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Remote Sensing Monitoring of Changes in Lake Aquatic Vegetation before and after the Removal of the Fence Based on Sentinel-2: A Case Study in Lake Futou, Hubei Province

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Abstract: Aquatic vegetation is an important component and main primary producer of lake ecosystems and plays an important role in improving water quality and maintaining biodiversity, which is critical to diagnosing the health of aquatic ecosystems in shallow lakes. It is therefore important to accurately obtain information on dynamic changes and spatial-temporal distribution of aquatic vegetation. Based on the Sentinel-2 satellite remote sensing images from 2016–2022, we studied the feasibility of using remote sensing technology to monitor the spatial-temporal changes of aquatic vegetation before and after the removal of the fence, taking Futou Lake in Hubei Province as a case study. Two vegetation indices, Normalized Difference Vegetation Index (NDVI) and Submerged Aquatic Vegetation Index (SAVI) were applied to identify the open water and the aquatic vegetation through two threshold determination methods, Otsu algorithm and manual division threshold method. The results show that: (1) the classification based on the NDVI and manual division threshold method performs the best, with the overall classification accuracy of 94.44% and the Kappa coefficient of 85.23%. (2) The growth of aquatic vegetation is divided into stages, the first stage is enclosing culture, and the distribution of aquatic vegetation is less in 2016–2017, all around 10 km^2. The second stage is after the removal of the fence, the distribution area of aquatic vegetation in 2018 is on an upward trend, and in 2019–2022 it is growing rapidly. (3) Spatially, the aquatic vegetation was mainly distributed at the former fence, specifically in the northeastern and southwestern waters of the Futou Lake and it spread to the core area of the lake, probably due to the elevation of the siltation of the lake bottom. (4) *Potamogeton crispus* and *Trapa* are the dominant species, the peak of the distribution range in Futou Lake occurs in 2021 with an area of about 50.89 km^2, which needs to be controlled moderately. (5) The area covered by *Potamogeton crispus* in the Futou Lake has increased significantly, probably due to the siltation and accumulation of nutrients in the Futou Lake caused by the history of purse seine farming.

Keywords: Sentinel-2 images; aquatic vegetation; Futou Lake; classification thresholds

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1. Introduction

Lakes are important carriers of water resources and play an important role in flood storage, water supply, transportation, and shipping, as well as providing biological habitats, purifying water quality, and regulating climate. In recent decades, the interference of human activities (i.e., river and lake partitioning and fish farming in seine nets) has destroyed aquatic plant resources and caused the simplification of lake ecosystem structure, resulting in its dysfunction [1,2], increasing the content of nutrients in water bodies (such as nitrogen and phosphorus), finally leading to the deterioration of lake water quality and even eutrophication [3]. The aquatic vegetation is an important part of the lake ecosystem and a major primary producer and plays an important role in improving water quality and maintaining biodiversity [4–6]. With the increase in nutrient concentration, shallow lakes will have the phenomenon of reverse evolution of grass-type lakes to algal-type lakes [7–9]. However, the aquatic vegetation can promote the transformation of lakes from algal-type ecosystems to grass-type ecosystems [10]. Thus, it is very important to obtain accurate information on the spatial-temporal distribution of aquatic vegetation, as well as its biomass, to correctly diagnose the health of aquatic ecosystems in shallow lakes [11,12].

Although traditional aquatic vegetation survey methods can accurately obtain aquatic vegetation species, distribution, and biomass [13,14], it is difficult to conduct direct, long-term ground monitoring of all areas within the lake due to the topography, cost, and many other factors [15,16]. With the development of high-resolution and high-spectral remote sensing technology, satellite remote sensing has opened up a new way of continuous monitoring aquatic vegetation [12,17]. Scholars at home and abroad have carried out the identification and classification of aquatic vegetation based on various methods and algorithms of remote sensing data. Zhang et al. [18] extracted aquatic vegetation using FAI and vegetation frequency method based on MODIS data from 2007 to 2017 and revealed that the degradation of aquatic vegetation caused by increased eutrophication of water bodies and deterioration of the underwater light environment in East Taihu Lake, and the phenomenon that environmental factors (such as nutrients, chlorophyll a concentration, water level, and transparency) are closely related to changes in aquatic vegetation. Although this article extracted the aquatic vegetation information of the Hongze Lake in long time series, the resolution of the image used was 250 m, from which it was difficult to extract the aquatic vegetation of the lake with curved shoreline. Yan et al. [19] established a Gaussian fitting-based method for calculating the threshold of aquatic vegetation remote sensing classification based on HJ-CCD image data combined with the Gaussian model to realize the extraction of aquatic vegetation taxa from Hongze Lake even without simultaneous situ data, and the overall accuracy of classification was 84%. The article used HJ-CCD images with 30 m resolution, but cyanobacterial blooms have appeared in some waters of Hongze Lake [18], which are incompatible with the aquatic ecology of the Futou Lake, and the method used is difficult to apply to the waters of the Futou Lake. Wang et al. [20] used a combination of the SAVI index and Otsu algorithm to extract the aquatic vegetation taxa of Cuiping Lake in Tianjin using Sentinel-2 satellite data, and the overall accuracy of classification was 88.57%, and the Kappa coefficient was 83.78%, which was a good classification result. The SAVI index was established for Sentinel-2 data; however, Cuiping Lake is a valley-type reservoir and the only source of drinking water in Tianjin, while Futou Lake is a typical shallow lake with natural multifunctional functions such as irrigation and aquaculture in the middle and lower reaches of the Yangtze River, the water environment parameters between them are far different, and the species and spatial and temporal distribution of aquatic vegetation are also very different. Therefore, the study is of academic significance to test whether the method is equally effective for Futou Lake. In recent years, the decision tree classification has been the most commonly used method for aquatic vegetation classification [15], which usually uses some indices as variables for decision tree classification. Cai et al. [15] built a decision tree based on NDVI for the extraction of aquatic vegetation information in Taihu Lake. Lin et al. [16] selected NDVI and NDWI to assist in the classification for the extraction of aquatic vegetation in the wetlands of Wild Duck Lake. Cao et al. [21] used NDVI index to classify the aquatic vegetation in Luoma Lake, etc. It can be seen that NDVI has strong spatial generalizability. Therefore, in this work, the use of NDVI for the extraction of aquatic vegetation in the Futou Lake is also necessary.

