A three-band semi-analytical model for deriving total suspended sediment concentration from HJ-1A/CCD data in turbid coastal waters

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A B S T R A C T
The accurate assessment of total suspended sediment (TSM) concentration in coastal waters by means of remote sensing is quite challenging, due to the optical complexity and significant variability of these waters. In this study, three-band semi-analytical TSM retrieval (TSTM) model with HJ-1A/CCD spectral bands was developed for the retrieval of TSM concentration from turbid coastal waters. This model was calibrated and validated by means of one calibration dataset and three independent validation data-sets obtained from three different turbid waters. It was found that the TSTM model may be used to retrieve accurate TSM concentration data from highly turbid waters without the spectral slope of the model requiring further optimization. Finally, the TSM concentration data were quantified from the HJ-1A/CCD images after atmospheric correction using the dark-object subtraction technique. Upon comparing the model-derived and field-measured TSM concentration data, it was observed that the TSTM model produced <29% uncertainty in deriving TSM concentration from the HJ-1A/CCD data. These findings imply that the TSTM model may be used for the quantitative monitoring of TSM concentration in coastal waters, provided that the atmospheric correction scheme for the HJ-1A/CCD imagery is available.

1. Introduction
Total suspended sediment matter (TSM) in coastal waters plays an important role in biogeochemical cycles in estuarine ecology, due to the fact that the fine-grained particles are an important carrier of various chemical compounds (Turner and Millward, 2002). TSM concentrations in estuaries are strongly affected by a combination of hydrodynamic physico-chemical and biological processes. Understanding the spatial and temporal dynamics of TSM in estuarine environments can allow for the estimation of the transport of terrestrial and anthropogenic materials to pelagic oceans. In addition to these, the interaction between TSM and seawater may strongly modify the nutrient concentration in estuarine systems (Chen et al., 2012a). These processes can rapidly alter the optical properties of coastal waters and their impacts can be clearly observed by water color. However, coastal regions are ecosystems with quickly hydrodynamics where events and processes operate over short time and small space scales, usually causing conventional station samples to be insufficient for the purpose of mapping patterns, thus new observational methods with the capability to rapidly sample at high resolution are needed. Fortunately, the recent advances in optical sensor technology have allowed scientists to utilize ocean color satellite images to synoptically investigate large-scale TSM concentration in coastal zones (Chen et al., 2013e).

Numerous works have demonstrated that remotely sensed data can be used to retrieve TSM concentration from turbid coastal waters (Miller and McKe, 2004; Nechad et al., 2010; Ouillon et al., 2008). Many TSM models based on empirical methods have been used in operational satellite remote sensing systems. These models were developed on the basis of statistical relationships between TSM concentrations and single-channel or multi-channel reflectance (Aguirre‐Gomez, 2000; Tassan, 1997). For example, the single waveband reflectance in the green–red regions has been proposed in the Delaware Bay (Stumpf and Pennock, 1989), Biscay Bay (Aguirre-Gomez, 2000), Hangzhou Bay (Wang et al., 2008), and Irish Sea (Bowers et al., 1998), with varying degrees of success. However, the exact form of the relationship between TSM and reflectance also depends on the mineralogy, color, and particle
scattering properties (incorporating particle size distribution and refractive indices) (Bing et al., 2005; Bowers and Binding, 2006). These factors can be highly variable in natural aquatic environments, and therefore the applicability of an empirical model is generally assumed to the setting in which the data were collected (Long and Pavelsky, 2013). More recently, the ratio of the red to NIR bands might be effectively applied to retrieve TSM concentration from satellite images (Doxaran et al., 2002; Doxaran et al., 2009; Min et al., 2012). It was suggested in these studies that the variability in reflectance resulting from changes in particle characteristics could be avoided by using the band ratio model (Bing et al., 2005; Doxaran et al., 2002; Moore et al., 1999).

Although these empirical models may be effectively applied to satellite images concurrent with the calibration dataset, their accuracy may be reduced outside the conditions of the calibration dataset because of the empirical basis (Nechad et al., 2010). Fortunately, a semi-analytical model which combines physical methods with statistical methods can overcome these limitations of empirical models, and thus may become a promising technique for TSM concentration retrieval (Chen et al., 2013a; Long and Pavelsky, 2013; Ouillon et al., 2008). Over the past several years, semi-analytical models have been established by many authors based on the relationship between the absorption or scattering properties and TSM concentration (Aguirre-Gomez, 2000; Chen et al., 2013a; Onderka and Pekarova, 2008; Ondrusek et al., 2012). Due to the fact that radiance scattered from particulate particles is generally the first-order determinant for variability in reflectance in coastal waters, the backscattering coefficients can be used to estimate the TSM concentration (Bowers and Binding, 2006; Volpe et al., 2011; Zawada et al., 2007). In addition, if the absorption coefficient of particles can be isolated from the apparent optical properties using an analytical model, it can then be used to quantify the TSM concentration (Binding et al., 2008; Bowers and Binding, 2006; Neukemans et al., 2009; Tassan and Ferrari, 2003). However, although these models may be effectively applied to satellite images concurrent with calibration datasets, some problems are encountered when they are applied to the turbid coastal waters of China. For example, when the TSM models proposed by Doxaran et al. (2009), Miller and McKeel (2004), and Fettweis et al. (2007) were applied to process satellite data in the Oujiang River Estuary, the values of the retrieved TSM concentrations were all less than 40 mg/l. Therefore, due to the optical complex in the coastal waters of China such as the Oujiang River Estuary, Changjiang River Estuary, and Bohai Sea, an innovative regional semi-analytical model is required, and such a model is still under development.

