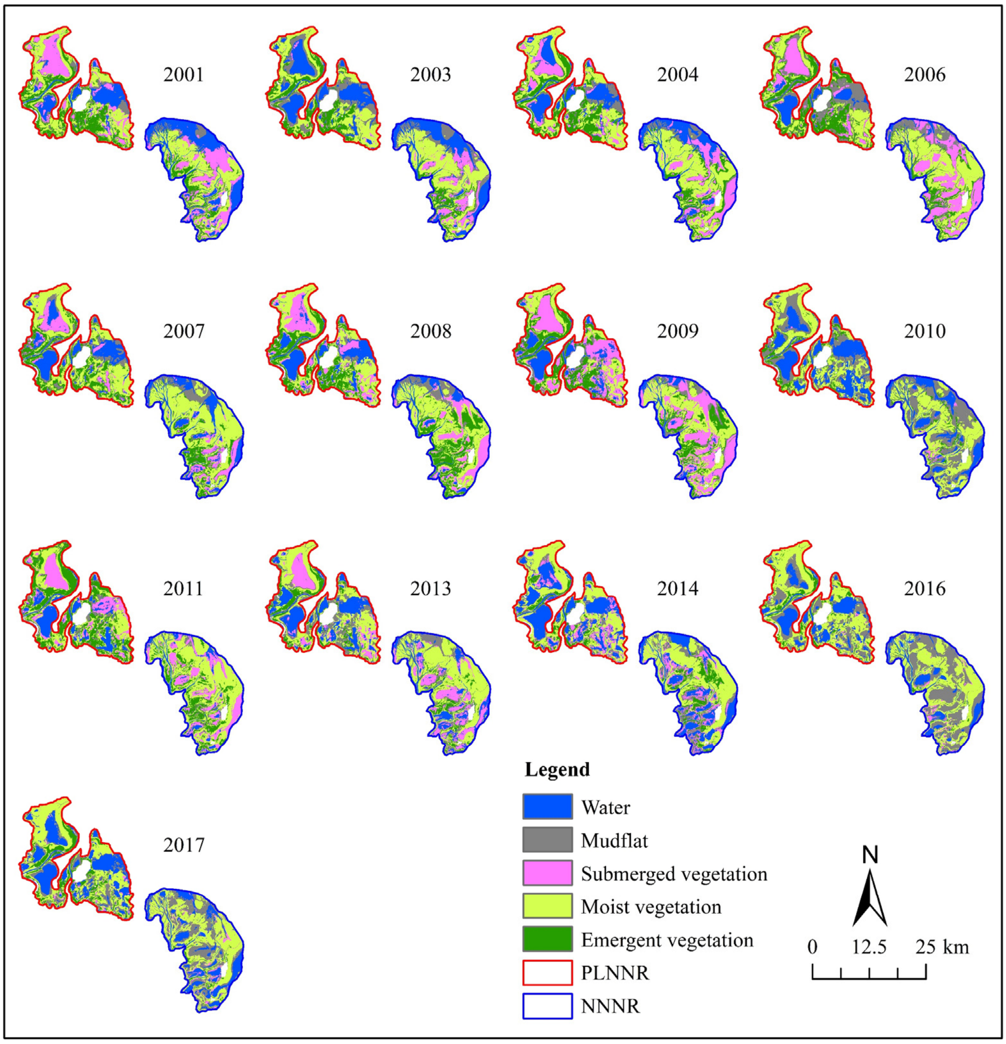


Figure 8. Spatial distribution results of different land-cover types in the PLNNR and NNNR during the dry season from 2001 to 2017. The location of two national nature reserves is shown in Figure 2b.

In the NNNR, the submerged vegetation was mainly distributed in the dish-shaped lakes. The average area of submerged vegetation in the NNNR was 54.0 km^2, with a maximum of 108.9 km^2 (2009) and a minimum of 5.4 km^2 (2010), showing relatively large fluctuations. There is a stable community and dominant position of moist vegetation in the NNNR region. The average area of moist vegetation was 133.1 km^2, with a maximum of 165.6 km^2 (2011) and a minimum of 108.2 km^2 (2001). The emergent vegetation was mainly distributed on the high beach southeast of the NNNR, with a multi-year average area of 37.0 km^2, which was the minimum of the three types, ranging from 5.2 km^2 (2016) to 78.0 km^2 (2008).

