

Absorption coefficient characteristics of the Three Gorges Dam water

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Abstract: The absorption coefficient of water color constituents is an inherent optical parameter. It is the main factor which influences the distribution of the water optical field, and plays a very important role in the researches of water optics remote sensing. This paper analyses the absorption coefficient characteristics for particle matter, phytoplankton and colored dissolved organic matter (CDOM), using the absorption coefficient of water color constituents in situ measured at the Three Gorges Dam in April, 2007. The results show that, for the Three Gorges Dam water: (1) the absorption spectrum of non-algal particles is similar with that of total particle matter; (2) the absorption coefficient of non-algal particles decreases power exponentially from short to long wavelength, and the absorption coefficient in different bands has a definite relationship; (3) the absorption coefficient of phytoplankton has a better polynomial relationship with chlorophyll a concentration in the Three Gorges Dam water; (4) piece-wise function can express the absorption coefficient characteristics of CDOM. The absorption spectrum below 500nm decreases power exponentially from short to long wavelength, and the precision of the fitting R^2 approaches to 1; the absorption spectrum between 501 and 700nm fits well using polynomial relationship, and the precision R^2 is above 95%.

Key words: Three Gorges Dam, absorption coefficient, particle matter, phytoplankton, colored dissolved organic matter (CDOM)

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1 INTRODUCTION

The optics characteristics of water are related with it is components; in condition that the bladder of water and onflow domino effects are not considered, the chlorophyll, suspended substance and color dissolved organic matter (CDOM) are the “three factors of water color” to influence the optic characteristics of case water, and the other factor is pour water molecule (Yang & Chen, 2007). The inherence optic characteristics of water including absorption coefficient, scatter coefficient and attenuation coefficient are considered as the idiocratic nestification of those factors (Li, 2006). As the attenuation effect of pour water is the same to all kinds of water, water optics characteristics of different cases in different regions are mainly related with the concentration and constitutes of the non-algal particle, phytoplankton and CDOM. The inherence optic characteristics of those constitutes are the essential parameters to estimate elementary productivity and ray radiation transmission, and to simulate biology-optics pattern and ecological process of water

color remote sensing (Kirk, 1994). In recent years, the quantitative researches of water optics characteristic and water color remote sensing have been focused. Most of the absorption spectrum researches are based on those substances in foreign countries, while it is deficient in China. Cao (2003) researched the absorption spectrum of suspended substance in Zhujiang Estuary, while did not involve the absorption spectrum of CDOM; Yu and Cai (1998) measured the water absorption coefficient and scatter coefficient at different seasons in Meiliangwan Bay, while did not distinguish the phytoplankton and non-algal particles. For the Three Gorges Reservoir, the research is scarce. Dong (2006) analyzed the water quality of the Three Gorges Reservoir with spectrum characteristic, and established the experience model to inverse the water color constituents, but did not come down to the water inherent optical properties (IOPs). Based on the researches and work we have done, the absorption coefficients of the total particle matter, non-algal particle, phytoplankton, CDOM in the Three Gorges Dam water were measured, and the data was analyzed.

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2 SAMPLING AND MEASUREMENT

On 7th November 2007, one campaign was carried out for 30 samples near the Three Gorges Dam (Fig.1). Considering the water quality difference between the fringe and the center of the reservoir, samples points were distributed homogeneously along the bench section (Fig. 1). Water samples and remote sensing reflectance were measured synchronously.

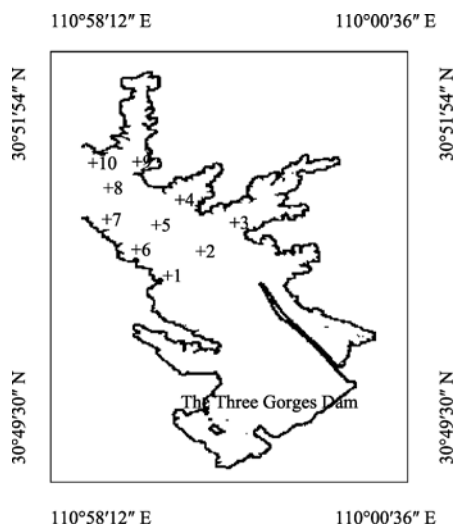


Fig. 1 Sketch map of sample points' position (“+”—sample)

