AQUATIC ECOSYSTEM
HEALTH & MANAGEMENT

Retrieving total suspended matter in Lake Taihu from HJ-CCD near-infrared band data

Junsheng Li,[1] Qian Shen,[1] Bing Zhang,[1,*] and DongMei Chen[2]
[1]*Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, 9 Dengzhuang South Road, Beijing 100094, China*
[2]*Department of Geography, Queen's University, Kingston, Ontario K7L 3N6, Canada*
**Corresponding author: zhangbing@ceode.ac.cn*

Among water quality parameters, total suspended matter is important for the evaluation of inland waters. A recently launched satellite sensor, HJ-CCD, by China possesses high temporal resolution, medium spatial resolution, and wide swath, so it is convenient for monitoring this parameter in large inland waters. However, no operational method currently exists for retrieving the total suspended matter concentration of turbid inland waters from HJ-CCD data. Using Lake Taihu in Eastern China as a study area, we obtained and analyzed optical properties of the lake during all seasons, and found that the absorption coefficient of suspended matter, chlorophyll, and colored dissolved organic matter of the near-infrared band may approximate zero. Based on this analysis, we found that a single band method of retrieving concentration using the near-infrared band was suitable using HJ-CCD data. We parameterized the single band method with specific inherent optical properties of Lake Taihu, and validated it using the results retrieved from a HJ-CCD image taken on 14 March 2009, as well as water-surface quasi-synchronous measured data. The concentration retrieved from the image is precise and stable; the single band method uses the established specific optical property database in the study area for input parameters, and does not need support from synchronous data. With this method, HJ-CCD may be applied to retrieve total suspended matter of other highly turbid inland waters.

Keywords: remote sensing, inland water, water quality, bio-optical model

Introduction

Total suspended matter (TSM), an important parameter in the evaluation of the quality of inland waters, determines the transparency and primary productivity of water (Zhang et al., 2004). Compared to the routine monitoring method, monitoring TSM concentration through remote sensing has many advantages as it has a wide spatial coverage, is fast, less expensive, and convenient for long-term dynamic monitoring (Qi and Wang, 1999).

On 6 September 2008, two optical remote sensing micro-satellites HJ-1A and HJ-1B of the environment monitoring and disaster forecasting micro-satellite constellation were successfully launched in China (Zhang et al., 2009a). Both satellites carried a wide coverage multi-spectral CCD camera, (HJ-CCD). The HJ-CCD has four bands, with spectral ranges of 0.43 μm to 0.52 μm, 0.52 μm to 0.60 μm, 0.63 μm to 0.69 μm, and 0.76 μm to 0.90 μm, respectively; the spatial resolution is 30 m; and the swath is over 700 km (Zhu et al., 2009). The satellites repeatedly pass over study

Aquatic Ecosystem Health & Management, 17(3):280–289, 2014. Copyright © 2014 AEHMS. ISSN: 1463-4988 print / 1539-4077 online
DOI: 10.1080/14634988.2014.941776

sites once every two days (Li, 2009). The HJ-CCD possesses high temporal resolution, medium spatial resolution, and wide swath, so it is extremely suitable for monitoring TSM concentration of large inland waters.

No operational method currently exists, especially based on HJ-CCD data, to retrieve TSM concentration of inland waters due to the complex optical properties of inland waters as well as its regional and seasonal differences. The present methods of retrieving TSM concentration of inland waters include three main families (Ruddick et al., 2008): single band (Nechad et al., 2010; Neukermans et al., 2009), band ratio (Doxaran et al., 2002) and multispectral (Dekker et al., 2002; Sun et al., 2010). Among these methods, the single band method has relatively low requirements on remote sensing data. Therefore, the single band method may be more suitable for HJ-CCD remote sensing data, which has only four wide spectral bands in blue, green, red, and near-infrared wavelength regions. In the single band method, there are two issues to be clarified: (1) which band of remote sensing data is used and (2) how to determine the parameters. These two things are related to the optical properties of each inland water body.

In this study, we obtained and analyzed the inherent and apparent optical properties of Lake Taihu in Eastern China during four seasons, and found that the single band method of retrieving TSM concentration using near-infrared band was suitable for retrieving TSM from HJ-CCD data. We parameterized the single-band-method with specific inherent optical properties of Lake Taihu, and validated it using the results retrieved from a HJ-CCD image taken on 14 March 2009, and water-surface quasi-synchronous measured data.

Data and methods

Acquisition of experimental data

Overview of experimental area

In this study, we used Lake Taihu as the experimental area. The lake, located in Eastern China, is between 30°55′40″ to 31°32′58″N and 119°52′32″ to 120°36′10″E (Qin et al., 2004). In recent decades, Lake Taihu has become extremely eutrophic, and the study on the optical properties of Lake Taihu has become a research hotspot (Duan et al., 2009; Le et al., 2011; Wang et al., 2011; Zhang et al., 2010). The TSM concentration of Lake Taihu water is relatively high all year round (Zhang et al., 2004).

