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Abstract: We analyzed the distribution of suspended sediments concentration (SSC) in the Yellow River Estuary based on data from GaoFen-1 (GF-1), which is a high-resolution satellite carrying a wide field-of-view (WFV) sensor and panchromatic and a multispectral (PMS) sensor on it. A new SSC retrieval model for the wide field-of-view sensor (M-WFV) was established based on the relationship between in-situ SSC and the reflectance in blue and near infrared bands. SSC obtained from 16 WFV1 images were analyzed in the Yellow River Estuary. The results show that (1) SSC in the study area is mainly 100–3500 mg/L, with the highest value being around 4500 mg/L. (2) The details of suspended sediment injection phenomenon were found in the Yellow River Estuary. The SSC distribution in the coastal water has two forms. One is that the high SSC water evenly distributes near the coast and the gradient of the SSC is similar. The other is that the high SSC water concentrates at the right side of the estuary (Laizhou Bay) with a significantly large area. Usually, there is a clear-water notch at the left side of the estuary. (3) Currents clearly influenced the SSC distribution in the Yellow River Estuary. The SSC gradient in the estuary was high against the local current direction. On the contrary, the SSC gradient in the estuary was small towards the local current direction. Eroding the coast and resuspension of the bottom sediments, together with currents, are the major factors influencing the SSC distribution in nearshore water in the Yellow River Estuary.

Keywords: GF-1; suspended sediment injection; Yellow River

1. Introduction

Characteristics of suspended sediment and its transportation have a critical impact on water pollution, nutrients [1], natural basins, and hydraulic structures [2,3]. Therefore, the study of the suspended sediment concentration (SSC) is essential for near-shore management, diagnosis of the consequence of the land use and handling [3], as well as harbor construction. Meanwhile, SSC analysis can also contribute to the management of the coastal ecosystem, such as mangrove habitat [1], dredging operations for dynamic estuaries [4], and compound extreme events prediction [5], etc.

Well-understanding the distribution and variances of SSC is necessary in addressing many estuarine problems. Many studies have focused on surface suspended sediment concentration (SSSC), defined as the dry mass of particles per unit volume of sea surface water (units are mg/L) [6], in different watersheds, especially in the estuary. SSSC of the estuary is usually very high, ranging from 30 to 2100 mg/L in the Yellow River Estuary [7], and from 0 to 2000 mg/L in the Yangtze Estuary [8]. SSC can be influenced by the flow stratification, distance seaward of the river, tidal height, river discharge, salt-wedge position, flow velocity, sediment properties, water quality and salinity, etc. [1,9]. Wave action brings turbulence and bed shear stress, inducing the sediments’ resuspension and transportation [10]. The geographical shape of the estuary, annular flume, and river–sea interaction influence the condition
of the flow, therefore affecting the concentration of the suspended sediments [11,12]. In the area with a salt-wedge, SSC decreases due to the buoyancy changing [13]. Furthermore, human activities [1] and unusual natural phenomena, flood events [14] for example, can also greatly change the ecosystem and the sediment load.

Traditionally, the study of the SSC based on in-situ data is expensive, and it consumes a lot of time [3]; the result derived, however, cannot describe the overall changes [7]. Moreover, the complexity and randomness of the suspended sediments in the estuary determine the necessity of the macroscopical regime detection of suspended sediment distribution and changes [15]. Furthermore, researchers have also developed methods to study SSC using the alternative variables that link to the SSC; the methods includes acoustic methods [16], scattered light measurement methods [17,18], and so on.

Remote sensing is one of the most promising regional detecting techniques for ocean environment. It can actively or passively remote survey the target areas, using cameras and sensors, from which we can obtain the concrete data [19]. Prior researchers found that the spectrometers can successfully identify solute types, in which the suspended sediments scattering dominated the multispectral response [19]. The spectral digital data from LISS-II [20] reveals that the spectral response increases with the increase of SSC. Therefore, based on the relationship between SSC and water-leaving radiance, we can efficiently retrieve SSC from remote sensing data [20,21].

The new technique of remote sensing has made up for the lack of the spatiotemporal data [19], however the accuracy of remote sensing data was lower than the synchronous in-situ data in prior studies. Therefore, many studies were performed focusing on SSC retrieval based on satellite data and high-precision synchronous data [22]. Since the artificial re-routing in 1996, the changes of the Yellow River estuary have been analyzed [23]. Based on Landsat and CZCS, the link between ocean color and SSC was established to inverse SSC [24]. Furthermore, using MODIS, the high-precision binary-parameter retrieval models, concerning the grain size and the water-leaving radiance, were developed [22]. Meanwhile, the distribution of SSC along the Tamil Nadu coast during monsoon and non-monsoon periods was mapped using (IRS) IA and IB digital data [25].

