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Ocean Chlorophyll-a retrieval using GF1-WFV data-a case study of the central Bohai Sea

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Abstract. Chlorophyll-a (Chl-a) concentration is an important indicator of phytoplankton bloom and water eutrophication. It is also a basic parameter of water quality. Remote sensing technology has been widely used for water quality monitoring in the past. In this study, the Chinese GF1 (Gaofen-1) WFV (Wide Field of View) images acquired on May 19th, 2016 were used to retrieve Chl-a concentration of central Bohai sea in order to assess the recovery condition of marine ecosystem which has been seriously polluted by the Penglai 19-3 platform oil spill accident in 2011. The remote sensing model of Chl-a concentration was developed using the linear regression method. The leave-one-out cross-validation (LOOCV) method showed that the average relative error and root mean square error (RMSE) between retrieved Chl-a concentration and in situ measurement was 11.67% and 0.1808, respectively. It indicated that the remote sensing model could correctly reflect the Chl-a concentration and its spatial distribution of the study area. The average Chl-a concentration in the buffer regions with the distance of 2km, 4km, 6km to the Penglai 19-3 platform was 0.32μg/L, 0.37μg/L and 0.40μg/L, respectively. They were in normal range and lower than that of the coastal waters. The spatial distribution of the result was similar to previous studies of Bohai sea in spring. These results indicated that Chl-a concentration of central Bohai sea was returned to normal after oil spill accident occurred for 5 years. The growth of phytoplankton in surface seawater has been returned to normal. The major causes for Chl-a concentration in the Bohai Sea was the land-sourced pollutant during the study period.

Keywords: Chlorophyll-a Retrieval; GF1-WFV Data; Remote Sensing; Bohai Sea

1. Introduction

The Bohai Sea is the only semi-enclosed inland sea of China, which has a low capacity of water exchanging, self-purification and dirt holding with the other ocean. Several big inland rivers, such as the Liaohe River, the Luanhe River, the Haihe River and the Yellow River, empty into the Bohai Sea

and transport large amounts of nutrients and suspended matters from the continent into the sea[1,2].There is the largest number of offshore oil platforms and submarine pipelines of China. Oil spill causes serious damage to the marine environment, especially in coastal waters[3,4]. Moderate petroleum hydrocarbon in oil can effectively promote the growth and reproduction of phytoplankton. At the same time, zooplankton's feeding ability is damaged by petroleum hydrocarbon. Besides, dissolved organic matter in the water increases due to the degradation of marine bacteria[5]. All these will contribute to phytoplankton blooms in a short time, which causes significant increase of Chl-a concentration. On June 4th, 2011, the Penglai 19-3 platform located in central Bohai sea faced serious oil spill accident. It was the largest offshore oil spill accident along the Chinese coastline in recent decades. On July 5th, 2011, preliminary investigation report released by State Oceanic Administration showed that the average concentration of petroleum hydrocarbon around the platform was almost 40.5 times higher than historical observations. The highest Chl-a concentration was 86.4 times of record values[6]. On June 12th, 2011, Chl-a concentration over an area of 800km^2 about 56km northeast away from the platform was 13.66μg/L[7]. Another phytoplankton bloom was observed in June 2012 when the monthly Chl-a concentration reached to 6.40μg/L[8].