Experimental time and distribution of sampling stations

The optical properties of inland waters usually vary with the seasons. To obtain data on the optical properties of Lake Taihu during different seasons, we performed four experiments in July 2006, October 2006, January 2007, and April 2007, respectively. From these experiments we collected data on the inherent and apparent optical properties of Lake Taihu during the four seasons.

We designed 50 sampling stations that covered different lake regions. Among these stations, 16 points are located in the heavily polluted Meiliang Bay of northern Lake Taihu and were measured intensively. Figure 1 illustrates the distribution of sampling stations.

Measuring method of experiments

Experiments conducted at each water-surface sampling station were comprised of two parts: water-surface spectral measurement and water sampling. The water-surface spectral measurement was taken by an ASD portable field spectrometer FieldSpec® Pro FR (wavelength range 350 nm to 2500 nm) and FieldSpec® Pro VNIR (wavelength range 350 nm to 1000 nm) to measure the water-surface spectrum with the "above water method" (Mueller et al., 2003; Tang et al., 2004). We obtained the measurement signals when the spectrometer faced a standard gray panel, a water body, and skylight: $L_p(\lambda)$, $L_{sw}(\lambda)$, $L_{sky}(\lambda)$. Using these three values, we calculated the common parameter-remote sensing reflectance ($R_{rs}(\lambda)$):

$$R_{rs}(\lambda) = \frac{L_w(\lambda)}{E_d(\lambda)} = \frac{L_{sw}(\lambda) - r_{sky}L_{sky}(\lambda)}{\pi L_p(\lambda)/\rho_p(\lambda)} \quad (1)$$

where $L_w(\lambda)$ is water-leaving radiance, $E_d(\lambda)$ is downward irradiance above water surface, $\rho_p(\lambda)$ is reflectance of gray panel calibrated in laboratory and r_{sky} is reflectance of skylight at air-water interface, as calculated by using a Fresnel formula.

Standard sampling barrels were used in the water sampling, gathering water from approximately 0 cm to 50 cm deep. Water samples collected at the water surface were sent quickly to the lab for analysis so that data about the water quality parameters and inherent optical properties of the

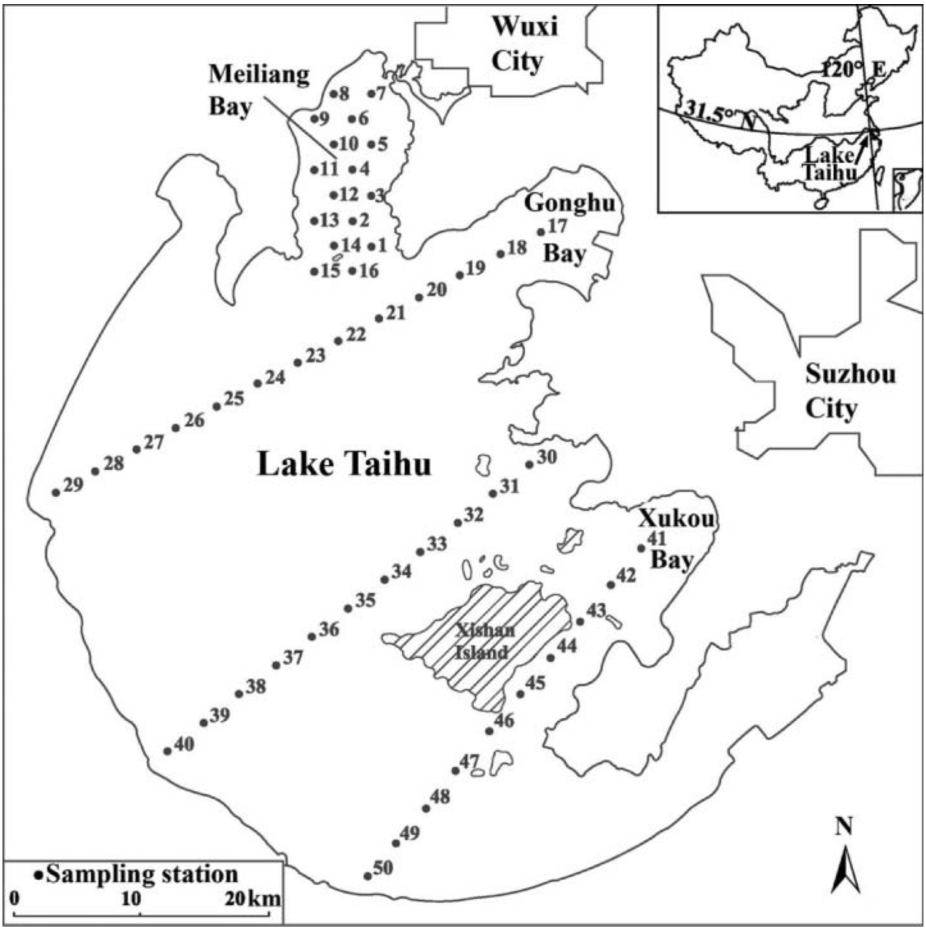

Figure 1. Map for experimental sampling stations distribution of Lake Taihu.

water were obtained (Zhang et al., 2007). Concentrations of TSM (C_s) were measured by filtering the water samples on Whatman fiberglass GF/F filters, and then drying and weighting on electronic balance.