Figure 9 shows the area changes of different vegetation communities in the two national reserves. In the PLNNR, the linear fitting results for the area of submerged and moist vegetation both showed no significant variation trend. Only the area of emergent vegetation was decreasing at the rate of -3.5 km^2/a, and the decreasing trend was significant. In the NNNR, the area changes of the submerged, moist, and emergent vegetation all failed to pass the significance test with a confidence level of 95%, indicating that the variation trends of different vegetation areas were not significant.

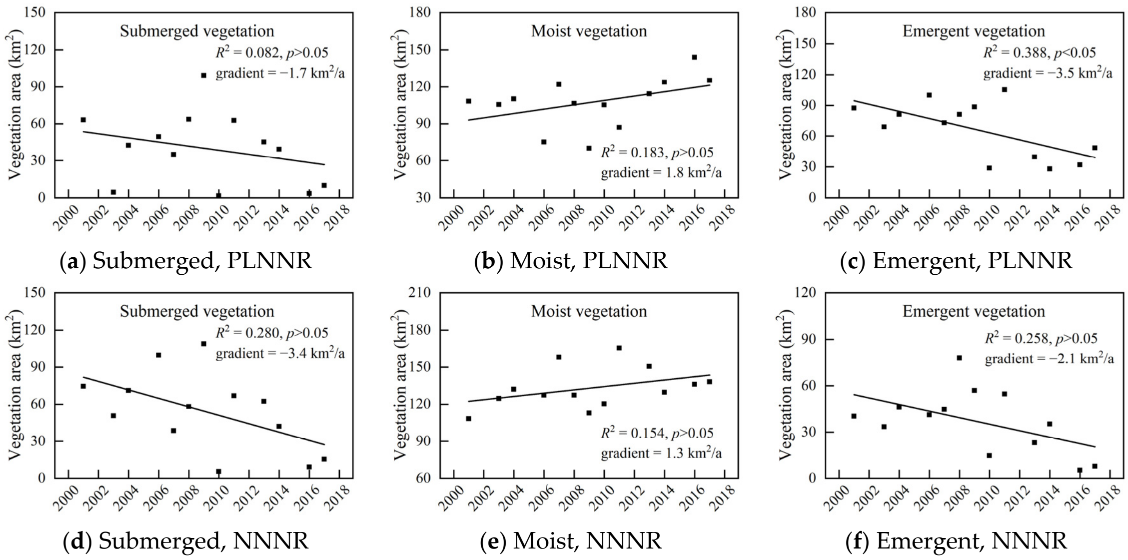


Figure 9. Area changes of aquatic vegetation communities in the PLNNR and NNNR.

Figure 10 shows the changes in the average distribution elevation of aquatic vegetation communities during the dry season in the PLNNR and NNNR. In the PLNNR, the average elevations of moist and emergent vegetation both showed no significant change trend, and the average elevation of moist vegetation was the most stable. Only the average elevation of submerged vegetation gradually increased at the rate of 0.064 m/a, and the increasing trend was significant.