Remote sensing techniques have been successfully used to monitor Chl-a due to its advantages of rapidness, low cost, wide coverage and dynamic monitoring in the past[9]. Gaofen-1(GF-1) is the first satellite of Chinese high-resolution earth observation system. This satellite is equipped with four wide field of view (WFV) cameras which have the swath width of 830 km and revisit period of 4 days. It provides important data sources for large-scale and short-term monitoring of water environment[10,11]. Preliminary studies have shown its significant potential use in inland water quality parameters monitoring. Radiant, spectral, spatial characteristics of GF1-WFV data were evaluated by Liang et al.[12]. The result showed that GF1-WFV data had potential application in dynamic monitoring of inland water environment. Zhu et al. [13] estimated Chl-a concentration of Taihu Lake using GF1-WFV data, which was consistent with the result using HJ-1A Satellite data. The result could correctly reflect the distribution of water quality parameters including Chl-a concentration, suspended solids concentration, transparence and eutrophication index. GF1-WFV data were used in monitoring suspended particulate matter (SPM) of Poyang Lake by Li et al. [14] and achieved ideal results. Tian et al. [15] monitored total suspended matter concentration (TSM) of Deep Bay of Hong Kong, using GF1-WFV and MODIS data. The accuracy of semi-analytical algorithm based on bio-optical model was high in Chl-a concentration retrieval, especially for Case-II water, which is mainly located in the coastal places and is seriously affected by land-based pollution. However, this algorithm was mainly used for hyperspectral data, which limited its application. In order to obtain the recovery condition of marine ecosystem in central Bohai sea after Penglai 19-3 oil spill accident occurred for 5 years, a full investigation was conducted from May 17th, 2016 to May 20th, 2016, including ocean sea surface and submarine environment monitoring, water quality parameters measuring, water and sediment sampling. This study retrieved the Chl-a concentration in central Bohai sea by using the Chinese GF1-WFV images acquired on May 19th, 2016 and in situ measurements data. Based on remote sensing results, the Chl-a concentration and its distribution characteristics in the study region and the Bohai Sea was analyzed and discussed.

2. Study area and dataset

2.1. Study area

The study area is on the east side of Penglai 19-3 platform. This platform is located in the Central Bohai Sea (Figure 1). Surface area covers approximately 12 km^2 and water depths range from 27 m to 29m.
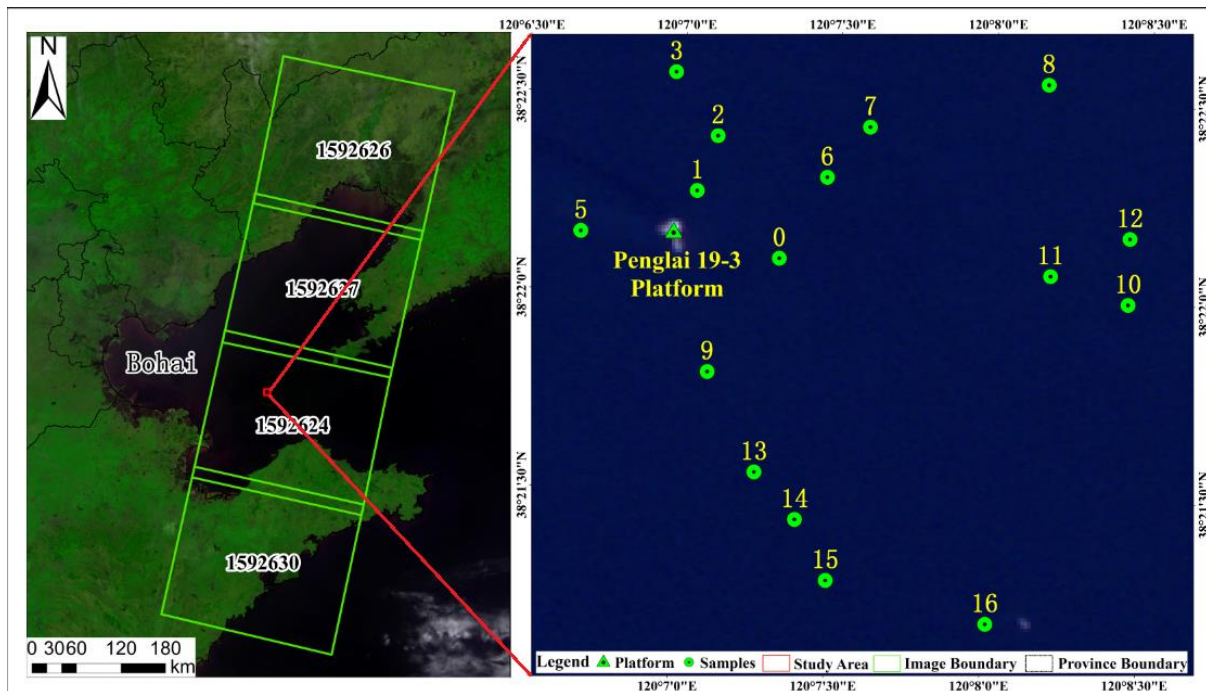
Figure 1. The study area and location of sample stations.

