Estimation of total suspended solids concentration by hyperspectral remote sensing in Liaodong Bay

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Present study consists the potential of the satellite hyperspectral data — Hyperion image for mapping total suspended solids (TSS) concentration of coastal water in Liaodong Bay, China. After processing and atmospheric correction, the reflectance of water extracted from Hyperion image can be used to express the spectral characteristics of different TSS concentration. Estimated algorithms of TSS concentration based on water reflective spectra data collected in situ. The results indicated near infrared wavelength had better correlation with TSS concentration. Exponential algorithm was found to have better accuracy in estimate the concentration less than 200 mg l⁻¹ and linear algorithm was suited for the concentration range in 200–500 mg l⁻¹ and logarithm algorithm can better describe the correlation between the reflectance and concentration range in 500–1000 mg l⁻¹.

[Keywords: Total suspended solids, Hyperion, Hyperspectral remote sensing, Coastal zone]

Introduction

Light attenuation is an important factor regulating physical and biological processes in aquatic systems¹. Scattering effect by suspended solids plays a major role in the vertical attenuation of light in coastal waters. Total suspended solids concentration is one of the basic parameters of aquatic ecosystems¹. Such information is useful for the management of water quality² and the monitoring of water pollution³.

The estimation of TSS concentration over large areas of water using in situ sampling is lengthy, expensive and do not provide a synoptic view of TSS distribution. Remotely sensed spectral reflectance measured by aircraft or satellite sensors can provide an alternative, synoptic, speedy and economic method for assessing the TSS concentration of coastal waters⁴. A great deal of work has been carried out on the measurement of TSS concentration using remote sensing data, such as MSS, TM, AVHRR, HRV and MODIS⁵-⁸.

In coastal water, the signature measured above the water is influenced by variations arising from changes in water depth, bottom type, and scattering and absorption in the water column (by chlorophyll, suspended sediments, colored dissolved organic matter, etc.). Hyperion is the first civilian hyperspectral and high spatial resolution image in space⁹. Such an image can be used to detect and extract small signals of submerged water features. Hyperion image has
been used in the retrieval of water quality concentration in coastal area\textsuperscript{10, 11}. Additional in situ samples and field spectra can aid in finding new methods and estimation of accuracy\textsuperscript{12}.

In this study satellite hyperspectral remote sensing image combined with ground unimaging spectrometer were used to estimate TSS concentration in coastal zone. Hyperion image was investigated the potential ability for TSS concentration mapping in coastal water. And TSS concentration estimated algorithms were built based on analyses of field hyperspectral data and TSS concentration in Liaodong Bay coastal water.

**Materials and Methods**

Liaodong Bay is suited at the northeast of Bohai Sea and it is the sea entrance of several big rivers. Abounding in wetland resources, Liaodong Bay has important position in ecosystem. The distribution and content of suspended solids is an important influencing factor of aquatic ecological environment and provides a basis for engineering construction in coastal zone\textsuperscript{13}.

Field measurements were carried out in Liaodong bay in two years which were from September 15 to 19, 2006 and from August 7 to 13, 2007. Twenty two samples were collected in 2006 and twenty three samples were collected in 2007. All the forty five samples were located from the near shore extending to the direction of the sea within twenty five miles. Hyperspectral data and water samples were collected simultaneously. Field spectra were measured with a high resolution spectroradiometer (ASD FieldSpec Pro FR) under natural sunlight on board. The spectrometer has a wavelength range of 350–2500nm and a wavelength resolution of \( \pm 1\)nm. The spectral resolution is 3.5nm in the range of 350–1050nm and 10nm of 1050–2500nm. Data were taken from a boat at about 1m above the water surface in vertical downward direction with a field of view of 25°. The measuring probe was put far enough not to be affected by the boat shadow. Upwelling radiance measured from the water body has been retrieved as reflectance in relation to the white reference plate.