The Yellow River (HuangHe) estuary is the Yellow River outlet to the sea. In the past 30 years, researchers have done much work on the SSC retrieval using remote sensing data of the Yellow River estuary. A novel cubic retrieval model was built using the SSSC data derived from Landsat8 OLI [7], and a theoretical model for studying the scaling effects on the two-band ratio of red to near-infrared band (TBRRN) was developed based on MODIS data [26]. Studies also analyzed the temporal and spatial changes of SSC in the Yellow River Estuary using the MODIS L1B remote-sensing images and found that the local wind field had a certain influence on the SSC distribution [27]. The spatial resolution of these satellite data, however, is too low to detect the detail SSC information in coastal waters such as the Yellow River (HuangHe) estuary. It is necessary to develop a new method for the detection of detailed SSC distribution based on high-resolution satellite data.

GaoFen-1 (GF-1) is the first high-resolution satellite for earth observation in China, carrying wide field-of-view (WFV) sensors and panchromatic and multispectral (PMS) sensors on it. Four WFV sensors provide a combined swath of 800 km, with 16-m resolution and four-day revisit recycle [28,29]. GF-1 is widely used in the field of environmental monitoring [30] and its wide field data are sensitive to the variations of suspended particulate matter and can observe the spatial variation of SSC in high turbid waters [31]. Based on GF-1 WFV image data, Guo and Zhang have built a retrieval model of SSC in Zhoushan coastal area [32].

In this paper, we analyzed the spatial and temporal distribution details of SSC in the Yellow River Estuary using a newly built SSC retrieval model based on satellite data acquired from GF-1 WFV sensors.

The structure of this article is as follows. Section 2 is the introduction of the data and methods. Section 3 describes the retrieved SSC distribution using a new model. Sections 4 and 5 are the discussion and conclusion.
2. Data and Method

2.1. Study Area

The Yellow River flows into the Bohai Sea in Dongying, Shandong Province, China, forming the Yellow River Estuary (Figure 1). In Figure 1b, 80 points represented the position of 80 SSC in-situ measurements used in this study; red points represented 40 SSC in-situ measurements for establishing the model and blue points represented 40 SSC in-situ measurements for verification. The Yellow River Estuary, comprised of three estuarine zones, as a major region of fisheries in China and one of the most biodiverse zones in the world, is situated at the intersection of Laizhou Bay and the notch. The estuary has a warm-temperate monsoon climate. The annual surface water temperature varies from the lowest temperature of °C in winter to the highest temperature of °C in summer \cite{33,34} in the Yellow River estuary. The annual average precipitation of Dongying city is mm \cite{35}. The Yellow River originates from Qinghai Province, stretching from southwest to northeast and flowing across nine provinces in Northern China. It has the second largest sediment load in the world with \(1.05 \times 10^7\) of sediment load \cite{36} and \(33.21 \times 10^9\ m^3\ of\ runoff\ \cite{37}\ per\ year.\ The\ sediments\ mainly\ come\ from\ the\ wind-deposited\ Loess\ Plateau.\ The\ strength\ of\ self-consolidated\ sediments\ in\ the\ Yellow\ River\ linearly\ increases\ with\ the\ depth\ \cite{38}.\ Estuaries\ are\ the\ primary\ fresh–salt\ water\ interfaces.\ In\ the\ vicinity\ of\ the\ estuary,\ flow\ rate\ slows\ down\ and\ sediment\ deposition\ rate\ accelerates,\ resulting\ in\ a\ floodplain\ environment\ and\ a\ very\ specific\ and\ fragile\ wetland\ landscape\ \cite{39}.\ Dongying\ dam\ (or\ Dongying\ Port)\ is\ located\ in\ the\ north\ of\ the\ Yellow\ River\ Estuary,\ about\ 18\ nautical\ miles\ from\ the\ estuary.\ Dongying\ dam\ is\ surrounded\ by\ south\ groyne\ and\ north\ groyne\ from\ the\ northeast\ to\ the\ southwest.\ The\ north\ groyne\ body\ is\ a\ riprap\ slope\ embankment,\ with\ a\ length\ of\ 1800\ m,\ and\ water\ cannot\ flow\ through\ it.\ In\ 2009,\ the\ dam\ extended\ 5220\ m\ of\ trestle\ type\ approach\ embankment\ from\ the\ north\ groyne\ (riprapped\ slope\ embankment)\ to\ the\ northeast\ and\ water\ can\ flow\ through\ it.\ Since\ then,\ the\ trestle\ type\ approach\ embankment\ has\ continued\ to\ extend\ about\ 1.4\ nautical\ miles\ to\ the\ northeast\ \cite{40}.\nThe Bohai Sea is shallow with the mean depth about 20 m \cite{41}. The water depth near the Yellow River Estuary is lower than 15 m and the isobath is distributed along the coast \cite{42}. Owing to the heavy sediment load of the Yellow River and the rapid sedimentation in some areas, the bathymetry of the Yellow River estuary is continuously changing \cite{43}. In addition, changes in tidal wave height can also influence the water depth near the estuary \cite{44}.