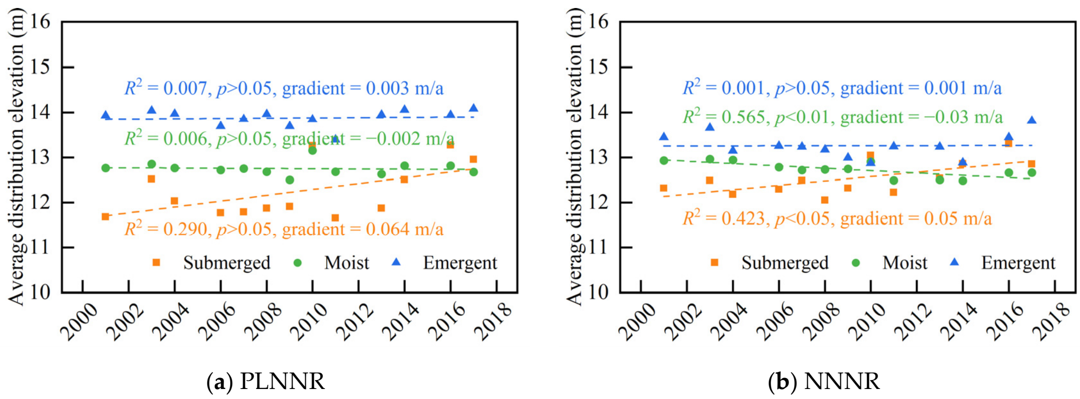


Figure 10. Changes of average distribution elevations of aquatic vegetation communities in the PLNNR and NNNR.

In the NNNR, the average elevation of emergent vegetation was the most stable, and the variation trend was insignificant. The average elevation of submerged vegetation fluctuated the most significantly. From 2001 to 2017, the average elevation of submerged vegetation gradually increased at the rate of 0.05 m/a, whereas the average elevation of moist vegetation decreased significantly, at a rate of −0.03 m/a.

4.3. Landscape Patterns of Different Vegetation Communities

To comprehensively reflect the landscape pattern changes of different vegetation communities over the past 20 years, the research cycle was divided into two periods, 2001–2009 (period 1) and 2010–2017 (period 2), and the multi-year mean values in the two periods were compared to analyze the evolutionary characteristics of landscape patterns.

Figure 11 shows the results of the different landscape pattern metrics. Compared with period 1, the NP and PD of submerged, moist, and emergent vegetation all increased during period 2. The NP of moist vegetation increased from 3287 to 4357, showing the most significant change, whereas the NP variation of emergent vegetation was the smallest, increasing from 5768 to 6567, with an increase of 13.9%. However, it is impossible to judge the heterogeneity and fragmentation of all landscapes only from the changes in NP and PD owing to differences in vegetation areas. Therefore, the MPS was introduced to reflect the degree of fragmentation of different landscapes.

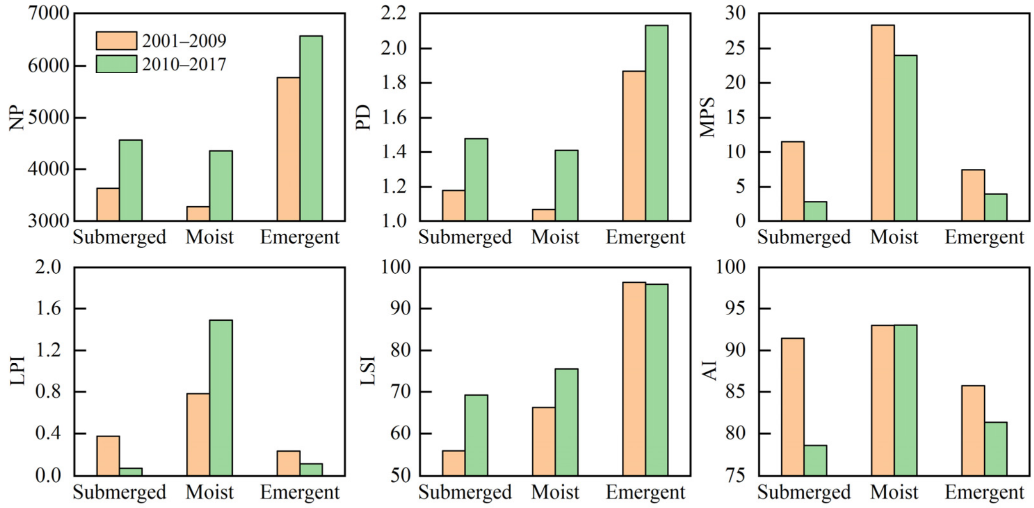


Figure 11. Results of different landscape pattern metrics.