The Futou Lake, located in southeastern Hubei Province, is a typical shallow lake in the middle and lower reaches of the Yangtze River with functions of irrigation and aquaculture. Early studies have shown that the Futou Lake has a full range of aquatic vegetation types and rich biomass [22]. However, the eutrophication of Lake Futou has increased due to the activities of seine farming since the 1980s, which has led to the rapid disappearance of aquatic vegetation [13]. For this reason, the Hubei Provincial Department of Agriculture and Rural Affairs required removing fences, seine nets, and netting in rivers, lakes and reservoirs during 2016–2017, to protect the ecological environment of fisheries. Li et al. [13] studied the changes in aquatic plant species and dominant species in the Futou Lake over the last 20 years from 1988 to 2009, and the results indicated that the main reasons of species replacement of aquatic plant were human disturbances. Although the article analyzed the changes of aquatic vegetation in the Futou Lake over a long time series, the study period was during the seine breeding stage, and the changes of aquatic vegetation after the removal of the seine remain to be studied. Dai et al. [5] studied the changes in the spatial distribution of submerged vegetation in the Futou Lake during 1986–2018, but only total annual aquatic vegetation was calculated and at 3-year intervals, without specific analysis of aquatic vegetation species. Therefore, further studies are needed on the current status and changes of the vegetation in Futou Lake before and after the removal of the fence.

This paper classifies the waters of Futou Lake into two types of open water and aquatic vegetation. Firstly, the results of the four methods are compared and validated by the in situ data on 4 May 2022 to determine the optimal method: (1) SAVI–Otsu method: using the Submerged Aquatic Vegetation Index (SAVI) combined with the Otsu algorithm to extract the aquatic vegetation taxa; (2) SAVI–Manual method: using SAVI combined with manual threshold method to extract the aquatic vegetation taxa; (3) NDVI–Otsu method: using Normalized Difference Vegetation Index (NDVI) combined with Otsu algorithm to extract the aquatic vegetation taxa; and (4) NDVI–Manual method: using NDVI combined with Manual method to extract the aquatic vegetation taxa. Then, based on the Sentinel-2 image data from 2016–2021, the optimal method was used to extract the aquatic vegetation taxa. Finally, we analyzed the spatial-temporal changes of aquatic vegetation from 2016–2022 and discussed the reasons for the changes.

2. Materials and Methods

2.1. Study Area

The Futou Lake (Figure 1) is the fourth largest lake in Hubei Province, located in the south of Wuhan City and Xianning City border (114°09′ E–114°20′ E, 29°55′ N–30°07′ N), covering the Wuhan Jiangxia District, the Xianning Xianan District, and the Jiayu County. It is named Futou Lake because the shape of the lake is similar to an axe, while "Futou" means axe in Chinese. The lake is located at the junction of the Jianghan Plain and the hills, and has a subtropical continental monsoon climate, with a clear alternation of winter and summer seasons, abundant rainfall, and a mild climate, with rainfall mainly concentrated in the spring and summer. The lake has a water area of about 130 km^2, a shoreline of 430 km, an average water depth of 2.9 m, and a water storage capacity of 3.3×10^8 m^3 [13]. The Futou Lake is a typical shallow throughput lake in the middle and lower reaches of the Yangtze River with multi-functional irrigation and aquaculture [23]. There are 16 main rivers entering into the lake and the river out of the lake is the Jinshui River, which connects the lake with the Yangtze River through Jinshui River and is a throughput lake regulating runoff. The reclamation from the early 1950s to the early 1980s caused a dramatic reduction in the surface area of the lake. Since the late 1980s, large-scale seine aquaculture has severely damaged its aquatic vegetation, especially submerged vegetation [22].

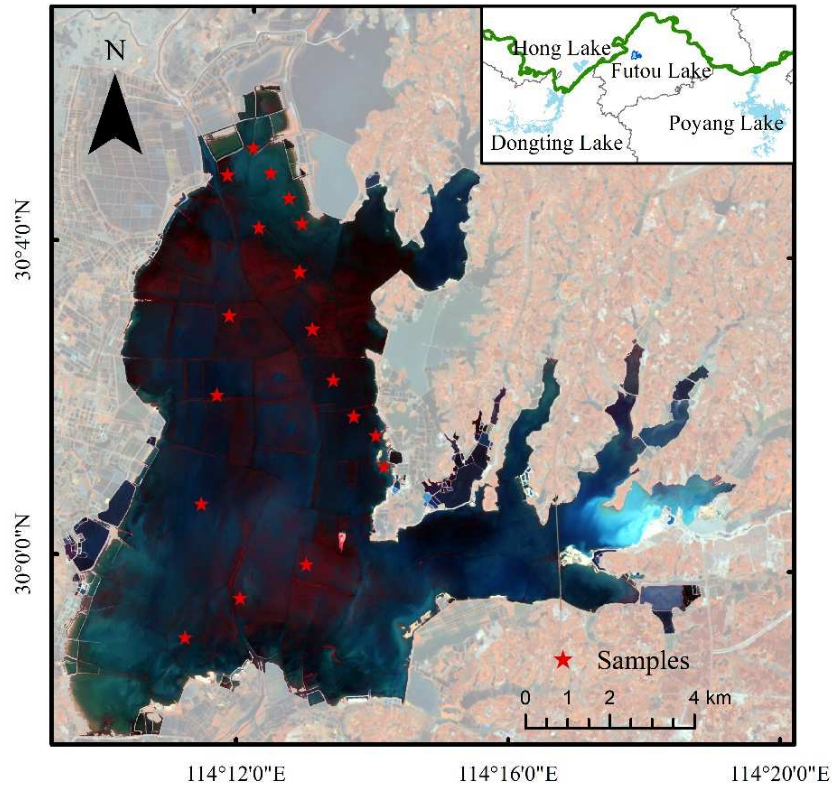

Figure 1. Location of the study area and distribution of sampling points.