The Yellow River Estuary is a microtidal estuary, dominated by an irregular semi-diurnal tide. Tides and tidal currents around the river mouth are controlled by amphidromic point of the main semidiurnal constituent of the lunar calendar (M2 tide). The tide elevation varies from 0.6 to 0.8 m around the estuary, and increases to 1.5–2.0 m in the south of Laizhou Bay. The duration of floods and ebbs was asymmetrical in the river mouth. Since 2000, the delta has retreated successively \cite{23}.\
2.2. Satellite Data

Satellite data from GF-1 wide field-of-view (WFV1), whose spatial resolution is 16 m, were applied in this paper (Table 1). The GF-1 satellite was successfully launched by Long March 2nd D carrier rocket, and its main payloads are WFV1 and PMS sensors. The WFV1 sensor is a multi-spectral camera with the spatial resolution of 16 m and the image width greater than 800 km [28], which is convenient for regionalized fine observation. The data used in this study are derived from the National Satellite Ocean Applications Centre data distribution system (http://dds.nsoas.org.cn/mainIndex.do). The PMS sensor with a revisit cycle of 26 days, can cover the entire country each 52 days. Images of the PMS sensor have the image width of 60 km and the spatial resolution of 2 m/8 m [45].

| Sensor   | Band No. | Spectral Range/µm | Resolution/m | Repetition Cycle/d |
|----------|----------|-------------------|--------------|--------------------|
| GF-1 WFV1| Band 1 (Blue) | 0.450-0.520       | 16           | 4                  |
|          | Band 2 (Green) | 0.520-0.590      |              |                    |
|          | Band 3 (Red)   | 0.630-0.690       |              |                    |
|          | Band 4 (NIR)   | 0.770-0.890       |              |                    |
| GF-1 PMS | Band 1 (Blue) | 0.450-0.520       | 8            | 41                 |
|          | Band 2 (Green) | 0.520-0.590      |              |                    |
|          | Band 3 (Red)   | 0.630-0.690       |              |                    |
|          | Band 4 (NIR)   | 0.770-0.890       |              |                    |
|          | Band 5 (PAN)   | 0.450-0.900       |              | 2                   |
2.3. Sample Data

In this study, SSC measurements were performed on 15 May 2019, from 10:53:13 to 11:33:13, and 80 SSC water samples (Figure 1b) were acquired including the latitude, longitude, and remote sensing reflectance.

SSC is the per unit volume of particulate matter \[46\]. We collected the SSC samples from the underwater samples in the study area. Three samples were taken at 1 m below the sea surface in every point using GCC2 plexiglass water bottle (3 L) and each sample was weighed, dried, and measured, then averaged to get the sampled point value \[46\].

The remote sensing reflectance (\(R_s\)) value was detected by an ISI921VF visible, near-infrared (NIR) spectral radiometer with a spectral range of 380–1080 nm. The measured \(R_s\) is calculated from Formula (1):

\[ R_s = \frac{L_w - \rho L_s}{\pi L_p / \rho_p} \]

where \(L_w\) is the radiance received by the ISI921VF above the sea-water surface; \(L_s\) is the radiance of the sky; \(\rho_p\) is the reflectance of the plate; \(L_p\) is the radiance received by the ISI921VF above the plate; and \(\rho\) is calculated assuming a black ocean at wavelength from 1000 to 1020 nm and wavelength independence \[46\].

2.4. Data Processing

2.4.1. Data Preprocessing

The preprocessing of GF-1 WFV1 data include ortho-rectification, radiometric calibration, and atmospheric correction. Ortho-rectification can correct the spatial and geometrical distortion of remote sensing images \[47\]. For the image with the rational polynomial coefficient (RPC) file and the resolution less than or equal to 15 m, it is practical to perform geometric rectification using ortho-rectification, whose precision is better \[48\]. The selected GF-1 WFV1 images in this study are L1A products, providing the RPC file for satellite direct orbit data production. Therefore, for the GF-1 WFV1 image, we performed geometric rectification using ortho-rectification based on RPC file and RPC model \[49\]. The elevation used in this study is The Global Multi-resolution Terrain Elevation Data 2010 with a resolution about 200 m.

Radiometric calibration changes DN-value received from the satellite sensors into apparent radiance, apparent reflectance, etc. \[47\]. Radiometric calibration is the preparation work for atmospheric correction. In this study, the radiometric calibration module in toolbox of ENVI 5.3 (L3Harris Geospatial, Boulder, CO, USA) was applied to perform the radiometric calibration according to GF-1 calibration parameters.