The water samples were sampled with Niskin sampler. Two samples are sampled at each sample point, which were prepared for measuring the absorption coefficient of particle matter and CDOM respectively. Water samples were collected from the surface to about 30cm below in the vertical direction, which they were held on the deepfreeze half with ice bags for reserving. Then they were returned to the laboratory for concentration and absorption measurement. The measurement of the IOPs is difficult. For field measurement, the measurements are mainly optical spectrometer, such as AC-S, HS-6, AC-9, BB9 and so on. While in laboratory, the instruments are various spectral photometers. For this work, the UV-2401PC spectral photometer is used to obtain the absorption coefficients of water constituents.

2.1 Absorption measurement of total particles/non-algal particles and phytoplankton

The absorption coefficients were measured according to the ‘quantitative filter technique (QFT)’ method, which was brought forward by Konovalov and Bekasova (1959), recommended by Mitchell. The approach is as follows:

First, water samples were filtrated by 47 mm Whatman GF/F pre-dipped filters. The volume of filtered water V , ranging from 40 to 600 ml, was determined by SPM concentration. The baseline was corrected using a blank filter dipped in filtered water, the same wet as the filter with particle. The optical den-

sity (OD) of total particle matter on the filter, OD_f , was measured by a UV2401 spectrophotometer with 1 nm interval in the range 350 to 800 nm, but the values only in the range of 400 to 700 nm were used because of less disturbance by noise. The sample closed highly with the detector/collimator and the distance was about 2—3 mm, no diffuser was used between them. OD_f was normalized to zero at 750 nm and then corrected for increasing in path-length caused by multiple scattering in the glass-fibre filter using Eq. (1). Finally, the absorption coefficients $a_p(\lambda)$ were calculated by Eq. (2).

$$OD_s = 0.378OD_f + 0.523OD_f^2 \quad OD_f \leq 0.4 \quad (1)$$

$$a_p(\lambda) = 2.303 \times \frac{S}{V} OD_s(\lambda) \quad (2)$$

where S is the clearance area covered by the particle matter filtrated to the filter, of which effective diameter is 45 mm in this measurement.

After measurement of the total particle absorption, the filters were deposited in a refrigerator 30 to 180 minutes, and then pigment was removed from the filtered paper by extracting with 90% hot ethanol for about 4 h. To prevent non-algal particle, namely detritus, from outrunning during extraction, the filtered paper was held on a filter base, which was prepared in the same way, and then the extract solution was passed through the filter. Finally we measured the spectral optical density of non-algal particle with the same spectrophotometer and their absorption coefficients $a_d(\lambda)$ were calculated with the same method as $a_p(\lambda)$. Subsequently, phytoplankton pigments absorption coefficients, $a_{ph}(\lambda)$ were calculated by Eq. (3).

$$a_{ph}(\lambda) = a_p(\lambda) - a_d(\lambda) \quad (3)$$

2.2 Absorption measurement of CDOM

Colored dissolved organic matter (CDOM), which is combined with humic acid, aromatic compound and other substance, is mainly the production of the soil and water plant aquatic degradation. It is consisted in all kinds of water, and is an important part of the dissolvability organic matter (DOC) (Kirk, 1994). The optics characteristic of CDOM is singleness that is mainly presented as absorption, and decreases with the band increasing in the ultraviolet and blue band. Because the absorption of CDOM at blue band is superposed with the absorption of the chlorophyll a (Bricaud, 1981), the remote sensing reflectance is influenced and the chlorophyll a concentration is over-rated.

