Environ Monit Assess (2008) 145:339–347
DOI 10.1007/s10661-007-0043-2

A bio-optical model based method of estimating total suspended matter of Lake Taihu from near-infrared remote sensing reflectance

B. Zhang · J. Li · Q. Shen · D. Chen

Received: 4 May 2007 / Accepted: 30 October 2007 / Published online: 8 December 2007

Abstract Total suspended matter is an important water quality parameter, and plays a key role in water quality evaluation, especially of inland waters. Many different methods have been developed to estimate TSM from remote sensing data, in which empirical methods and model-based methods are two types of commonly used methods. Compared with empirical methods, model-based methods have the advantages of definite physical meanings, high robustness and retrieval accuracy. In model-based methods, matrix inversion method is commonly used in monitoring water qualities of inland waters. However, matrix inversion method has to predetermine some optical parameters by empirical values or simplified optical model, which may introduce some errors in retrieved water quality parameters. In order to overcome the shortcomings of matrix inversion method and increase the estimating accuracy of total suspended mater, in this paper, a bio-optical model based method is developed, which estimates total suspended mater by using remote sensing reflectance of two near-infrared bands. This method is validated by in-situ experiment data measured in Lake Taihu, a big turbid lake in eastern China. The results show that this method has better performance than matrix inversion method. The average relative error of the estimated total suspended matter by this method is only 13.0%, which is much smaller than the errors by matrix inversion method (32.7%). This method has the advantages of definite physical meaning, easiness to carry out, and high estimating accuracy. However, the applicable scope of this method has limitations: it can only be applied to optically deep waters with high concentrations of total suspended matter.

Keywords Bio-optical model · Total suspended matter · TSM · Lake Taihu · Remote sensing reflectance · Empirical method · Model-based method · Matrix inversion method

Introduction

Total suspended matter (TSM) is an important water quality parameter, and plays a key role in water quality evaluation, especially of inland waters (e.g. lake, reservoir, and river). TSM determines the transparency of water, and ultimately determines the primary productivity of water (Zhang et al. 2004). TSM is traditionally measured by collecting water samples and analyzing them in laboratory. Monitoring TSM in this way can be time consuming and require a large amount of human and material resources if a

B. Zhang · J. Li (✉) · Q. Shen
State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing Applications of Chinese Academy of Sciences, Beijing, China
e-mail: hrsjsli@163.com

D. Chen
Department of Geography, Queen's University, Kingston, ON K7L 3N6, Canada

large area is involved. Furthermore, a limited number of field samples often cannot truly characterize the spatial variation of TSM within a body of water. With the development of remote sensing technology, remote sensing data have been utilized to assess TSM (Hoogenboom et al. 1998; Ammenberg et al. 2002; Dekker et al. 2002; Pozdnyakov et al. 2005; Kishino et al. 2005; Chen et al. 2007). Estimating TSM from remote sensing has four main advantages: ability to cover large areas, rapid results, low cost, and convenience for dynamic monitoring (Qi and Wang 1999).

Many different methods have been developed to link remote sensing data with TSM, in which empirical methods and model-based methods are two types of commonly used methods (IOCCG 2000). Empirical methods are based on statistical relationships between remote sensing data and in-situ measured water quality data. However, because of the differences among experiment conditions, these statistical relationships are often not stable; as a result, they are difficult to compare and extend from one study to another. In contrast, model-based methods are based on bio-optical models, and have the advantages of definite physical meanings, high robustness and retrieval accuracy (Dekker et al. 2002).

In model-based methods, matrix inversion method is commonly used in monitoring water qualities of inland waters (Hoogenboom et al. 1998; Dekker et al. 2002). Matrix inversion method transforms a bio-optical model into a matrix and then retrieves three types of water quality parameters (TSM, chlorophyll-a and CDOM) simultaneously through matrix inversion operation. Matrix inversion method has been proven to have higher robustness and retrieval accuracy than empirical methods in monitoring inland water qualities in different seasons and different areas (Dekker et al. 2002). However, in matrix inversion method, the values of some optical parameters must be predetermined, such as ratio of upward irradiance to upward radiance under water (Q) and anisotropy factor of the light filed in the water (f). These parameters are often affected by many factors, such as viewing geometry of remote sensor, roughness of water surface, bidirectional reflectance of water, and atmospheric conditions (Morel and Gentili 1993). It will cause some errors by estimating the values of these optical parameters from simplified optical models or empirical values.

In order to overcome the shortcomings of matrix inversion method and improve the accuracy of TSM estimating, this study focuses on developing a new bio-optical model based method. This method is based on a transformed bio-optical model, and TSM can be retrieved from remote sensing reflectance of two near-infrared bands. Then, this method is validated by in-situ experiment data measured in Lake Taihu, a big turbid lake in eastern China.

Materials and methods

Description of the filed sampling data

Lake Taihu is selected as the study area in this study. Lake Taihu is located between 30°55′40″N and 31°32′58″N, and 119°52′32″E and 120°36′10″E in eastern China. It is the third largest lake in China. With the increasing pollution from both urban and rural areas surrounding Lake Taihu Region over the past two decades, water pollution is becoming a serious problem, and more efficient water quality monitoring of the lake is urgently needed (Ma and Dai 2005).