In this study, a three-band semi-analytical TSM retrievals model (TSTM) was developed for deriving TSM concentration from HJ-1A/CCD data in turbid coastal waters. The specific goals of the study are as follows: (a) to evaluate the accuracy of four existing models for accurately estimating TSM concentrations in turbid coastal waters; (b) to improve the performance of four exiting models by a proposed TSTM model with the spectral bands of HJ-1A/CCD sensor; and (c) to compare the accuracy of three existing models and TSTM model in estimating TSM from highly turbid and productive coastal waters in China.

2. Study area

The Oujiang River Estuary (Fig. 1) is located between longitudes 120°48’E and 121°32’E, and latitudes 27°36’N and 28°12’N, near the center of Wenzhou City, Zhejiang Province, a location which is well known in China for its rapid economic development over the past two decades. The optical properties of coastal waters such as the Oujiang River Estuary are vital to local human activities and needs, and play a critical role in the regional ecosystem, which may also impact climate changes. Due to the rapid economic development and population growth in this region, enormous quantities of nutrients and other pollutants have been transported from land
to the estuary, which may have largely resulted in the increasing number and scale of harmful algal bloom events in the local coastal waters (Gao et al., 2010). Thus, there is an urgent need to effectively monitor and manage the aquatic environment in the Oujiang River Estuary, and to better understand the optical, biological and ecological processes and phenomena which occur there (Chen et al., 2013c). In order to obtain useful bio-optical information from the Oujiang River Estuary, it is necessary to perform research regarding the development of specific, regional, and high resolution remote sensing algorithms in this area, which will assist in the effective monitoring and management of water color in coastal regions.

In order to validate the applicability of the TSTM model for accurately deriving TSM concentrations from other coastal waters, another two coastal regions are selected for model validation in this study, namely the Changjiang River Estuary and the Bohai Sea (Fig. 1). The Changjiang River, at 6300 km in length, is the longest river in Asia and the third longest in the world. The annual mean suspended sediment load from the Changjiang River reaches $4.9 \times 10^8$ tons (Hsu and Lin, 2010). The Changjiang River also supplies sediment to the continental shelf. More than 95% of suspended sediment, which is applied to 45 cm sediments above the bed of the Changjiang River Estuary, provides a good example of a turbid estuary (Shi, 2010). The Bohai Sea is located in the northern part of east coast China, with an area of $7.8 \times 10^4$ km$^2$. Several large rivers flow into the Bohai Sea, including the Yellow River, carrying a large amount of inorganic and organic suspended matter, with an average annual run-off up to $4.86 \times 10^{10}$ m$^3$, and annual sediment transport of $4.86 \times 10^{10}$ tons (Cui et al., 2010). Therefore, the optical properties of the Bohai Sea are quite complex and its water is classified as Case II.

3. Materials and methods

3.1. Accuracy assessment

In this study, the Root-Mean-Square (RMS) of the ratio of modeled-to-measured values is used to assess the accuracy of the atmospheric correction. This statistic is referred to simply as RMS and is described by the following equation:

$$RE_i = \left| \frac{x_{\text{mod},i} - x_{\text{obs},i}}{x_{\text{obs},i}} \right| \times 100\%$$

where $RE_i$ is the relative uncertainty of the $i$th observation, $x_{\text{mod},i}$ is the modeled value of the $i$th element, $x_{\text{obs},i}$ is the observed value of the $i$th element, and $n$ is the number of elements.

3.2. Field measurements

In order to evaluate the accuracy of the TSTM model in coastal waters, the bio-optical dataset consisting of simultaneous measurements of above-water remote sensing reflectance and TSM concentration was collected from the Oujiang River Estuary in September, 2012. The dataset was then divided into two smaller datasets, namely the calibration and validation datasets. The calibration dataset (Fig. 2(a) and Table 1(a)) containing 48 samples, which was used to initialize the TSTM model, was collected during six independent cruises in the Oujiang River Estuary respectively on September 9, 10, 18, 19, 21, and 25, 2012; and the validation dataset (Fig. 2(b) and Table 1(b)) containing 30 samples, which was used to estimate the stability and accuracy of the TSTM model, was collected on September 12 and 17, 2012. To further validate the applicability of the TSTM model in coastal waters, which have bio-optical properties that differ from those of the Oujiang River Estuary, another two independent datasets were collected from the Changjiang River Estuary and Bohai Sea. The experiment in the Changjiang River Estuary (Fig. 2(c) and Table 1(c)) was carried out on October 14 and 15, 2009 and included 29 samples; that in the Bohai Sea (Fig. 2(d) and Table 1(d)) was performed in August and September, 2006 and included 53 samples.

Remote sensing reflectance (Fig. 2) was measured by means of a field spectroradiometer (Spectral Devices, Boulder, CO, ASD), simultaneous with in-water optical measurements according to the NASA ocean-optics protocols (Mueller and Fargion, 2002). The performance of a local TSM model depends on several factors, including sufficient samples representing different conditions in the study area and careful data quality control of in situ measurements. The reflectance measured by ASD may include errors caused by instrument calibration, ocean conditions (e.g. sea surface roughness and wind speed), and data processing methods (Mao et al., 2012). It is important to inspect the data quality carefully and remove inaccurate measurements of the reflectance before the data are analyzed. In order to improve the accuracy of the field

![Fig. 2. Spectral curves.](image-url)
measurements, the spectroradiometer had been calibrated annually by the manufacturer. Various measurements (three repeated measurements in a short time) were repeated at each station in order to estimate the uncertainty (RMS values of three repeated measurements) associated with each measurement, and the average measurements (mean values of the three repeated measurements) with <5% RMS at each station were selected for model calibration and validation.