CDOM absorption was measured spectrophotometrically in a 10 cm cuvette using 0.70 mm Whatman GF/F-filtered lake water by the same UV-2401 spectro-photometer, with distilled water as reference. Scans were taken with 1 nm interval between 280 and 700 nm. The absorption coefficient was calculated using Eq. (4). Some fine particles possibly remained in the filtered solution, so it is necessary to correct for scattering by fine particles with Eq. (5).

$$a'_g(\lambda) = 2.303 \frac{OD_g(\lambda)}{r} \quad (4)$$

$$a_g(\lambda) = a'_g(\lambda) - a'_g(700) \times \frac{\lambda}{700} \quad (5)$$

where $a'_g(\lambda)$ and $a_g(\lambda)$ are the pre-corrected and corrected absorption coefficient respectively. $OD_g(\lambda)$ is the optical density measured at the wavelength λ . r is the optical path length and the factor 2.303 converts from base 10 to base e logarithms.

3 DATA RESULTS AND ANALYSIS

3.1 The absorption coefficient analysis of total particles

Fig.2 is the absorption spectrum of total particles, non-algal

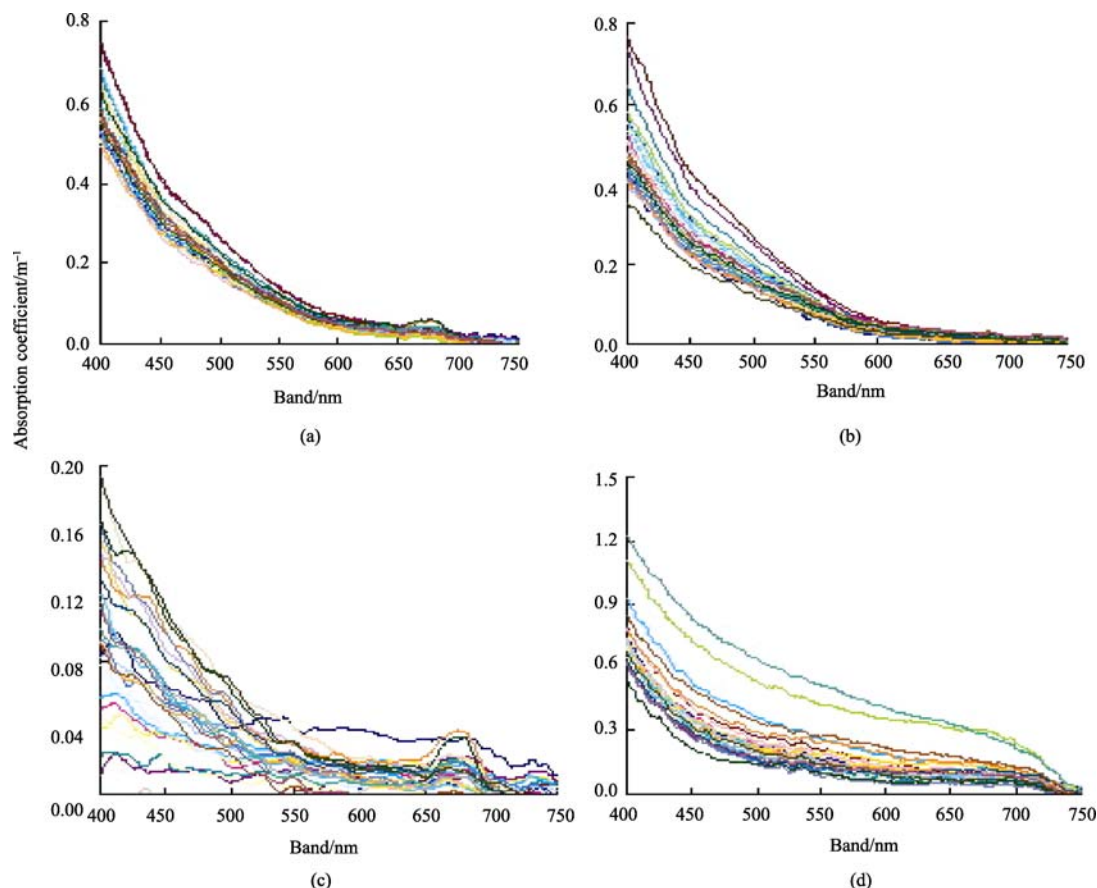


Fig. 2 Absorption spectra of total particles(a), non-algal particles(b), phytoplankton(c) and CDOM(d)