From 9 A.M. on Jan. 7, 2006 to 4 P.M. on Jan. 9, 2006, a field campaign was carried out in Lake Taihu. Water surface spectra were measured and water samples were collected on 47 sampling stations. The distribution of the 47 sampling stations in Lake Taihu is shown in Fig. 1.

Water surface spectra were measured by using an ASD field spectrometer, with a spectral response range of 350 to 1,000 nm and a spectral resolution of 3 nm. The "above water method" was used to measure water surface spectra (Tang et al. 2004). When the boat was anchored, the radiance spectra of light from the reference panel, water, and sky were measured 10 times each. On each sampling station, these measured radiance spectra of each object were averaged, and then remote sensing reflectance spectra $R_{rs}(\lambda)$ were calculated. The remote sensing reflectance spectra $R_{rs}(\lambda)$ on the 47 sampling stations are shown in Fig. 2.

The water samples collected from the 47 sampling stations were immediately sent to a laboratory, where the concentrations of water quality parameters and inherent optical properties (IOPs) were measured. Concentrations of TSM (C_s) were measured by filtering the water samples on GF/C filters, and then drying and weighting on electronic balance. Concen-

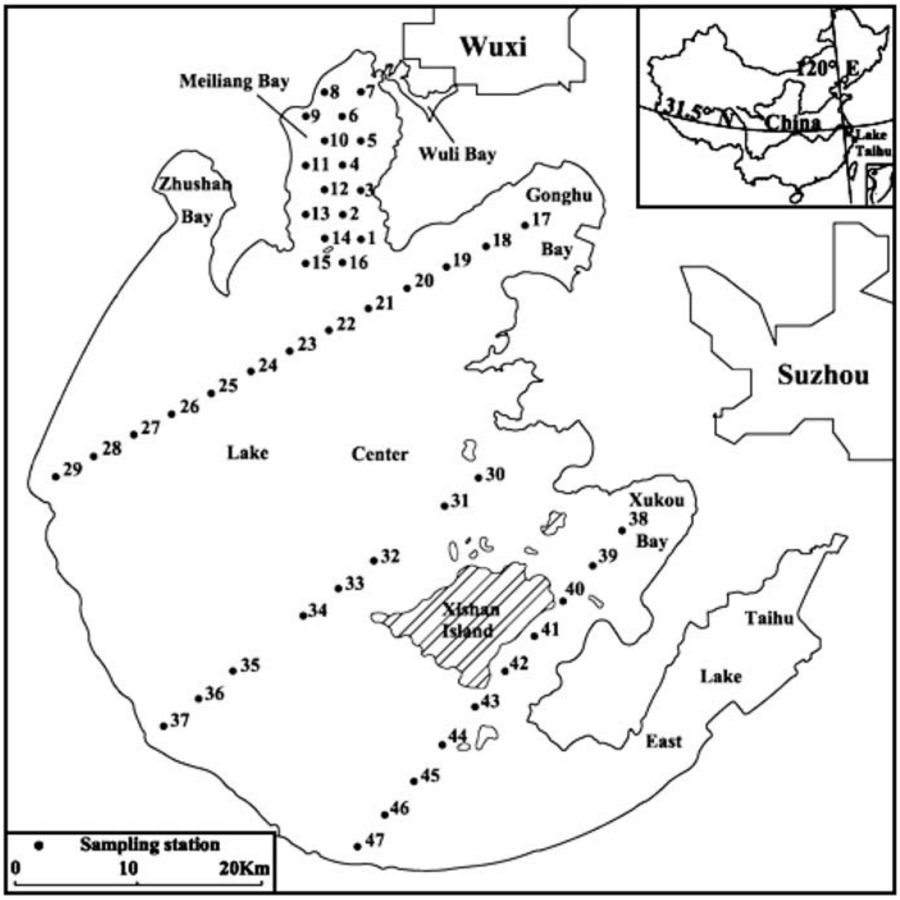

Fig. 1 Distribution of the 47 sampling stations in Lake Taihu

trations of chlorophyll-a ($C_{chl\text{-}a}$) were measured by filtering the water samples on GF/C filters, extracting with ethanol (90%) at 80°C, and analyzing spectrophotometrically at 750 and 665 nm (Moed and Hallegraeff 1978).

According to NASA ocean optics protocols (Pegau et al. 2003) we measured and calculated the IOPs, including absorption coefficient spectra of TSM [$a_p(\lambda)$], absorption coefficient spectra of phytoplankton [$a_{ph}(\lambda)$], absorption coefficient spectra of nonpigment suspended matter [$a_d(\lambda)$], absorption coefficient spectra of CDOM [$a_{CDOM}(\lambda)$], scattering coefficient spectra of TSM [$b_p(\lambda)$], beam attenuation coefficient spectra [$C(\lambda)$]. The spectra of $a_p(\lambda)$, $a_d(\lambda)$, and $C(\lambda)$ were obtained directly between wavelength region of 400 and 750 nm at 1-nm intervals using a UV2401PC spectrometer. The spectra of $a_{ph}(\lambda)$ were calculated by subtracting $a_d(\lambda)$ from $a_p(\lambda)$. The spectra of $b_p(\lambda)$ were calculated by subtracting total absorption coefficients of water [$a(\lambda)$] and scattering coefficients of pure water