The MPS of submerged, moist, and emergent vegetation all decreased during period 2. The MPS of submerged vegetation decreased from 11.56 to 2.87 (−75.2%), and the MPS variation of emergent vegetation was the smallest, decreasing from 28.29 to 24.02 (−15.01%). The results indicated that the degree of fragmentation of aquatic vegetation in Poyang Lake had increased and that the change in submerged vegetation was the most significant. For different vegetation types, the MPS of moist vegetation was the largest, and that of emergent vegetation was the smallest during period 1. In period 2, the MPS of moist vegetation remained the highest, indicating that the degree of fragmentation of moist vegetation in Poyang Lake was the lowest, and meanwhile, the MPS of submerged vegetation became the smallest, indicating that the vegetation type with the highest degree of fragmentation changed from emergent vegetation to submerged vegetation.

The LPI of submerged and emergent vegetation decreased from 0.37 to 0.07 (−81.1%) and from 0.23 to 0.11 (−52.2%), respectively. The LPI of the moist vegetation increased from 0.78 to 1.49 (91.0%). The LPI of moist vegetation was always the highest, indicating that moist vegetation was the dominant species in the wetlands. Over the past two decades, the dominance of moist vegetation has increased, whereas the dominance of submerged and emergent vegetation has decreased.

The LSI was adopted to represent the complexity of the vegetation distribution shape, and its value was independent of the patch area. The LSI of submerged and moist vegetation increased from 55.84 to 69.15 (23.8%) and from 66.28 to 75.46 (13.9%), respectively, showing the increasing trend of irregularity and complexity of the patch edge. The LSI of emergent vegetation decreased from 96.44 to 95.99 (−0.47%), basically unchanged, and remained the largest among the three types, indicating that its complexity of the patch edge was always the highest.

The AI represents the degree of aggregation of landscape patches, which is often used to measure the degree of landscape fragmentation and isolation of various patches. Its value is larger when the vegetation is composed of few larger patches with good connectivity. The AI of submerged and emergent vegetation decreased from 91.48 to 78.54 (−14.1%) and from 85.70 to 81.33 (−5.1%), respectively. The AI of moist vegetation remained unchanged and was always the largest in the two periods, meaning that the distribution of moist vegetation in Poyang Lake was invariably the most concentrated. The vegetation with the smallest AI varied from emergent vegetation to submerged vegetation, indicating that the spatial distribution of submerged vegetation became the most fragmented and disordered.

4.4. Correlation Analysis between Vegetation Area and Hydrologic Processes

4.4.1. Hydrologic Factors

Hydrological processes are important external environmental factors for the growth of wetland vegetation and play a decisive role in the vegetation type, biomass, health status, and spatial distribution [37–40]. The annual water level in Poyang Lake shows periodic fluctuations at both high and low water levels. Several hydrological factors were selected in Table 3 to quantify the potential impact of water-level fluctuations, including the average water level, maximum water level, minimum water level, coefficient of variation of the water level, maximum variation amplitude of the water level, and recession time. Meanwhile, considering that the aquatic vegetation in Poyang Lake is mainly distributed in the beach area at an elevation of 10–16 m, the recession time is defined as the time when the water level falls below 14, 13, 12, and 11 m. Days with water levels higher than 10, 12, and 14 m were used to quantify the potential impact of flood inundation time. All hydrological factors were calculated using the water level at Tangyin Station as it is located in the middle of the lake area.

Table 3. Definitions and notations of the selected hydrological factors.