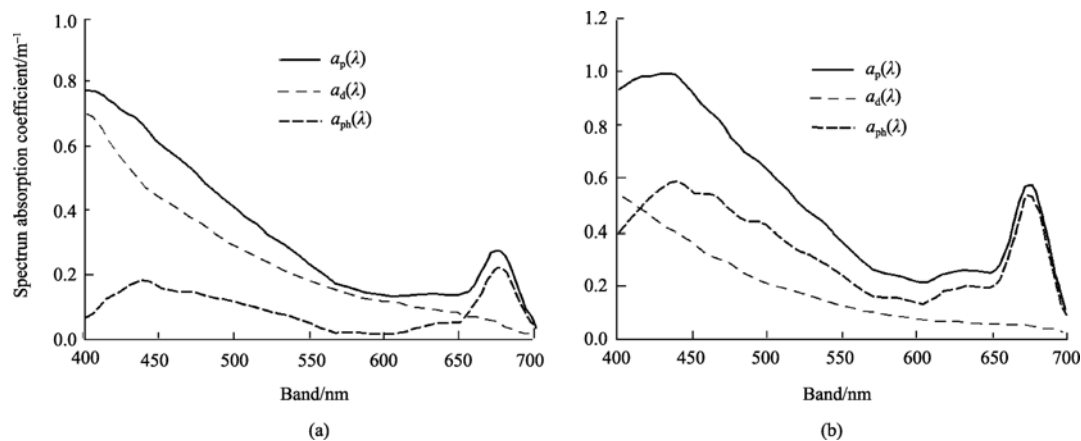


Fig. 3 Two typical spectral patterns of total particle absorption
 (a) The first type; (b) The second type

particles, phytoplankton and CDOM. Except the anthropogenic factor (such as fish breeding and poultry raising, beaching) at individual samples, the absorption coefficient of total particles and CDOM at different samples do not change obviously and the variation range of $a_p(440)$ is 0.22—0.43 m⁻¹.

As we all know, the absorption coefficient distribution of total particles has two types. The absorption coefficient comparison of total particles, phytoplankton and non-algal particles between the two types is shown in Fig.3. For the first type, the absorption coefficient of non-algal particles is bigger than that of phytoplankton expect at the red band, which is the absorption band of chlorophyll; the absorption coefficient distribution of total particles is similar with that of non-algal particles (Fig.3

(a)) and it decreases with the band increases. Contrarily, for the second type, in most bands, the absorption coefficient of phytoplankton is bigger than that of non-algal particles, and the absorption coefficient distribution of total particles is similar with that of phytoplankton (Fig.3 (b)). The results show that the first spectrum type is mainly distributed in inland water, of which the salinity is between 15 and 27. The spectrum type transits from the inland water to the sea, and for the sea, the spectrum absorption characteristic belongs to the second type (Cao, 2003).

The absorption coefficient of total particles in the Three Gorges Dam water is accorded with the first type spectrum pattern. On one hand, the absorption coefficient of total particle decreases with the bands increasing at different samples, and the results are similar to the conclusions that Xu and Cao (2004) got at Zhu River; on the other hand, the absorption coefficient spectrum of total particles is shown in Fig.3 (a), which is related with the water environment around the samples. After the reservoir constructed, the complexion of stream has changed, and the jet flow turn into a reservoir. It leads to the intensive absorption of non-algal particles in particle matter which is carried-over by the upstream water, and the absorption of non-algal particles is the main factor of total particles absorption coefficient in estuary (Xu, 2004), which is dominant in the size and varieties of total particles. In addition, the band 670nm is the absorption apex of phytoplankton, which is dominant the varieties of the total absorption coefficient in this band. In Fig.2, the absorption coefficient of most samples decreases as negative exponent with the band increasing except in sample #22, #27, which have a faint absorption apex at band 675nm. With the records we have, the sample #22, #27 are located at the abouchement of anabranch and the breed aquatics region respectively, which are influenced by external environment. Therefore, it is concluded that the absorption coefficient of total particles is presented as the absorption coefficient of non-algal particles in the Three Gorges Dam water, which is different from that in the sea (Bricaud & Stramski, 1990).