All water samples were collected from the surface layer at 0-0.5m and had been taken to the lab for TSS concentration analyses. Samples were sieved, dried, and weighed for measuring TSS concentration by environmental testing center of Liaohe oilfield. The concentration of TSS ranged from 87 to 914 mg l\(^{-1}\), with the average being 368 mg l\(^{-1}\).

Hyperion is a pushbroom hyperspectral imaging spectrometer system. It covers the visible, near-infrared, and shortwave infrared bands (400–2500nm) with 10nm bandwidths and typically 198 bands were provided in the calibrated data and the spatial resolution is 30m. The instrument can image a 7.65 km by 185 km area, has 12-bit radiometric resolution and its signal-to-noise ratio (SNR) is between 140 and 190 (between 550 and 700 nm) according to the on-orbit calibration. The SNR drops rapidly towards shorter wavelengths and longer wavelengths\textsuperscript{14}. The image acquired in October 7, 2006 was used in this study.

Hyperion L1Gst product was used in this study which had been radiometrically corrected and resampled for geometric correction and registered to a geographic map projection. For atmospheric
correction, the FLAASH (Fast Line of sight Atmospheric Analysis of Spectral Hypercubes) software package in ENVI was applied to Hyperion image. The FLAASH module incorporates MODTRAN 4 radiation transfer code with all MODTRAN atmosphere and aerosol types to calculate a unique solution for each image. FLAASH also includes a correction for the adjacency effect, provides an option to compute a scene-average visibility (aerosol/haze amount), and utilizes the most advanced techniques for handling particularly stressing atmospheric conditions (such as clouds). Mid-Latitude summer atmosphere model with maritime aerosol were used as initial settings, which most closely match the conditions at the time the image was taken. Minimum Noise Fraction (MNF) transformation was carried out to reduce spectra noise. Though Hyperion L1Gst product was resampled for geometric correction, there is more than five-pixel error in longitude direction in contrast with ground control points (GCP) measured by GPS in this study. Twenty four GCPs with relative even distribution in image, which were measured by GPS in situ were used to carry out geometric precision rectification and average error was beyond one pixel.

Since the transparent capability of water in short wave infrared (SWIR) wavelengths is very low, the reflection intensity of this band could help to distinguish whether a pixel observed in the Hyperion image is above or below water and where the coastline is. In our research area sea water in Hyperion image was distinguished by using average reflectance of 1600–1700nm.

After image processing and reflectance retrieval, several reflective spectra of water were extracted from Hyperion image as shown in Fig. 2. Several studies have been conducted to address the impact of suspended sediments on the spectral profile of surface waters. The reflectance of turbid water near the land is higher than clear water far from the land in VNIR wavelength. There are two major reflective peaks of suspended solids. One of them is at the yellow light wavelength and the other is at near infrared wavelength. The first reflective peak has moved from yellow light wavelength to longer wavelength as the suspended solids concentration raised which can be confirmed by the reflectance of coastal water extracted from Hyperion image in our study. Reflective spectra of the water extracted from Hyperion image made difference mainly in the red and near infrared wavelengths.

Fig. 2—Reflective spectra of water extracted from Hyperion image

Fig. 3 showed field reflectance spectra of seven water samples with different concentrations of TSS in situ. The reflectance of water at 350-400nm and 900-2500nm was very low because of the strong absorption of water.
Hyperion image had no radiometric calibration value in the first seven bands (Band 1 to 7). So, the reflectance outside the 500–900nm range was not included in this study. The first reflective peak was near 580nm which expressed strong backscattering effect of inorganic suspended solids and algal biomass\textsuperscript{19} and the second reflective peak was near 810nm which was researched to be effect of weak absorption of water and backscattering of sediments in the water\textsuperscript{20}. The reflective spectra of sample 5–7 had similar characteristics in 580–700nm. In 600–650nm range, the three samples had reflective shoulder, which was researched to be the absorption of phycocyanin\textsuperscript{19} and the other reflective shoulder was near 670nm which was the absorption of chlorophyll\textsuperscript{21}. The four samples (Sample 1 to Sample 4) which had bigger TSS concentration had not the similar reflective characteristics as sample 5–7 at 580–700nm because of the strong backscattering effect of inorganic suspended solids. Among the seven samples, the lowest reflective curve was found in sample 7, which had the lowest TSS concentration. The highest reflective curve was sample 1 which had the highest concentration of TSS. Compared with sample 2, sample 3 had less TSS concentration and their reflective spectra were similar in 400–690nm and made difference in 700–900nm. The reflective spectra of sample 4 and sample 5 had a cross at 561nm. The reflectance of sample 4 between 400–560nm was less than sample 5 and the value between 562–900nm was higher than sample 5.