The TSM concentration was measured by means of a weighing method (Mueller and Fargion, 2002). The water sample was filtered with a 450 nm filter (Whatman GF/F filters) and vacuum filtration system. The filter pad was flushed with 0.00005 m\(^3\) of distilled water 3 times, in order to flush away the salt. The dry-weight of the filter pad was weighed with an electronic analytic scale. The blank filter and sampled filter pad were weighed until the difference between two successive TSM concentrations calculated from the scale reading was within 0.01 mg/l (Chen et al., 2014).

3.3. Satellite observations

The Chinese environment and disaster monitoring and forecasting small satellite HJ-1A was successfully launched into an ascending orbit at 10:30 AM on September 6th, 2008, from the Taiyuan Satellite Launch Center of Shanxi Province (Li et al., 2012). The small optical satellite HJ-A provides remote sensing information for higher scattering coastal waters. In fact, the values of for Case II waters may vary with particle phase function, which cannot be determined from the water body, respectively. Gordon et al. (1988) suggested that the values of \(l_0 = 0.0949\) and \(l_1 = 0.0794\), while Lee et al. (1999) suggested that the values of \(l_0 = 0.084\) and \(l_1 = 0.17\) are more suitable for higher scattering coastal waters. In fact, the values of \(l_0\) and \(l_1\) may vary with particle phase function, which cannot be determined remotely. Without local bio-optical information or a model to predetermine the values of \(l_0\) and \(l_1\) in a semi-analytical algorithm, Gordon et al. (1988) suggested values which may be used in Case I waters, while Lee et al. (1999) determined values which are suitable for Case II waters.

Traditionally, the expression for total backscatter is given as follows (Morel, 1997):

\[
b_{\text{bw}}(\lambda) = \frac{1}{4}\left[l_0 + \frac{1}{2}\sqrt{l_0^2 + 4l_1r_{\text{abs}}(\lambda)}\right]
\]

where \(b_{\text{bw}}(\lambda)\) is the backscatter caused by particles. In order to isolate \(b_{\text{bw}}(\lambda)\) from \(s(\lambda)\), here the spectral slopes of both the absorption and backscatter between two neighboring wavelengths (Smyth et al.,

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
\textbf{Band} & \textbf{B1} & \textbf{B2} & \textbf{B3} & \textbf{B4} \\
\hline
\textbf{Wavelengths} & 430–520 nm & 520–600 nm & 630–690 nm & 760–900 nm \\
\hline
\textbf{Spatial resolution} & 30 m & 16 bits &  \\
\hline
\textbf{Radiometric resolution} &  \\
\hline
\textbf{Revisit time} & 4 days &  \\
\hline
\textbf{Swath width} & 700 km &  \\
\hline
\textbf{Side observation ability} & ±30° &  \\
\hline
\end{tabular}
\caption{Technical parameters of HJ-1A/CCD sensor.}
\end{table}
The parameter $\varepsilon_{ba}$, the spectral ratio for total absorption, is defined as follows:

$$a(485) = \varepsilon_{ba}a(560)$$ (6)

The analogous expression for total backscatter is defined as follows (Bowers and Binding, 2006; Chen et al., 2013d; Smyth et al., 2006):

$$b_{b}(485) = \varepsilon_{bb}b_{b}(560) + \varepsilon_{ba}$$ (7)

where $\varepsilon_{bb}$ and $\varepsilon_{ba}$ represent the spectral slope and intercept for the total backscattering coefficient. Fig. 3 shows the spectral relationship of $a(485)$ vs. $a(560)$ and $b_{b}(485)$ vs. $b_{b}(560)$ in the Oujiang River Estuary, indicating that the values for $\varepsilon_{bb}$, $\varepsilon_{ba}$ and $\varepsilon_{ba}$ converged to a narrow range of values for all the components in which $\varepsilon_{ba} = 1.6498$, $\varepsilon_{bb} = 0.4237$ and $\varepsilon_{ba} = 0.2024$ and the corresponding determination coefficients are 0.9974 and 0.9727, respectively. These findings imply that the values for $\varepsilon_{bb}$, $\varepsilon_{ba}$ and $\varepsilon_{ba}$ may be approximated to the unknown constants. Substituting Eqs. (6) and (7) into the difference $s(560) - \varepsilon_{ba}a(485)$ yields the following formula:

$$s(560) - \varepsilon_{ba}a(485) = \frac{\varepsilon_{bb}}{\varepsilon_{ba}}$$ (8)

$s(660)$ divided by Eq. (8) results in the following equation:

$$\frac{s(660)}{s(560) - \varepsilon_{ba}a(485)} = \frac{b_{bw}(660) + b_{bp}(660)}{\varepsilon_{bb}}$$ (9)

$b_{bp}(\lambda)$ may be assumed to depend on the TSM concentration, as proposed by Mobley (1994), as follows:

$$C_{TSM} \propto b_{bw}(660)$$ (10)

Substituting Eq. (10) into Eq. (9) yields the conceptual TSM retrieval models, as follows:

$$C_{TSM} \propto \frac{s(660)}{s(560) - \varepsilon_{ba}a(485)}$$ (11)

4. Results

4.1. Characterizing TSM concentration

The field measurements used in this study encompassed varying optical conditions and included a wide range of TSM concentrations, varying from 4 to 441 mg/l (Table 1). In each of the datasets obtained from the Oujiang River Estuary, the concentrations of TSM, as well as those of chl a, varied over two orders of magnitude, namely 4–158 mg/l of TSM and 0.5–63.05 μg/l of chl a. This large variation also occurred in the Changjiang River Estuary. The TSM concentration was high in both the Oujiang and Changjiang River estuaries, the respective averaged TSM concentrations of which were 40.04 and 162.65 mg/l. In the Bohai Sea, the TSM concentration varies from 3 to 23.6 mg/l, and the averaged value is 8.58 mg/l. By comparison, the TSM concentration in the Changjiang River Estuary is averaged to be ~7 times higher than in the Oujiang River Estuary and ~19 times higher than in the Bohai Sea.