2.2. Field Data Collection

According to field surveys, the main lake area of Futou Lake is dominated by its aquatic vegetation from April to May each year by the *Trapa*–*Potamogeton crispus* community. *Potamogeton crispus* (P.C) is a monocotyledonous perennial submerged herb of the family Potamogetonaceae. It germinates in autumn, grows in winter and spring, flowers and fruits from April to May, and gradually declines and rots after June in summer while forming scale branches (winter buds) to survive uncomfortable conditions. The *Trapa bispinosa Roxb.*, is a Trapaceae, and *Trapa* is an annual floating aquatic herb of the genus *Trapa* L., flowering from May to October and fruiting from July to November. Although P.C is a submerged plant when it grows vigorously or is partially floated to the water surface after being broken by wind and waves, it has similar reflectance spectral characteristics to *Trapa*, and the two are close to each other during the growing period, and they are often mixed, forming a unique *Trapa*–*Potamogeton crispus* community in Futou Lake. Combining the growth cycle of the dominant community and the time of image transit, a field survey of aquatic vegetation in the Futou Lake was conducted on 11 May 2022, with a total of 18 sample points (13 sample points of *Trapa*–*Potamogeton crispus* community and 5 sample points of open water). The information collected included the longitude and latitude of sample points, the type of aquatic vegetation, the coverage, and the photos. When collecting the sample points, we chose to locate and sample at the center of the aquatic vegetation area of 30×30 m (Figure 2).

Figure 2. The field photos of aquatic vegetation in Futou Lake on 11 May 2022.

2.3. Sentinel-2 Data and Pre-Processing

Sentinel-2 satellite consists of A and B double stars, launched on 23 June 2015 and 7 March 2017, respectively. This is a high-resolution multispectral imaging satellite, covering 13 spectral bands, up to a spatial resolution of 10 m, with the altitude of 786 km, the width of 290 km, and the dual-star complementary re-entry period down to 5 d [24]. The image data can be downloaded from the European Space Agency (ESA) data distribution website (https://scihub.copernicus.eu/, accessed on 26 September 2022), where the L1C level data are geometrically and radiometrically corrected atmospheric apparent reflectance products, which need to be atmospherically corrected. In this paper, we use the Sen2cor module in the official SNAP software (India) provided by ESA to perform atmospheric correction on the images, resample all bands to 10 m resolution by nearest-neighbor interpolation, and then use ENVI 5.3 to perform band synthesis and cropping.

To monitor the spatial and temporal changes of aquatic vegetation in the Futou Lake after the fence removal, this paper extracts the distribution range of aquatic vegetation in the Futou Lake using a total of six image data on 30 April 2016, 5 May 2017, 10 April 2018, 10 May 2019, 29 April 2020, 9 May 2021, and 4 May 2022, in conjunction with the growth cycle of aquatic vegetation.

2.4. Remote Sensing Extraction Method for Aquatic Vegetation

2.4.1. The SAVI–Otsu Method

The Otsu algorithm is suitable for threshold calculation in decision tree classification methods [19]. The Otsu algorithm uses the clustering idea to divide the original image into two classes, foreground and background, according to the image grayscale characteristics, so that the maximum variance of grayscale values between classes and the minimum variance within classes, where the partition threshold t is the value with the maximum variance between classes using the traversal method. The principle is as follows.

$$g = \omega_0\omega_1(\mu_0 - \mu_1)\wedge^2 \quad (1)$$

where g is the interclass variance; ω_0 is the proportion of foreground pixel points to the image; μ_0 is the average grayscale of foreground pixel points; ω_1 is the proportion of the number of background pixel points to the image; μ_1 is the average grayscale of background pixel points; $\mu = \omega_0 \times \mu_0 + \omega_1 \times \mu_1$ is the total average grayscale of the image.

The SAVI was proposed by Wang et al. [20], and the SAVI was constructed by using the red edge band at 705 nm and the green band at 560 nm, where the difference between the spectral of water bodies and submerged vegetation is most prominent. It therefore contributes to achieving the extraction of submerged vegetation.

$$\mathrm{SAVI} = \frac{\rho_{red\_edge} - \rho_{green}}{\rho_{red\_edge} + \rho_{green}} \tag{2}$$

where ρ_{red_edge} is the red-edge band reflectance of the image data with a central wavelength of 705 nm; ρ_{green} is the green band reflectance of the image data with a central wavelength of 560 nm.

2.4.2. The SAVI–Manual Method

Theoretically, the probability density distribution of both the target feature and the background feature can be characterized by normal distribution after the image is transformed by an index sensitive to the study object, so the probability density distribution of the image will present multiple normal distributions after the waveband transformation process. Assuming that the spectral index is sensitive to a target feature, then the feature image probability density distribution shows an obvious normal distribution with less overlap with the normal distribution of the background feature and strong separability [19]. Then, the frequency histogram of the vegetation index can be visually discriminated, and the shape of the normal distribution of the target and background land types can be maximally preserved for manual threshold delineation.

Based on the SAVI, the classification results of the Otsu algorithm and manual division threshold were compared, and the applicability of the Otsu algorithm in extracting aquatic vegetation could also be verified. Therefore, for Sentinel-2 data, it is also necessary to extract aquatic vegetation in the Futou Lake using the SAVI combined with the manual division threshold.

2.4.3. The NDVI–Otsu Method

The spectral characteristics of healthy vegetation are high absorption and low reflection in the red band, while the spectral characteristics in the NIR band are high reflectance, and the reflectance rises sharply at 705 nm around, forming the phenomenon of "red edge". Therefore, the NDVI is used to distinguish between aquatic vegetation and water bodies, which is calculated as follows:

$$\mathrm{NDVI} = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \tag{3}$$

where ρ_{nir} is the NIR band reflectance of the image data with a central wavelength of 842 nm; ρ_{red} is the red band reflectance of the image data with a central wavelength of 665 nm.

The method first enables the images to enhance the differences between aquatic vegetation and water bodies through the feature index transformation, and then uses the Otsu algorithm for the determination of classification thresholds.

