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Prediction of chlorophyll *a* concentration using HJ-1 satellite imagery for Xiangxi Bay in Three Gorges Reservoir

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Abstract: Since the impoundment of the Three Gorges Reservoir in 2003, algal blooms have frequently been observed in it. The chlorophyll *a* concentration is an important parameter for evaluating algal blooms. In this study, the chlorophyll *a* concentration in Xiangxi Bay, in the Three Gorges Reservoir, was predicted using HJ-1 satellite imagery. Several models were established based on a correlation analysis between *in situ* measurements of the chlorophyll *a* concentration and the values obtained from satellite images of the study area from January 2010 to December 2011. Chlorophyll *a* concentrations in Xiangxi Bay were predicted based on the established models. The results show that the maximum correlation is between the reflectance of the band combination of B4/(B2+B3) and *in situ* measurements of chlorophyll *a* concentration. The root mean square errors of the predicted values using the linear and quadratic models are 18.49 mg/m^3 and 18.52 mg/m^3, respectively, and the average relative errors are 37.79% and 36.79%, respectively. The results provide a reference for water bloom prediction in typical tributaries of the Three Gorges Reservoir and contribute to large-scale remote sensing monitoring and water quality management.
Key words: *chlorophyll a concentration; HJ-1 satellite; remote sensing prediction; correlation analysis; Xiangxi Bay; Three Gorges Reservoir*

1 Introduction

The Three Gorges Reservoir, at Sandouping in Yichang City, has played an important role in flood control, power generation, and navigation. As a typical river-type reservoir, the Three Gorges Reservoir has characteristics of both rivers and reservoirs (Wang et al. 2009). Algal blooms have been observed in the Three Gorges Reservoir since its impoundment in 2003 (MEPC 2011), including a particularly severe cyanobacteria bloom in the summer of 2008 (Yang et al. 2012b). Algal blooms in the tributaries of the Three Gorges Reservoir have

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received a lot of attention in recent years (Yang et al. 2012a; Yang et al. 2013).

Chlorophyll *a*, an indicator of algal blooms, is one of the most important components of phytoplankton organisms. It is an important parameter for evaluating water quality in inland lakes (Gitelson et al. 1993). The concentration of chlorophyll *a* is closely related to the total abundance of algae in the water (Reynolds 1984; Huang 2001). Remote sensing images have been used to identify the chlorophyll *a* concentration, analyze the extent of eutrophication and the risk of algal blooms, and then provide a reference for managing the water quality of reservoirs (Duan et al. 2007; Schultz and Engman 2000). The principle of extracting the chlorophyll *a* concentration using remote sensing images is based on the fact that the chlorophyll *a* concentration corresponds significantly to the reflectance within a certain wavelength range. Based on different spectral characteristics of algal chlorophyll *a* concentrations, quantitative relationships between the water reflectance and chlorophyll *a* concentration can be established. Remote sensing monitoring of the chlorophyll *a* concentration has the advantage of wide range, rapid interpretation, low cost, and ease of long-term dynamic monitoring (Gohin et al. 2008). A study in Dianchi Lake shows a significant relationship between the natural logarithm of chlorophyll *a* concentration and the ratio of gray values at band 4 to band 3 of Thematic Mapper (TM) images (Zhao et al. 2001). Li et al. (2002) developed a chlorophyll *a* remote sensing quantitative model with the reflectance ratio method and first-order differential method using the hyperspectral data. Sun et al. (2009) established linear models and a support vector machine model for retrieving chlorophyll *a* concentrations in Taihu Lake. Gurlin et al. (2011) developed near infrared-red models for the remote estimation of chlorophyll *a* concentrations in turbid productive waters.