2.2. Remote sensing data

Four GF1-WFV level-1A images (ID=1592624, 1592626, 1592627, 1592630) were used in this study. These images were acquired on May 19th, 2016. GF1-WFV image have four bands of Blue (0.45-0.52μm), Green (0.52-0.59μm), Red (0.63-0.69μm) and Near Infrared (0.77-0.89μm) with 16 m spatial resolution (Table 1). Image pre-processing was primarily performed using software ENVI 5.3. The procedures included radiance calibration, atmosphere correction and geometric correction. Radiometric calibration was carried out using the absolute radiation calibration coefficient of GF-1 satellite in 2016. MORTRAN model was used to correct the atmospheric effects. Geometric correction was conducted based on Landsat-8 image to make sure that the RMSE is less than 0.5 pixel.

Table 1. Specifications of GF-1 Satellite.

Specifications	Band	PMS	WFV
Band Width	1	0.45-0.52μm	
	2	0.52-0.59μm	
	3	0.63-0.69μm	
	4	0.77-0.89μm	
Spatial Resolution	8m/2m		16m
Swath width	60km(2 cameras)		800km(4 cameras)
Revisit time	41 days		4days

2.3. In situ data

Seventeen water samples of Chl-a concentration were collected in surface seawater of the study region from May 18th to 19th, 2016. These samples were kept on ice until the arrival in the laboratory. Chl-a concentration was analyzed using fluorescence method according to GB/T 12763.4-2007[16,17]. Coordinates for each sample station was recorded using a global positional system (GPS). The in situ measurements range from 0.18 to 0.47μg/L with an average concentration of 0.30μg/L. The maximum and minimum Chl-a concentration appeared on the fourth and sixteenth sample, respectively (Table 2).

Table 2. In situ Chl-a concentrations of samples.

Samples	Depth(m)	Concentration(μg/L)
P0	28.5	0.38
P1	28.3	0.36
P2	28.6	0.31
P3	28.6	0.35
P4	28.3	0.47
P5	28	0.32
P6	28	0.32
P7	28	0.34
P8	28	0.30
P9	27.9	0.28
P10	28.2	0.26
P11	28.3	0.28
P12	28	0.23
P13	28.4	0.27
P14	28.3	0.26
P15	28.5	0.24
P16	28.4	0.18

3. Method

Remote sensing reflectances were computed as mean values of the pixel corresponding to the sampling station location and its eight surrounding pixels. It was considered that this averaging was able to reduce WFV instrument noise and geometric error. By referring to the existing models, this study developed lots of band combination for Chl-a concentration retrieval. They were fitted through the correlation analysis between in situ measured Chl-a concentration and the remote sensing reflectance (Table 3). It was found that the relativity between green band reflectance and in situ measured Chl-a concentration was the highest.

Table 3. Different band combinations and correlation coefficients.

| Band combination	R	Band combination	R
B_2	0.74	B_3/B_2	0.28
B_1/B_2	0.60	$(B_2-B_3)/(B_2+B_3)$	0.28
B_2/B_4	0.60	B_1/B_3	0.24
B_4/B_1	0.39	$B_3/(B_1+B_4)$	0.22
B_1	0.37	B_3	0.14
B_4	0.33	$B_2/(B_1+B_4)$	0.14
B_2/B_3	0.32	$(B_4-B_3)/(B_4+B_3)$	0.04

Then the polynomial model, linear model, logarithmic model, exponential model and power function model were used to develop the retrieval model between green band reflectance and in situ Chl-a measurements. The correlation analysis result showed that the polynomial model had the highest correlation coefficient(R) (Table 4).