Optical density spectra of original water samples were measured using a UV2401PC spectrometer with a 4 cm length quartz cuvette and with Milli-Q water as reference. Then, the attenuation coefficient spectra (C) were calculated by formulas proposed by Bricaud et al. (1981). Water samples were filtered through a Millipore filter membrane with 0.22 μm pores, and then optical density spectra of the filtered water samples were measured using a UV2401PC spectrometer with a 4 cm length quartz cuvette and with Milli-Q water as reference. Then, the absorption coefficient spectra of Colored Dissolved Organic Matter (CDOM) ($a_{cdom}(\lambda)$) were calculated by formulas proposed by Bricaud et al. (1981).

TSM absorption coefficient ($a_p(\lambda)$) and non-pigment suspended matter absorption coefficient ($a_d(\lambda)$) were measured by the quantitative filter technique (Mitchell, 1990). The absorption coefficient spectra of phytoplankton of $a_{ph}(\lambda)$ were calculated by subtracting $a_d(\lambda)$ from $a_p(\lambda)$. The scattering coefficient spectra of TSM $b_p(\lambda)$ were calculated by subtracting $a_p(\lambda)$ and $a_{cdom}(\lambda)$ from $C(\lambda)$.

Analysis of experimental data

Analysis of the inherent optical properties

The average phytoplankton pigment absorption coefficient $a_{ph}(\lambda)$, non-pigment suspended matter absorption coefficient $a_d(\lambda)$, the CDOM absorption

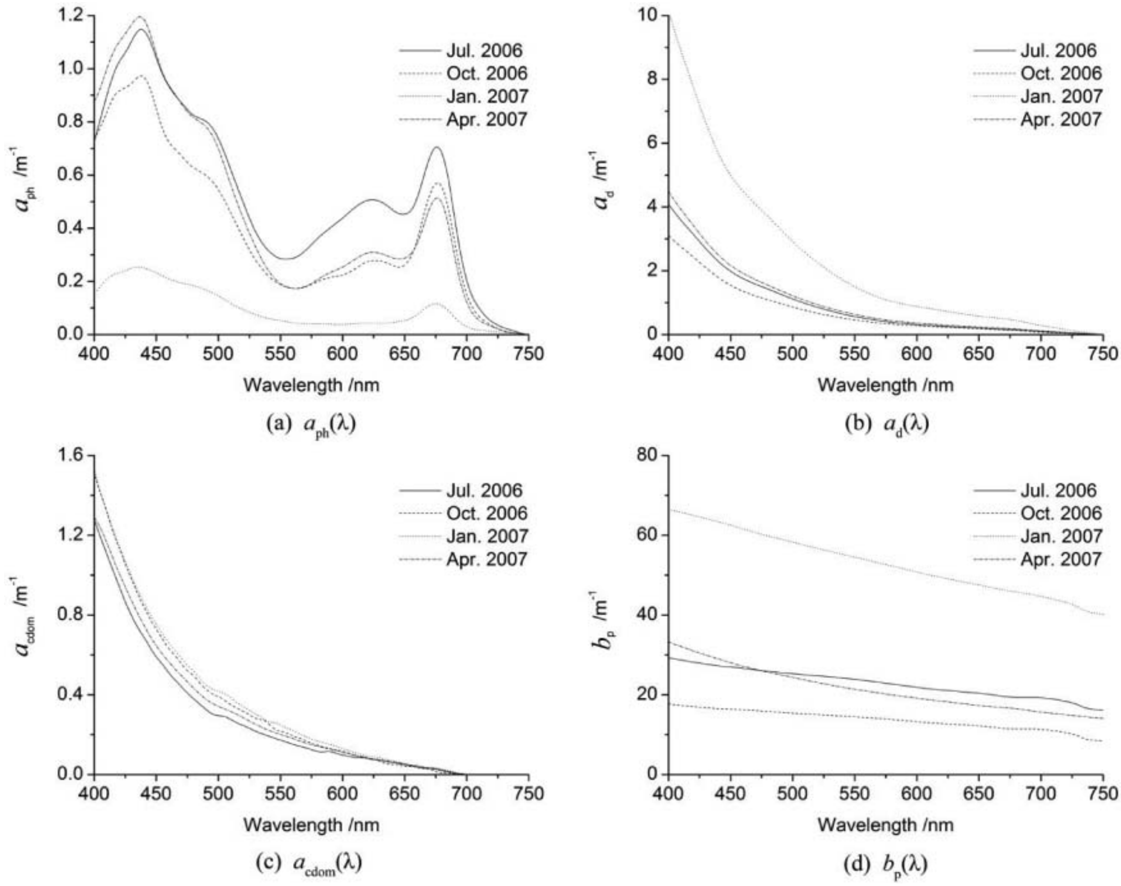

Figure 2. Average values of $a_{ph}(\lambda)$, $a_{cdom}(\lambda)$, $a_d(\lambda)$ and $b_p(\lambda)$ measured at four different times during the Lake Taihu experiments.

coefficient $a_{cdom}(\lambda)$, and the TSM scattering coefficient $b_p(\lambda)$ of Lake Taihu during the four seasons were measured in four experiments, and are illustrated in Figure 2.