The Small Satellite Constellation A and B for Environment and Disaster Monitoring and Forecasting (HJ-1A/B satellites) were successfully launched on September 6, 2008. HJ-1A is equipped with a charge coupled device (CCD) camera and hyperspectral imager (HSI), whereas HJ-1B is equipped with a CCD camera and an infrared scanner (IRS). They are combined to produce four-band pushbroom images, whose spectral response ranges are from 430 to 520 nm for band 1 (B1), from 520 to 600 nm for band 2 (B2), from 630 to 690 nm for band 3 (B3), and from 760 to 900 nm for band 4 (B4), with a ground swath width of 700 km and ground pixel resolution of 30 m (Wang et al. 2010; Chen et al. 2013). As the first environmental monitoring and forecasting system set up by China, HJ-1A/B satellites are widely used to predict the chlorophyll *a* concentration in rivers and reservoirs. Bao and Tian (2011) found that there was an appreciable scale effect on chlorophyll *a* concentration measurements at the resolution of 250 m using HJ-1 CCD images, and the degree of spatial heterogeneity increased with scale. The red and near infrared bands of HJ-1A/B CCD data are sensitive to the chlorophyll *a* concentration (Kuang et al. 2010). It has been found that the three-band model is excellent for retrieval of chlorophyll *a* concentrations (Dall'Olmo and Gitelson 2005; Zimba and Gitelson 2006). Yang et al. (2010a) found that combination of the remote sensing theory and image would be helpful in optimizing the three-band model and in achieving the goal of quantitatively retrieving chlorophyll *a* concentrations.

In this study, HJ-1A/B CCD satellite imagery for Xiangxi Bay in the Three Gorges Reservoir was used to establish several models of chlorophyll *a* concentration based on the correlation between *in situ* chlorophyll *a* concentrations and the values obtained from satellite imagery of the study area. The models were further applied to predict the chlorophyll *a* concentration in Xiangxi Bay.

2 Materials and methods

2.1 Study area

The Xiangxi River (with a longitude from 110°25'E to 111°06'E and a latitude from 31°04'N to 31°34'N), the largest tributary of the Three Gorges Reservoir in Hubei Province and also the closest tributary to the Three Gorges Dam, is located in the west of Hubei Province, north of the Xiling Gorge of the Yangtze River and between the Jingshan Mountains and Wushan Mountains (Huang et al. 2012). Its elevation is between 1 200 m and 2 000 m. The main stream of the Xiangxi River is about 94 km long, and its watershed contains the entirety of Xingshan County and Zigui County, and parts of Shennongjia Forest, with a total area of 3 099 km^2. The Xiangxi Estuary, with an average gradient of 1.42%, is about 34.5 km away from the Three Gorges Dam and 2 995 m above the elevation of the river source (Liu et al. 2012). Since the impoundment of the Three Gorges Reservoir in 2003, a backwater zone was formed from the Xiangxi Estuary to a place near the Zhaojun Bridge, which is named Xiangxi Bay (Ye et al. 2007). The water level of Xiangxi Bay ranges from 145 m to 175 m, and the corresponding water surface width is between 45 m and 685 m. The sampling site XX06 (111°77'E, 31°13'N) lies upstream of Xiangxi Bay, close to the Xiakou Bridge. Its water surface width ranges from 302 m to 460 m. The location and a satellite image of the sampling site XX06 in Xiangxi Bay are shown in Fig. 1.

2.2 Satellite imagery and pre-processing

The HJ-1A/B satellite images of Xiangxi Bay in the years 2010 and 2011 were downloaded from the Satellite Environmental Center of the Ministry of Environmental Protection of China (http://www.secmep.cn). The pre-processing includes radiometric calibration, data clipping, geometric correction, atmospheric correction, and band extraction. A patch for reading the data from HJ-1 satellite was used to calibrate the radiance of the raw images. To increase the speed of computation, the raw images were clipped to obtain the images for the study area. Geometric correction was conducted to eliminate geometric distortions, correct errors in the relative positions of pixels, and define images in a common coordinate system (Sertel et al. 2007; Ormeci et al. 2009). We also used a Landsat 7 image with geometric precision correction in advance as the reference base map to correct the geometric