The concentration of TSM also influences the scattering of light on the under-water surface: the more TSM concentrations there are, the more scattering there will be (Lee et al., 2009). For this reason, the optical properties of the waters in the Oujiang and Changjiang River estuaries and Bohai Sea are not only dominated by chl a and covarying detrital pigments, but also greatly depend on substances such as suspended sediment particles that do not covary with chl a concentration. High TSM concentrations are responsible for the high turbidity of these waters. Therefore, the optical types of these three waters are very complex, and the waters fall into the Case II category (Morel and Prieur, 1977).

4.2. Spectral characteristics

As shown in Fig. 2, the spectra curves for the four datasets are quite similar in shape to the typical reflectance spectra collected in highly turbid waters (Chen et al., 2013b, 2012b; Gitelson et al., 2008). The reflectance in the blue range (400–500 nm) was very low due to the strong absorption by all optically active constituents. A reflectance trough at around 440 nm, corresponding to the chl a absorption peak (Chen et al., 2014), was indistinct for the dataset used in this study, due to the low chl a concentration, and was only distinct when the chl a concentration was >150 μg/l (Gitelson et al., 2008). Remote sensing reflectance in the green region was much higher than in the blue and red ranges, which are primarily representative of absorption by CDOM and TSM, as well as backscattering caused by suspended particles. In the red range (600–700 nm), the reflectance was highly variable and several spectra characteristics exist from this region. A second minimum at approximately 674 nm corresponds to the red chl a absorption maximum (Ahn and Shanmugam, 2006). However, this spectral trough is not very distinct when the chl a concentration is low but the suspended sediment concentration is high (Chen and Quan, 2013). A distinct peak is located between 690 and 710 nm, which is the result of both high backscattering and a minimum in absorption by all optically active constituents, with the exception of pure water (Gitelson and Merzlyak, 1994). However, the reflectance values are larger than the reflectance values around 570 nm when the TSM concentrations are greater than 60 mg/l. The reflectance in the near-infrared (NIR) range (700–800 nm) varied widely. The spectral curves are very flat at this range (Robert et al., 1995), due to the low backscattering and absorption caused by optically active constituents, except for pure waters. Finally, a third distinct peak is shown at approximately 815 nm, due to the high backscattering suspended particles when the TSM concentration is greater than 32 mg/l. However, the reflectance values of this peak are typically lower than those at around 570 and 700 nm, because of the high absorption by pure waters.

The magnitudes of the reflectance curves in the four datasets all differ from one another, clearly indicating that they represent very different optical environments, ranging from turbid to highly turbid waters. Fig. 4 shows the respective mean values of the remote sensing reflectances measured in the Oujiang and Changjiang River estuaries and Bohai Sea. Due to the fact that it has the highest TSM concentration, the $R_{o}(\lambda)$ in the Changjiang River Estuary is lower.
than those in both the Oujiang River Estuary and Bohai Sea. By comparison, the $R_a(\lambda)$ in the Changjiang River Estuary is averaged to be ~7 times higher than the Oujiang River Estuary and ~12 times higher than the Bohai Sea, while the TSM concentration in the Changjiang River Estuary is averaged to be ~7 times higher than the Oujiang River Estuary and ~19 times higher than the Bohai Sea. These findings imply that the $R_a(\lambda)$ is very sensitive to the TSM concentration. Qiao et al. (2010) reported that the mean grain sizes of sediment in the Bohai Sea are >200 $\mu$m (calculated from 1197 suspended sediment samples at 386 samples). Shi et al. (2003) announced that the estuarine suspended cohesive sediments generally have grain sizes of <62 $\mu$m, and that the grain sizes of sediment in the Changjiang River Estuary are <32 $\mu$m. Bowers and Binding (2006) indicated that the smaller sized sediments generally lead to a higher spectral reflectance. Therefore, particles suspended in the Changjiang River Estuary are more efficient at reflecting light than those in the Bohai Sea, due to their finer grain sizes. This is to say, the fact that the reflectance in Changjiang River estuaries is higher than in the Bohai Sea is due not only to higher TSM concentrations, but also to the smaller grain size.

### 4.3. TSTM model: calibration and validation

Due to the fact that the HJ-1A/CCD sensor is a broad-band scanning radiometer, the field-measured $s(\lambda)$, $a(\lambda)$, and $b_0(\lambda)$ must be weighted by the HJ-1A/CCD sensor spectral response functions before model calibration and validation. The flow chart for deriving TSM products from satellite data using TSTM model is shown in Fig. 5.

#### 4.3.1. Evaluation of four existing models

Lathrop, Dekker, Doxran I and Doxran II models have been described in detail in several previous studies (Dekker et al., 2002; Doxaran et al., 2003; Doxaran et al., 2009; Lathrop et al., 1991). The special formulas of these four models were adjusted according to the bio-optical information taken from turbid coastal waters. Briefly, for a given TSM model, the statistical regression relationships such as logarithmic, polynomial, exponential, and power functions are used to find out the optimal mathematical formula for these four existing models. The optimal mathematical formula must have the minimum RMS value. Our practical experiments indicate that the models as shown in Table 3 are proposed as the optimal Lathrop, Dekker, Doxran I and Doxran II models. Use of the Lathrop model can account for more than 80% variation in TSM concentrations in the Oujiang River Estuary. These findings imply that if the local bio-information is used to reinitialize the site-specific coefficients of Lathrop model, then the Lathrop model produces good performance in estimating TSM concentration from the Oujiang River Estuary, which has a coefficient of determination ($R^2$) of 8663.