2.4.4. The NDVI–Manual Method

The method firstly transforms the images by the NDVI so that the images can enhance the differences between aquatic vegetation and water bodies, and then uses the probability density distribution function of the transformed feature images to manually divide the thresholds for the determination of the classification threshold using the assumption that the probability density distribution function of each class of features conforms to a normal distribution.

3. Results

Based on Sentinel-2 images, the aquatic vegetation in the Futou Lake was extracted through the four methods, the SAVI–Otsu, the SAVI–Manual, the NDVI–Otsu, and the NDVI–Manual.

3.1. Accuracy Verification Based on the Four Methods

Figure 3 shows the frequency histograms of SAVI and NDVI on 4 May 2022 for the Futou Lake, and the segmentation thresholds of 0.0275 and 0.0824 for SAVI–Otsu and NDVI–Otsu, respectively, were calculated using MATLAB 2019b. The manual division thresholds were obtained as −0.0408 and −0.02 for SAVI–Manual and NDVI–Manual, respectively.

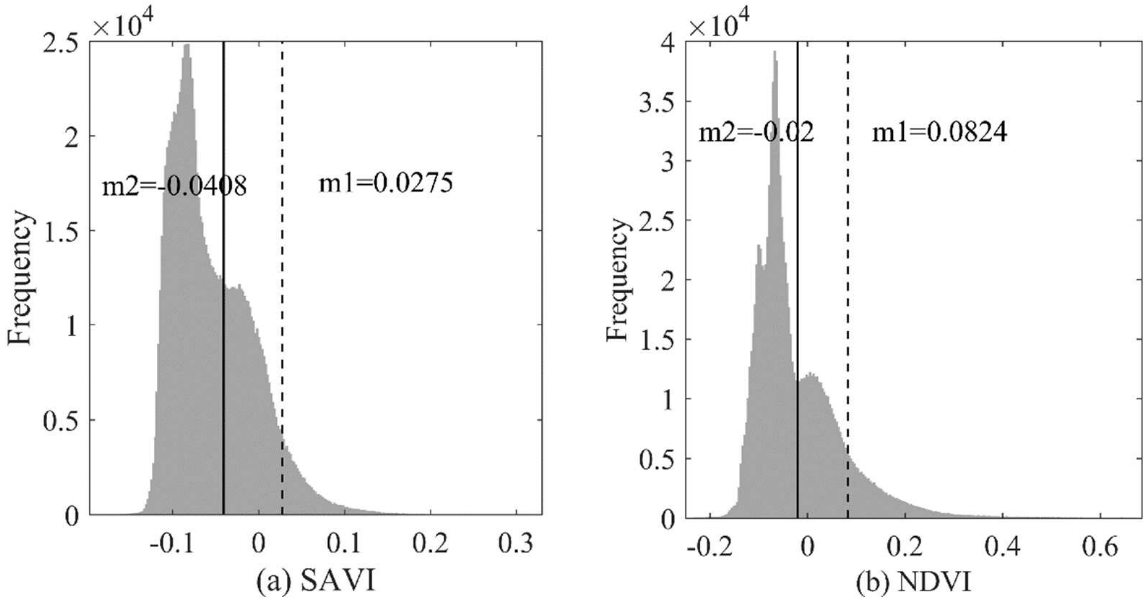

Figure 3. SAVI histogram and NDVI histogram of spectral classification features of the Futou Lake on 4 May 2022. (m1: segmentation threshold derived from the Otsu algorithm; m2: segmentation threshold derived from the manual method.).

A decision tree (Figure 4) was constructed based on the segmentation thresholds, and aquatic vegetation extraction (Figure 5) was performed for the 4 May 2022 image. The field data were also used for validation, and Table 1 shows the classification error matrix. The results showed that the overall accuracy and Kappa coefficient of aquatic vegetation classification of SAVI–Otsu and NDVI–Otsu methods were 66.67% and 39.33%, respectively, which were much smaller than the extraction accuracy of SAVI–Manual and NDVI–Manual. Therefore, the classification effect of manual threshold segmentation method far exceeded that of Otsu algorithm. The NDVI–Manual method achieves 100% extraction accuracy of aquatic vegetation, which far exceeds 92.31% of SAVI–Manual method. Comparing the precision, F1, overall accuracy, and Kappa coefficient of the two methods, the accuracy of the NDVI–Manual method is higher than that of SAVI–Manual. Therefore, the NDVI extracted better. Finally, we chose the result of aquatic vegetation extraction by the NDVI–Manual method, and the overall accuracy of aquatic vegetation classification was 94.44% and the Kappa coefficient was 85.23%.

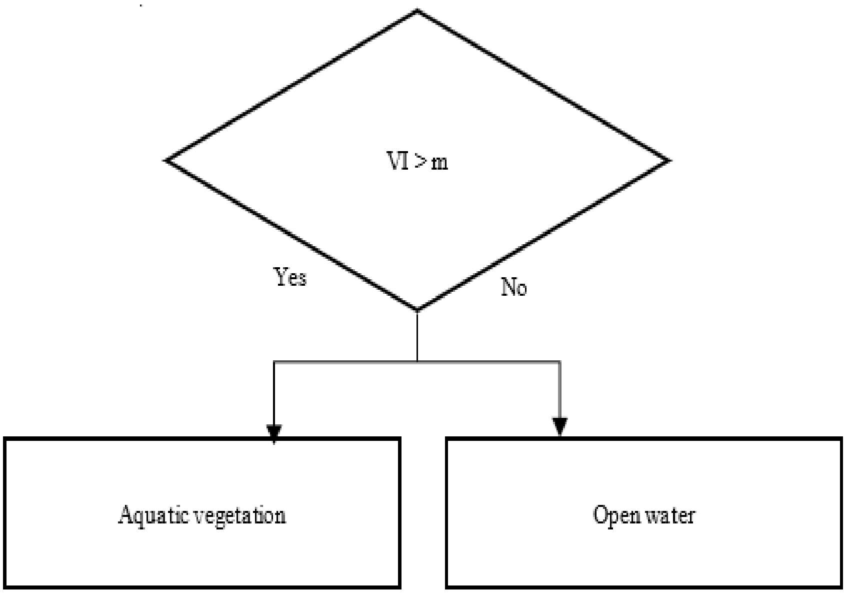

Figure 4. Futou Lake aquatic vegetation remote sensing classification decision tree. (VI: vegetation index, including SAVI, NDVI; m is the classification threshold).