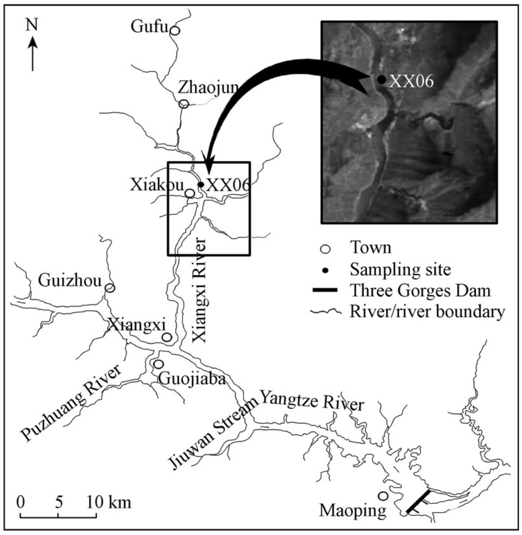

Fig. 1 Location and satellite image of sampling site in Xiangxi Bay in Three Gorges Reservoir

position. Furthermore, atmospheric correction was conducted using the ENVI 4.7 software with a spectral curve based on the spectral response function provided by the HJ-1 satellite data system.

2.3 Research methods

Water samples were collected from January 2010 to December 2011 for analyzing the chlorophyll *a* concentration according to the acetone extraction method (Huang et al. 2009). The air temperature, humidity, and wind speed were recorded accordingly.

Satellite images from sunny days were chosen as the raw data, to avoid the negative impact of cloud shield on the remote sensing imagery. The relationship between satellite image data and *in situ* observations of chlorophyll *a* concentrations in 2010 was analyzed using Statistical Product and Service Solutions (SPSS) 18.0. Predicted models for the chlorophyll *a* concentration were established based on the relationship. Furthermore, the satellite images and *in situ* observation data from 2011were used to validate the model.

3 Results and discussion

3.1 Data selection

There were 100 processed HJ-1 remote sensing images for the sampling site in Xiangxi Bay, of which 29 were deleted due to cloud shield. Of the remaining 71 images, 42 images from 2010 were used for developing models, and the other 29 images from 2011 were used for model validation. Each remote sensing image data point had corresponding *in situ* observation data.

3.2 Correlation analysis

A correlation analysis was conducted between the satellite image data and *in situ* observations of the chlorophyll *a* concentration from 2010. In the correlation analysis, the

Pearson simple correlation coefficient was used to measure the linear correlation between scale variables, whereas the Spearman rank correlation coefficient was used to measure the linear relationship for both continuous and discrete variables, including ordinal variables. The core issue in remote sensing monitoring of the chlorophyll *a* concentration is to establish quantitative relationships between the water reflectance and chlorophyll *a* concentration. To explore this quantitative relationship, the water reflectance was shown by 72 kinds of band combination. The Pearson and Spearman correlation coefficients for water reflectance and chlorophyll *a* concentration were displayed using SPSS. The results are shown in Table 1.

Table 1 shows that the correlation between reflectance of band combination B4/(B2+B3) and *in situ* measurements of the chlorophyll *a* concentration is the highest with the Pearson correlation and Spearman correlation coefficients, respectively. The correlation coefficients of other band combinations with *in situ* observations of the chlorophyll *a* concentration are lower.

3.3 Prediction models

Reflectance of B4/(B2+B3) was used as the independent variable in the models for predicting the chlorophyll *a* concentration in Xiangxi Bay, as shown in Fig. 2.

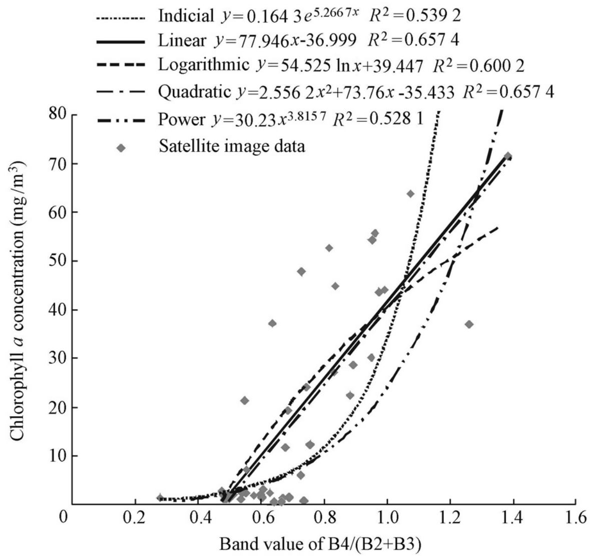

Fig. 2 Scatterplot of *in situ* chlorophyll *a* concentration and different fitting models