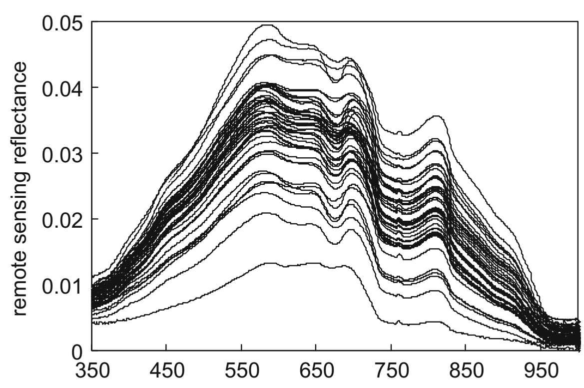

Fig. 2 Remote sensing reflectance spectra on the 47 sampling stations in Lake Taihu

$[b_w(\lambda)]$ from $C(\lambda)$, which was based on the following equation (Mobley, 1994):

$$C(\lambda) = a(\lambda) + b(\lambda) = a_w(\lambda) + a_{ph}(\lambda) + a_d(\lambda) + a_{cdom}(\lambda) + b_w(\lambda) + b_p(\lambda) \quad (1)$$

Many scientists have measured the values of $a_w(\lambda)$ and $b_w(\lambda)$ (Buiteveld et al. 1994; Pope and Fry 1997; Kou et al. 1993). The measurements of $a_w(\lambda)$ and $b_w(\lambda)$ proposed by NASA ocean optics protocols is adopted in this study (Pegau et al. 2003). These measurements include Pope and Fry's (1997) measurement of $a_w(\lambda)$ from 400 to 705 nm, the measurement of Kou et al. (1993) of $a_w(\lambda)$ from 705 to 900 nm, the measurement of Buiteveld et al. (1994) of $b_w(\lambda)$ from 400 to 750 nm.

Average values of these IOPs on the 47 sampling stations are shown in Fig. 3.

The IOPs of each water constituent are assumed to be linear functions of the concentration of each water constituent. The specific inherent optical properties (SIOPs) are just the IOPs per unit concentration of each water constituent, including specific absorption coefficient of nonpigment suspended matter(a'_d), specific absorption coefficient of CDOM(a'_{CDOM}), specific absorption coefficient of phytoplankton (a'_{ph}), specific scattering coefficient of total suspended matter (b'_p). Then, total absorption and scattering coefficients of water can be expressed by SIOPs with the following equations (Dekker et al. 2001):

$$a(\lambda) = a_w(\lambda) + a'_{ph}(\lambda) \cdot C_{chl-a} + a'_d(\lambda) \cdot C_n + a'_{cdom}(\lambda) \cdot a_{cdom}(\lambda_0) \quad (2)$$

$$b(\lambda) = b(\lambda) + b'_p(\lambda)^* C_s. \quad (3)$$

where λ_0 is reference wavelength, which is often set to be 440 nm; C_n is the concentration of nonpigment suspended matter. In waters with high concentrations of TSM, C_n can be approximately replaced by C_s.

Since the concentrations and IOPs of water constituents in Lake Taihu were measured and calculated, the SIOPs of water constituents in Lake Taihu were calculated. Average values of these SIOPs on the 47 sampling stations are shown in Fig. 4.

Another important IOP is the total backscattering coefficient of water $[b_b(\lambda)]$, which is commonly used in bio-optical models. $b_b(\lambda)$ can be calculate from the following equation (Dekker et al. 2001):

$$b_b(\lambda) = 0.5^* b_w(\lambda) + \widetilde{b}_{bp}{}^* b'_p(\lambda)^* C_s. \quad (4)$$

where $\widetilde{b}_{bp}$ is backscattering to total scattering ratio of TSM.

The values of $\widetilde{b}_{bp}$ can be measured in laboratory (Pegau et al. 2003). However, due to the lack of relevant instrument in this field campaign, the value

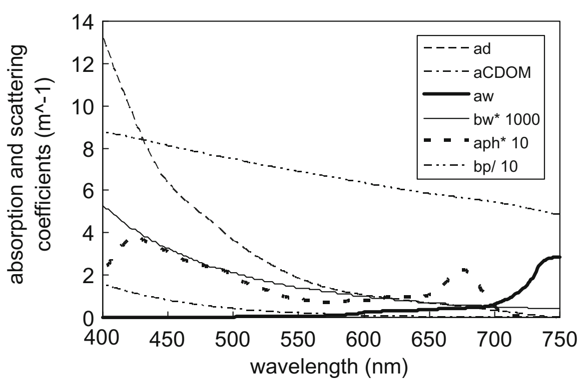

Fig. 3 Average spectra of the IOPs measured on the 47 sampling stations in Lake Taihu (*ad* absorption coefficient of nonpigment suspended matter, *aCDOM* absorption coefficient of CDOM, *aw* absorption coefficient of pure water, *bw* scattering coefficient of pure water, *aph* absorption coefficient of phytoplankton, *bp* scattering coefficient of total suspended matter)