Atmospheric correction corrects the image from the scattering and absorption noise created by the interaction between solar radiation and the atmosphere, getting the reflectance of objectives \[47\]. In this study, atmospheric correction of GF-1 images were performed using the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) module \[50\] based on the MODerate resolution atmospheric TRANsmission (MODTRAN) code, a radiative transfer model solving the radiative transfer equation. The FLAASH module output a bottom-of-atmosphere reflectance value for each pixel and an average scene visibility as well as water amount estimate, providing accurate, physically based derivation of atmospheric properties \[51,52\]. If the suitable initial visibility value was not adopted in the FLAASH module, the high amount of negative pixels will appear \[53\]. The atmospheric model in FLAASH module was selected according to the season and coordinate. In many studies, atmospheric correction based on FLAASH was applied to remote sensing images for both aquatic environments and terrestrial environments \[51,54\]. After the atmosphere correction using FLAASH model, a regional soil organic carbon prediction model was developed based on a discrete wavelet analysis of GF-5 satellite data \[55\]. In prior studies, the comparison among three types of atmospheric correction models, FLAASH, the second simulation of the satellite signal in the
solar spectrum (6S), and acolite, was performed, indicating that FLAASH can be used for the research of water body [56]. The chlorophyll-a concentrations in the lake of Lagos Lagoon were validated using the Landsat data based on FLAASH atmospheric correction [57]. Water body was extracted from the Resource-3 (ZY-3) multispectral images, GF-1 multispectral images, and GF-2 multispectral images [58] using neural network after the procession of FLAASH. Furthermore, algorithms for aquatic colored dissolved organic matter after FLAASH were also proposed based on the Thematic Mapper (TM) images of Landsat 5 [59]. In addition, the remote sensing reflectance of water varies in different bands [60]. Meanwhile, based on FLAASH atmosphere correction, the water quality including chlorophyll-a of inland waters can be monitored well using the hyperspectral HJ-1A HSI and the Enhanced Thematic Mapper Plus (ETM+) of Landsat 7 images. Applying the Medium Resolution Imaging Spectrometer (MERIS) images, a two-step approach was developed based on FLAASH to estimate particulate organic carbon concentrations in a shallow eutrophic lake [61].

The shortcoming of the FLAASH model exists, for example, in the fact that it cannot eliminate other effects such as specular reflectance and sun glint. However, the acquisition time of the GF-1 WFV1 data is noon (Table 2). At noon, the solar irradiance on the east and west sides of the orbit is the same, which can avoid the specular reflection caused by solar flares effectively [62].

| Date of Data Acquisition (Y-M-D HH:MM:SS) |
|-----------------------------------------|
| 2013-08-21 10:52:34                     |
| 2013-09-07 11:13:59                     |
| 2013-12-04 10:54:16                     |
| 2014-03-20 11:01:08                     |
| 2014-05-04 11:00:55                     |
| 2014-08-07 11:20:39                     |
| 2014-09-04 11:04:55                     |
| 2014-10-15 11:06:14                     |
| 2015-01-01 11:11:04                     |
| 2015-03-24 11:13:07                     |
| 2018-04-20 11:09:31                     |
| 2019-05-23 11:08:13                     |

All the processes were completed in ENVI 5.3 and Python 3.7.

In order to show the effectiveness of FLAASH, we compared the in-situ Rrs with the Rrs obtained after FLAASH correction in this study. The in-situ data were measured simultaneously with the satellite data using IS1921VF visible, near-infrared (NIR) spectral radiometer with a spectral range of 380–1080 nm. The remote sensing reflectance (after atmospheric correction based on the FLAASH model) has a good consistency with the in-situ reflectance, as shown in Figure 2e, with the correlation coefficient $R^2$ of 0.9533. Therefore, the FLAASH model can be applied for atmospheric correction in this paper.

2.4.2. SSC Retrieval Model

From the 80 SSC in-situ measurements (Figure 1), 40 measurements were used to analyze the relationship between the SSC and the remote sensing reflectance, so as to select suitable band to establish the SSC retrieval model for the GF-1 WFV1. The remaining 40 measurements were used for model validation. The correlation coefficient ($R^2$) and the root-mean-square error (RMSE) between the verification values and the model inversion values were calculated, and we selected one retrieval model with the highest correlation.
Figure 2. Profile of the SSC and the remote sensing reflectance (after atmospheric correction) of each single band (a–d). The linear fitting plot of the in-situ reflectance and the remote sensing reflectance after atmospheric correction based on the FLAASH model (e).
3. Results

3.1. Sensitive Band of SSC

The changes of SSC could be represented by the changes of remote sensing reflectance of water [63,64]. The SSC in the Yellow River estuary is very high (>200 mg/L). The reflectance curve changes with the change of the SSC. The first reflectance peak appears in the range of 590–730 nm (red band), while the second reflectance peak appears at around 800 nm (NIR band). With the increase of SSC, the reflectance value in near infrared band clearly changes, showing an increasing trend. In the red band, the reflectance value also increases, however not as obviously as the near infrared band. In green band, the reflectance value shows no obvious change with the change of SSC [65,66]. Therefore, finding out the most sensitive band of SSC is crucial to establishing the quantitative retrieval model.

In general, for clear water, the remote sensing reflectance of the water reduces with the rise of wavelength ranging from blue to near infrared. However, for high SSC water in the Yellow River Estuary, the in-situ remote sensing reflectance of the water increases with the raise of wavelength and the reflecting peak of SSC moves from green band to the longer wavelength such as red band and NIR band [66,67].