Time Scale [1]	Notation	Definition
Whole year	Y_{mean}, Y_{max}, Y_{min}, Y_{cv}, Y_{a}, $Y_{\geq 10m}$, $Y_{\geq 12m}$, $Y_{\geq 14m}$, $Y_{<14m}$, $Y_{<13m}$, $Y_{<12m}$, $Y_{<11m}$	Y, D, R, W, and F are different time scales. The subscripts mean, max, min, cv, and a represent the average water level, maximum water level, minimum water level, coefficient of variation of water level, and maximum variation amplitude of water level, respectively. The subscript $\geq$ 10 m means the days with a water level higher than 10 m, and the subscript < 10 m means the time when the water level falls below 10 m.
Low-water period	D_{mean}, D_{max}, D_{min}, D_{cv}, D_{a}, $D_{\geq 10m}$	
Rising period	R_{mean}, R_{max}, R_{min}, R_{cv}, R_{a}, $R_{\geq 10m}$, $R_{\geq 12m}$	
High-water period	W_{mean}, W_{max}, W_{min}, W_{cv}, W_{a}, $W_{\geq 12m}$, $W_{\geq 14m}$	
Falling period	F_{mean}, F_{max}, F_{min}, F_{cv}, F_{a}, $F_{\geq 10m}$, $F_{\geq 12m}$	

Note: [1] The time scales of the water situation consisted of the entire year, dry season (January, February, November, and December), rising period (March, April, and May), wet season (June, July, and August), and falling period (September and October).

4.4.2. Regression Models between Vegetation Areas and Hydrologic Factors

A stepwise regression analysis method was utilized to construct a quantitative relationship between the areas of different vegetation communities and the above hydrological factors. Table 4 shows the regression models between vegetation areas and hydrological factors. Figure 12 presents the evaluation results for the proposed regression models.

Table 4. Regression models between vegetation area and hydrologic factors.

Vegetation	Regression Model	Key Hydrological Factors
Submerged vegetation	$S_1 = -95.60Y_{max} + 1868.16\ (R^2 = 0.600, p < 0.01)$	Y_{max}
Moist vegetation	$S_2 = -122.03R_{min} + 71.89W_{max} - 1.77Y_{\geq 12m} + 1303.37\ (R^2 = 0.882, p < 0.001)$	R_{min}, W_{max}, $Y_{\geq 12m}$
Emergent vegetation	$S_3 = -4.21W_{14m} + 613.37\ (R^2 = 0.582, p < 0.01)$	$W_{\geq 14m}$

