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RESEARCH ARTICLE

Inversion of Chlorophyll-a Concentrations in Chaohu Lake Based on GF-1 WFV Images

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ABSTRACT Chlorophyll-a is an important parameter that is used to measure the water quality, and its concentrations indicate the degree of eutrophication. Taking the waters of Chaohu Lake as the research area, four remote sensing inversion models of the chlorophyll-a concentrations were constructed based on GF-1 WFV images using empirical and semiempirical/semianalytical methods. The optimal model was selected by evaluating the model validation accuracies, and this model was used to invert the spatial distributions of the chlorophyll-a concentrations in the waters of Chaohu Lake from May to July 2017. The results show that the NDCI model is the most suitable for inverting chlorophyll-a concentrations in the waters of Chaohu Lake based on GF-1 WFV images. This model has the highest validation accuracy, with a determination coefficient of 0.933, a Root mean square error of 2.85 μg/L and a mean absolute percentage error of 19.69%. The spatial distributions of the chlorophyll-a concentrations in the waters of Chaohu Lake from May to July 2017 all showed decreasing trends from Western Half Lake to Eastern Half Lake, the areas of higher chlorophyll-a concentrations in May and June were mainly concentrated in the northern waters of Western Half Lake, and the area with the highest chlorophyll-a concentrations in July was located in the northwestern waters of Middle Half Lake. The mean chlorophyll-a concentration in the waters of Chaohu Lake from May to July 2017 was 12.5 μg/L, which indicated slight eutrophication.

INDEX TERMS Chlorophyll-a concentration, GF-1 WFV, Chaohu Lake, remote sensing inversion, spatial distribution.

I. INTRODUCTION

Rapid economic growth and frequent human activities have led to increasing water pollution levels, lake ecosystems have been damaged, cyanobacterial blooms have begun to appear, and the problems in aquatic environments and ecological issues have become increasingly serious [1]. The chlorophyll-a concentrations are an important factor for representing the ecological status of lakes and, to some extent, reflect the water quality and phytoplankton abundances, which make these concentrations one of the most important parameters for remote sensing monitoring of water quality [2], [3]. Therefore, obtaining timely and accurate knowledge of the spatial and temporal distributions and evolutionary trends of the chlorophyll-a concentrations are one of the key initiatives for sustainable watershed development and environmental protection [4].

At present, the main methods that are used for monitoring chlorophyll-a concentrations are the direct method of manual monitoring and the indirect method of remote sensing monitoring. The direct method mainly involves collecting water samples from lakes in the field and testing the water samples in the laboratory to determine the chlorophyll-a concentrations at the time of sampling. Although this method can accurately analyze and evaluate the chlorophyll-a concentrations at sampling points, it requires human, material

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and financial resources, and we obtain only sample data. This approach has certain limitations when monitoring the chlorophyll-a concentrations over large areas of water, and it is difficult to meet the requirements for high-frequency and large-scale monitoring [5]. In comparison, the remote sensing monitoring method is based on sampling point data to mathematically analyze the reflectivity factors and chlorophyll-a concentrations in remote sensing images to construct an appropriate chlorophyll-a concentration inversion model and to then use this model to invert the chlorophyll-a concentrations in the whole watershed; this approach has the advantages of wide coverage and cyclical monitoring, allowing continuous monitoring of large areas of water [6], [7], [8].

The main methods that are used to construct models for remote sensing inversion of chlorophyll-a concentrations include empirical models, semiempirical/semianalytical models and analytical models, all of which have their own strengths and weaknesses [9], [10]. Among them, the empirical and semiempirical/semianalytical models have been widely used for inverting the chlorophyll-a concentrations in lakes. Liu et al. [11] performed remote sensing inversion of chlorophyll-a concentrations by using a semiempirical model based on OLCI image data, and the results showed that this method can be effectively used to estimate the chlorophyll-a concentrations under different turbidity conditions. Fan et al. [12] applied a stepwise regression model to invert the chlorophyll-a concentrations in the southwestern sea area of Hainan Island using the red and near-infrared bands that were obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) images based on the empirical model of OC_3M. Bu et al. [13] used the inversion model of PMS-C, constructed from the band combinations of GF-4 PMS images for remote sensing inversion, and combined with HY-C CZI images to analyze the spatial distribution of chlorophyll-a concentration in the Yangtze River Mouth. Feng et al. [14] achieved high accuracy in inverting the chlorophyll-a concentrations in the waters of Chaohu Lake using a three-band model based on a combination of bands from OHS-2A images and concluded that the highest concentrations were present in the northern waters of Western Half Lake at the time of the study. Diao et al. [15] used GF-1 WFV images as the data source, adopted an empirical model inversion algorithm, correlated the reflectances of a single band or combination of bands with the measured chlorophyll-a concentrations of the water body, selected the three-band model with the largest coefficient of determination as the inversion model to validate the accuracy of the model, and applied the model to the remote sensing inversion of the chlorophyll-a concentrations in Nansihu Lake. Jin et al. [16] selected a single-band model consisting of the red bands as the inversion model for their study based on previous research results and inverted the chlorophyll-a concentrations in Zhejiang Province from 1990 to 2022 based on Landsat series data. Using Sentinel-2 images, Zhao et al. [17] developed an OWT-based chlorophyll-a concentration inversion model and achieved dynamic monitoring and analysis of the chlorophyll-a concentrations in the world's 3067 largest lakes ($\geq$50 km^2) through the use of the Google Earth Engine platform. Although additional research has been carried out by national and international scientists, there are still challenges associated with the remote sensing of chlorophyll-a concentrations:

1) Accuracy of the inversion model: The accuracy of the inversion model is affected by a number of factors, such as the data quality, optical properties of the water body and contingencies of the model algorithm. In the chlorophyll-a concentration inversion study, although the optimal band combination of chlorophyll-a concentrations and remotely sensed reflectance correlation was selected, the coefficients of determination for inversion models that do not consider different model forms and different band combinations differ very little, even by as little as 0.01 [13]; only through using the coefficients of determination to screen for the best inversion model without evaluating the model accuracy of this approach does this approach contain a certain degree of chance and does not fully prove the accuracy of the inversion model.