In Figure 2, the average values of $a_{ph}(\lambda)$, $a_d(\lambda)$, $a_{cdom}(\lambda)$, and $b_p(\lambda)$ diminish with wavelength after 700 nm and are reduced to close to 0 at 750 nm, far less than the absorption coefficient of pure water, indicating that the light field in water of Lake Taihu at the near-infrared band is not affected by absorptions of phytoplankton pigment, non-pigment suspended matter, and CDOM, but mainly is affected by the absorption of pure water.

The measured response range of $b_p(\lambda)$ was 400 nm to 750 nm, and the $b_p(\lambda)$ from 750 nm to 950 nm was obtained by fitting of the negative exponential model. The minimal value of $b_p(\lambda)$ at 950 nm obtained by curve fitting of four experiment data was larger than 7.0, far more than the scattering coefficient of pure water (lower than 0.0004), indicating that the scattering of light field at the near-infrared band was mainly affected by TSM.

To sum up, the light field of Lake Taihu at the near-infrared band is influenced jointly by pure water's absorptive action and the scattering action of TSM. As the absorption coefficient of pure water is invariable, the light field of water in Lake Taihu at the near-infrared band changes under the influence of TSM.

Analysis of apparent optical properties

The average values of remote sensing reflectance $R_{rs}(\lambda)$ measured at four different times during the Lake Taihu experiments are illustrated in Figure 3.

Based on Figure 3, the average values of remote sensing reflectance $R_{rs}(\lambda)$ measured during four different experiments at Lake Taihu during four seasons are close to 0 after 950 nm, but

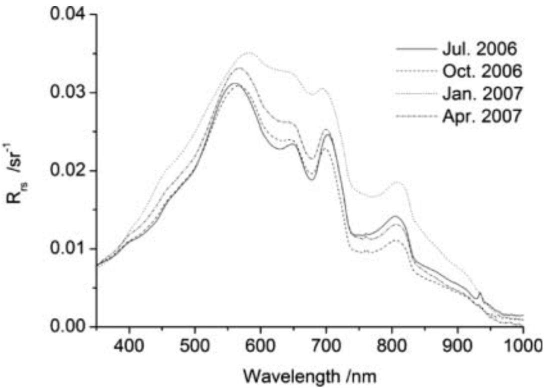

Figure 3. Average values of remote sensing reflectance $R_{rs}(\lambda)$ measured at four different times during the Lake Taihu experiments.

obviously are larger than 0 from 750 nm to 950 nm of the near-infrared wavelength region. This generally is caused by the strong scattering action of TSM.

Method of retrieving TSM concentration

The turbid water of Lake Taihu has a very high reflectance at the near-infrared wavelength region. This reflectance is determined by the scattering action of TSM and has little to do with other water-quality parameters; therefore, the near-infrared band is the best band for retrieving TSM concentration of the lake (Zhang et al., 2008). The HJ-CCD has only one near-infrared band, thus the HJ-CCD based method of retrieving TSM concentration can only use this near-infrared band.

There are mainly two categories of methods for retrieving TSM concentration: empirical method and analytical method. Empirical method is built on the statistical relationship between TSM concentration and remote sensing data, and has low robustness. In contrast, analytical method is based on bio-optical model, and has the advantages of definite physical meanings, higher robustness, and wider applicability (Dekker, 1993). Ocean optical model is often called the bio-optical model (Gordon et al., 1975), because it is phytoplankton that dominates the optical properties of oceanic water. Bio-optical model was first introduced by Gordon et al. (1975), which describes the relationship between the irradiance ratio just under water surface and the absorption coefficient and backscattering coefficient of oceanic water. Dekker (1993) introduced a new bio-optical model, which is more suitable for turbid inland waters:

$$R(0-)(\lambda) = f * \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} \quad (2)$$

where $R(0-)$ is the irradiance ratio just under water surface, f is a parameter related to the distribution of the optical field, $a(\lambda)$ is the total absorption coefficient of water body, and $b_b(\lambda)$ is the total backscattering coefficient of the water body.

Unfolding the absorption coefficients and scattering coefficients in the above equation and expressing $R(0-)(\lambda)$ with remote sensing reflectance $R_{rs}(\lambda)$, we got the following:

$$\frac{R_{rs}(\lambda)}{(1 - r(\theta_v)) * (1 - r(\theta_s))/n^2} = \frac{f}{Q} * \frac{b_{bw}(\lambda) + \tilde{b}_{bp} * b'_p(\lambda) * C_s}{a_w(\lambda) + a_{ph}(\lambda) + a_d(\lambda) + a_{cdom}(\lambda) + b_{bw}(\lambda) + \tilde{b}_{bp} * b'_p(\lambda) * C_s} \quad (3)$$