Table 4. Regressive equations and relation coefficients between Chl-a measurements and the remote sensing reflectance.

Model	Regressive equation	R
Polynomial model	Chla = 204955*B_2^2-3002.5*B_2+11.249	0.82
Linear model	Chla = 118.07*B_2-0.5952	0.74
Logarithmic model	Chla = 0.8904*ln(B_2)+4.6483	0.74
Exponential model	Chla = 0.0161*$e^{(382.39*B_2)}$	0.72
Power function model	Chla = 383120*$B_2^{2.8838}$	0.71

The polynomial model was then applied to the whole image reflectance values in order to test its performance of Chl-a concentration estimation. It was found that the mean Chl-a concentration was 2432.08μg/L, which was abnormal by contrast with observed and retrieved results in previous studies[18], especially in Liaoning and Laizhou Bay. Whereas, the performance of the linear model in delivering the Chl-a maps was the best. It can reflect the spatial distribution of water quality parameters correctly. Therefore, the linear was used to develop the Chl-a retrieval model. The correlation analysis between the green band reflectance and Chl-a concentration was shown in Figure 2. The Chl-a concentration retrieval model was as follows, where B_2 is the reflectance of GF1-WFV green band.

$$Chla = 118.07 * B_2 - 0.5952 \tag{1}$$
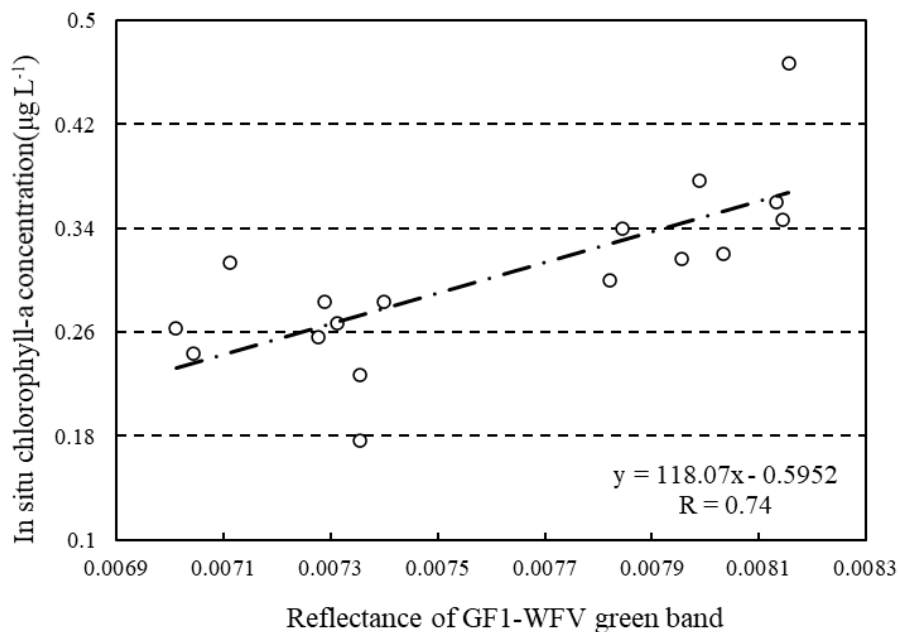
Figure 2. Relationship between in situ Chl-a concentration and GF1-WFV green band.

4. Accuracy Assessment

The leave-one-out cross-validation (LOOCV) method was used to evaluate the performance of Chl-a retrieval model. This method has been proved to evaluate inductive characteristics of statistical model effectively, and its result is almost unbiased[19]. A sample was randomly selected from all samples, and the retrieval model was developed by remaining samples. Then the selected sample was used to evaluate the model. This method can make a good use of all samples. It is more suitable for the condition when there is small number of samples[20].