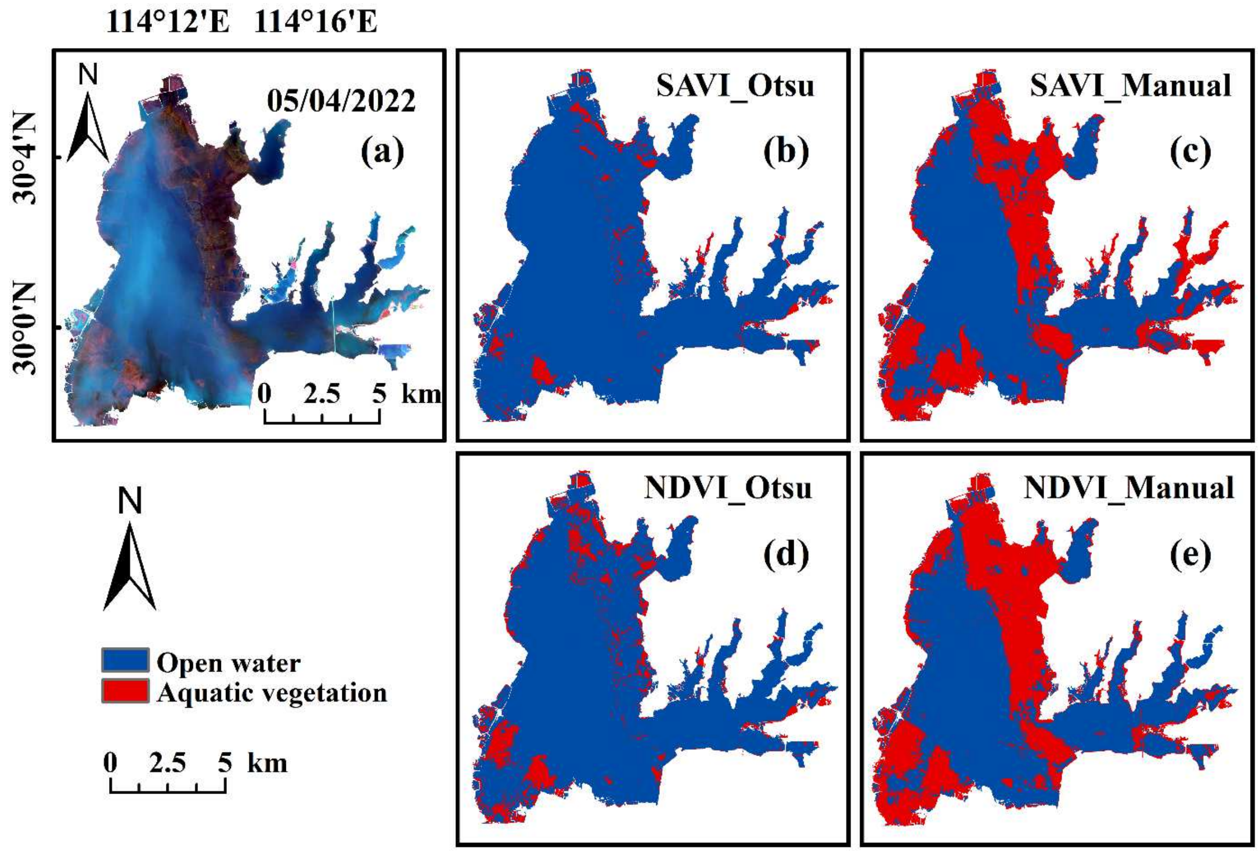

Figure 5. The false color image map and aquatic vegetation classification results on 4 May 2022.

Table 1. Classification accuracy of aquatic vegetation in Lake Futou.

4 May 2022			Classification Results							
			Aquatic Vegetation	**Open Water**	**Accuracy/(%)**	**Precision/(%)**	**F1/(%)**	**Overall Accuracy/(%)**	**Kappa/(%)**
In situ data	SAVI–Otsu	Aquatic vegetation	7	6	53.85	100	70	66.67	39.33
		Open water	0	5	100				
	SAVI–Manual	Aquatic vegetation	12	1	92.31	92.31	92.31	88.89	72.31
		Open water	1	4	80				
	NDVI–Otsu	Aquatic vegetation	7	6	53.85	100	70	66.67	39.33
		Open water	0	5	100				
	NDVI–Manual	Aquatic vegetation	13	0	100	92.86	96.30	94.44	85.23
		Open water	1	4	80				

3.2. Classification of Aquatic Begetation Based on the NDVI–Manual Method

The NDVI–Manual method was used to classify the aquatic vegetation in the Futou Lake from 2016 to 2021 (Figure 6). The results show that the classification results match well with the original images on the same date in terms of visual effects. From the classification results, it can be seen that the overall distribution area of the aquatic vegetation in Futou Lake is mainly in the northeast, followed by the southwestern waters, and a small amount of aquatic vegetation is also distributed in the branching part of the lake. The distribution of the aquatic vegetation in the Futou Lake on 30 April 2016 and 5 May 2017 is less, and it is mainly distributed in the shoreline waters of the northern part of the lake. The classification results on 10 April 2018 show that the NDVI extracts the aquatic vegetation growing at the original seine, the grid-like features are clearly visible, and the aquatic vegetation is mainly distributed in the main body of the lake. The classification results on 10 May 2019 showed that the aquatic vegetation was mainly distributed in the waters of the northeastern and southwestern part of the lake. The distribution of aquatic vegetation on 29 April 2020 began to expand to the lake center area and the distribution area increased. The image classification on 9 May 2020 results showed that on the basis of the distribution in the waters of the northeastern and southwestern part of the lake, the distribution of aquatic vegetation also began to be found in the southeastern lake branch.