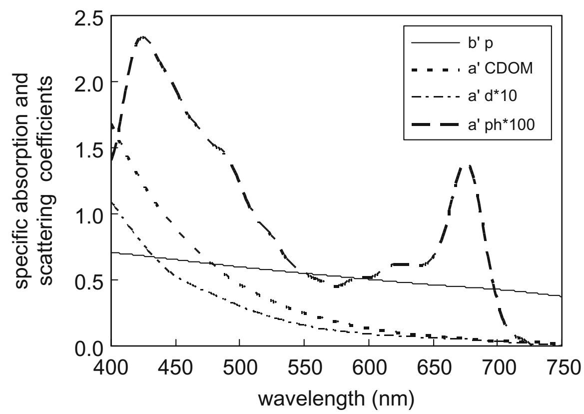

Fig. 4 Average spectra of the SIOPs measured on the 47 sampling stations in Lake Taihu (*b'p* specific scattering coefficient of total suspended matter, *a'CDOM* specific absorption coefficient of CDOM, *a'd* specific absorption coefficient of nonpigment suspended matter, *a'ph* specific absorption coefficient of phytoplankton)

of $\widetilde{b}_{bp}$ has to be determined from former literature or empirical models. Li (2007) calculated the value of $\widetilde{b}_{bp}$ in Lake Taihu in winter by optimization of a bio-optical model with water surface spectra and IOPs, and the average value of $\widetilde{b}_{bp}$ was calculated to be 0.052. Since the values of $\widetilde{b}_{bp}$ are almost constant for water bodies in the same region and the same season, this value of $\widetilde{b}_{bp}$ is used in this study.

Derivation of the new TSM estimating method

Dekker (1993) found that the following form of bio-optical model was an appropriate model for turbid inland waters:

$$R(0-)(\lambda) = f^* \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)}, \tag{5}$$

where R(0-) is sub-surface irradiance reflectance, which is the bridge linking water surface spectra and IOPs; $b_b(\lambda)$ is the total backscattering coefficient of water; f is a factor that accounts for the anisotropy of the light filed in the water (Tassan and d'Alcalá 1993; Hoogenboom et al. 1998; Dekker et al. 2002).

$R(0-)$ can be calculated from $R_{rs}(\lambda)$ with the following equation (Tzortziou et al. 2007):

$$R(0-)(\lambda) = \frac{R_{rs}(\lambda)^* Q}{(1 - r(\theta_v))^*(1 - r(\theta_s))/n^2}, \tag{6}$$

where Q is the ratio of upward irradiance to upward radiance under water; θ_v is the viewing zenith angle; θ_s is the sun zenith angle; $r(\theta_v)$ and $r(\theta_s)$ are reflectance over the water-atmosphere surface, which can be calculated by Fresnel formula; n is the refractive index of water, and is about 1.333.

Replacing the variables $R(0-)(\lambda)$, $a(\lambda)$ and $b_b(\lambda)$ in Eq. 5 by Eqs. 6, 2 and 4, a new equation is obtained:

$$\frac{R_{rs}(\lambda)^* Q}{(1 - r(\theta_v))^*(1 - r(\theta_s))/n^2} = f^* \frac{0.5^* b_w(\lambda) + \widetilde{b}_{bp}{}^* b'_p(\lambda)^* C_s}{a_w(\lambda) + a'_{ph}(\lambda)^* C_{chl-a} + a'_d(\lambda)^* C_s + a'_{cdom}(\lambda)^* a_{cdom}(\lambda_0) + 0.5^* bw(\lambda) + \widetilde{b}_{bp}{}^* b'_p(\lambda)^* C_s} \tag{7}$$

In Eq. 7, $R_{rs}(\lambda)$, $a_w(\lambda)$, $b_w(\lambda)$, $b'_p(\lambda)$, $a'_{ph}(\lambda)$, $a'_d(\lambda)$, $a'_{cdom}(\lambda)$, θ_s, θ_v, n, and $\widetilde{b}_{bp}$ are often regarded as known parameters, and C_s, $C_{chl\text{-}a}$, $a_{cdom}(\lambda_0)$, f, and Q are often regarded as unknown parameters. If the values of f and Q can be estimated from optical models or from empirical knowledge, there are only three unknown parameters: C_s, $C_{chl\text{-}a}$, and $a_{cdom}(\lambda_0)$. Equation 7 can be transformed into a matrix. Using remote sensing reflectance values from three or more bands (or wavelengths) in visible region, the values of C_s, $C_{chl\text{-}a}$, and $a_{cdom}(\lambda_0)$ can be solved by matrix inversion operation. This is the so-called matrix inversion method (Hoogenboom et al. 1998).

As can be seen from above, the values of Q and f have to be predetermined in matrix inversion method. However, these optical parameters can be affected by many factors, including viewing geometry of sensor, roughness of water surface, bidirectional reflectance of water, atmospheric condition, and are often different at different water locations and times (Morel and Gentili 1993). Estimating the values of Q and f by simplified optical models or empirical values will introduce some errors in retrieved water qualities.

In order to overcome the shortcomings of matrix inversion method and improve the estimating accuracy of TSM, this study develops a bio-optical model based method of estimating TSM from near-infrared remote sensing reflectance.