The relative error (2) and root mean square error(RMSE) (3) between in situ measurements and retrieved Chl-a concentration is 11.67% and 0.1808, respectively, where MV is in situ measurement and IV is retrieved Chl-a concentration. The relative error of each sample is showed in Table 5. It indicates that the remote sensing model correctly reflected the Chl-a concentration.

$$R = \frac{(MV - IV)}{MV} \times 100\% \tag{2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(MV - IV)^2}{n}} \tag{3}$$

Table 5. Relative error of leave-one-out cross-validation (LOOCV) method.

Samples	In situ concentration(μg/L)	Retrieved concentration(μg/L)	Relative error
P0	0.38	0.34	10.53%
P1	0.36	0.36	0%
P2	0.31	0.23	25.81%
P3	0.35	0.37	5.71%
P4	0.47	0.35	25.53%
P5	0.32	0.35	9.37%
P6	0.32	0.36	12.50%
P7	0.34	0.33	2.94%
P8	0.30	0.33	10.00%
P9	0.28	0.28	0%
P10	0.26	0.26	0%
P11	0.28	0.26	7.14%
P12	0.23	0.28	21.74%
P13	0.27	0.27	0%
P14	0.26	0.23	11.54%
P15	0.24	0.24	0%
P16	0.18	0.28	55.56%

5. Results

The spatial interpolation of all the in situ Chl-a concentration was estimated using the inverse distance weighted (IDW) method, as illustrated in Figure 3. In the northwestern regions, Chl-a concentration was significantly higher than other regions on May 19th, 2016. Although Chl-a concentration in the northeastern region near the platform was higher than other regions, the value of Chl-a concentration ranged from 0.18μg/L to 0.47μg/L in the study region, which is in normal range. Furthermore, the average Chl-a concentration in buffer regions with the distance of 2km, 4km, 6km to the Penglai 19-3 platform is 0.32μg/L(ranging between 0 and 0.69μg/L), 0.37μg/L(ranging between 0 and 1.0μg/L) and 0.40μg/L(ranging between 0 and 1.12μg/L), respectively, during the study period. They were notably lower than in coastal regions. The results indicated that Chl-a concentration near the platform was back to normal during the observation time. There was higher concentration of Chl-a near P0, P1, P3 and P4 than in other samples.

The spatial distribution of Chl-a concentration in the Bohai Sea was obtained by applying the retrieval model to all the GF1-WFV images. On May 19th, 2016, Chl-a spatial distribution showed an obvious increasing trend from offshore to coastal waters. In coastal waters, the Chl-a concentration is higher than that in offshore waters, especially in Laizhou Bay and Liaodong Bay(Figure 4). The possible reasons for these results were that numerous rivers and various agriculture and industry activities along the coastline have significantly contributed to high nutrient levels in coastal waters, which resulted in higher Chl-a concentration near shore. Moreover, the Bohai Sea is shallower and has a longer water exchange with the Yellow Sea due to the limitation of Bohai strait and thus a vertical

well-mixed water and long retention time can increase nutrient concentrations and help phytoplankton growth[21,22,23].
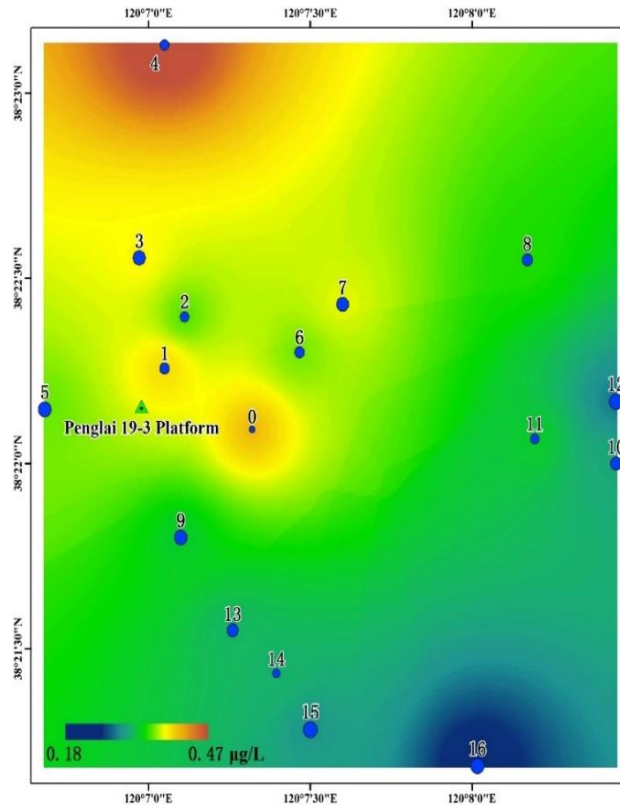