A common method is to relate remotely sensed reflectance measured in the red wavelength to TSS concentration because scattering from suspended materials frequently dominates the reflectance spectra when compared to pure water and phytoplankton absorption\textsuperscript{8}. In order to have accurate comparison with Hyperion image, water reflective spectra of field hyperspectral data were resampled in Hyperion wavelength settings. To test if the reflectance value at a specific wavelength could be used to estimate TSS concentration, the linear correlative coefficient ($R$) between TSS concentration and reflectance was calculated at the wavelength range 400–900nm as shown in Fig. 4. They showed better correlation at near infrared wavelength (760–900nm) and average value of $R$ was 0.83. Band ratio method can reduce the difference in water attenuation coefficient and bottom reflectance. Since the sensitive wavelength of TSS concentration was broad in near infrared wavelength, the average reflectance of 760–900nm were taken as numerator and the other visible wavelength band were set as denominator separately. The results indicated that the reflectance ratio between near infrared band and every visible band had good correlation with TSS concentration and the values of $R$ were all more than 0.82(see Fig. 4). Derivative technique has been used previously in the analysis of suspended sediment\textsuperscript{22}. The correlative coefficients between first derivative of reflectance and TSS concentration were shown in Fig. 4. The correlation between first derivative of reflectance and TSS concentration were better than correlation between reflectance and TSS concentration in 570–690nm.

![Fig. 4—Comparison of correlation between TSS concentration and spectral reflectance and reflectance band ratio and first derivative of reflectance in situ](image-url)

**Results and Discussion**

The TSS concentration estimated algorithms were built by forgoing analyses on the field spectra and measured TSS concentration in situ.
based on least-squares method. Thirty samples were used to determine the empirical coefficients of algorithms and fifteen samples were used to test the accuracy of algorithms. The accuracy characteristics determined for the algorithms were coefficient of determination ($R^2$) and mean relative error (MRE) (see Table 1).

Sensitive bands were decided by correlative analyses in advance. The reflectance in 760–900 nm had the better correlation with TSS concentration. Reflectance of 820–900nm were excluded as for the stripes in Hyperion image and reflectance of 813.48nm was chosen to build three algorithms. Compared with single band, band ratio between 813.48nm and 711.72nm had similar accuracy and first derivative of reflectance at 803.3nm had less accuracy according to the MRE which can be shown in Table 1. Since TSS concentration had a broad range in this study, they were divided into three groups. Reflectance of 813.48nm was also chosen to build three algorithms for three concentration ranges. As for the concentration of TSS less than 200 mg l$^{-1}$, exponential algorithm had better accuracy and linear algorithm was suited for the concentration range in 200–500 mg l$^{-1}$ and logarithm algorithm can better describe the correlation between the reflectance and concentration range in 500–1000 mg l$^{-1}$ (see Table 2).

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>$R^2$</th>
<th>MRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y = 4025.6 \times X_1 + 89.76$</td>
<td>0.68</td>
<td>24%</td>
</tr>
<tr>
<td>$y = 267.93 \times \ln(X_1) + 1137.7$</td>
<td>0.65</td>
<td>24%</td>
</tr>
<tr>
<td>$y = 142.97 \times \exp(11.16 \times X_1)$</td>
<td>0.64</td>
<td>25%</td>
</tr>
<tr>
<td>$y = 1083.6 \times X_2 - 359.6$</td>
<td>0.67</td>
<td>25%</td>
</tr>
<tr>
<td>$y = 725.41 \times \ln(X_2) + 678.71$</td>
<td>0.66</td>
<td>25%</td>
</tr>
<tr>
<td>$y = 39.173 \times \exp(3.0732 \times X_2)$</td>
<td>0.66</td>
<td>26%</td>
</tr>
<tr>
<td>$y = 2E+06 \times X_3 + 155.46$</td>
<td>0.68</td>
<td>28%</td>
</tr>
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</table>