Of the five models shown in Fig. 2, the determination coefficients (R^2) of both linear and quadratic models are 0.66, higher than those of the other models. Therefore, the linear model and quadratic model were chosen to predict the chlorophyll *a* concentration in Xiangxi Bay in the Three Gorges Reservoir. For the linear model:

$$y = 77.946x - 36.999 \tag{1}$$

For the quadratic model:

$$y = 2.556\,2x^2 + 73.76x - 35.433 \tag{2}$$

Table 1 Correlation between chlorophyll *a* concentration and band reflectance combinations of HJ-1 satellite images

No.	Band reflectance combination	Correlation coefficient		No.	Band reflectance combination	Correlation coefficient	
		Pearson	Spearman			Pearson	Spearman
1	B1	−0.335*	−0.412**	37	B1/(B3+B4)	−0.593**	−0.616**
2	B2	−0.338*	−0.441**	38	B1/(B2+B3+B4)	−0.542**	−0.514**
3	B3	−0.257	−0.269	39	B2/(B1+B3)	−0.126	−0.210
4	B4	−0.023	0.042	40	B2/(B1+B4)	−0.595**	−0.701**
5	B1+B2	−0.338*	−0.446**	41	B2/(B3+B4)	−0.599**	−0.693**
6	B1+B3	−0.298	−0.388**	42	B2/(B1+B3+B4)	−0.559**	−0.685**
7	B1+B4	−0.166	−0.184	43	B3/(B1+B2)	0.188	0.320*
8	B2+B3	−0.299	−0.355**	44	B3/(B1+B4)	−0.591**	−0.495**
9	B2+B4	−0.171	−0.174	45	B3/(B2+B4)	−0.612**	−0.484**
10	B3+B4	−0.131	−0.079	46	B3/(B1+B2+B4)	−0.425**	−0.287
11	B1-B2	0.076	0.016	47	B4/(B1+B2)	0.767**	0.689**
12	B1-B3	−0.245	−0.301	48	B4/(B1+B3)	0.805**	0.695**
13	B1−B4	−0.492 **	−0.563**	49	B4/(B2+B3)	0.811 **	0.728 **
14	B2−B3	−0.417**	−0.473**	50	B4/(B1+B2+B3)	0.805**	0.714**
15	B2−B4	−0.527**	−0.626**	51	B1/(B2×B3)	0.432**	0.298
16	B3−B4	−0.488**	−0.548**	52	B1/(B2×B4)	−0.063	−0.035
17	B1×B2	−0.214	−0.445**	53	B1/(B3×B4)	−0.096	−0.121
18	B1×B3	−0.191	−0.370*	54	B1/(B2×B3×B4)	0.288	0.166
19	B1×B4	−0.138	−0.202	55	B2/(B1×B3)	0.393*	0.275
20	B2×B3	−0.190	−0.354*	56	B2/(B1×B4)	−0.088	−0.037
21	B2×B4	−0.149	−0.218	57	B2/(B3×B4)	−0.101	−0.152
22	B3×B4	−0.129	−0.142	58	B2/(B1×B3×B4)	0.132	0.116
23	B1/B2	0.037	0.049	59	B3/(B1×B2)	0.451**	0.493**
24	B1/B3	−0.080	−0.237	60	B3/(B1×B4)	−0.014	0.043
25	B1/B4	−0.663**	−0.654**	61	B3/(B2×B4)	0.023	0.045
26	B2/B1	−0.051	−0.049	62	B3/(B1×B2×B4)	0.231	0.238
27	B2/B3	−0.102	−0.318	63	B4/(B1×B2)	0.589**	0.650**
28	B2/B4	−0.613**	−0.727**	64	B4/(B1×B3)	0.622**	0.552**
29	B3/B1	0.144	0.237	65	B4/(B2×B3)	0.603**	0.613**
30	B3/B2	0.197	0.318*	66	B4/(B1×B2×B3)	0.504**	0.532**
31	B3/B4	−0.718**	−0.675**	67	(B1−B2)/(B1+B2)	0.042	0.049
32	B4/B1	0.742**	0.654**	68	(B1−B3)/(B1+B3)	−0.123	−0.237
33	B4/B2	0.751**	0.727**	69	(B1−B4)/(B1+B4)	−0.710**	−0.654**
34	B4/B3	0.743**	0.675**	70	(B2−B3)/(B2+B3)	−0.161	−0.318*
35	B1/(B2+B3)	−0.069	−0.044	71	(B2−B4)/(B2+B4)	−0.722**	−0.727**
36	B1/(B2+B4)	−0.613**	−0.568**	72	(B3−B4)/(B3+B4)	−0.770**	−0.675**