Figure 3. Spatial interpolation of in situ Chl-a concentrations in study region.
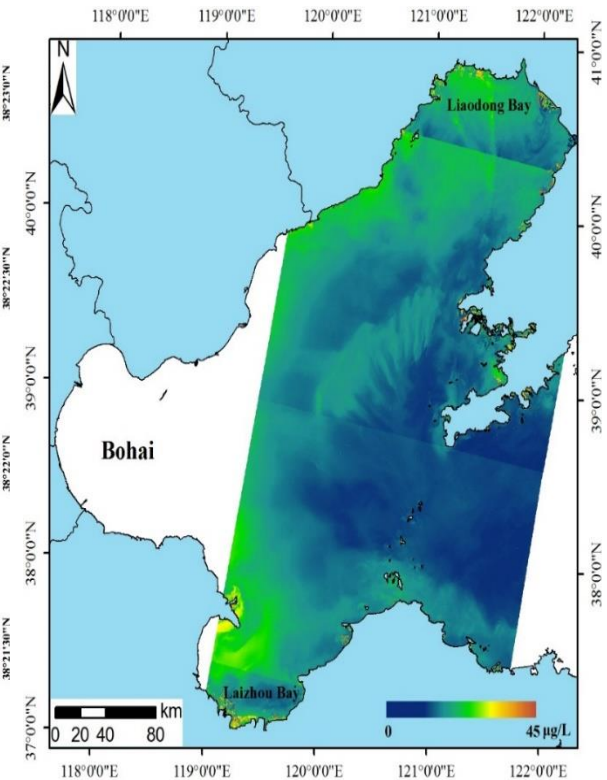
Figure 4. Spatial distribution of retrieved Chl-a concentrations in central Bohai sea.

6. Conclusions and discussion

This study introduced a remote sensing method to estimate Chl-a concentration of central Bohai sea by using GF1-WFV images and in situ measurements. The results indicated that reliable Chl-a concentration data was obtained to assess the ecological environment impact from the Penglai 19-3 platform after the oil spill accident occurred for 5 years. The LOOCV method showed that the average relative error and RMSE between retrieved Chl-a concentration and in situ measurement was 11.67% and 0.1808, respectively. It also indicated that the proposed linear model can correctly reflect the Chl-a concentration and its spatial distribution of central Bohai sea. Buffer analysis shows that the average Chl-a concentration near the platform is in normal range and notably lower than coastal regions. The major pollution of Bohai sea is the land-sourced pollutant at present.

If more in situ observations can be done in synchronism with the satellite image acquiring. Some abnormal observation samples like P16 can be eliminated. And the model will then provide more accurate results. In fact, regardless of P16, the relative error and RMSE between in situ measurements and retrieved Chl-a concentration is 8.93% and 0.1206, respectively. This is considered as more sufficient for Chl-a concentration retrieval. In order to overcome the extrapolation application limitations of empirical relational model, our future study will develop the bio-optical model for Chl-a concentration retrieving based on absorption coefficient, scattering coefficient and backscattering coefficient.

Acknowledgments

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