2) Universality of the inversion model: The optical properties of inland waters in lakes exhibit strong regional and seasonal variations [18], which lead to the inversion models of the water quality parameters that are established in each region not being universal. Therefore, for different water bodies, different seasons and different spatial resolutions of the satellite image data, the methods used to construct inversion models differ, and it is necessary to determine the appropriate inversion model according to the actual properties of the inversion object.

3) Spatial resolution of remote sensing images: The spatial resolution of remote sensing images determines their ability to capture small-scale spatial information. For chlorophyll-a concentration inversions in inland waters, mostly low- and medium-resolution remote sensing images are used; moreover, there is a lack of related research based on the application of high-resolution remote sensing images, and the accuracy of the constructed models needs to be improved to improve the accuracy and reliability of chlorophyll-a concentration inversions.

4) Complexity of water bodies: Inland waters have complex optical properties, such as suspended solids and yellow substances, and these factors can cause interference in remote sensing inversions of chlorophyll-a concentrations. To improve the accuracy of the inversion results, certain methods are needed to reduce or eliminate the interference due to these factors.

The 16-m resolution camera of GF-1 WFV has a wide field of view and multispectral detection capability and can effectively capture the absorption characteristics of chlorophyll-a in bands with different wavelengths; moreover, the higher spatial resolution can provide detailed spatial information on water bodies and more accurate remotely sense the reflectance data at the sampling points [19] to accurately

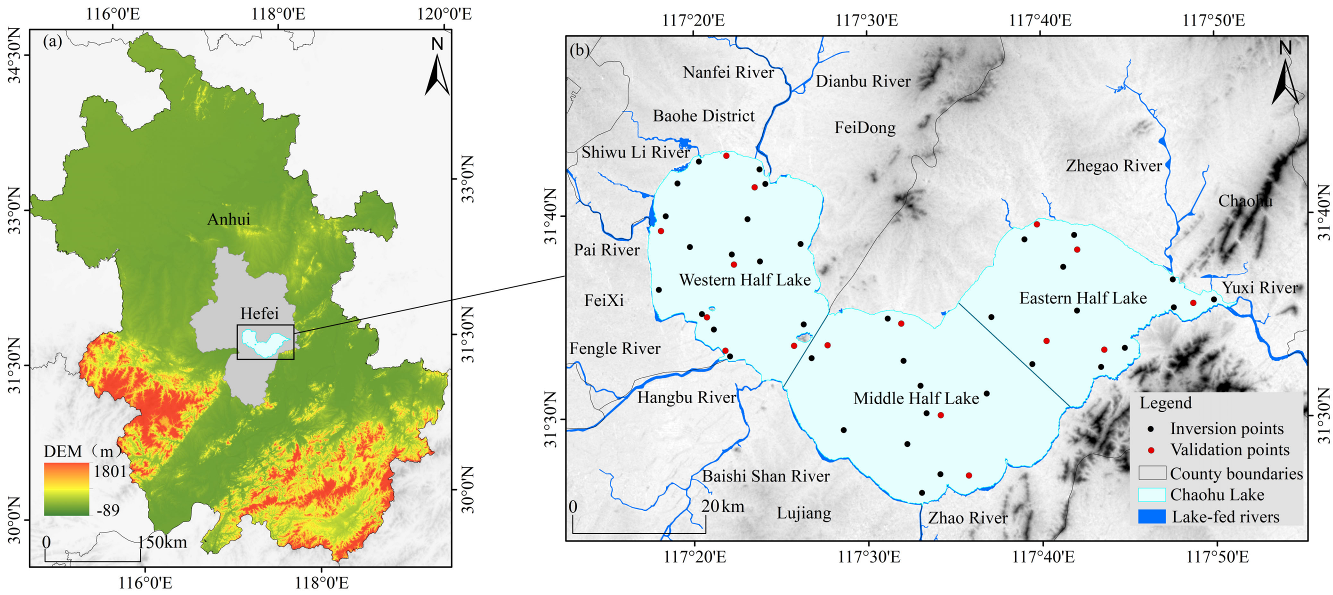

FIGURE 1. (a) Overview of the research area. (b) Locations of the sampling points.

estimate the chlorophyll-a concentrations in the water body; thus, this camera has been widely used in the remote sensing monitoring of water quality.

Chaohu Lake is an important source of drinking water in China, and the water quality affects the drinking water safety for people living around the lake. In recent years, a eutrophication trend in the waters of Chaohu Lake has been obvious, and quantitative inversions of the chlorophyll-a concentrations are one of the methods used to monitor the eutrophication of water bodies. At present, most chlorophyll-a concentration inversions are based on low- and medium-resolution image data. To improve the accuracy and reliability of the chlorophyll-a concentration inversion model, the present study used measured chlorophyll-a concentration data and high spatial resolution GF-1 WFV image data to construct inversion models by combining multiple wavebands; from these data, an inversion model with high accuracy was selected, and the validation accuracy of the models was subsequently compared to determine the best model for chlorophyll-a concentration inversions. The best model for chlorophyll-a concentration inversions can effectively avoid the randomness that can occur when determining the optimal model. The model was used to invert the chlorophyll-a concentrations in Chaohu Lake and to analyze its spatial distribution characteristics and the possible reasons for these changes. The research results can serve as a reference for large-scale water quality monitoring and assessments of lake waters and are of great practical significance for the management and control of lake water blooms and for the rational use of water resources and ecological and environmental protection in basins. Moreover, this approach has promoted the development of a domestically produced GF satellite series and the application of remote sensing technology.

The specific contributions of our research are as follows:

1) We propose an optimal model for inverting the chlorophyll-a concentrations in Chaohu Lake based on GF-1 WFV images; this model overcomes the influence of the optical properties of certain waters to some extent, has good generalizability and is able to accurately determine the chlorophyll-a concentrations.