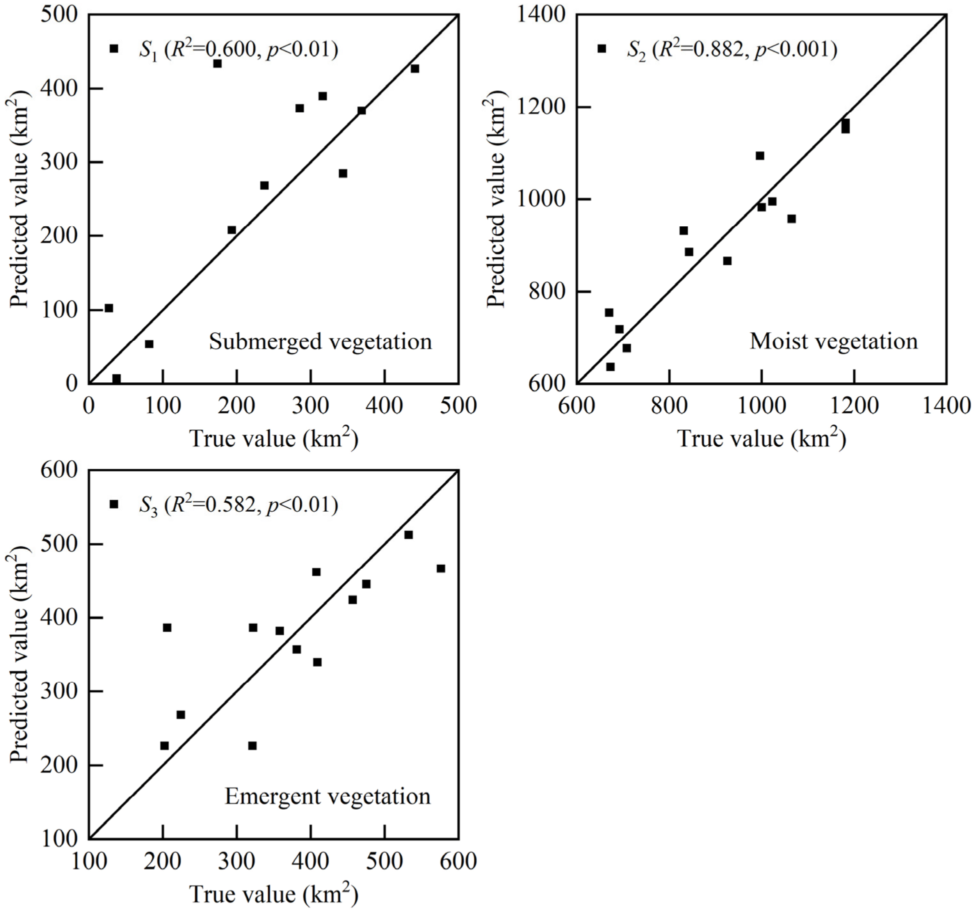


Figure 12. Evaluation results of the proposed regression models.

The regression model of the submerged vegetation shows that the key hydrological factor affecting its area is Y_{max}, with a determination coefficient of $R^2 = 0.600$ ($p < 0.01$). The negative correlation between the two indicated a larger area of submerged vegetation during wetter years (such as 2010 and 2016). There exist three key hydrological factors affecting the area of moist vegetation, including R_{min}, W_{max}, and $Y_{\geq 12m}$, and the determination coefficient of the regression model is $R^2 = 0.882$ ($p < 0.001$). The area of moist vegetation has a negative correlation with R_{min} and $Y_{\geq 12m}$ and a positive correlation with W_{max}. $W_{\geq 14m}$ is the key hydrological factor that influences the area of emergent vegetation, with a determination coefficient of $R^2 = 0.582$ ($p < 0.01$) and a negative correlation. More inundation days at high water depths cause environmental stresses as the emergent vegetation has the worst tolerance to inundation. High water depth inhibits the aerobic respiration of vegetation roots and indirectly affects water temperature and nutrients, thus restricting the growth of emergent vegetation.

For the moist vegetation, when R_{min} increases or decreases by 10%, the predicted area decreases or increases by 128.4 km^2; when W_{max} increases or decreases by 10%, the predicted area increases or decreases by 118.4 km^2; and when $Y_{\geq 12m}$ increases or decreases by 10%, the predicted area decreases or increases by 29.6 km^2. In general, R_{min} has the highest sensitivity, and W_{max} has a slightly lower sensitivity in the regression model. These two factors have a dominant effect on the area of moist vegetation.

5. Discussion

In 2001 and 2017, the average annual runoff entering into Poyang Lake was 1210.7×10^8 m^3 and 1208×10^8 m^3, respectively, and meanwhile, the annual average water levels at Tangyin Station were 12.36 m and 12.17 m, respectively, indicating similar hydrological conditions between the two years. Therefore, the transition map of land-cover types in Poyang Lake was demonstrated from the starting year (2011) to the ending year (2017) (Figure 13). Table 5 shows the transition matrix for land-cover types in Poyang Lake between 2001 and 2017. Approximately 56% of the grids in the lake area had undergone changes in their land-cover types. The most significant changes occurred in the northern river channel and the central part of the main lake area, where a large area of water (375.3 km^2) was transformed into mudflats (dark green in Figure 9). For different types of aquatic vegetation, the submerged vegetation experienced the greatest changes, as 37% (186.0 km^2), 32% (160.8 km^2), and 27% (138.7 km^2) of the submerged vegetation were transformed into water, mudflat, and moist vegetation, respectively. The submerged vegetation in the dish-shaped lake has significantly decreased. Other changes exceeding 100 km^2 include the following: 46% (160.3 km^2) of the mudflat and 46% (178.7 km^2) of the emergent vegetation were transformed into moist vegetation, respectively, indicating an increase in the dominance of moist vegetation, which is consistent with previous research [15,26,41]. From 2001 to 2017, the areas of water, submerged vegetation, and emergent vegetation showed a decrease of 180.8 km^2, 429.3 km^2, and 216.8 km^2, respectively, whereas the areas of moist vegetation and mudflat increased by 379.1 km^2 and 447.8 km^2, respectively.