* $y$ was TSS concentration, $X_1$ was the reflectance of 813.48nm, $X_2$ was the reflectance ratio between 813.48nm and 711.72nm, $X_3$ was the first derivative of reflectance at 803.3nm.

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>Concentration range (mg l$^{-1}$)</th>
<th>MRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y = 4025.6 \times X_1 + 89.76$</td>
<td>0–200</td>
<td>65%</td>
</tr>
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<td></td>
<td>200–500</td>
<td>28%</td>
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<tr>
<td></td>
<td>500–1000</td>
<td>19%</td>
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<tr>
<td></td>
<td>0–200</td>
<td>61%</td>
</tr>
<tr>
<td>$y = 267.93 \times \ln(X_1) + 1137.7$</td>
<td>200–500</td>
<td>34%</td>
</tr>
<tr>
<td></td>
<td>500–1000</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>0–200</td>
<td>53%</td>
</tr>
<tr>
<td>$y = 142.97 \times \exp(11.168 \times X_1)$</td>
<td>200–500</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>500–1000</td>
<td>22%</td>
</tr>
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</table>

† $y$ was TSS concentration, $X_1$ was the reflectance of 813.48nm.

Three algorithms in Table 2 were used in Hyperion image to estimate TSS concentrations. Since they had better accuracy in three TSS concentration ranges separately, three maps of TSS concentration distribution were combined to generate one result. The results were shown in
Fig. 5. The map of TSS concentration were based on three algorithms in which exponential algorithm was used to estimate the concentration less than 200 mg l\(^{-1}\) and linear algorithm was for the concentration range in 200–500 mg l\(^{-1}\) and logarithm algorithm for concentration range in 500–1000 mg l\(^{-1}\). As shown in Fig. 5, the TSS concentrations were reduced with the increased of distance from the shore.

As a result in this study, field spectra remote sensing data can be used to estimate TSS concentration in coastal area. Average TSS concentration was 368mg l\(^{-1}\) in our test area. As for the high concentration of TSS, the reflective spectra measured in the field were dominated by backscattering effect from suspended solids. The correlation between spectral reflectance and TSS concentration was better in near infrared wavelength which had the correlative coefficient(\(R\)) reach 0.83. Reflectance ratio between near infrared wavelength and every visible wavelength could improve the correlation with TSS in our case. Derivative technology was proved to be useful to improve the correlation between reflectance and TSS concentration in the range of 570–690nm. After evaluating the accuracy of estimated algorithms, compared with band ratio algorithms and derivative algorithm single band algorithm based on reflectance at 813.48nm had better result. Higher TSS concentration had the better estimated accuracy. By comparison, the exponential algorithm was found to have better accuracy in estimate the concentration less than 200mg l\(^{-1}\) and linear algorithm was suited for the concentration range in 200–500 mg l\(^{-1}\) and logarithm algorithm can better describe the correlation between the reflectance and concentration range in 500–1000 mg l\(^{-1}\).

Water depth, content of molecules and particles in the water column and sea surface conditions are various in coastal areas, so water quality parameters such as TSS concentration had different radiance reflective responses in complex water environment. More attention should be paid to the elimination and reduction of environmental effects on the signals of TSS concentration in the future works.

**Conclusion**

As the first civilian hyperspectral and high spatial resolution image in space, Hyperion image was test to have potential ability to map TSS concentration in coastal water. Water reflective
signal can be calculated by atmospheric correction by using the band information of Hyperion imagery. As for the water reflective characteristics and SNR of Hyperion, the VNIR wavelength would be suited for TSS concentration.

Acknowledgments
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