In this study, fitting analysis using quadratic polynomial between the remote sensing reflectance of single band and SSC was performed (Table 3 and Figure 2), showing that the band 4 (NIR) was optimal with the correlation coefficient (R^2) of 0.9823.

| Band (X) | Quadratic Polynomial | Correlation Coefficient (R^2) |
|----------|----------------------|-------------------------------|
| Band 1 (Blue) | 0.0222X^2 − 42.731X + 21080 | 0.5019 |
| Band 2 (Green) | 0.0086X^2 − 17.748X + 9585.3 | 0.6138 |
| Band 3 (Red) | 0.0026X^2 − 5.1238X + 3067.5 | 0.8264 |
| Band 4 (NIR) | 0.0017X^2 − 1.5078X + 1017.1 | 0.9823 |

3.2. SSSC Quantitative Retrieval Model

Prior researchers found that the spectral reflectance ratio of two bands or multiband can eliminate a part of influence caused by refractive coefficient of suspended sediments and backscatter [68]. Furthermore, it can eliminate the product effect of atmospheric influence and the noises on the water surface, emphasizing the target information [69,70]. Therefore, the spectral reflectance ratio is more suitable than the single band in establishing the model.

Based on the analysis above (Table 3 and Figure 2), the band 4 (NIR) and the band ratios of the band 4 (NIR) and the other three bands were applied as the remote sensing factors [71,72], marked as X. The fitting analysis for the remote sensing reflectance of X and the SSC was performed to establish the quantitative retrieval models. The exponential function, linear function, quadratic polynomial function, cubic polynomial function, power function, and logarithmic function [68,73] were selected as fitting functions, and we screened out the fitting models whose correlation coefficient (R^2) were higher than 0.9 (Table 4).

We took the remaining 40 in-situ SSC values as verification data (blue points in Figure 1). The SSC for verification were marked as SSC_{test} (sampling SSC). Based on the fitting models (Table 4), the SSC of GF-1 WFV1 image (acquired time: 15 May 2019) was retrieved and marked as SSC_{sim} (inversed SSC). The root-mean-square error (RMSE) between the SSC_{test} and SSC_{sim} was calculated to evaluate the modeling precision of the fitting models following the RMSE formula (Formula (2)).

\[
RMSE = \sqrt{\frac{\sum (SSC_{test} - SSC_{sim})^2}{N}}
\]  

(2)

The variable N in the RMSE formula was the amount of the verification points.
SSC = 1420X^3 - 1902.3X^2 + 2337.5X - 268.43  \tag{3}

\[ X = \frac{R_{\text{rs}}(B4)}{R_{\text{rs}}(B1)} \tag{4} \]

The reflectance of the band 1 (Blue) was marked as \( R_{\text{rs}}(B1) \) and the reflectance of the band 4 (NIR) was marked as \( R_{\text{rs}}(B4) \).

The scatter diagram of the SSC_{\text{test}} (sampling SSC) and the SSC_{\text{sim}} (inversed SSC) was analyzed (Figure 3). The linear fitting analysis was made to the SSC_{\text{test}} and the SSC_{\text{sim}}. The slope of the trend line was 0.9994 and the SSC_{\text{test}} and the SSC_{\text{sim}} were highly correlated, showing a high precision.

The new built model M-WFV was shown in Formula (3).