2) We used the NDCI model to quantitatively determine the chlorophyll-a concentrations in the waters of Chaohu Lake and analyzed the spatial distribution characteristics and possible reasons for the changes in the chlorophyll-a concentrations in the waters of Chaohu Lake, which provides a reference for large-scale water quality monitoring and assessments of inland water bodies.

The remainder of this paper is organized as follows: Section II provides an overview of the study area. Section III presents the data used, the data sources and the research methods. In section IV, the process of determining the optimal inversion model is described, and the inversion model is used to invert the spatial distributions of the chlorophyll-a concentrations in the waters of Chaohu Lake; in section V, the spatial distribution characteristics of the chlorophyll-a concentrations are analyzed, as are the possible reasons for the variations. Finally, we summarize this study in Section VI.

II. STUDY AREA OVERVIEW

Chaohu Lake, located in Hefei city, Anhui Province (Fig. 1), is the fifth largest freshwater lake in China, with a total area of approximately 780 km^2 and geographic coordinates ranging from 31°26′ 29″ N to 31°44′ 30″ N and from 117°17′ 05″ E to 117°50′ 56″ E; these lakes can be classified into three regions: Western Half Lake, Middle Half Lake, and Eastern

TABLE 1. Statistics of the chlorophyll-a concentrations in the waters of Chaohu Lake (N represents the number of samples).

Sampling time	Maximum value/(μg/L)	Minimum value/(μg/L)	Mean value/(μg/L)	Standard deviation/(μg/L)
2017/5 (N=13)	10.65	8.65	9.90	0.540
2017/6 (N=27)	16.50	8.33	12.07	2.379
2017/7 (N=12)	18.96	8.92	11.24	3.132
Inversion points (N=36)	18.96	8.33	10.94	2.324
Validation points (N=16)	17.06	9.36	12.24	2.512

TABLE 2. Main technical specifications for the WFV cameras used for the GF-1 satellite.

Spectral Segment	Range/nm	Spatial resolution/m	Width/km	Return time/day
1	450-520	16	800 (combination of four cameras)	4
2	520-590			
3	630-690			
4	770-890			

Half Lake [14] (Fig. 1b). The study area has a subtropical monsoon climate with south and southeast winds prevailing in the summer. More than 30 rivers enter the lake, which are dominated by confluence tributaries such as the Hangbu River, Fengle River, Nanfang River and Yuxi River, and lake water flows into the Yangtze River through the Yuxi River. For the whole lake, the flow rate in Eastern Half Lake was greater than that in Western Half Lake. Due to the accelerated urbanization process around Chaohu Lake, the expanding scale of industrial and agricultural production and the rapid population growth, the amount of sewage discharged into the lake has increased rapidly, and large amounts of nutrients have been discharged into the lake, resulting in the eutrophication of the waters of Chaohu Lake and frequent cyanobacterial blooms [20].

III. STUDY DATA AND METHODS

A. STUDY DATA

1) MEASURED CHLOROPHYLL-A DATA

The chlorophyll-a concentrations were collected on 15-17 May, 16-18 June and 23-25 July in 2017. Fifty-two sampling stations were established in the waters of Chaohu Lake (Fig. 1b), and a handheld GPS was used at each station to obtain the latitudinal and longitudinal coordinates, while 500-mL water samples were collected. The samples were encapsulated in brown sampling bottles with preservatives, placed in a collection box at 0-4°C and taken to the laboratory for analysis. The test method used was spectrophotometry [21]. A total of 52 samples were collected and randomly divided into two groups, of which 36 samples were used for modeling and the remaining 16 samples were used for model validation (Table 1).

2) REMOTE SENSING IMAGE DATA AND PREPROCESSING

GF-1 is the first high-resolution domestic satellite in the dedicated Earth Observation System of Systems series and was successfully launched on 26 April 2013. It carries four multispectral cameras with resolutions of 16 m, and the multispectral bands are blue, green, red and near-infrared. It is possible to achieve a large field of view with a width of 800 km by using the field-of-view splicing technique with four cameras named WFV1, WFV2, WFV3 and WFV4 [22]. The specific technical parameters of the WFV cameras used for the GF-1 satellite are shown in Table 2.

The image data of Chaohu Lake that were obtained from the GF-1 satellite wide field-of-view sensor on 16 May, 17 June and 24 July 2017 were acquired at the China Resource Satellite Application Centre (http://www.cresda.com/CN/). These image data are disturbed by the atmospheric environment, the Earth's rotation and other factors, which cause errors and make it difficult to obtain accurate data standards, thus affecting the accuracy of quantitative inversions. Preprocessing of the GF-1 WFV image data was carried out using the tools in the ENVI 5.3 software toolbox, which mainly included radiometric calibration, atmospheric corrections and ortho-corrections. The selection of the atmospheric correction model strongly influenced the quantitative image inversion, and the ENVI 5.3 software provided two atmospheric correction models, FLASSH and QUAC. The FLASSH model has the advantages of supporting a wide range of sensors and high algorithmic accuracy, and it has been shown that [23], for water bodies, the FLAASH atmospheric corrections provide better results; therefore, this study used the FLAASH model for the atmospheric corrections.

3) METEOROLOGICAL ELEMENT DATA

The relationships among the changes in chlorophyll-a concentrations and environmental factors are complex, and meteorological factors can significantly influence these changes [24]. The meteorological factor dataset for Hefei city for May to July 2017 used in this study was obtained from the 2345 Historical Weather website (www.aqistudy.cn/historydata) by accessing the National Earth Observation Data Center (https://www.chinageoss.cn/), which records the daily temperature changes and basic air quality data for 288 prefecture-level cities in China from 2015 to 2019.

B. REMOTE SENSING INVERSION METHOD

In remote sensing inversions of chlorophyll-a concentrations, the relationships among the spectral response characteristics of the water quality parameters and chlorophyll-a concentrations are determined based on combinations of empirical and statistical methods; additionally, the spectral bands are analyzed, and different bands or combined bands are used to increase the differences between the absorption and reflectance peaks of chlorophyll-a. Additionally, an inversion model is constructed using mathematical analysis of the remote sensing data with the measured data [25].