After classifying the aquatic vegetation in the study area from 2016 to 2021 using the NDVI–Manual method, the average reflectance spectral curves were calculated for each category (Figure 7). It can be seen that the spectra extracted based on the NDVI–Manual method are consistent with the actual spectral: the reflectance of aquatic vegetation is lower than that of the water body in the blue and green bands, but the reflectance rapidly climbs to form a "red edge" at 705 nm, as well as a continuous high reflectance peak in the near-infrared band. The spectral curves of the two vegetation species are a combination of submerged and floating leaf vegetation spectral features, which is consistent with the field observation of the *Trapa–Potamogeton crispus* community. Table 2 shows the segmentation thresholds.

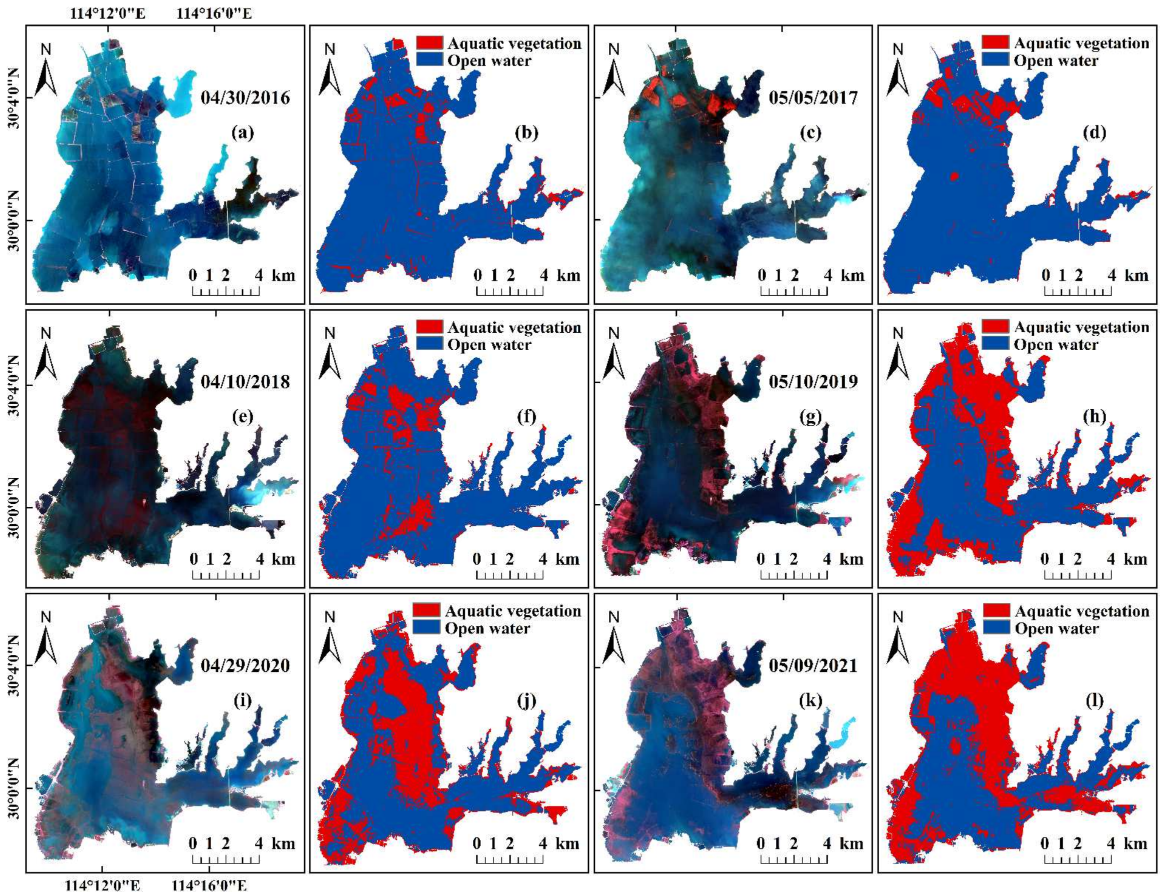

Figure 6. False-color satellite images from 2016 to 2021 and aquatic vegetation classification results were obtained by the NDVI–Manual method.

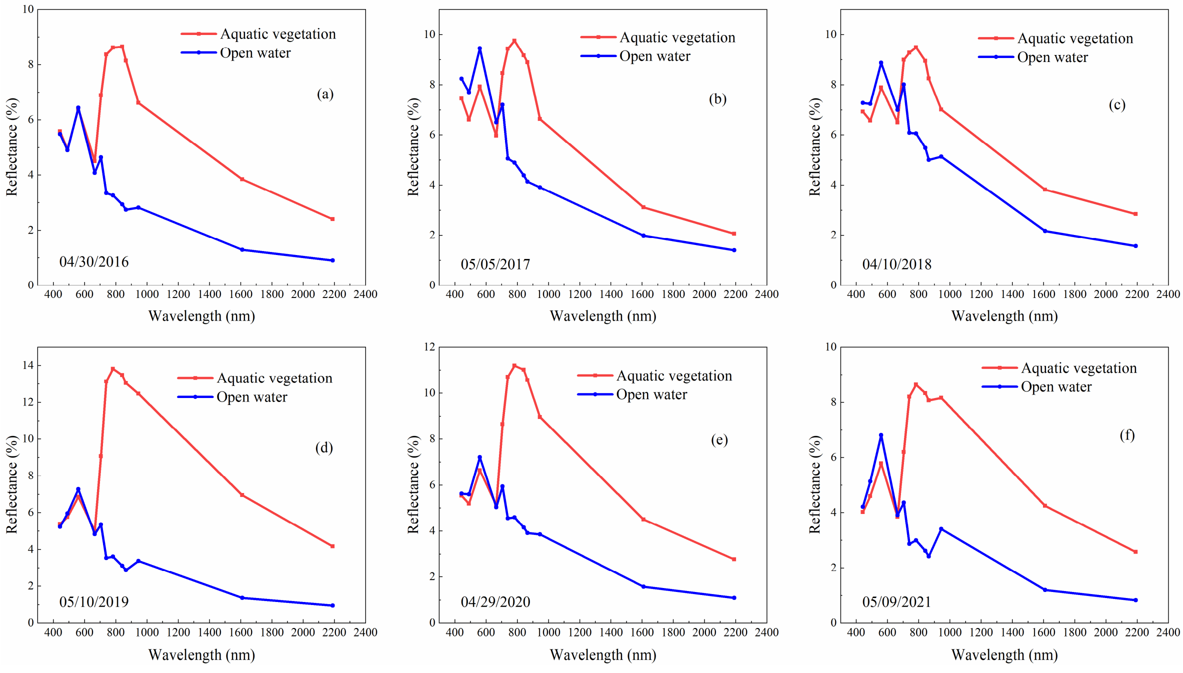

Figure 7. Average reflectance spectral curve of each category.