#### 4.3.2. TSTM model initialization

As shown in Fig. 3, the mean values for $\delta_{bb}$, $\delta_{ba}$ and $\delta_{aa}$ converged to a narrow range of values for all the components, so that the value of $\delta_{bb}\delta_{ba}$ may also be approximated to an unknown constant, whose value is 0.7155. For the purpose of prediction, statistical regression relationships were established between the $s(660)/s(560)$ and field-measured TSM concentrations. Based on 48 field samples collected from the Oujiang River Estuary in September 2012, an optimal TSTM model was proposed in Fig. 7. It was found that the field-measured TSM concentration strongly correlated to TSM concentration, whose determination coefficient is 0.9635. Judging by determination coefficient, the TSTM model is an effective predictor in deriving the TSM concentration from HJ-1A/CCD data in the turbid coastal waters of the Oujiang River Estuary.

#### 4.3.3. TSTM model evaluation and comparison

In this section of the paper, an evaluation of the Doxran I, Doxran II, Dekker and Lathrop models and TSTM model is presented. The evaluation was based on the comparison of TSM concentration predicted by these four models with TSM measured analytically for the independent dataset collected from Oujiang River Estuary in September 2009 (Table 1(b) and Fig. 2(b)). Fig. 8(a)–(e) shows the accuracy and stability of the Doxran I, Doxran II, Dekker and Lathrop models and TSTM model in deriving TSM concentration from the Oujiang River Estuary. It was found that for the range of TSM concentration from 4 to 122 mg/l, the TSTM model ($RMS = 14.11\%$) had a superior performance in comparison to the Doxran I ($RMS = 32.28\%$), Doxran II ($RMS = 65.05\%$), Dekker ($RMS = 31.46\%$) and Lathrop models ($RMS = 25.74\%$). Use of the TSTM model for deriving TSM concentration in the Oujiang...
River Estuary decreased by 50.93% RMS from the Doxran II model, 13.35% RMS from the Doxran I model, 13.17% RMS from the Dekker model, and 11.17% RMS from the Lathrop model. It appears that any one of the Doxran I, Dekker, and Lathrop models and TSTM model may be used to retrieve TSM concentrations from turbid coastal waters, but in these waters the TSTM model is more effective than the Doxran I, Dekker and Lathrop models.

The relationship between \( R_E \) and the scale of the TSM concentration (TSM/chl\( \alpha \)) was also presented to demonstrate the ability of the Doxran I, Doxran II, Dekker and Lathrop models and TSTM model in estimating TSM concentration. Fig. 8(f) shows a scale plot of the TSM concentration against the \( R_E \) of the Doxran I, Doxran II, Dekker and Lathrop models and TSTM model. It can be found that the \( R_E \) decreases with the increases of scale of the TSM concentration, but no statistically significant relationship exists between the two. These findings imply that due to overlapping and the uncorrelated absorption and backscattering of chl\( \alpha \) (Chen et al., 2013b; Gitelson et al., 2008), all of these five models may result in poor predictability. This is to say, these models may be capable of estimation in turbid coastal waters, but produce better accuracy in waters with low-chl\( \alpha \) than in those with high-chl\( \alpha \) concentration.

### Table 3
TSM quantitative retrieval models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Adjusted model</th>
<th>( R^2 )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>a. Model adjusted according to bio-optical information taken in Oujiang River Estuary</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Lathrop</td>
<td>( 4.6311 \times 1 \exp \left( \frac{1.5921 \times R_{660}}{R_{412}} \right) )</td>
<td>0.8663</td>
<td>Lathrop et al. (1991)</td>
</tr>
<tr>
<td>Dekker</td>
<td>( 5.6982 \times 1 \exp \left( \frac{22.488 \times R_{660} - 5.5905}{R_{528}} \right) )</td>
<td>0.7259</td>
<td>Dekker et al. (2002)</td>
</tr>
<tr>
<td>Doxran-I</td>
<td>( 12.298 \times 1 \exp \left( \frac{4.1011 \times R_{660}}{R_{528}} \right) )</td>
<td>0.7193</td>
<td>Doxran et al. (2003)</td>
</tr>
<tr>
<td>Doxran-II</td>
<td>( 9.631 \times 1 \exp \left( \frac{5.1105 \times R_{660}}{R_{528}} \right) )</td>
<td>0.5604</td>
<td>Doxran et al. (2009)</td>
</tr>
</tbody>
</table>

| **b. Model adjusted according to bio-optical information taken in Changjiang River Estuary** | | | |
| Lathrop | \( 95.776 \exp \left( 0.3686 \times R_{660} \right) \) | 0.4533 | Lathrop et al. (1991) |
| Dekker | \( 227.16 \exp \left( -12.9 \times R_{660} + 5.032 \right) \) | 0.4098 | Dekker et al. (2002) |
| Doxran-I | \( 120.29 \exp \left( 0.9529 \times R_{660} \right) \) | 0.2712 | Doxran et al. (2003) |
| Doxran-II | \( 109.55 \exp \left( 1.3191 \times R_{660} \right) \) | 0.2631 | Doxran et al. (2009) |

| **c. Model adjusted according to bio-optical information taken in Bohai Sea** | | | |
| Lathrop | \( 3.1002 \exp \left( 1.0796 \times R_{660} \right) \) | 0.5921 | Lathrop et al. (1991) |
| Dekker | \( 3.8795 \exp \left( 49.692 \times R_{660} \right) \) | 0.6868 | Dekker et al. (2002) |
| Doxran-I | \( 5.6432 \exp \left( 4.8512 \times R_{660} \right) \) | 0.2287 | Doxran et al. (2003) |
| Doxran-II | \( 7.7544 \exp \left( -0.3015 \times R_{660} \right) \) | 0.0143 | Doxran et al. (2009) |