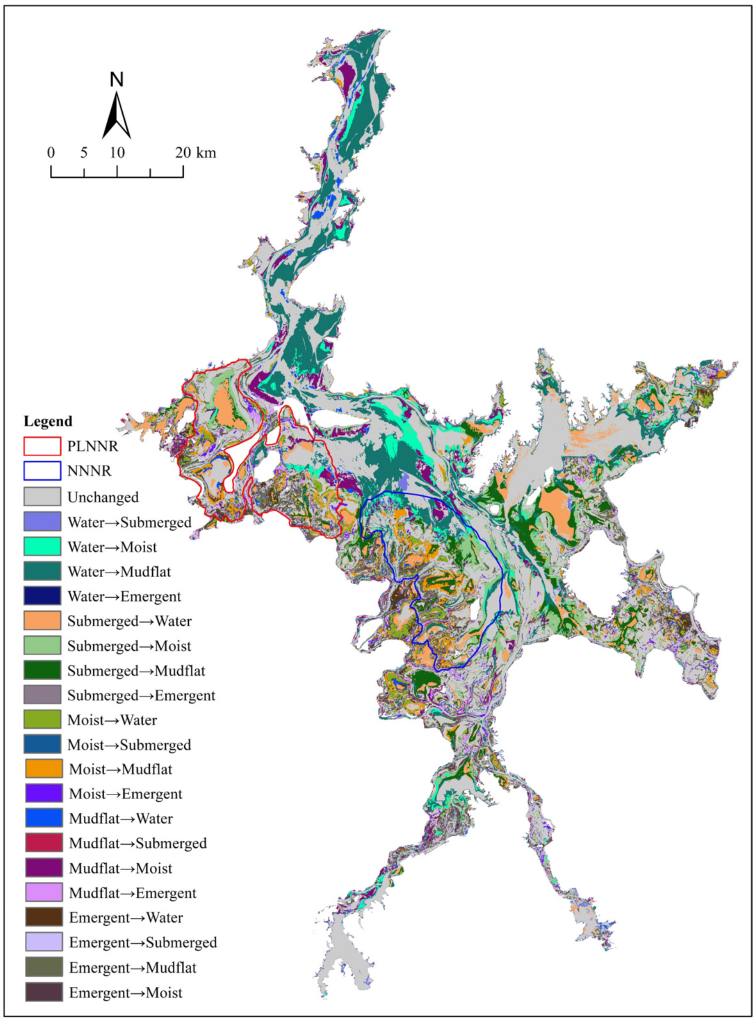


Figure 13. The transition map of land-cover types in Poyang Lake between 2001 and 2017.

Table 5. Transition matrix for land-cover types in Poyang Lake between 2001 and 2017 (unit: km^2).

Year		2001					
	Types	**Water**	**Submerged**	**Moist**	**Mudflat**	**Emergent**	**Total**
2017	Water	605.8	186.0	59.2	42.5	32.1	925.6
	Submerged	14.6	19.2	19.7	11.4	11.7	76.6
	Moist	109.6	138.7	517.0	160.3	178.7	1104.3
	Mudflat	375.3	160.8	92.7	110.7	60.5	800
	Emergent	1.1	1.2	36.6	27.3	106.4	172.6
	Total	1106.4	505.9	725.2	352.2	389.4	3079.1
Changes from 2001 to 2017		−180.8	−429.3	379.1	447.8	−216.8	

Previous research indicated that the distribution of vegetation and mudflats in Poyang Lake was significantly affected by the hydrological processes [42–44]. In the past two decades, Poyang Lake has experienced significant inundation shrinkage and water level decrease under the combined impacts of climate variability and the impoundment of the Three Gorges Dam in 2003 [24,45]. Figure 14a shows the variation of the annual average water level at Xingzi and Tangyin stations since their establishment. Taking Tangyin Station as an example, the total series was divided into seven periods with a 10-year cycle. The results indicate that the minimum annual average water level at Tangyin Station occurred from 2021 to 2023 (11.23 m). If a complete 10-year cycle is considered, the minimum occurred from 2011 to 2020 (12.16 m), whereas the maximum occurred from 1991 to 2000. This further indicates that the water level of Poyang Lake has significantly decreased in the past 20 years, which is also an important reason for the increase of mudflats in the lake area.