In near-infrared wavelength region (750~1,000 nm), the values of $a_{ph}(\lambda)$, $a_d(\lambda)$, $a_{cdom}(\lambda)$ and $b_w(\lambda)$ are approximately equal to zero. Therefore, in near-infrared wavelength region, Eq. 7 transforms into the following form, when divided by Q on both sides of the equal sign:

$$\frac{R_{rs}(\lambda)}{(1 - r(\theta_v))^*(1 - r(\theta_s))/n^2} = \frac{f}{Q}^* \frac{\widetilde{b}_{bp}{}^* b'_p(\lambda)^* C_s}{a_w(\lambda) + \widetilde{b}_{bp}{}^* b'_p(\lambda)^* C_s}. \tag{8}$$

In Eq. 8, $R_{rs}(\lambda)$, $a_w(\lambda)$, $b_p'(\lambda)$, $\widetilde{b}_{bp}$, θ_s, θ_v and n are known parameters, while only C_s and $\frac{f}{Q}$ are unknown parameters. The value of C_s can be solved by the following equation with remote sensing reflectance of two near-infrared bands:

$$C_s = \frac{r_{rs}(\lambda_1)a_w(\lambda_1)b_p'(\lambda_2) - r_{rs}(\lambda_2)a_w(\lambda_2)b_p'(\lambda_1)}{\widetilde{b}_{bp}b_p'(\lambda_1)b_p'(\lambda_2)(r_{rs}(\lambda_2) - r_{rs}(\lambda_1))}, \tag{9}$$

where λ_1 and λ_2 are wavelengths in near-infrared region, and $r_{rs}(\lambda)$ is defined by the following equation:

$$r_{rs}(\lambda) = \frac{R_{rs}(\lambda)}{(1 - r(\theta_v))*(1 - r(\theta_s))/n^2}. \tag{10}$$

This is the bio-optical model based method of estimating TSM from remote sensing reflectance of two near-infrared bands, which can be called Two Near-Infrared Bands Method or TNIB method for short.

The two near-infrared bands method needs input remote sensing reflectance of two near-infrared bands (750~1,000 nm). It can be seen from Fig. 2 that the values of $R_{rs}(\lambda)$ at wavelength region between 750 and 850 nm are not small. However, in wavelengths longer than 850 nm, the values of $R_{rs}(\lambda)$ drop fast with wavelength increasing, and almost drop to zero at 1,000 nm. When the values of $R_{rs}(\lambda)$ are small, the signal-to-noise of these data are low. It will cause much error in estimating TSM from remote sensing reflectance with low signal-to-noise. Therefore, the two near-infrared bands method require inputting remote sensing reflectance of two bands in wavelength region from 750 to 850 nm to ensure enough accuracy of estimated TSM.

$R_{rs}(\lambda)$ at 814 and 828 nm are selected as inputs in this study. Eight hundred fourteen and 828 nm are characteristic wavelengths of the $R_{rs}(\lambda)$ spectra shown in Fig. 2. Eight hundred fourteen nanometer is the extreme value of the $R_{rs}(\lambda)$ spectra, and 828 nm is the inflexion point of the $R_{rs}(\lambda)$ spectra.

Results

Results by the two near-infrared bands method

The inputs of the two near-infrared bands method include $R_{rs}(\lambda_1)$, $R_{rs}(\lambda_2)$, $a_w(\lambda_1)$, $a_w(\lambda_2)$, $b_p'(\lambda_1)$, $b_p'(\lambda_2)$, $\widetilde{b}_{bp}$, θ_s, and θ_v, where λ_1 and λ_2 are selected to be 814 and 828 nm in this study. The values of θ_s can be calculated through the locations and sampling time of each sampling station. The values of θ_v are set to be 40° in the experiment. The measurement of Kou et al. (1993) of $a_w(\lambda)$ from 750 to 900 nm is adopted in this study, so a_w(814 nm) equals 2.2230, and a_w(828 nm) equals 2.9139.

The spectrum of $b_p'(\lambda)$ from 400 to 750 nm is shown in Fig. 4. The spectrum of $b_p'(\lambda)$ decreases exponentially with wavelength increasing. The negative exponential function can be used to fit the spectral dependence of $b_p'(\lambda)$:

$$b_p'(\lambda) = b_p'(\lambda) \cdot \exp\left[S \cdot (\lambda_0 - \lambda)\right] \tag{11}$$

where λ_0 is the reference wavelength, which is often set to be 440 nm; S is the slope parameter in the function. The value of S is calculated to be 0.0017, when the fitted spectrum best fit the original spectrum of $b_p'(\lambda)$. Then, $b_p'(814\ nm)$ is calculated to be 0.3485 by Eq. 11, and $b_p'(828\ \ nm)$ is calculated to be 0.3402.

With all these inputs, the concentrations of TSM on the 47 sampling stations are calculated by the two near-infrared bands method. The comparison between the retrieved TSM and in-situ measured TSM are shown in Fig. 5 as squares. Average relative error and root mean square error (RMSE) of the estimated TSM are 13.0% and 20.24 mg/l respectively.