The most commonly adopted method is to establish ratio models or combined models for the bands sensitive to chlorophyll-a when performing chlorophyll-a concentration inversions [26]. The band ratio model was first expressed as the blue-green two-band ratio, which has a high inversion accuracy in Class I water bodies such as oceans [27], but is not suitable for remote sensing inversions of the chlorophyll-a concentrations in inland lakes. Therefore, the two-band ratio model using near-infrared and red light was proposed [28]; this model interferes with optical effects such as suspended sediment and yellow matter during the inversions, but the accuracy when estimating the chlorophyll-a concentrations in water bodies is poor; therefore, the three-band ratio model [29] and four-band ratio model [30], which are suitable for highly turbid water bodies, were proposed. Furthermore, to improve the applicability of chlorophyll-a concentration inversion models in different waters, the normalized difference chlorophyll index (NDCI) model has been widely used in remote sensing monitoring efforts of water quality [31]. The expressions for the four models are shown below:

$$C_{Chla} \propto \frac{R_{rs}(B1)}{R_{rs}(B2)} \tag{1}$$

$$C_{Chla} \propto \frac{R_{rs}(B1) - R_{rs}(B2)}{R_{rs}(B1) + R_{rs}(B2)} \tag{2}$$

$$C_{Chla} \propto \left(\frac{1}{R_{rs}(B1)} - \frac{1}{R_{rs}(B2)}\right) \times R_{rs}(B3) \tag{3}$$

$$C_{Chla} \propto \left(\frac{1}{R_{rs}(B1)} - \frac{1}{R_{rs}(B2)}\right) \times \left(\frac{1}{R_{rs}(B3)} - \frac{1}{R_{rs}(B4)}\right) \tag{4}$$

Equations (1) to (4) denote the two-band model, the NDCI model, the three-band model and the four-band model, respectively, where C_{Chla} is the chlorophyll-a concentration and $R_{rs}(B1)$, $R_{rs}(B2)$, $R_{rs}(B3)$, and $R_{rs}(B4)$ are the remote sensing reflectance values involved in the calculations.

The four models are among the most common inversion models used for remote sensing inversions of water quality; these models involve easy computations and have high estimation accuracies; can overcome differences due to the differences in solar elevation angles and observation angles; can effectively eliminate the interference from certain meteorological factors; and can overcome to some extent the effects of water surface smoothness and tiny waves in space and time [32], [33]. In this study, we first analyzed the correlations among individual bands and the chlorophyll-a concentrations to determine the bands that were sensitive to the chlorophyll-a concentrations, and we then obtained a model with a higher inversion accuracy by combining multiple bands from a two-band model, an NDCI model, a three-band model and a four-band model. Finally, we determined the optimal inversion model based on the validation points to evaluate the model accuracies and inverted the chlorophyll-a concentrations in the waters of Chaohu Lake.

C. ASSESSMENT OF MODEL ACCURACY

To assess the reliability and accuracy of the inversion model for determining the chlorophyll-a concentrations, the coefficient of determination (R^2), root mean square error (RMSE) and mean absolute percentage error (MAPE) values were used as accuracy indices in this study. Larger R^2 and smaller RMSE and MAPE values indicate that the model has better performance and is able to fit and estimate the target variables more accurately. The formulas for calculating the RMSE and MAPE are as follows [34]:

$$\text{RMSE}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(C_{Chla} - C'_{Chla}\right)^2} \tag{5}$$

$$\text{MAPE}=\frac{1}{n}\sum_{i=1}^{n}\left|\frac{C_{Chla} - C'_{Chla}}{C'_{Chla}}\right| \times 100\% \tag{6}$$

where n is the number of validation samples and C_{Chla} and C'_{Chla} are the measured and estimated chlorophyll-a concentrations, respectively.

IV. RESULTS AND ANALYSIS

A. SENSITIVE BAND FOR CHLOROPHYLL-A

The reflectance of the remotely sensed images that were generated by GF-1 WFV at wavelengths ranging from 450 nm to 890 nm were correlated with the chlorophyll-a concentrations that were measured at 36 inversion points (Fig. 2). The red band showed the highest correlation with the chlorophyll-a concentrations, with a coefficient of determination of 0.570 (Fig. 2c) but still did not meet the accuracy requirements of the inversion study [35]. In addition to those of the red band, the coefficients of determination of the blue (Fig. 2a),