Note: ** means that the significance level is less than 0.01, and * means that the significance level is less than 0.05.

3.4 Prediction and validation of chlorophyll *a* concentration

The predicted values of chlorophyll *a* concentrations corresponding to the 29 remote sensing images from 2011 were provided by the linear and quadratic models. In addition, the *in situ* observations of chlorophyll *a* concentrations were used to validate the models. The relative error (σ) and root mean square error (*RMSE*) were calculated using the following equations:

$$\sigma = \frac{|X_i - T_i|}{T_i} \times 100\% \tag{3}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(T_i - X_i)^2}{n}} \tag{4}$$

where X_i is the *i*th predicted chlorophyll *a* concentration at the sampling site, T_i is the *i*th measured chlorophyll *a* concentration at the sampling site, and *n* is the amount of data groups at the sampling site.

Table 2 shows that the relative errors between the predicted and measured values of chlorophyll *a* concentrations from January 28 to February17, on March 12, from September 21 to September 23, and on November 10 of 2011 are greater than 100%. The results are due to the characteristics of water in Xiangxi Bay. First, the vertical stability coefficient of water in Xiangxi Bay is large in spring, resulting in stratification (Yang et al. 2010b), which contributes to algae growth and algal blooms. When water is impounded in the Three Gorges Reservoir in

Table 2 Comparison of relative errors between predicted and measured chlorophyll *a* concentrations

No.	Date	Relative error (%)		No.	Date	Relative error (%)	
		Linear model	Quadratic model			Linear model	Quadratic model
1	2011-01-07	31	15	16	2011-06-22	43	43
2	2011-01-28	125	133	17	2011-07-06	84	84
3	2011-02-13	356	357	18	2011-07-26	10	9
4	2011-02-17	464	470	19	2011-08-09	21	21
5	2011-02-24	65	58	20	2011-08-10	3	4
6	2011-03-12	117	110	21	2011-08-12	1	0
7	2011-03-26	9	10	22	2011-08-14	81	80
8	2011-04-14	44	45	23	2011-08-15	61	60
9	2011-04-18	32	32	24	2011-08-16	2	2
10	2011-05-04	17	17	25	2011-09-21	156	152
11	2011-05-27	56	56	26	2011-09-23	623	620
12	2011-06-01	80	83	27	2011-10-17	41	40
13	2011-06-03	12	12	28	2011-10-21	47	47
14	2011-06-15	67	66	29	2011-11-10	202	205
15	2011-06-16	25	24				

autumn, a density current usually forms in Xiangxi Bay, which means that water from the Yangtze River invades Xiangxi Bay from the middle or surface, causing water mixture, limiting the proliferation of algae, and, ultimately, decreasing the chlorophyll *a* concentration in Xiangxi Bay (Jones and Poplawski 1998; Huang and Li 2007). Second, the production date of HJ-1 satellite imagery is not thoroughly synchronized with the *in situ* sampling date. The chlorophyll *a* concentration in midday is obviously different from that at night, thus resulting in somewhat errors between measured and predicted values of the chlorophyll *a* concentration.