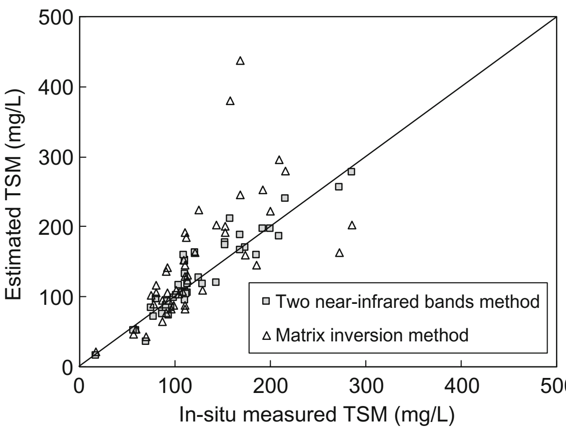

Fig. 5 Comparison of estimated TSM and in-situ measured TSM of the 47 sampling stations

Results by matrix inversion method

The inputs of matrix inversion method include $R_{rs}(\lambda)$, $a_w(\lambda)$, $b_w(\lambda)$, $b'_p(\lambda)$, $a'_{ph}(\lambda)$, $a'_d(\lambda)$, $a'_{cdom}(\lambda)$ at three or more wavelengths, and also include θ_s, θ_v, $\widetilde{b}_{bp}$, f, Q.

Considering that TSM affects the optical properties of water more greatly at longer wavelength in visible region, three characteristic wavelengths of the $R_{rs}(\lambda)$ are selected in this study, which are 677, 696, and 734 nm. Six hundred seventy-seven and 696 nm are extreme values of the $R_{rs}(\lambda)$ spectra, and 734 nm is the inflexion point of the $R_{rs}(\lambda)$ spectra.

The values of $a_w(\lambda)$, $b_w(\lambda)$ are shown in Fig. 3, and the values of $b'_p(\lambda)$, $a'_{ph}(\lambda)$, $a'_d(\lambda)$, $a'_{cdom}(\lambda)$ are shown in Fig. 4.

Both f and Q are factors that depend upon the light field distribution of the water. The values of f and Q are set to be constants in some studies, for instance f equals 0.33 (Gons 1999; Krijgsman 1994), and Q equals π (Hoogenboom et al. 1998; Dekker et al. 2002). While in other studies, the values of f and Q are calculated from optical models, which take the mean cosine (μ_0) or θ_s as inputs (Walker 1994; Gons 1999). It is more appropriate to calculate the values of f and Q from optical models than to set them to be constants. Therefore, the values of f are calculated from the optical model of Walker (1994) and the values of Q are calculated from the optical model of Gons (1999) in this study.

With all these inputs, the concentrations of TSM on the 47 sampling stations are calculated by matrix inversion method. The comparison between the retrieved TSM and in-situ measured TSM are shown in Fig. 5 as triangles. Average relative error and RMSE of the estimated TSM are 32.7% and 66.56 mg/l respectively.

Discussion and conclusion

This study develops a bio-optical model based method of estimating suspended matter concentrations from remote sensing reflectance of near-infrared bands. When this method is applied to estimate TSM in Lake Taihu from in-situ measured remote sensing reflectance, the errors of the estimated TSM are quite small. Average relative error and RMS of the estimated TSM are only 13.0% and 20.24 mg/l respectively.

It further shows the advantages of the two near-infrared bands method by comparing with matrix inversion method. When matrix inversion method is applied to the same remote sensing reflectance of Lake Taihu, the errors of the estimated TSM are much bigger: average relative error and RMSE of the estimated TSM are 32.7% and 66.56 mg/l respectively. The comparison of the in-situ measured TSM and TSM retrieved from both two near-infrared bands method and matrix inversion method are shown in Fig. 5, where squares represent TSM retrieved from two near-infrared bands method, triangles represent TSM retrieved from matrix inversion method, and the diagonal is the 1:1 line. All of the squares are close to the 1:1 line, while some triangles are quite far from the 1:1 line, especially when the in-situ measured TSM (*X*-axis) are bigger than 155 mg/l. When the in-situ measured TSM are smaller than 155 mg/l, the average relative error and RMSE of the TSM retrieved by matrix inversion method are 27.1% and 36.12 mg/l respectively. However, when the in situ measured TSM are bigger than 155 mg/l, the average relative error and RMSE of the TSM estimated by matrix inversion method are 50.6% and 121.56 mg/l respectively. All these show that matrix inversion method works poorly when TSM are bigger than 155 mg/l, while two near-infrared bands method works well no matter TSM are big or small.