**Fig. 6.** Lathrop, Dekker, Doxran I, and Doxran II models-derived plotting against field measured TSM concentration, 48 samples.
The stability and performance of the Doxran I, Doxran II, Dekker and Lathrop models and TSTM model were further evaluated using the independent dataset collected from the Changjiang River Estuary on October 14 and 15, 2009, indicating that the TSTM model allows the TSM concentration to be predicted quite accurately (Fig. 9). By comparison, the TSTM model is superior to the Doxran I, Doxran II, Dekker and Lathrop models (Table 3(b)). Use of the TSTM models can account for more than 89% variation in the TSM concentration, which is >50% more than that of the Doxran I, Doxran II, Dekker and Lathrop models. In addition to these, Fig. 9 also indicates that the TSTM model does not require further optimization of $e_{a,obs}$ in water bodies with widely varying bio-optical characteristics (Table 1). These findings imply that the TSTM model may be used to accurately estimate the TSM concentration in the highly turbid coastal waters of the Changjiang River Estuary, even though some local bio-optical information is needed.

![Fig. 7. Optimal TSTM model in deriving TSM concentration in Oujiang River Estuary.](image)

![Fig. 8. Performance of five TSM retrieval models (30 samples): (a) Lathrop model; (b) Dekker model; (c) Doxran I model; (d) Doxran II model; (e) TSTM model; and (f) relationship of RE vs. field measurements.](image)
to reinitialize some parameters of the TSTM model when the bio-optical properties are different from those used for model development.

4.4. Atmospheric correction

Although three field campaigns were conducted to obtain field measurements, only the one HJ-1A/CCD image (Fig. 10A) scanned on September 12, 2012 in the Oujiang River Estuary met the requirements of the study; the images obtained on the other dates were not adequate, due to overly heavy cloud cover or lack of broadband satellite overpass. In order to further validate the applicability of the TSTM model in deriving TSM concentration in coastal waters, another HJ-1A/CCD image (Fig. 10B) was collected when the field measurements were being performed in the Changjiang River Estuary on October 15, 2009. In order to accurately retrieve TSM concentration from the turbid Oujiang River Estuary and Changjiang River Estuary, the dark-object subtraction technique proposed by Chavez (1988) was used to remove the effects of atmospheric scattering on the remotely sensed multispectral digital image data. The dark-object subtraction technique (DST) assumes that there are usually some shadows occurring due to the topography in the image, where the pixels would be completely dark (Miura et al., 2001). As a matter of fact, there are many mountains and high buildings located around the Oujiang River Estuary and Changjiang River Estuary. These mountains and high buildings can provide some effective shallows for atmospheric correction. A dark pixel was selected from among the pixels with values not within the bottom 0.5% of the histogram in the HJ-1A/CCD images, due to the fact that the pixels belonging to the bottom 0.5% were considered to be error values (Chen et al., 2013c). For example, the aerosols are generally located much lower than the clouds, so that the signal over the cloud shadow underestimates the path reflectance.

Fig. 11 shows the satellite-derived reflectance at 660 nm using the DST model from the HJ-1A/CCD images, indicating that the values of remote sensing reflectance at 660 nm are very high in both the Oujiang and Changjiang River estuaries. The tidal hydrodynamics in these estuaries are generally much stronger than those in the adjacent waters (Shi et al., 2006), thus the reflectance at 660 nm in the inshore areas or around islands are higher than those in the other areas, among which the highest value was found in the estuarine turbidity maximum zone near the estuarine mouth. Therefore, the tidal hydrodynamics generally determine the optical properties of waters in estuaries. The accuracy of the atmospheric correction algorithms was evaluated through comparison of the retrieved and observed water-leaving reflectance. The observation samples within a ± 3 h time window of satellite overpass and their respective measurements were selected. The atmospheric conditions are reasonably stable within this ± 3 h period (Bailey and Werdell, 2006). For the data match-up analysis, the procedure described by Bailey and Werdell (2006) was used to produce the satellite data for comparison with the in situ measurements. For a given satellite-derived water-leaving reflectance, pixels with a 3 × 3 box centered at the location of the in situ measurement were briefly extracted, and the retrievals of the 3 × 3 pixels were averaged for the validation. In order to evaluate the accuracy of the CSAC model in water-leaving reflectance prediction, nine independent field measurements were collected from the Oujiang River Estuary within a ± 3 h time window of satellite overpass on September 12, 2012.

Fig. 12A shows comparisons of satellite-derived and field-measured remote sensing reflectance. It was found that the DST model performs effectively in deriving the remote sensing reflectance from HJ-1A/CCD images, the RMS values of which are <17%. In order to evaluate the applicability of the DST model in other estuarine regions, the model was further evaluated using the dataset obtained from the Changjiang River Estuary on October 15, 2009. Fig. 12B shows the HJ-1A/CCD-derived remote sensing reflectance plotted against the field measurements obtained from the Changjiang River Estuary. It is found that the DST model produces 13–17% RMS in deriving remote sensing reflectance retrieval from the HJ-1A/CCD data. These findings indicate that the DST model is sufficiently stable and accurate for deriving remote sensing reflectance at 485, 560, and 660 nm from broadband satellite data for the purpose of remote sensing applications in estuarine waters.