Table 2. Segmentation threshold table of NDVI.

Segmentation Threshold	Image Date					
	30 April 2016	**5 May 2017**	**10 April 2018**	**10 May 2019**	**29 April 2020**	**9 May 2021**
m (NDVI)	0.0524	−0.0109	0.0853	0.0682	0.1465	0.0064

3.3. Analysis of Classification Results

The area change statistics of aquatic vegetation extraction results based on the NDVI-Manual method were obtained in Figure 8. As shown in the figure, the change of the aquatic vegetation area of Lake Futou is divided into two stages. The first stage is enclosing culture, and the distribution of aquatic vegetation is less in 2016–2017, all around 10 km^2. The second stage is after the removal of the fence, the distribution area of aquatic vegetation in 2018 is on an upward trend, and in 2019–2022 is growing rapidly, and the distribution range is all above 40 km^2, while the peak of the distribution area of aquatic vegetation appears in 2021, which is about 50.90 km^2, accounting for about 47.9% of Futou Lake.

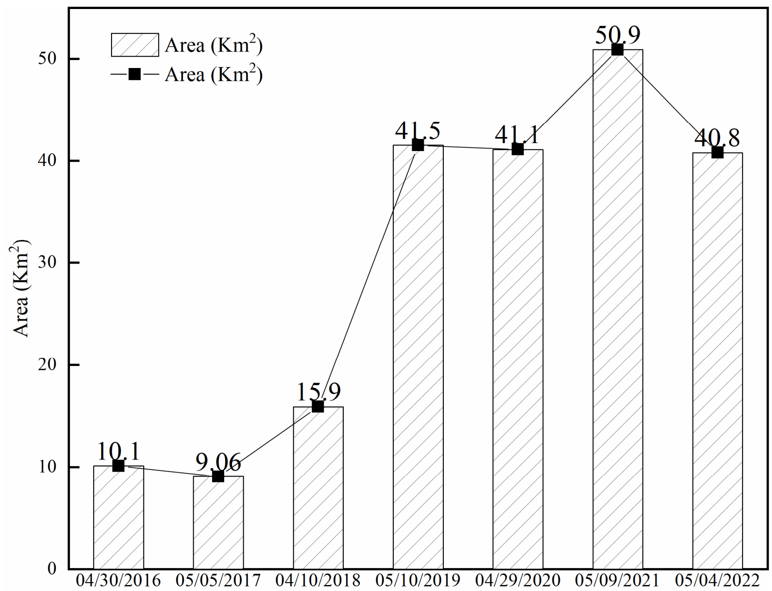

Figure 8. Area changes of aquatic vegetation taxa in Futou Lake from 2016 to 2022.

From the results (Figure 6), it can be seen that the aquatic vegetation was mainly distributed at the former fence, specifically in the northeastern and southwestern waters of the lake. In terms of temporal changes, the aquatic vegetation taxa gradually recovered after the removal of the fence, and the distribution area peaked in 2021 and slightly retracted until 2022.

4. Discussion

(1) Aquatic vegetation monitoring using Sentinel-2 data. Sentinel-2 is a high-resolution multispectral imaging satellite, which can improve classification accuracy and get finer results on the distribution of aquatic vegetation [20]. With a complementary re-entry period of 5 days and a spatial resolution of up to 10 m, Sentinel-2 is the only data containing 3 bands in the red-edge range, which is very effective for monitoring the spectral information of vegetation, especially aquatic vegetation.

(2) The current growth condition of the aquatic vegetation in the Futou Lake is still influenced by the history of purse-net farming. From the late 1980s, high-density seine farming activities was carried out in the Futou Lake, resulting in a significant reduction in the number of aquatic vegetation communities and eutrophication in some water bodies [22].

In 2008–2013, the succession of aquatic vegetation in the Futou Lake began to develop toward a cis-successional stage, resulting in a significant increase in the area covered by the P.C community and the *Zizania latifolia* association in the Futou Lake [13]. Although the fencing of Futou Lake has now been fully carried out, the history of seine farming has resulted in the degradation of the structure and function of the water ecosystem of the Futou Lake and the simplification of the structure of the aquatic plant community, so the recovery of the water ecosystem is still a long process. Meanwhile, due to historical siltation and accumulation of nutrients, conditions are provided for the outbreak of spring PC community [25]. In addition, suitable temperatures during the alternate spring and summer seasons are also an important factor in the outbreak of P.C [26]. In 2019–2022, the growth area of aquatic vegetation was above 40 km^2 and started to occupy the location of the lake center area, which is accelerating the process of swampiness of Futou Lake.