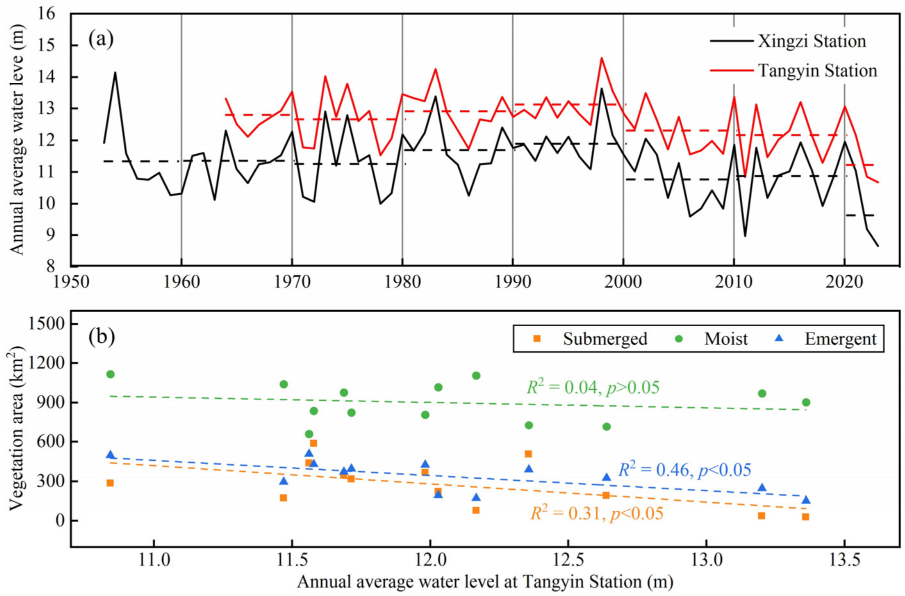


Figure 14. (**a**) Variation of the annual average water level in the lake area, and (**b**) relationship between vegetation area and annual average water level at Tangyin Station.

Figure 14b shows the relationship between vegetation area and annual average water level at Tangyin Station. Except for moist vegetation, both submerged and emergent vegetation were negatively correlated with the average water level, and the variation trend was significant ($p < 0.05$), which is consistent with the results shown in Figure 6, as the water level in Poyang Lake is experiencing a continuous decline.

It is crucial to acknowledge that hydrological conditions, albeit significant, do not constitute the sole determinant of the distribution of aquatic vegetation in Poyang Lake. Additionally, the driving forces of water regimes may vary for the transformations of different vegetation types. Consequently, to better protect and restore different aquatic vegetation communities, more studies are needed on the relationship between vegetation and hydrology in the future.

6. Conclusions

The Poyang Lake wetland was interpreted into five land-cover types using Landsat remote sensing images and a support vector machine classifier. The distribution maps of different types of aquatic vegetation in Poyang Lake from 2001 to 2017 indicated significant spatiotemporal dynamics, particularly with a remarkably increase in moist vegetation and a remarkably decrease in submerged and emergent vegetation. The average elevation of the submerged vegetation showed a significant increasing trend, with a rate of 0.06 m/a. Meanwhile, the corresponding landscape patterns showed that the fragmentation degree of aquatic vegetation communities in Poyang Lake had increased gradually. The vegetation type with the lowest degree of aggregation changed from emergent to submerged vegetation, which means that the submerged vegetation became the most fragmented and disordered vegetation in the spatial morphology. The connection between vegetation communities and hydrological processes was revealed with the assistance of simultaneous hydrological measurements. The findings showed that hydrological conditions during the rising- and high-water periods may be the key factor affecting the area of aquatic vegetation in Poyang Lake during the dry season. Considering the close correlation between vegetation communities and hydrological factors, the protection and restoration of this unique ecosystem requires refined lake management.

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