4.5. TSM concentration retrievals

4.5.1. Spatial distribution characteristics of TSM concentration

Based on the results from the atmospheric correction algorithm, the TSM concentrations were calculated (Fig. 13), which indicated that the TSM concentration in the estuarine turbidity maximum zone near the estuarine mouth was higher than those in the adjacent sea waters. Particle trapping dynamics in the turbidity maximum zone most likely differ among estuaries. The complex processes involved have been addressed from the viewpoints of residual currents, tidal forcing, density stratification, and sediment transport (Wu et al., 2012). It is well known that the Changjiang River is the fourth largest river in the world, in terms of both water and sediment discharge (Shi et al., 2006). As a result, the TSM concentration in the estuarine turbidity maximum zone in the Changjiang River Estuary is much higher than that in the Oujiang River Estuary (Fig. 13).

From the perspective of physical oceanography, an estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and contains a measurable quantity of sea salt (Morel and Prieur, 1977). Thus, tidal hydrodynamics generally determine the transport of sediments in estuaries. The TSM concentration from the estuary in all directions has the sharpest decline to the east. The apparent offshore decreases of the TSM concentration indicate that the TSM carried by the Oujiang and Changjiang Rivers quickly subside near the estuaries, due to both the estuarine gravitational circulation and tidal asymmetry.

4.5.2. Overall comparison results

The procedure described Bailey and Werdell (2006), which was addressed in the previous section of this paper, was used to produce the satellite products for comparison with the in situ measurements. Fig. 14 provides an overall comparison between the HJ-1A/CCD-derived and in situ measured TSM concentration for two cases, i.e. the TSM concentration retrieved from the HJ-1A/CCD images obtained on September 12, 2012 in the Oujiang River Estuary and those obtained on October 15, 2009 from the Changjiang River Estuary were compared with the nearly simultaneous measurements carried out on these two days. The results indicate that the TSTM produces high accuracy in estimating the TSM concentration from the HJ-1A/CCD images, the RMS values
of which are <29%. These findings imply that provided that an atmospheric correction procedure for the visible bands is available, the extensive database of HJ-1A/CCD imagery could be used for quantitative monitoring of TSM concentrations using the TSTM model in turbid coastal waters.

5. Discussion

The TSTM model (Eq. (11)) was calibrated using data obtained from over the Bohai Sea, and the specific conceptual form of this model expressed as $g_{\text{660}} = 0.7155 s_{\text{485}} / C_{\text{01}}$ was applied for deriving the TSM concentration for independent datasets obtained from coastal waters. The results show that the TSTM model allows the TSM concentration to be quantified quite accurately (Fig. 15). The model accounts for more than 90% variation in TSM concentration, which is >20% higher than the Doxran I, Dekker, and Lathrop models. Thus, the TSTM model may be used to accurately estimate the TSM concentration in the highly turbid waters of the Bohai Sea. In addition, the TSTM model does not require any further optimization of spectral slope of $s_{\text{660}}/s_{\text{485}}$ to accurately retrieve the TSM concentration in water bodies with different bio-optical characteristics, namely the Oujiang and Changjiang River estuaries (Table 1 and Fig. 2).
Fig. 13. TSM concentration retrieved using TSTM model. (A) TSM concentration calculated using TSTM model in Fig. 4 from HJ-1A/CCD images on September 12, 2012; and (B) TSM concentration calculated using TSTM model in Fig. 6 from HJ-1A/CCD images on October 15, 2009.

Fig. 14. Comparison between the satellite-derived and field-measured TSM concentration.

Since the Doxran I model and Doxran II model rely strongly on remote sensing reflectance in the NIR region, these models usually produce poor performance in the turbid coastal waters of China, despite the fact that these models may produce a strong performance in deriving TSM concentrations from some sediment-dominated waters (Doxaran et al., 2003; Doxaran et al., 2009). The remote sensing reflectance in the NIR region is a multiplicative factor in the Doxran I and Doxran II models, thus making the models sensitive to the magnitude of reflectance in the NIR region. The strong absorption by water in the NIR greatly reduces the magnitudes of remote sensing reflectance in the NIR region, thus reducing the signal-to-noise ratio and enhancing the effect of inherent noise in the recorded signal (Gitelson et al., 2008). Whatever the source may be, such inherent noise would have a higher proportional effect in the NIR region because of the lower remote sensing reflectance, thus affecting the models' output. In addition to these factors, as of yet, no operational atmospheric correction has been developed that has proven universally robust in the NIR region across waters varying geophysical characteristics. Therefore, the success of the application of the Doxran I and Doxran II models to satellite data depends heavily on the accuracy of the atmospheric correction and field measurement procedures.

Even though the Dekker and Lathrop models may work better than the Doxran I and Doxran II models in theory, the Dekker and Lathrop models may still produce poor performance in optically complex waters such as the coastal waters of China. In addition to TSM, the water-leaving signs in the visible region are also affected by the light behaviors of chlor and CDOM. If chlor and CDOM vary between samples, remote sensing reflectance would be different for the same TSM. Due to the different spectral shape of total absorbing and backscattering coefficients, the effects of absorption due to chlor and CDOM in $R_a\, (660)$ is difficult to minimize using $R_a\, (485)$. Thus, the output of Dekker model still affected by the light behavior of chlor and CDOM, which may cause the Dekker model to produce poor accuracy in deriving TSM concentration from optical complex waters. Fortunately, these limitations in the Doxran I, Doxran II, Dekker and Lathrop models may be minimized by the TSTM models. The study results indicate that the TSTM model works better than the Doxran I, Doxran II, Dekker and Lathrop models in the Oujiang River Estuary, Changjiang River Estuary and Bohai Sea. These findings imply that the TSTM model should be used to deriving TSM concentration from optically complex coastal waters, even though some local bio-optical information may be needed to reinitialize some parameters of the TSTM model.