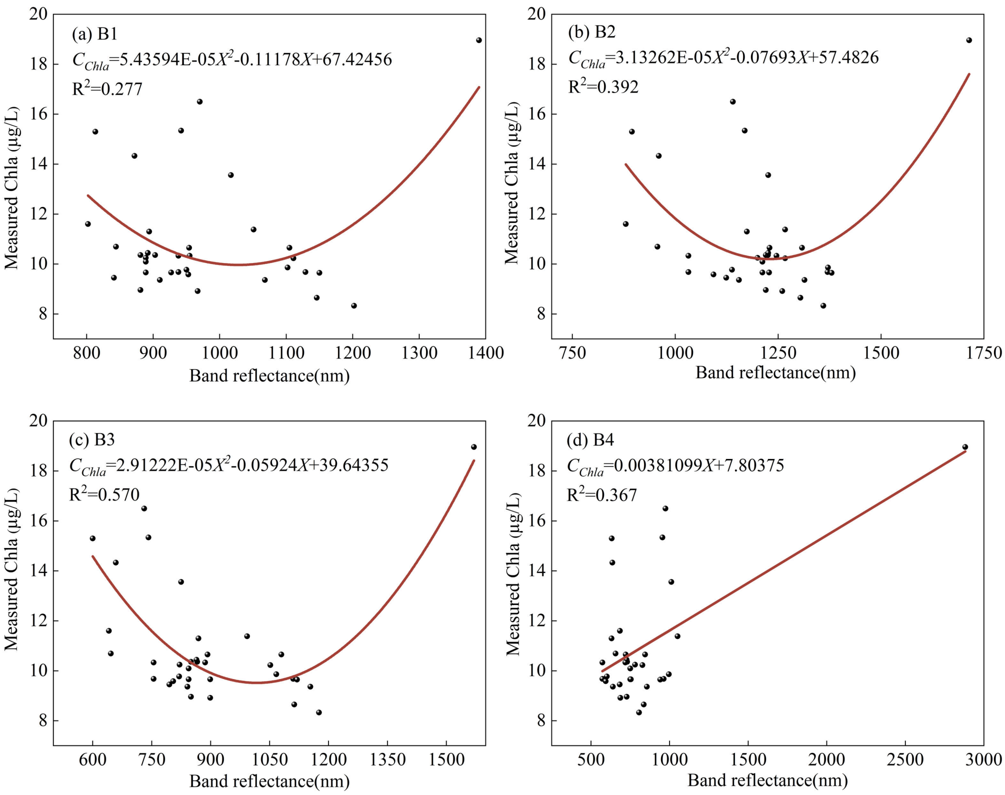

FIGURE 2. Correlations of single band reflectance values with the measured chlorophyll-a concentrations.

green (Fig. 2b) and near-infrared (Fig. 2d) bands were 0.277, 0.392 and 0.367, respectively, with the blue band having the lowest correlation with the chlorophyll-a concentrations. Therefore, inversion modeling of chlorophyll-a concentrations using a single band is inappropriate, and inversion modeling using a combination of bands should be considered [35], [36].

B. MODEL CONSTRNCTION

Four single bands were randomly combined according to the expressions defining the two-band model, NDCI model, three-band model and four-band model to analyze their correlations with the measured chlorophyll-a concentrations.

The coefficients of determination of the 60 band combinations used in this study ranged from 0.092 to 0.806. Linear, quadratic and exponential functions were fitted to the expressions of the selected band combinations with the measured chlorophyll-a concentration data, and 24 models with larger coefficients of determination were selected. The regression equations for the models with the corresponding functional relationships and coefficients of determination are shown in Table 3.

As shown in Table 3, the quadratic functions fitting the two-band B4/B3 band combination, the NDCI (B4-B3)/(B4+B3) band combination, the three-band $(1/\mathrm{B3} - 1/\mathrm{B4}) \times$ B2 band combination and the exponential function fitting of the four-band $(1/\mathrm{B3} - 1/\mathrm{B4}) \times (1/\mathrm{B2} - 1/\mathrm{B1})$ band combination had the largest coefficients of determination, namely, 0.786, 0.791, 0.806 and 0.773, respectively; moreover, the fitting results are shown in Fig. 3, and it can be assumed that all four models can be used to perform remote sensing inversions of the chlorophyll-a concentrations in the waters of Chaohu Lake. Therefore, the optimal inversion model needs to be determined after evaluating the model accuracies.

C. DETERMINING THE OPTIMAL MODEL

Sixteen sample points that were not involved in modeling were used to validate the accuracy of the model. A correlation analysis of the inversion estimates of the chlorophyll-a concentrations with the measured values (Table 4) revealed that the R^2 value for the NDCI model was 0.933, the R^2 values for the two-band and four-band models were 0.914 and 0.905, respectively, which were slightly lower than that of the NDCI model; moreover, the R^2 value for the three-band model was only 0.077, indicating that the inversion values of the chlorophyll-a concentrations obtained using the three-band model fit the measured values poorly and were not suitable for this study. The MAPEs of the four models were all in the range of 17.34-23.11%, which indicated that the prediction accuracies were relatively close; among them, the four-band model had the best MAPE, and the NDCI model had the second best. The RMSEs of the two-band, NDCI,

TABLE 3. **Band combination models and coefficients of determination.**

Model	Band Combination(*X*)	Function	Fitting Model	R^2
Two-band model	B4/B3	Linear	$C_{Chla} = 9.407X + 2.393$	0.785
	B4/B3	quadratic	$C_{Chla} = -0.585X^2 + 10.779X + 1.660$	0.786
	B4/B3	Exponential	$C_{Chla} = 6.166 \times 1.943^X - 0.470$	0.766
	B4/B2	Linear	$C_{Chla} = 9.293X + 4.697$	0.581
	B4/B2	quadratic	$C_{Chla} = -6.103X^2 + 22.237X - 1.022$	0.618
	B4/B2	Exponential	$C_{Chla} = 8.198 \times 1.768^X + 1.155$	0.543
NDCI model	(B4-B3)/(B4+B3)	Linear	$C_{Chla} = 20.792X + 12.154$	0.765
	(B4-B3)/(B4+B3)	quadratic	$C_{Chla} = 25.851X^2 + 19.449X + 11.745$	0.791
	(B4-B3)/(B4+B3)	Exponential	$C_{Chla} = 4.818 \times 24.064^X + 7.517$	0.780
	(B4-B2)/(B4+B2)	Linear	$C_{Chla} = 18.359X + 14.748$	0.612
	(B4-B2)/(B4+B2)	quadratic	$C_{Chla} = -0.660X^2 + 18.270X + 14.765$	0.612
	(B4-B2)/(B4+B2)	Exponential	$C_{Chla} = 5.403 \times 19.880^X + 9.439$	0.549
Three-band model	(1/B3-1/B4)×B2	Linear	$C_{Chla} = 7.458X + 12.380$	0.699
	(1/B3-1/B4)×B2	quadratic	$C_{Chla} = 9.965X^2 + 8.667X + 11.561$	0.806
	(1/B3-1/B4)×B2	Exponential	$C_{Chla} = -2.778 \times 4.599^X + 15.264$	0.778
	(1/B3-1/B4)×B1	Linear	$C_{Chla} = 8.867X + 12.319$	0.684
	(1/B3-1/B4)×B1	quadratic	$C_{Chla} = 14.548X^2 + 10.557X + 11.541$	0.801
	(1/B3-1/B4)×B1	Exponential	$C_{Chla} = -0.812 \times 7.129^X + 13.231$	0.786
Four-band model	(1/B4-1/B3)×(1/B2-1/B1)	Linear	$C_{Chla} = 1.041X + 11.935$	0.498
	(1/B4-1/B3)×(1/B2-1/B1)	quadratic	$C_{Chla} = 0.337X^2 + 1.800X + 11.509$	0.756
	(1/B4-1/B3)×(1/B2-1/B1)	Exponential	$C_{Chla} = -41.100 \times 0.979^X + 52.999$	0.481
	(1/B3-1/B4)×(1/B2-1/B1)	Linear	$C_{Chla} = -1.041X + 11.935$	0.498
	(1/B3-1/B4)×(1/B2-1/B1)	quadratic	$C_{Chla} = 0.337X^2 - 1.800X + 11.509$	0.756
	(1/B3-1/B4)×(1/B2-1/B1)	Exponential	$C_{Chla} = 1.951 \times 0.505^X + 9.1937$	0.773