There are three main reasons why the two near-infrared bands method gets smaller errors in estimating TSM in Lake Taihu. Firstly, in near-infrared region, the optical properties of water are only controlled by absorption of pure water and backscattering of TSM. Because the absorption coefficient spectrum of pure water is known, the remote sensing reflectance spectra in near-infrared region are directly affected by TSM. While in visible region, the optical properties of water are jointly affected by the absorption and backscattering of pure water, phytoplankton, CDOM, and suspended matter. These facts can be reflected from the remote sensing reflectance spectra in Fig. 2. The $R_{rs}(\lambda)$ spectra curves on the 47 sampling stations do not cross in wavelength region from 750 to 850 nm. This reflects the fact that TSM controls the optical properties of water in near-infrared region, and the higher the concentration of TSM is, the higher the spectra is. In contrast, the $R_{rs}(\lambda)$ spectra curves cross in visible region, which reflects the fact that the optical properties of water in visible region are controlled by multi factors. Therefore, it is more difficult to estimate TSM from remote sensing reflectance in visible region. Secondly, there is only one SIOP parameter as input in the two near-infrared bands method, which is $b_p'(\lambda)$. Furthermore, the variation of the values of $b_p'(\lambda)$ on different sampling stations is small. In contrast, there are four kinds of SIOPs as inputs in matrix inversion method, which are $b_p'(\lambda)$, $a_{ph}'(\lambda)$, $a_d'(\lambda)$, $a_{cdom}'(\lambda)$. It is more difficult to prepare the values of the four kinds of SIOP. Furthermore, the variations of the values of the four kinds of SIOPs on different sampling stations are much bigger. Therefore, it may cause bigger errors when average values of the four kinds of SIOPs are introduced into matrix inversion method. Thirdly, matrix inversion method need predetermine the values of optical parameters Q and f, while the two near-infrared bands method need not. The values of Q and f can be affected by many factors, including the viewing geometry of remote sensor, the roughness of water surface, the bidirectional reflectance of water, and the atmospheric conditions (Morel and Gentili 1993). It will cause some errors by estimating the values of Q and f from some simplified optical models.

However, the applicable scope of the two near-infrared bands method has limitations. Firstly, the two near-infrared bands method can only be applied to waters with high concentrations of TSM. The values and signal-to-noise ratios of water surface spectra in near-infrared region should be big and high, otherwise the noise of the water surface spectra in near-infrared region will cause big errors on estimated TSM. In the experiment in Lake Taihu, most of the concentrations of TSM on the 47 sampling stations are bigger than 50 mg/l, and the measured remote sensing reflectance spectra in wavelength region from 750 to 850 nm have big values and high signal-to-noise ratio. Secondly, the two near-infrared bands method can only be applied to optically deep waters, because the bio-optical model, which is used in development of the two near-infrared bands method, neglects the reflection of light from water floor. Nevertheless, because the waters with high concentrations of TSM are often optically deep waters, the latter limitation of optically deep water can be neglected.

In a word, the two near-infrared bands method developed in this study has definite physical meaning; is easy to carry out; can estimate TSM with high accuracy in waters with high concentrations of TSM.

Acknowledgment This work has been supported by the Key Project of the Knowledge Innovation Program of the Chinese Academy of Sciences, China (grant no. KZCX3- SW-350).

Appendix

List of main symbols

TSM	total suspended matter
CDOM	colored dissolved organic matter
IOPs	inherent optical properties
SIOPs	specific inherent optical properties
$C_{chl\text{-}a}$	concentration of chlorophyll-a ($\mu g/L$)
C_s	concentration of total suspended matter (mg/l)
C_n	concentration of nonpigment suspended matter (mg/l)
R_{rs}	remote sensing reflectance
$R(0-)$	sub-surface irradiance reflectance
F	anisotropy factor of the light filed in the water
Q	ratio of upward irradiance to upward radiance under water
θ_s	sun zenith angle
θ_v	viewing zenith angle
$a(\lambda)$	total absorption coefficient of water (m^{-1})
$a_w(\lambda)$	absorption coefficient of pure water (m^{-1})
$a_p(\lambda)$	absorption coefficient of total suspended matter (m^{-1})
$a_{ph}(\lambda)$	absorption coefficient of phytoplankton (mainly chlorophyll; m^{-1})
$a_d(\lambda)$	absorption coefficient of nonpigment suspended matter (m^{-1})
$a_{cdom}(\lambda)$	absorption coefficient of CDOM (m^{-1})
$a_{ph}'(\lambda)$	specific absorption coefficient of phytoplankton (mainly chlorophyll; $m^2\ mg^{-1}$)
$a_d'(\lambda)$	specific absorption coefficient of nonpigment suspended matter($m^2\ mg^{-1}$)
$a_{cdom}'(\lambda)$	specific absorption coefficient of CDOM
$b(\lambda)$	total scattering coefficient of water (m^{-1})
$b_w(\lambda)$	scattering coefficient of pure water (m^{-1})
$b_p(\lambda)$	scattering coefficient of total suspended matter (m^{-1})
$b_p'(\lambda)$	specific scattering coefficient of total suspended matter ($m^2\ g^{-1}$)
$b_b(\lambda)$	total backscattering coefficient of water (m^{-1})
$\tilde{b}_{bp}$	backscattering to total scattering ratio of total suspended matter

References

Ammenberg, P., Flink, P., Lindell, T., Pierson, D., & Strömbeck, N. (2002). Bio-optical modelling combined with remote sensing to assess water quality. *International Journal of Remote Sensing*, *23*(8), 1621–1638.

Buiteveld, H., Hakvoort, J. H. M., & Donze, M. (1994). The optical properties of pure water. *Ocean Optics XII SPIE*, *2258*, 174–183.

Chen, Q. L., Zhang, Y. Z., & Hallikainen, M. (2007). Water quality monitoring using remote sensing in support of the EU water framework directive (WFD): A case study in the Gulf of Finland. *Environmental Monitoring and Assessment*, *124*, 157–166.

Dekker, A. G. (1993). *Detection of optical water quality parameters for eutrophic waters by high resolution remote sensing*. *PhD dissertation*. Amsterdam, The Netherlands: Vrije University.