where $a_{ph}(\lambda)$ is the pigment absorption coefficient of phytoplankton, $a_d(\lambda)$ is the absorption coefficient of non-pigment suspended matter, $a_{cdom}(\lambda)$ is the absorption coefficient of CDOM, $a_w(\lambda)$ is the absorption coefficient of pure water, $b_{bw}(\lambda)$ is the backscattering coefficient of pure water, θ_v is the viewing zenith angle, $r(\theta_v)$ is the reflectance at water-air interface, θ_s is the solar zenith angle, $r(\theta_s)$ is the reflectance at air-water interface, n is the refractive index of water body, Q is the ratio of upward irradiance and radiance brightness under water, C_s is the TSM concentration, $b'_p(\lambda)$ is a specific scattering coefficient of TSM and $\tilde{b}_{bp}$is the backscattering proportional coefficient of TSM.

As the near-infrared band, $a_{ph}(\lambda)$, $a_d(\lambda)$, and $a_{cdom}(\lambda)$ diminish to approximately zero and the backscattering coefficient of pure water $b_{bw}(\lambda)$ also reduces to a very small value, far less than the back scattering coefficient of TSM, so it can be ignored. At this time, Equation (3) can be simplified as:

$$\frac{R_{rs}(\lambda)}{(1-r(\theta_v))*(1-r(\theta_s))/n^2} = \frac{f}{Q}*\frac{\tilde{b}_{bp}*b'_p(\lambda)*C_s}{a_w(\lambda)+\tilde{b}_{bp}*b'_p(\lambda)*C_s} \quad (4)$$

Transforming the above equation, we arrived at an equation of TSM concentration C_s:

$$C_s = \frac{R_{rs}(\lambda_1)}{\frac{f}{Q}*\frac{(1-r(\theta_v))*(1-r(\theta_s))}{n^2}-R_{rs}(\lambda_1)}*\frac{a_w(\lambda_1)}{\tilde{b}_{bp}b'_p(\lambda_1)} \quad (5)$$

Equation (5) is algebraically equivalent to the 12th Equation of Nechad et al. (2010), but it has specific differences: Equation (5) is specially used for highly turbid waters such as Lake Taihu, and only spectral data in near-infrared wavelength region can be used; while the 12th equation of Nechad et al. (2010) can be used for more waters, and spectral data in other wavelength region can be used. Just for highly turbid waters such as Lake Taihu, Equation (5) is more straightforward and easier to be used.

We can see from Equation (5) that C_s can be calculated using remote sensing reflectance ($R_{rs}(\lambda_1)$) of one near-infrared band λ_1. However, 9 parameters in Equation (5) must be determined first: the refractive index n of inland water body may take a constant of 1.333; the solar zenith angle θ_s and the viewing zenith angle θ_v can be taken from the property files of the remote sensing images; $r(\theta_v)$ and $r(\theta_s)$ can be calculated using a Fresnel formula; the absorption coefficient of pure water $a_w(\lambda_1)$ can be gathered from documents (Buiteveld et al., 1994); and the f and Q values can be calculated using empirical equations (Walker, 1994; Gons, 1999). The specific scattering coefficient $b'_p(\lambda)$ and the backscattering proportional coefficient $\tilde{b}_{bp}$ of TSM are the most difficult to determine, as different values are taken from different regions at different seasons, but a priori data of $b'_p(\lambda)$ and $\tilde{b}_{bp}$ can be provided by the inherent optical property data of the water body at different seasons through water-surface experiments in the study area.

The inherent optical property data measured in the four experiments at Lake Taihu during the four seasons can constitute a database, providing a priori data of $b'_p(\lambda)$ and $\tilde{b}_{bp}$of Lake Taihu. The spectral range of the TSM scattering coefficient $b_p(\lambda)$ measured in this study is 400 nm to 750 nm, and no measured data is available for the near-infrared band (750 nm to 950 nm). In this study, the 400–750 nm $b_p(\lambda)$ spectrum was fitted through the negative index model, then extrapolated to the 750–950 nm $b_p(\lambda)$ spectrum. If $b_p(\lambda)$ is divided by the corresponding C_s, we get $b'_p(\lambda)$. As our intentions was to apply the method of retrieving TSM concentration to the HJ-CCD near-infrared band, the band equivalent calculation of the $b'_p(\lambda)$ spectrum can be carried out using the spectral response function of the HJ-CCD near-infrared band. The specific scattering coefficient b'_p(HJ-CCD4) corresponding to the HJ-CCD near-infrared band was then calculated, where HJ-CCD4 stands for the HJ-CCD near-infrared band or the 4th band. Due to the limitations of our scientific instruments, the $\tilde{b}_{bp}$ data are not directly measured, but $\tilde{b}_{bp}$ can be obtained by fitting the remotely sensed reflectance and the inherent optical properties taken during the experiments at four different times based on the bio-optical model. The final b'_p(HJ-CCD4) and $\tilde{b}_{bp}$ during the Lake Taihu experiments at four different seasons are expressed in Table 1, from which corresponding data can be extrapolated according to the seasons acquired by images when using HJ-CCD near-infrared band in calculation of TSM concentration.