where X is the reflectance of the band combination; B1, B2, B3 and B4 are the blue, green, red and near-infrared bands, respectively; and C_{Chla} is the measured chlorophyll-a concentration, unit µg/L.

three-band and four-band models were 2.93 μg/L, 2.85 μg/L, 5.06 μg/L and 3.24 μg/L, respectively, indicating that the inversion results of the two-band model and NDCI model were better and that those of the three-band model were worse.

In conclusion, the NDCI model is the optimal inversion model for determining the chlorophyll-a concentrations in the waters of Chaohu Lake based on the GF-1 WFV images. This model uses remotely sensed reflectance values in the red and near-infrared bands to construct the reflectance factors; this approach is more stable in waveband selection, yields a greater estimation accuracy when the optical differences in the water column are further extended [26], and is one of the most widely used empirical modeling algorithms for chlorophyll-a concentration inversions [9]. Compared with the commonly used empirical models and semiempirical/semianalytical models, the NDCI model yields a high estimation accuracy and good applicability to different months, different waters and different remote sensing image data; additionally, the NDCI model involves simple calculations and provides high estimation accuracies and practical inversion methods for determining the chlorophyll-a concentrations in inland lake waters [26].

D. SPATIAL DISTRIBUTION OF CHLOROPHYLL-A CONCENTRATIONS

Based on the inversion results obtained from the NDCI model, spatial distribution maps of the chlorophyll-a concentrations in the waters of Chaohu Lake from May to July 2017 were drawn (Figure 4). Studies have shown that when the chlorophyll-a concentrations in water bodies are greater than 20 μg/L, cyanobacterial blooms occur more frequently [37]; therefore, 20 μg/L can be used as the cutoff point for high and low chlorophyll-a concentrations. As seen from Figure 4, the chlorophyll-a concentrations in the waters of Chaohu Lake from May to July all showed a spatial distribution state that the concentrations in West Half Lake were higher than those in Eastern Half Lake, and all showed an obvious trend of diffusion from the high-concentration waters in the northern part of the Western Half Lake to Middle Half Lake and Eastern Half Lake, which is consistent with the results of the study conducted by Zhang et al. [38].

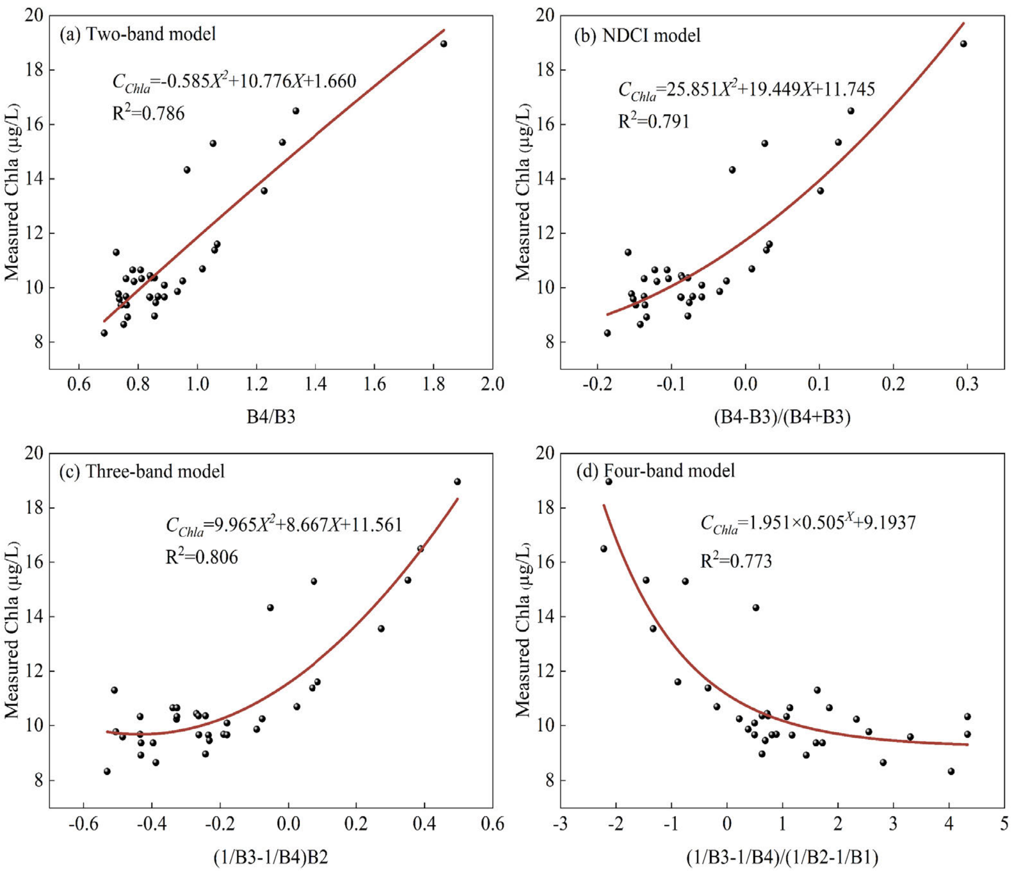

FIGURE 3. The fits with the largest coefficients of determination for each model.