It is worth noting that in the TSTM model, although $s\, (660)$ is a multiplicative factor, the difference $s\, (560) - 0.7155s\, (485)$ is a division factor. The ratio of these two factors is beneficial to eliminating the impacts of some multiplicative uncertainty in the TSTM model outputs. However, a certain number of key aspects still remain which must be considered when attempting to apply this conceptual model to HJ-1A/CCD data. First, the particle size distribution may affect the TSM-reflectance relation, due to the fact that smaller sized sediments generally result in a higher spectral reflectance for similar TSM. As a result, the TSTM model outputs would be different for the same TSM concentration. Second, since the launching of the HJ-1A satellite, the data obtained from the satellite sensor have been somewhat problematic due to the degradation of the optics (Yu and Wu, 2011). Poor calibration would reduce the signal-to-noise radiation and enhance the effects of inherent noise in the satellite-recorded signal. Finally, it is well known that estuaries are dynamic aquatic regions where biochemical events and processes occur over both very high spatial scales and short temporal scales (Chen and Quan, 2013; Matthews et al., 2012). If the intra-daily TSM changes are periodic, then the samples should be obtained at a representative time determined by experiments. The temporal discrepancy between satellite overpass and timing of sediment collection may explain the errors...
occurring in TSM concentration in a situation where the intra-daily TSM changes are dramatically in the match-up analyzed procedures.

Importantly, the calibration and validation datasets only contain a narrow range of optical properties of natural coastal waters, as the datasets were only obtained from the Oujiang and Changjiang River estuaries and Bohai Sea in 2012, 2009 and 2006, respectively. These datasets are insufficient to completely validate the accuracy of the model in other waters with different bio-optical properties. Consequently, it is concluded that the TSTM model should be used for specific bio-optical properties in coastal waters, although it will be essential to accordingly optimize the site-specific parameterization for the given aquatic bio-optical conditions. The researchers also suggest the calibration and validation of the algorithms based on more in situ measurements of waters with different optical properties. More importantly, the backscattering of suspended particles at 660 nm not only depended on the TSM concentration, but also depended heavily on the sizes of suspended particles. Bowers and Binding (2006) indicated that the smaller sized sediments generally lead to a higher backscattering coefficient of TSM. As a result, if the sizes of suspended particles vary between samples, the model output would be different for the same TSM concentration. This may be the reason why the special formulas of the TSTM model in the Oujiang River Estuary, Changjiang River Estuary, and Bohai Sea are different from each other.

6. Summary

In this study TSM concentrations retrievals are presented, based on the observations respectively made in the Oujiang and Changjiang River estuaries and Bohai Sea, in 2006–2012. The HJ-1A/CCD data was processed using the DST model to derive remote sensing reflectance from the HJ-1A/CCD images collected from the Oujiang River Estuary on September 12, 2012 and Changjiang River Estuary on October 15, 2009. Then, the TSM concentration was calculated based on these atmospheric correction results using the TSTM model. Two independent bio-optical datasets nearly simultaneously with those scanned by the HJ-1A/CCD sensor were used to evaluate the stability and accuracy of the TSTM models in predicting remote sensing reflectance and TSM concentration in turbid coastal waters. These two bio-optical datasets were obtained from the Oujiang and Changjiang River estuaries, respectively. Finally, in order to further validate the applicability of the TSTM model in turbid waters, an independent bio-optical dataset obtained from the Bohai Sea in 2006 was used to evaluate the performance of the TSTM model in predicting the TSM concentration from these waters. The findings of the study are summarized as follows:

(1) The DST model can be used to accurately retrieve remote sensing reflectance from the Oujiang River Estuary and Changjiang River Estuary, because there are many mountains and high buildings located around these two estuaries. By comparing the nearly simultaneous field measurements of the two cases of the Oujiang and Changjiang River estuaries, it was found that the DST model provides remote sensing reflectance with <17% uncertainty.

(2) A semi-analytical model, i.e. the TSTM model, was developed to retrieve the TSM concentration from coastal waters. This model was initialized and validated using one calibration dataset and three independent validation datasets respectively collected from the Oujiang and Changjiang River estuaries and the Bohai Sea. The study results indicate that the TSTM model may be used to accurately estimate the TSM concentration in highly turbid waters without requiring optimization of the spectral slope of the model.

(3) The TSM concentration was retrieved from the atmospheric correction results of HJ-1A/CCD images obtained from the Oujiang and Changjiang River estuaries, on September 12, 2012 and October 15, 2009, respectively. A comparison between the estimations of the models and the measured TSM concentration collected in the two turbid coastal waters shows that the TSTM model produces <29% uncertainty in deriving TSM concentration from HJ-1A/CCD data. These findings imply that, if the atmospheric correction scheme for the HJ-1A/CCD imagery is available, the TSTM model may be used for the quantitative monitoring of TSM concentration in coastal waters.

Finally, some aspects which require improvement in future studies still remain:

(1) It is suggested that a radiance calibration procedure should be carried out in the future to resolve the degradation of the optics of the HJ-1A/CCD sensor.

(2) Other researchers have also suggested the calibration and validation of the TSTM models based on more in situ measurements of waters with different optical properties.

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