### Table 4. Fitting models with correlation coefficient \((R^2)\) higher than 0.9.

| \( X \) | Function | Fitting Model | \( R^2 \) | RMSE (mg/L) |
|--------|----------|---------------|-----------|-------------|
| B4     | exponential | \( 334e^{0.0013X} \) | 0.953 | 124.175 |
| B4     | linear | \( 1.6543X - 345.08 \) | 0.939 | 209.314 |
| B4     | quadratic | \( 0.0017X^2 - 1.5078X + 1017.1 \) | 0.982 | 83.3048 |
| B4     | cubic | \( 7E-7X^3 - 3E-4X^2 + 0.5343X + 427.35 \) | 0.983 | 1050.560 |
| B4     | power | \( 0.3944X^{1.842} \) | 0.920 | 222.018 |
| B4/B1  | exponential | \( 244.63e^{1.8522X} \) | 0.998 | 37.342 |
| B4/B1  | linear | \( 2600.4X - 777.79 \) | 0.971 | 146.141 |
| B4/B1  | logarithmic | \( 2110.1\ln(X) + 1917.2 \) | 0.916 | 240.394 |
| B4/B1  | quadratic | \( 2022.3X^2 - 1047.8X + 638.88 \) | 0.999 | 33.264 |
| B4/B1  | cubic | \( 1420X^3 - 1902.3X^2 + 2337.5X - 268.43 \) | 0.999 * | 13.110 * |
| B4/B1  | power | \( 1696X^{1.5427} \) | 0.992 | 115.681 |
| B4/B2  | exponential | \( 195.2X^{2.3858X} \) | 0.961 | 98.125 |
| B4/B2  | linear | \( 3330.8X - 1082.5 \) | 0.924 | 204.531 |
| B4/B2  | quadratic | \( 4187.7X^2 - 3129.8X + 1159.7 \) | 0.986 | 85.899 |
| B4/B2  | cubic | \( -1937.2X^3 + 8659.8X^2 - 6373.3X + 1901.8 \) | 0.986 | 79.303 |
| B4/B2  | power | \( 2047.2X^{1.6806} \) | 0.920 | 187.968 |
| B1/B4  | quadratic | \( 106840X^2 - 82475X + 16432 \) | 0.931 | 237.609 |
| B1/B4  | cubic | \( -824540X^3 + 966772X^2 - 375254X + 48865 \) | 0.977 | 133.112 |
| B2/B4  | quadratic | \( 126006X^2 - 111280X + 25137 \) | 0.971 | 123.611 |
| B2/B4  | cubic | \( -10E6X^3 + 10E6X^2 - 590550X + 86430 \) | 0.990 | 155700.517 |
| B2/B4  | power | \( 39.62X^{-3.471} \) | 0.916 | 236.042 |
| B4/B1 + B2/B3 | exponential | \( 139.78e^{3.368X} \) | 0.941 | 128.962 |
| B4/B1 + B2/B3 | linear | \( 11771X - 1568.2 \) | 0.918 | 213.348 |
| B4/B1 + B2/B3 | quadratic | \( 48632X^2 - 13581X + 1500.5 \) | 0.977 | 114.790 |
| B4/B1 + B2/B3 | cubic | \( -159821X^3 + 173152X^2 - 44550X + 3968.9 \) | 0.979 | 103.838 |
| B4/B1 + B2/B3 | power | \( 20454X^{2.039} \) | 0.909 | 174.847 |
| (B1 + B4)/2 | quadratic | \( 0.006X^2 - 9.6123X + 4502.6 \) | 0.968 | 118.603 |
| (B1 + B4)/2 | cubic | \( 2E - 7X^3 + 0.005X^2 - 9.0522X + 4324.9 \) | 0.968 | 310.112 |
| (B2 + B4)/2 | quadratic | \( 0.005X^2 - 8.4793X + 4239.4 \) | 0.973 | 917604.028 |
| (B2 + B4)/2 | cubic | \( 2E - 6X^3 - 2.1E - 3X^2 - 1.3165X - 1902.6 \) | 0.975 | 3178.014 |
| (B3 + B4)/2 | quadratic | \( 0.0029X^2 - 4.8622X + 2626.2 \) | 0.967 | 146.347 |
| (B3 + B4)/2 | cubic | \( 2E - 6X^3 - 0.0034X^2 + 1.748X + 491.07 \) | 0.976 | 3616.066 |

The \( X \) is the remote sensing factor (band combination). * According to the evaluation results, a cubic polynomial fitting model based on the band ratio of the band 4 (NIR) and the band 1 (Blue) was the best model named M-WFV (Formula (3)) with the \( R^2 \) of 0.999 and the RMSE of 13.110 mg/L (Table 4).
3.3. The SSSC Distribution of the Yellow River Estuary

The SSC of the Yellow River estuary was obtained from GF-1 WFV1 images using the M-WFV model. The SSC in the study area was mainly in the range of 100–3500 mg/L. In the Yellow River and near the mouth of the Yellow River, the SSC was extremely high with the SSC being around 4500 mg/L. A lot of sediments injected from the Yellow River into the coastal water of the estuary led to high SSC there. Outside the river, the SSC decreased gradually with the increase of the distance away from the Yellow River mouth. Prior studies show that, generally, SSC in the study area mainly in the range of 100–3500 mg/L. The SSC of the Yellow River estuary and the offshore is usually higher than 2500 mg/L [7,74]. Meanwhile, the SSC of the Bohai Sea is usually lower than 500 mg/L. The SSC of our modeled results show a good consistency with prior studies.

Usually, facing the Bohai Sea, there exists high SSC area near the right-hand side of the estuary (Figure 4a–c,f,g), i.e., Laizhou Bay. On the left-hand side of the Yellow River Estuary, there occasionally appears a small high SSC area along the coastal line of the notch (Figures 4c and 5g).

The SSC in the coastal water mainly distributed in two forms (Figures 4 and 5). One was that the high SSC water evenly distributed near the coast and the gradient of the SSC was similar (Figure 4d,e,h and Figure 5d–f). The other was that the high SSC water distributed near the notch (Figure 5g) and the Laizhou Bay with a significantly large high SSC area (Figure 4a–c,f,g).

Currents influenced the SSC distribution in the Yellow River Estuary. The SSC gradient in the estuary was high against the local current direction. On the contrary, the SSC gradient in the estuary was small towards the local current direction (Figure 5a,c,h). The local current direction in the estuary could be recognized by the SSC gradient. The local current direction differed in different situations,
as in Figure 5a–c,e, the current direction was towards the Laizhou Bay. In Figure 5d,f, the current direction was unapparent. In Figure 5g,h, the current direction was towards the notch. From the SSC distribution in the study area (Figures 4 and 5), we found a clear water body in the notch, with normally low SSC and occasionally high SSC there.