Results

At 10:58 Beijing time on 14 March 2009, we captured a scene using the HJ-CCD satellite. No cloud was above Lake Taihu, and the image was of good quality. Within a half-hour before and after the image was acquired, we performed an experiment on the water surface of Lake Taihu and measured the TSM concentration at three sampling stations using the method stated in this

Table 1. b'_p(HJ-CCD4) and $\tilde{b}_{bp}$ values in the Lake Taihu experiments during the four seasons.

	Spring	Summer	Autumn	Winter
b'_p(HJ-CCD4)	0.330	0.319	0.278	0.325
$\tilde{b}_{bp}$	0.052	0.040	0.056	0.054

Table 2. Measuring time, longitude, latitude, TSM concentration and wind speed data at three sampling stations.

Number of sampling stations	Measuring time	Longitude	Latitude	C_s (mg l^{-1})	Wind Speed (ms^{-1})
1	10:35	120.172472	31.349500	82.00	0.1
2	10:54	120.171667	31.331611	94.67	0.5
3	11:21	120.167861	31.295500	140.00	0.5

article. In addition, wind speed was measured at each sampling station. Table 2 gives the measuring time, longitude and latitude, TSM concentration (C_s), and data of wind speed.

In carrying out the experiments on water surface, a CE318 sun-photometer was used to measure the aerosol optical thickness and the water vapor content. At the time when the HJ-CCD image was acquired, the measured aerosol optical thickness was 0.35, and the measured water vapor content was 0.20 g cm^{-2}.

In this study, we retrieved the TSM concentration of Lake Taihu using this HJ-CCD data on the basis of the method developed in this article. Then we validated our results using quasi-synchronously measured data of TSM concentration at three sampling stations. To use the HJ-CCD data for retrieving TSM concentration of Lake Taihu, atmospheric correction must first be implemented for the HJ-CCD image. We used atmospheric radiation transfer software 6s for the atmospheric correction of the HJ-CCD image and calculated the

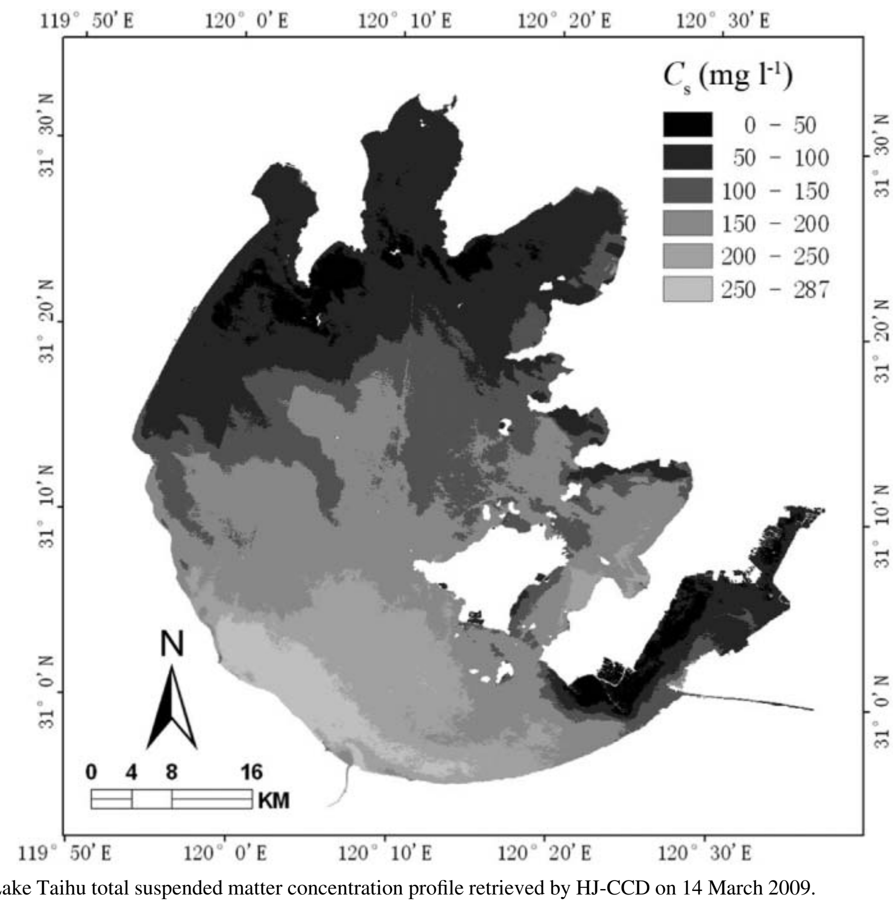

Figure 4. Lake Taihu total suspended matter concentration profile retrieved by HJ-CCD on 14 March 2009.

Table 3. Comparison between TSM concentration measured at water surface and retrieved from the HJ-CCD image.