(3) The spatial distribution range of aquatic vegetation in Futou Lake from 2016 to 2022 was mainly at the original seine culture, expanding to the lake center area in 2020 and also in the southeastern lake branch area in 2021. The change in the area of aquatic vegetation from 2016–2022 was divided into two parts, with a small distribution of aquatic vegetation from 2016–2017 and a significant increase in 2018–2022. In 2016–2017, aquatic vegetation was mainly distributed at the original seine culture, and grid-like dividing lines were clearly visible. It was clearly visible, which may be due to the accumulation of nutrient salts such as nitrogen and phosphorus caused by the seine culture period, which provides conditions for the growth of aquatic vegetation. In 2018, aquatic vegetation was evenly distributed in the main waters of the lake, and grid-like features were still clearly visible. Xu et al. [23] showed that most of the aquatic plants in Jianghan Lake area grow in the shallow water area along the lake and at the intersection of land and water, while now, the aquatic vegetation in the Futou Lake has started to spread to the center of the lake on a large scale, which should be due to the siltation and elevation of the lake bottom. In 2019, aquatic vegetation started to grow in succession, and the distribution area expanded rapidly, about 41.5 km^2, mainly in the near-shore area in the northeast of the lake and the southwestern waters. In 2020, the distribution of aquatic vegetation based on the near-shore area started to expand to the lake center area, and the pH value was found to be abnormally high in the lake center of the Futou Lake during the same period, with the pH value exceeding 9, perhaps due to the large growth of PC. By 2021, the distribution of aquatic vegetation in the Futou Lake reached its peak area of 50.9 km^2, and a large amount of aquatic vegetation started to grow in the southeastern branch of the lake based on the original spatial distribution, and it connected with the northeastern aquatic vegetation growth area. According to the website of the China Meteorological Administration (https://weather.cma.cn, accessed on 26 September 2022), from 1 May 2021 to 9 May 2021, the southeastern wind prevailed in the Futou Lake area, so the phenomenon of connected distribution may be caused by the wind direction. Dai et al. [5] found that wind disturbance promoted the growth of submerged vegetation in the Futou Lake. In 2022, the distribution area of aquatic vegetation decreased, but the distribution range is still dominated by the near-shore area in the northeastern part of the lake and the southwestern waters.

(4) The choice of the threshold segmentation method has a much greater impact on the classification results of aquatic vegetation than the choice of vegetation index. Comparing the aquatic vegetation extraction results of the four methods on 4 May 2022 (Figure 5) and the classification accuracy of the aquatic vegetation of the Futou Lake (Table 1), it can be seen that the extraction results based on the Otsu algorithm are poor, and the aquatic vegetation extraction results of the SAVI–Manual method are much better than those of the SAVI–Otsu method, but the extraction results are similar to those of NDVI–Manual. However, the NDVI index works better in distinguishing the aquatic vegetation growth area and the lake branch with high algal density.

(5) According to the field survey, the aquatic vegetation community in the Futou Lake is dominated by the *Trapa*–*Potamogeton crispus* community. Aquatic vegetation is an important part of the lake ecosystem and plays an important role in improving water quality [1];

however, moderate local and interval harvesting should be carried out when aquatic vegetation (especially P.C) is overgrown because P.C absorbs nitrogen and phosphorus during growth and purifies the water quality, but decomposition and oxygen consumption after death and decay will cause ammonia nitrogen and high manganese index to rise and dissolved oxygen to decrease. Correspondingly, the absorbed nitrogen and phosphorus will be re-released and cause water quality to deteriorate [25]. Therefore, the PC should be salvaged in time after death to reduce nutrient salt concentration in lake water. In addition, the species of aquatic plants in the Lake Futou are too homogeneous at present. In this viewpoint, increasing and restoring the diversity of aquatic plants appropriately is an important aspect to promote the health of the lake ecosystem and improve water quality.

(6) Aquatic vegetation is an important part of the lake ecosystem and has an important impact on water quality. Further discussions need to be conducted in the future on how aquatic vegetation affects water quality, the different intervals of water quality in areas with and without aquatic vegetation growth, and the quantitative relationship between aquatic vegetation and water quality.

(7) Limitations: Since the Futou Lake area has a subtropical continental monsoon climate with abundant rainfall and more clouds, there are not many images available throughout the year, and it is difficult to collect remote sensing images with short time series intervals. The next step can be to try to carry out a coordinated multi-source remote sensing image to conduct a more detailed study on the dynamic changes of aquatic vegetation taxa after the removal of the fence in the Futou Lake. Moreover, the contribution of atmospheric path radiance in the visible spectrum exceeds water-leaving radiance by at least 80–90% [27]. However, due to the complexity and variability of the atmospheric environment, there is no good way to eradicate the atmospheric influence so far. Many scholars are currently working on atmospheric correction methods, but this is not the subject of this work, so we do not explore it too much. We only choose to use the Sen2cor plug-in published by ESA, which is dedicated to atmospheric correction of L1C-level data. Therefore, we will do a comparison of atmospheric correction methods based on Sentinel-2 images in the future to get better quality data.

5. Conclusions

In this paper, we developed four methods through the combinations of two vegetation indices (SAVI and NDVI) and two threshold algorithms (Otsu and manual division) for the aquatic vegetation monitoring. The four methods (SAVI–Otsu, SAVI–Manual, NDVI–Otsu, and NDVI–Manual) were applied to extract the aquatic vegetation of Futou Lake on 4 May 2022, as well as being analyzed to decide the better method. Then, the optimal method was used to extract the aquatic vegetation from 2016 to 2021. The main conclusions are the following.

(1) The NDVI and Manual method perform the best in extracting aquatic vegetation from the Futou Lake. NDVI is good in distinguishing between lake branches with high algae density and turbid water and aquatic vegetation, and the manual division threshold method can achieve the identification of aquatic vegetation under thin cloud coverage based on this index. SAVI is constructed using B3 and B5 bands, and the B5 band is sensitive to both submerged vegetation and algae. The Otsu algorithm works well in extracting actively growing aquatic vegetation but is not very sensitive to submerged vegetation.

(2) The two threshold determination methods do not depend on the in situ data and focus more on the vegetation index selection. The segmentation threshold of each image is calculated according to the characteristics of the image, but the basis of the algorithm application is the vegetation index, and the classification effect of the same method is different for images processed with different vegetation indices.

(3) The spatial distribution of aquatic vegetation in the Futou Lake is mainly concentrated in the former seine culture area, and the grid-like demarcation line can be seen. The inter-annual variation shows that the distribution area was small from 2016 to 2017, began to increase in 2018, and increased significantly from 2019 to 2022.

(4) The enclosing farming activities may affect the growth of aquatic vegetation. The distribution area of aquatic vegetation in the Futou Lake showed a gradual increase from 2017 after the basic abolition of the purse-net farming activities, indicating that the previous enclosing farming activities hindered the growth of aquatic vegetation and disrupted the normal succession process of large aquatic vegetation in the lake.

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