These findings above were of great significance to the clearing of sediment in the Yellow River estuary. A large amount of sediments are transported into the estuary and the composition of the sediment is relatively fine, leading the delta shore line to change quickly and frequently [75]. The coastline of the estuary changed at different time in the image because of the silting and erosion occurred in the Yellow River Estuary (Figure 5). In the notch area on 7th August 2014 (Figure 5h), the high concentration was mainly induced by the alongshore currents, which induced Ekman transport, leading to the bottom sediments’ resuspension there.

Figure 4. Retrieved from GF-1 WFV1 image. The red arrow in the figure present the local current direction. The red box in (a) is the location of Dongying Dam (Dongying port). The black box in (i) is the area of the retrieved images in the study area.
Figure 5. SSC distribution in the notch at the left side of the estuary. The black arrows in the picture indicate the current directions. The black dotted arrow in (e) indicates that the current is weak. The black box in (i) is the area of the retrieved images in the study area.

4. Discussion

4.1. Applicability of Cubic Model

The NIR band is sensitive to SSC in high-turbid water, which is consistent with prior studies [76,77]. The band ratio of band 1 (Blue) and band 4 (NIR) eliminates some external factors of atmosphere and the noise on the water surface [7]. The new cubic retrieval model was built to retrieve SSC in high-turbid water such as the Yellow River Estuary based on GF-1 WFV1 (M-WFV), which can preferably reflect the SSC distribution and changing details. The SSC retrieved from GF-1 WFV1 images using M-WFV model showed a good consistency with in-situ SSC with correlation coefficient ($R^2$) of 0.9998 and RMSE of 13.1102 mg/L.

The SSC obtained from GF-1 WFV1 gives a good view of SSC distribution not only in the Yellow River Estuary but also in the Yellow River, showing an interesting phenomenon of suspended sediment injection into the Bohai Sea in detail.

Comparing our result based on the M-WFV with prior studies, the SSC distribution shows good consistency with prior studies, with high SSC mainly at the south side of the estuary, and low SSC at the left side of the estuary [47,74]. Many studies have compared different atmosphere correction methods such as ACOLITE, 6S [56], QUAC (Quick Atmospheric Correction) [78], and FLAASH for aquatic environments, and found that the ACOLITE method is the best. It can avoid unrealistic negative reflectance [79], amplification of glint, and adjacency effects in the atmospheric correction by default using the “dark spectrum fitting” approach [80]. The ACOLITE method is especially suitable for high-turbidity nearshore waters [56]. We will apply this method to perform atmospheric correction in the future studies of water information.
4.2. The Influence of Currents and Runoff on SSC Distribution

The Yellow River is a seasonal river. Large variations in both annual water discharge and sediment load occur in the Yellow River [81]. The water discharge from the Yellow River can be divided into three time intervals [82]: Large water stage (>1500 m$^3$/s), medium water stage (1500–800 m$^3$/s), and small water stage (<800 m$^3$/s). The turbidity is always high in the Yellow River, which is due to the erosion of loess formations upstream, supporting 90% of the annual sediment load in the estuary. Outside the estuary, the SSC progressively decreases [83]. Most of sediments are deposited close to the coast or partly into the open waters of the Bohai Sea [84]. The intensity of the water–sediment interaction differs in different time intervals and the SSC in the coastal waters has big changes in different time intervals [85,86].

The variation of the SSC in the estuary is highly correlated with the annual total sediment discharge from the Yellow River [86]. In 2014, a serious drought happened in July and August in the middle and low reaches of the Yellow River while the autumn floods happened in September, and the increase of precipitation results in the increase of runoff and sediment transport of the Yellow River (Figure 5c) [87].

Tidal fronts and alongshore tidal currents are the major dynamic factors controlling the sediment dispersion [88,89]. Tides along the Yellow River Estuary are basically irregular semi-diurnal tides with a tidal cycle of about 6 h [86,88]. Tidal constituents M2 and the diurnal constituent of lunar and solar declination (K1 tide) are the most significant ones in the Yellow River Estuary. The tidal current in the estuary is a reversing current, and its direction is approximately parallel to the shore (Figure 5) [90]. Tidal current flows southward (Figure 4b,e,f,h and Figure 5c) during flood tide and northward (Figure 4c,d and Figure 5h) during ebb tide with an average speed of 0.5–1.0 m/s [91]. The Yellow River Estuary is the weak tidal estuary, whose tidal section is shorter, and sometimes there is even no tidal section. Furthermore, the increase of riverine runoff can promote tidal damping and the tide is noticeably affected by the decreasing trend in the upstream channel of the estuary [91,92]. There is a low-velocity zone inside the river mouth that can capture a huge amount of sediments until high tide level [89]. Within the range of tidal current, seawater flows upstream from the bottom of the water mass in the form of a brine wedge [93].

Tidal residual currents and tidal circulations appear because of the nonlinear benefit of tidal currents. Tidal circulation is closely related to the rotation direction of tidal current motion, and they are basically consistent [94].