Number of sampling stations	C_s measured at water surface (mg l^{-1})	C_s retrieved from HJ-CCD image (mg l^{-1})	Absolute error (mg l^{-1})	Relative error
1	82.00	79.16	2.84	3.46%
2	94.67	91.76	2.91	3.08%
3	140.00	135.16	4.84	3.46%

remotely sensed reflectance (Zhang et al., 2009b). The input parameters included aerosol type, aerosol optical thickness, water vapor, and ozone contents. A continental type of aerosol was used; the aerosol optical thickness and the water content were measured by CE318. For ozone content, the Aura OMI product can be downloaded from the NASA website (http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/omto3_v003.shtml). The ozone content of the sky above Lake Taihu on 14 March 2009 averaged 0.266 cm.

After obtaining remotely sensed reflectance from the HJ-CCD 4th band, the TSM concentration was calculated using Equation (5). As the HJ-CCD image was obtained during spring, the b'_p(HJ-CCD4) and $\tilde{b}_{bp}$values relevant to Lake Taihu in spring were selected from the database of specific inherent optical properties. Figure 4 shows a map of the calculated TSM concentration of the Lake Taihu.

On the basis of the longitude and latitude of three water-surface sampling stations, pixel values corresponding to the three points in the TSM concentration image were extracted and compared with TSM concentration measured at the water surface. The absolute and relative errors are listed in Table 3.

Discussion

Using data measured quasi-synchronously with the HJ-CCD image at three water-surface sampling stations, we evaluated the accuracy of retrieving TSM concentration from the HJ-CCD image. On the morning of 14 March, the wind speed on Lake Taihu was very small, with wind speed at the three sampling stations being less than or equal to 0.5 m s^{-1}, which can hardly generate re-suspension of bottom sediment of Lake Taihu. Therefore, the TSM concentration of Lake Taihu on 14 March was relatively stable. In addition, the time spent measuring at three sampling stations and the time for getting the HJ-CCD images are less than or equal to 23 min, thus the TSM measurement time at three sampling stations and the HJ-CCD image acquisition time are relatively consistent, which provides a reliable basis for this study using data measured at the three sampling stations to evaluate the accuracy of retrieving TSM concentration from the HJ-CCD image.

Table 3 shows that the absolute error of the TSM concentration retrieved by HJ-CCD is directly proportional to the ground-measured TSM concentration. The actual measured value at water surface at Station No. 3 was the largest, reaching 140 mg l^{-1}, and the corresponding retrieving absolute error was also the largest, reaching 4.84 mg l^{-1}. The actual measured value at Station No. 1 was the smallest, being only 82 mg l^{-1}, and the corresponding retrieving absolute error was the smallest, being only 2.84 mg l^{-1}. For evaluation of the precision of retrieving TSM concentration, the relative error was more useful than the absolute error to reveal the effectiveness of retrieving results. The relative error of the TSM concentration retrieved from HJ-CCD is very small, with relative error measured at Station No. 2 being only 3.08%, and relative error at both Station Nos. 1 and 3 was only 3.46%. Such small relative errors may be caused by the counteraction of errors in the retrieval method, the atmospheric correction, and in-situ measurement.

Conclusions

From the above analysis, the TSM concentrations of Lake Taihu retrieved from HJ-CCD images have relatively high accuracy and relatively rational spatial distribution. This reveals that the single band method of retrieving the TSM concentration of Lake Taihu based on HJ-CCD near-infrared band data has led to results with high accuracy. Apart from obtaining good retrieval accuracy, the method has good seasonal applicability. In this study, we have built up a database of inherent optical properties of Lake Taihu. This database is indexed by season and is shown in Table 1. When using the HJ-CCD image during certain seasons to estimate TSM concentration, the specific inherent optical property data corresponding to the season can be obtained as input parameters, thus improving the seasonal applicability of the retrieving method. In addition, the method is practical as it needs no support from synchronous data once the database is built. This single band method of retrieving TSM concentration of a turbid water body from near-infrared band data is also applicable to other remotely sensed data with near-infrared band, and to other inland turbid waters such as Lake Chaohu and Lake Dianchi, premised by the acquisition of data on specific inherent optical properties at all seasons in these lakes. However, this single band method applies only to a highly turbid water body, and not to a relatively clean water body as reflectance of clean water is extremely low at near-infrared band. In conclusion, this single band method of retrieving TSM concentration of Lake Taihu from the HJ-CCD near-infrared band data is practical.

Funding

This research has been jointly supported by the National Natural Science Foundation of China (Grant Nos. 41325004, 40901174 and 41001205) and High Resolution Earth Observation Systems of National Science and Technology Major Projects (Grant No. 05-Y30B02-9001-13/15-5).

References

Bricaud, A., Morel, A., Prieur, L., 1981. Absorption by dissolved organic matter of the sea (yellow substance) in the UV and visible domain. Limnology and Oceanography 26, 43–53.

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

Dekker, A. G., 1993. Detection of optical water quality parameters for eutrophic waters by high resolution remote sensing. Ph.D. dissertation, Vrije University - Amsterdam, Netherlands.

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.

Doxaran, D., Froidefond, J. M., Lavender, S., Castaing, P., 2002. Spectral signatures of highly turbid waters: Application with SPOT data to quantify suspended particulate matter concentrations. Remote Sensing of Environment 81(1), 149–161.