After elimination of the data whose relative errors are greater than 100%, the statistics of the two models show that the maximum, minimum, and average relative errors of the linear model for predicting the chlorophyll *a* concentration are 83.71%, 0.71%, and 37.79%, respectively, and the root mean square error is 18.49 mg/m^3; whereas the maximum, minimum, and average relative errors of the quadratic model are 83.81%, 0.07%, and 36.79%, respectively, and the root mean square error is 18.52 mg/m^3. Both models are reliable for predicting the chlorophyll *a* concentration in Xiangxi Bay. The concentration thresholds of the chlorophyll *a* concentration for evaluating eutrophication and algal blooms (i.e., 10 mg/m^3 and 30 mg/m^3, respectively) (Ji et al. 2010; Zheng et al. 2006) are used to compare the *in situ* measurements and the predicted values from the quadratic model, as shown in Fig. 3.

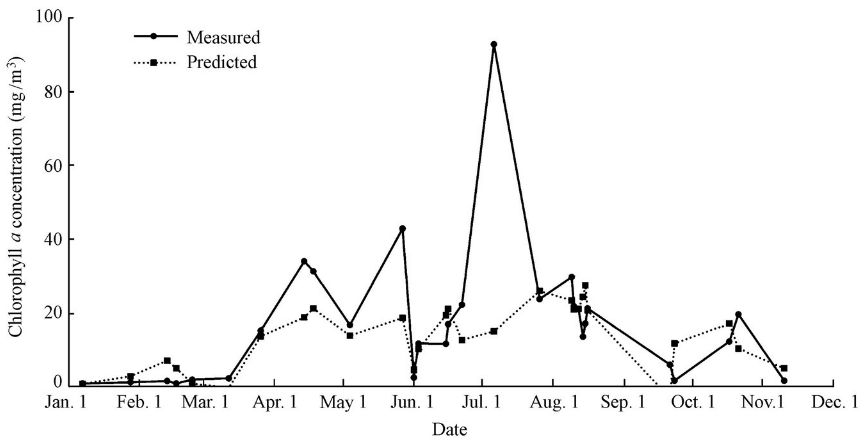

Fig. 3 Comparison of predicted and measured values of chlorophyll *a* concentrations in 2011

Fig. 3 shows that when the chlorophyll *a* concentration is lower than the algal bloom threshold, the predicted values are close to the *in situ* observation data. However, when chlorophyll *a* concentrations are higher than the algal bloom threshold, the predicted values are significantly lower than the *in situ* measurements. The peak points (on April 14, May 27, and July 6 of 2011) may be due to the outbreak of spring blooms, and a large number of suspended algae flocked together and were observed as terrestrial vegetation by the satellite (Zhou et al. 2011). The fact that the date of satellite imagery production is not thoroughly synchronized with the field sampling date is also one of the reasons.

4 Conclusions

This study analyzed the correlation between *in situ* measurements of the chlorophyll *a* concentration and different band combinations of HJ-1A/B CCD satellite images in 2010 and 2011 for Xiangxi Bay in the Three Gorges Reservoir. The results show that the reflectance of band combination B4/(B2+B3) has a maximum correlation with the measured chlorophyll *a* concentration. The regression analysis shows that the determination coefficients of both the linear model and the quadratic model are 0.66, higher than those of the other models. Both the linear and quadratic models are reliable for predicting the chlorophyll *a* concentration in Xiangxi Bay. When the chlorophyll *a* concentration is lower than the algal bloom threshold, the predicted values are close to the *in situ* observation data. However, when chlorophyll *a* concentrations are higher than the algal bloom threshold, the predicted values are significantly lower than the *in situ* measurements. This may be due to the outbreak of spring blooms, and a large number of suspended algae were observed as terrestrial vegetation by the satellite.

Since there are many factors influencing the chlorophyll *a* concentration, and satellite images are not thoroughly synchronized with the *in situ* measurements in the study area, errors exist between the predicted and *in situ* measured values. In further studies, other indicators for algal blooms, such as algal cell density and algal biomass, can be considered when predicting algal blooms using the HJ-1 satellite imagery.

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