Dekker, A. G., Brando, V. E., Anstee, J. M., Pinnel, N., Kutser, T., Hoogenboom, E. J., Peters, S., et al. (2001). Applications of imaging spectrometry in inland, estuarine, coastal and ocean waters. In F. D. Van Der Meer, & S. M. De Jong (Eds.) *Imaging spectrometry: Basic principles and prospective applications* (pp. 307–358). Dordrecht: Kluwer.

Dekker, A. G., Vos, R. J., & Peters, S. W. M. (2002). Analytical algorithms for lake water TSM estimation for retrospective analyses of TM and SPOT sensor data. *International Journal of Remote Sensing*, *23*(1), 15–35.

Gons, H. J. (1999). Optical teledetection of chlorophyll a in turbid inland water. *Enviroment Science & Technology*, *33* (7), 1127–1132.

Hoogenboom, H. J., Dekker, A. G., & de Haan, J. F. (1998). Retrieval of chlorophyll and suspended matter in inland waters from CASI data by matrix inversion. *Canadian Journal of Remote Sensing*, *24*, 144–152.

IOCCG (2000). Remote sensing of ocean colour in coastal and other optically complex waters. In S. Sathyendranath (Ed.) *Reports of the International Ocean Colour Coordinating Group no. 3*, IOCCG. Canada: Dartmouth.

Kishino, M., Tanaka, A., & Ishizaka, J. (2005). Retrieval of Chlorophyll a, suspended solids, and colored dissolved organic matter in Tokyo Bay using ASTER data. *Remote Sensing of Environment*, *99*, 66–74.

Kou, L., Labrie, D., & Chylek, P. (1993). Refractive indices of water and ice in the 0.65 to 2.5 μm spectral range. *Applied Optics*, *32*, 3531–3540.

Krijgsman, J. (1994). *Optical remote sensing of water quality parameters: Interpretation of reflectance spectra. Ph.D thesis*. Delft University of Technology, Delft, The Netherlands.

Li, J. S. (2007). *Study on retrieval of inland water quality parameters from hyperspectral remote sensing data by analytical approach – taking Taihu Lake as an example. Ph.D. dissertaion,* Graduate School of Chinese Academy of Sciences, Beijing, China.

Ma, R. H., & Dai, J. F. (2005). Investigation of chlorophyll-a and total suspended matter concentrations using Landsat ETM and field spectral measurement in Lake Taihu, China. *International Journal of Remote Sensing*, *26*(13), 2779–2795.

Mobley, C. D. (1994). *Light and water: Radiative transfer in natural waters* (pp. 60–142). Boston: Academic.

Moed, J. R., & Hallegraeff, G. M. (1978). Some problems in the estimation of chlorophyll-a and phaeopigments pre- and post-acidification spectrophotometric measurements. *International Review of Hydrobiology*, *63*, 787–800.

Morel, A., & Gentili, B. (1993). Diffuse reflectance of oceanic waters (2): Bi-directional aspects. *Applied Optics*, *32*, 6864–6879.

Pegau, S., Zaneveld, J. R. V., Mitchell, B. G., Mueller, J. L., Kahru, M., Wieland, J., et al. (2003). *Ocean optics protocols for satellite ocean color sensor validation, revision 4, volume IV: Inherent optical properties: Instruments, characterizations, field measurements and data analysis protocols. NASA Tech. Memo*, *2003-211621, Rev. 4*, *vol. IV*, Greenbelt, NASA Goddard Space Flight Center.

Pope, R. M., & Fry, E. S. (1997). Absorption spectrum (380–700 nm) of pure water. II. Integrating cavity measurements. *Applied Optics*, *36*, 8710–8723.

Pozdnyakov, D., Shuchman, R., Korosov, A., & Hatt, C. (2005). Operational algorithm for the retrieval of water quality in the Great Lakes. *Remote Sensing of Environment*, *97*(3), 352–370.

Qi, F., & Wang, X. J. (1999). Application of remote sensing techniques in monitoring and assessing inland water quality. *Advances in Environmental Science*, *7*(3), 90–99 (in chinese).

Tang, J. W., Tiang, G. L., Wang, X. Y., Wang, X. M., & Song, Q. J. (2004). The methods of water spectra measuring and analysis I: Above-water method. *Journal of Remote Sensing*, *8*(1), 37–44 (in chinese).

Tassan, S., & d'Alcalá, M. R. (1993). Water quality monitoring by thematic mapper in coastal environments: A performance analysis of local bio-optical algorithm and atmospheric correction procedures. *Remote Sensing of Environments*, *45*, 177–191.

Tzortziou, M., Subramaniam, A., Herman, J. R., Gallegos, C. L., Neale, P. J., & Harding Jr., L. W. (2007). Remote sensing reflectance and inherent optical properties in the mid Chesapeake Bay. *Estuarine, Coastal and Shelf Science*, *72*, 16–32.

Walker, R. E. (1994). *Marine light field statistics. Wiley series in pure and applied optics*. Wiley: New York.

Zhang, Y. L., Qin, B. Q., Chen, W. M., & Luo, L. C. (2004). A study on total suspended matter in lake taihu. *Resources and Environment in the Yangtze Basin*, *13*(3), 266–271 (in chinese).