TABLE 4. Validation results for the four inversion models.

Model	Function expression	R^2	MAPE/%	RMSE/(μg/L)
Two-band model	$C'_{Chla} = 0.6556\times C_{Chla} + 1.459$	0.914	22.08	2.93
NDCI model	$C'_{Chla} = 0.5103\times C_{Chla} + 3.445$	0.933	19.69	2.85
Three-band model	$C'_{Chla} = -0.1387\times C_{Chla} + 12.968$	0.077	23.11	5.06
Four-band model	$C'_{Chla} = -0.0524\times C_{Chla} + 11.099$	0.905	17.34	3.24

where C_{Chla} and C'_{Chla} are the measured and estimated chlorophyll-a concentrations, respectively, in μg/L.

As shown in Figure 4a, the chlorophyll-a concentrations in the waters of Chaohu Lake were relatively low in May, with most of the waters having chlorophyll-a concentrations less than 20 μg/L. There were stripe-shaped areas of clean water in the western waters of Western Half Lake, the northern waters of Middle Half Lake and the eastern waters of Eastern Half Lake. The water body with high chlorophyll-a concentrations was very small in area and was sporadically distributed in the northern part of western Half Lake.

As shown in Figure 4b, the chlorophyll-a concentrations in the waters of Chaohu Lake were relatively high, and the concentrations increased with increasing water concentrations (20 μg/L and above). The waters with high chlorophyll-a concentrations were mainly distributed in the northern waters of Western Half Lake in a patchy manner and in the eastern waters of Western Half Lake and Middle Half Lake in a sporadic manner, and there was a large zone with a relatively clean water body in Eastern Half Lake. The high chlorophyll-a concentrations diffused from the northern waters of western Half Lake to the eastern waters, and with increasing diffusion distance, the chlorophyll-a concentrations gradually decreased.

As shown in Figure 4c, the waters with high chlorophyll-a concentrations were relatively concentrated in July, and the boundaries between the clean water bodies and the waters with high chlorophyll-a concentrations were clearly defined. The clean water bodies were mainly distributed in the waters of Middle Half Lake and in the western part of Western Half

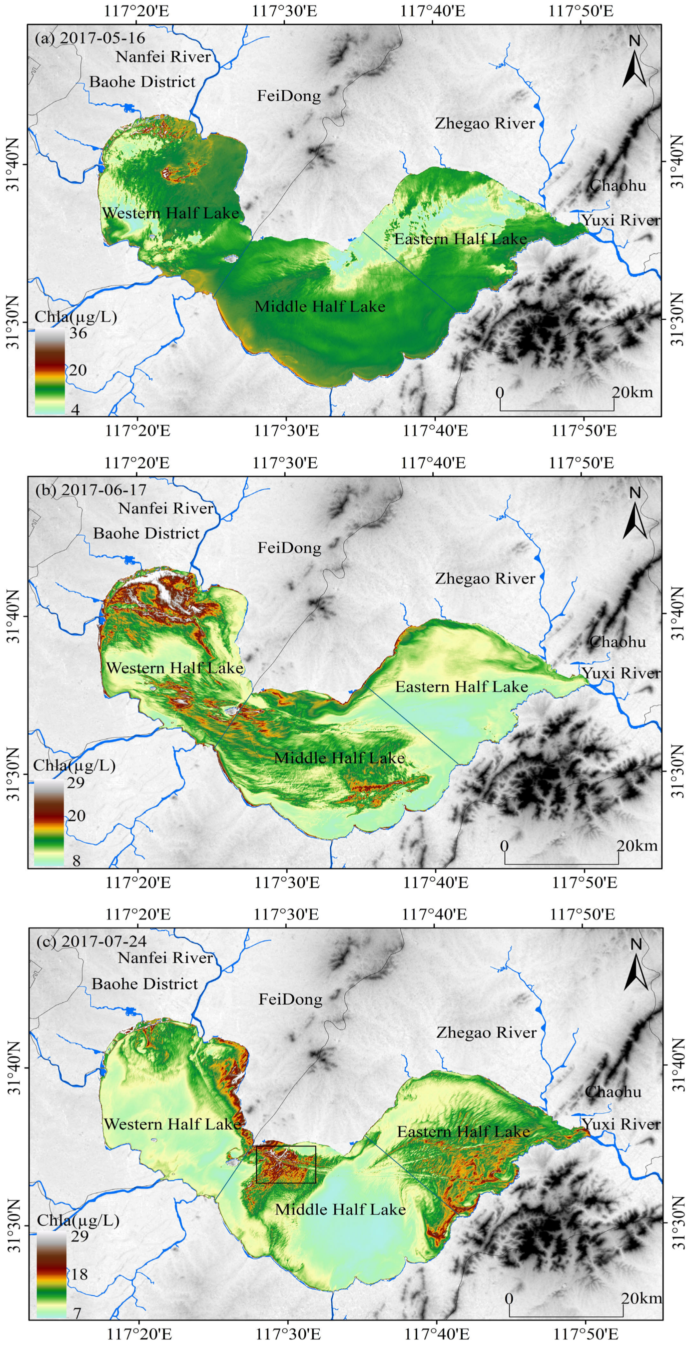

FIGURE 4. (a-c): Spatial distributions of the inversion of the chlorophyll-a concentrations in the waters of Chaohu Lake.

Lake. The water bodies with high chlorophyll-a concentrations were mainly distributed in the eastern littoral waters and northern waters of Western Half Lake, the northwestern waters and southeastern waters of Middle Half Lake, and the eastern waters of Eastern Half Lake, in which the highest chlorophyll-a concentrations appeared in the northwestern waters of Middle Half Lake, which are indicated by the box in Figure 4c, and were followed by the southeastern waters of Middle Half Lake and spreading to Eastern Half Lake; with increased diffusion distance, the chlorophyll-a concentrations also gradually decreased.