The central area in the Bohai Sea is dominated by micro tides with the tide range less than 2 m. The areas in the east, north, and west of the Bohai Sea are dominated by meso-tides with tide range between 2 and 4 m. In the far north end of the Bohai Sea, it is the region of macro-tides where the tide range exceeds 4 m [91]. The study area has two primary high-speed current zones, with one located near the present Yellow River mouth [95].

Ocean current and wind-wave forces explained high concentrations and intra-annual variations of SSC in Laizhou Bay (Figure 4a–c,f,g) [5]. In Figure 4f, high SSC water was concentrated at the right side of the estuary (Laizhou Bay) with significantly large areas. Currents at the left side of the estuary (notch) flowed towards Laizhou Bay. Meanwhile, currents at the right side of the estuary flowed towards the notch. It led the water level to increase in the estuary but to decrease outside the estuary. The water depth was relatively shallow in the Laizhou Bay. The current in the right side of the estuary was influenced by the Coriolis force [96], inducing the offshore Ekman transport. This process produced an upwelling in the southern shore of the estuary. The upwelling took the bottom water to the surface; meanwhile, it also took the bottom sediments to the surface, making the coastal water turbid. The currents [97], waves [98], and winds [93] erode the silt of coast and re-suspend the bottom fine matter in the right side of the estuary, Laizhou Bay, to the surface, forming the high SSC water. The SSC concentrations in Laizhou Bay is high in the dry season and low in the wet season.
4.3. Other Reasons Contributing to SSC Distribution

The low SSC water in the notch, at the left-side of the estuary (facing the Bohai Sea), keeps the low SSC (Figure 5). There is a clear water circulation in the notch [99]. It hinders, divides, and subtracts the direct northward movement of sediments from the estuary. Sometimes, the water is turbid in the notch (Figure 5c,g,h). In Figure 5c, the current in the estuary flowed towards Laizhou Bay, inducing a counterclockwise circulation in the notch because of the nonlinear benefit of tidal current. The circulation was influenced by the Coriolis force, producing the Ekman transport to the shore. Thus, there was a downwelling in the notch that took surface water to bottom. Although there was little re-suspended sediments in the notch, the strong precipitation happened in September 2014, eroding the shore, and taking lots of silts into the water, inducing high SSC in the notch. In Figure 5g,h, the currents in the estuary flowed towards the Bohai Bay. There was a clockwise circulation in the notch. The circulation, influenced by the Coriolis force, produced the Ekman transport offshore. Thus, there was an upwelling in the notch, taking bottom water and bottom sediments to surface, making high SSC in the notch.

Human activities such as the water-sediment regulation (WSR) scheme, operation of dams and reservoirs, Grain-for-Green campaign in the Loess Plateau, etc., can inevitably influence the sediments distribution in the Yellow River Estuary, as well as stream flow of the Yellow River and the shape of coastline [5,74]. Dongying dam (or Dongying Port) (Figure 1b), surrounded by south groyne and north groyne from the northeast to the southwest, is located in the north of the Yellow River Estuary. The currents of the Dongying Port are mainly the coastal currents from northwest to southeast or from southeast to northwest. The water depth of the port is about 5 m near the land to 15 m at the end of the trestle. The north groyne blocked the sea currents and lots of sediments were deposited on the north side of the groyne especially at the junction of the groyne and the trestle, inducing high SSC on the single side of the groyne. Therefore, the SSC on two sides of the north groyne was obviously different. The extended trestle also trapped the sediments when the sea water flows through with strong scour and the SSC decreases (Figure 4), though the difference of the SSC on the two side of the trestle was not as obvious as the north groyne [40,100].

5. Conclusions

The suspended sediment injection details of the Yellow River estuary were revealed by GF-1 WFV1 data, using a new built SSC retrieval model (M-WFV) based on the relationship between the blue and near-infrared bands and in-situ data.

The SSC retrieved from GF-1 WFV1 images shows that the Yellow River injects a large amount of sediments into the sea, and while most of the sediments quickly deposit near the estuary, inducing the high SSC gradient in the estuary, some are transported into the Laizhou Bay because of the currents, waves, and winds. Therefore, the SSC in the study area varies in the range of 100 mg/L in Bohai Sea to nearly 3500 mg/L in the estuary and Laizhou Bay, with the highest value being around 4500 mg/L. Furthermore, the SSC distribution in the coastal water has two forms. One is that the high SSC water evenly distributes near the coast and the gradient of the SSC is similar. The other is the high SSC water concentrates at the right side of the estuary (Laizhou Bay) with a significantly large area. The high SSC at the right side of the estuary is mainly influenced by the bottom sediments’ re-suspension and the erosion of the coast. Usually, there is a clear-water notch at the left side of the estuary because the circulation in the notch hinders the sediments being transported from the estuary.

Currents clearly influenced the SSC distribution in the Yellow River Estuary. The SSC gradient in the estuary was high against the local current direction. On the contrary, the SSC gradient in the estuary was small towards the local current direction. The local current direction in the estuary could be recognized by the SSC gradient. Other reasons such as river runoff, eroding the coast, and near shore constructions, etc., can also influence the SSC distribution.
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