Duan, H. T., Ma, R. H., Xu, X. F., Kong, F. X., Kong, W. J., Hao, J. Y., Shang, L. L., 2009. Two-decade reconstruction of algal blooms in China's Lake Taihu. Environmental Science & Technology 43(10), 3522–3528.

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

Gordon, H. R., Brown, O. B., Jacobs, M. M., 1975. Computed relationships between the inherent and apparent optical properties of a flat homogeneous ocean. Applied Optics 14, 417–427.

Le, C. F, Li, Y. M, Zha, Y., 2011. Remote estimation of chlorophyll a in optically complex waters based on optical classification. Remote Sensing of Environment 115(2), 725–737.

Li, H. P., 2009. Application of Environment and Disaster Monitoring Mini Satellite on environment emergency management. Chinese Journal of Environmental Management (in Chinese) 3, 29–32.

Mitchell, B. G., 1990. Algorithms for determining the absorption coefficient of aquatic particulates using the quantitative filter technique (QFT). Proceedings of SPIE. 1302, 137–148.

Mueller, J. L., Morel, A., Frouin, R., Davis, C., Arnone, R., Carder, K., Lee, Z. P., Steward, R. G., Hooker, S., Holben, B., Mobley, C. D., McLean, S., Miller, M., Pietras, C., Fargion, G. S., Knobelspiesse, K. D., Porter, J., Voss, K., 2003. Ocean optics protocols for satellite ocean color sensor validation, Revision 4, Volume III: radiometric measurements and data analysis protocols. National Aeronautical and Space Administration Report 21621, 1–72.

Nechad, B., Ruddick, K. G., Park, Y., 2010. Calibration and validation of a generic multisensor algorithm for mapping of total suspended matter in turbid waters. Remote Sensing of Environment 114(4), 4–866.

Neukermans, G., Ruddick, K., Bernard, E., Ramon, D., Nechad, B., Deschamps, P. Y., 2009. Mapping total suspended matter from geostationary satellites: a feasibility study with SEVIRI in the Southern North Sea. Optics Express 17(16), 14029–14052.

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

Qin, B. Q., Hu, W. P., Chen, W. M., 2004. *Course and Mechanism of Water Environmental Evolution of Lake Taihu*. Science Press, Beijing, China.

Ruddick, K., Nechad, B., Neukermans, G., Park, Y., Doxaran, D., Sirjacobs, D., Beckers, J. M., 2008. Remote sensing of suspended particulate matter in turbid waters: state of the art and future perspectives. Proceedings of the Ocean Optics XIX conference, 2008 October 6–10. Barga, Italy. Available on CD-ROM.

Sun, D. Y., Li, Y. M., Wang, Q., Lv, H., Le, C. F., Huang, C. C., Gong, S. Q., 2010. Detection of suspended-matter concentrations in the shallow subtropical Lake Taihu, China, using the SVR model based on DSFs. IEEE Geoscience and Remote Sensing Letters 7(4), 16–820.

Tang, J. W., Tian, 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 (in Chinese) 8(1), 37–44.

Walker, R. E., 1994. *Marine Light Field Statistics*. Wiley, New York, USA.

Wang, M. H., Shi, W., Tang, J. W., 2011. Water property monitoring and assessment for China's inland Lake Taihu from MODIS-Aqua measurements. Remote Sensing of Environment 15(3), 841–854.

Zhang, B., Chen, Z. C., Li, J. S., Gao, L. R., 2009a. Image quality evaluation on Chinese first earth observation hyperspectral satellite. IGARSS. Cape Town, South Africa.

Zhang, B., Li, J. S., Shen, Q., Chen, D. M., 2008. A bio-optical model based method of estimating total suspended matter of Lake Taihu from near-infrared remote sensing reflectance. Environmental Monitoring and Assessment 145, 339–347.

Zhang, B., Shen, Q., Li, J. S., Zhang, H., Wu, D., 2009b. Retrieval of three kinds of representative water quality parameters of Lake Taihu from hyperspectral remote sensing data. Journal of Lake Sciences (in Chinese) 21(2), 143–148.

Zhang, Y. L., Feng, L. Q., Li, J. S., Luo, L. C., Yin, Y., Liu, M. L., Li, Y. L., 2010. Seasonal-spatial variation and remote sensing of phytoplankton absorption in Lake Taihu, a large eutrophic and shallow lake in China. Journal of Plankton Research 32(7), 1023–1037.

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 (in Chinese) 13(3), 266–271.

Zhang, Y. L., Zhang, B., Wang, X., Li, J. S., Feng, S., Zhao, Q. H., Liu, M. L., Qin, B. Q., 2007. A study of absorption characteristics of chromophoric dissolved organic matter and particles in Lake Taihu, China. Hydrobiologia 592, 105–120.

Zhu, J., Wu, Y. L., Shen, Z., 2009. Analysis of system-level radiometric calibration data for HJ-1A/B wide coverage CCD camera. Spacecraft Engineering (in Chinese). 18(5), 73–79.