V. DISCUSSION

A. POSSIBLE CAUSES OF HIGH CHLOROPHYLL-A CONCENTRATIONS IN THE WATERS ALONG THE SHORES OF CHAOHU LAKE

The mean $PM_{2.5}$ concentrations in Hefei city from May to July 2017 were 43.19 $\mu g/m^3$, 43.20 $\mu g/m^3$ and 32.55 $\mu g/m^3$, respectively, and the air quality grades were slightly polluted, slightly polluted and benign, respectively. From the significant positive correlation between the aerosol optical thicknesses and $PM_{2.5}$ content [39], [40], it can be inferred that the aerosols in the waters of Chaohu Lake had higher concentrations. As shown in Figure 4, the chlorophyll-a concentrations in the water bodies along the shore of Chaohu Lake were greater than those in the other water bodies, which may be the reason for the high aerosol concentrations in the waters of Chaohu Lake. The spatial distributions of the chlorophyll-a concentrations were consistent when the aerosol concentrations were low; however, when the aerosol thicknesses were greater, the boundary effect caused the near-infrared band to be affected to a greater extent, and the magnitude of change along the edge of the lake toward the center increased, which had a certain effect on the spatial distributions of the chlorophyll-a concentrations in the inversion [41]. In addition, during this time of agricultural activity, phosphorus, nitrogen and other nutrients accumulated readily in the farmlands around Chaohu Lake and flowed into Chaohu Lake via the river, which also caused higher chlorophyll-a concentrations along the shore.

B. POSSIBLE REASONS FOR CHANGES IN THE SPATIAL DISTRIBUTIONS OF THE CHLOROPHYLL-A CONCENTRATIONS

Factors such as temperature and wind direction strongly influence chlorophyll-a concentrations and their spatial distributions. Elevated temperatures promote the proliferation and growth of algae in lakes, accelerating their metabolism and photosynthesis, but excessive sunlight inhibits algal photosynthesis [42], thus affecting chlorophyll-a concentrations. Studies have shown that when the temperature is higher than 18°C, the growth of cyanobacteria is proportional to the temperature, and the chlorophyll-a concentrations are greater; however, when the temperature is higher than 30°C, the activity of algae decreases [43], and the chlorophyll-a concentrations decrease. The mean temperatures in the waters of Chaohu Lake from May to June 2017 were 25°C and 26°C, respectively, and the chlorophyll-a concentrations increased with increasing temperature in an environment that was suitable for algae growth. Algal growth was limited by temperatures higher than 30°C in July, and the chlorophyll-a concentrations decreased under high temperatures and sufficient sunshine [44].

Chlorophyll-a concentrations above 25 μg/L were mainly distributed in the northern waters of the western half of Chaohu Lake, especially where the Nanfei River enters the lake, which is adjacent to the Baohe District and Feidong County of Hefei city. Under the influence of human activities, large amounts of domestic sewage and nutrient-rich substances converge into Chaohu Lake along the river, which is the probable reason why the eutrophication level of Western Half Lake is greater than that of Eastern Half Lake. Chaohu Lake has a subtropical monsoon climate with predominantly southeasterly winds in summer, and the algae accumulations that float on the water surface toward the windward waters, especially the lake bay [45], are also a possible reason for the high chlorophyll-a concentrations present in western Half Lake.

Phosphorus mines are widely distributed in the Chaohu Lake basin, and phosphorus sinks into Chaohu Lake when carried by rivers, which has a significant impact on eutrophication in the water body of Chaohu Lake. With the arrival of summer, the increased temperatures lead to increases in the chlorophyll-a concentrations in the waters of Chaohu Lake, changes in spatial distributions, an increase in the area with a high chlorophyll-a concentrations, and an increase in the cyanobacterial bloom phenomenon, which was consistent with the findings of previous studies [46]. The spatial distribution characteristics of the chlorophyll-a concentrations in the waters of Chaohu Lake in July were more varied than those in the other lakes, which was manifested by the occurrence of high chlorophyll-a concentrations in the eastern waters of Eastern Half Lake, but the overall degree of eutrophication was still lower than that in Western Half Lake near Hefei city. We believe that this could be attributed to the following reasons: Hefei city is the capital of Anhui Province, its industrial level is greater than those of the surrounding counties and cities, and its pollutant emissions are greater. The Eastern Half Lake has the Yuxi River, which connects Chaohu Lake and the Yangtze River. The water body of Chaohu Lake enters the Yangtze River through the Yuxi River, which contributes to pollutant discharges, and it also makes the water body mobility of Eastern Half Lake greater than that of Western Half Lake. Algal populations are affected by the flow of water into the environment, which leads to a reduction in the chlorophyll-a concentrations [47].

VI. CONCLUSION

Based on GF-1 WFV image data and measured chlorophyll-a concentration data, an optimal inversion model for determining the chlorophyll-a concentrations in the waters of Chaohu Lake that was suitable for use with GF-1 WFV image data was constructed by establishing empirical and semiempirical/semianalytical models, and the spatial distributions of the chlorophyll-a concentrations from May to July 2017 were inverted. The following conclusions were drawn.

The reflectance values of the near-infrared and red band combinations of the GF-1 WFV image data were significantly correlated with the chlorophyll-a concentrations in the waters of Chaohu Lake. The NDCI model was the optical inversion model used for chlorophyll-a concentrations in the waters of Chaohu Lake, with a determination coefficient of 0.791 for model construction and 0.933 for model validation, with a root mean square error of 2.85 μg/L and a mean absolute percentage error of 19.69% for model validation. The chlorophyll-a concentrations were all higher along the shores of the waters of Chaohu Lake, and the spatial distributions all showed gradual decreasing trends from western Half Lake to eastern Half Lake. Chlorophyll-a concentrations above

25 μg/L were mainly distributed in the northern waters of western Half Lake, especially at the entrance of the Nanfei River into the lake. The mean chlorophyll-a concentrations in the waters of Chaohu Lake increased during May-July, the spatial distributions changed significantly, and the areas of waters with high chlorophyll-a concentrations increased, which may be due to the combined influence of temperature and human activities.

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