In order to analyze the contribution of the non-algal particles and phytoplankton in absorption spectrum of total particles, the three constituents' absorption coefficients at different samples are analyzed (Fig.4). The results show that the non-algal parti-

cles are dominant in the absorption coefficient of total particles in the Three Gorges Dam water. The conclusion is the same with what we have obtained.

In addition, it is discovered that the contributions of the non-algal particles and phytoplankton at different bands is not only different, but also not a constant. It is a variable with the band. Concretely, the contribution of the non-algal particles at shortwave is bigger than that at long wave; and the contribution of phytoplankton is opposite with the non-algal particles. So, the absorption apex at band 675nm is existence consistently in water total particles absorption coefficient, even if in the three gorges dam water, of which the chlorophyll concentration is low-rise.

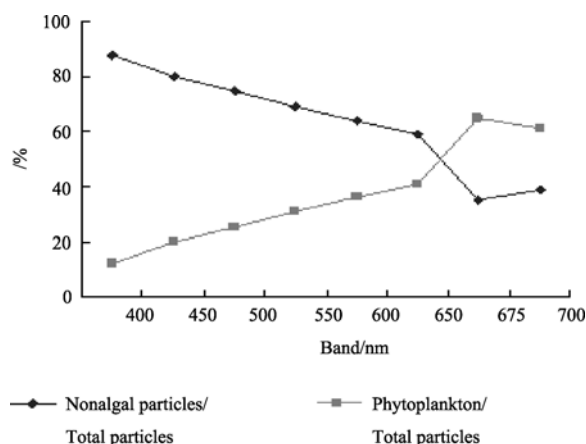


Fig. 4 Contributions of non-algal particles, phytoplankton in Absorption spectra of total particles

3.2 The absorption coefficient analysis of non-algal particles

The non-algal particles include the analytical remnants, substrate sludge and the humus, inorganic particle in soil. The absorption spectrum of it in all samples is similar, that is the absorption coefficient decreases with the band increasing (Fig.2). The simulation of the data measured *in-situ* is indicated that the variety of the absorption coefficient with band is presented as exponential damping and the absorption coefficient at different bands are correlative (Fig.5). It is important to establish the

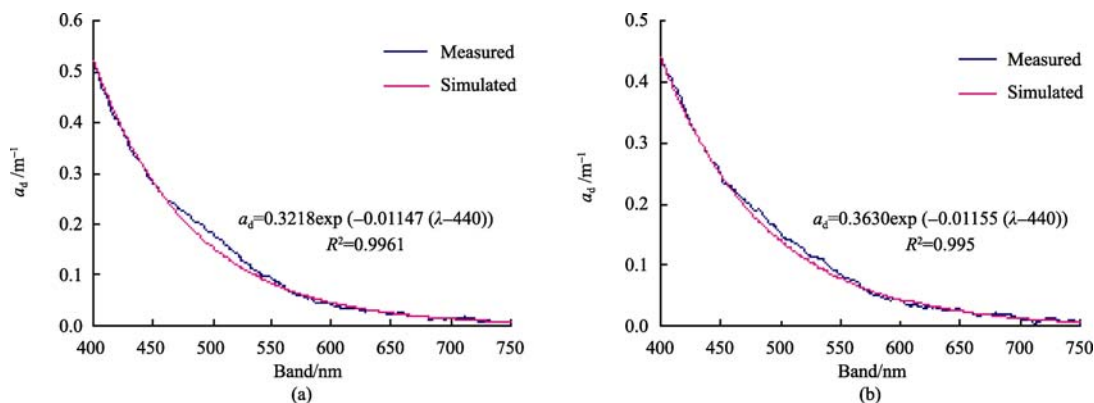


Fig. 5 Comparison between the measured data and the simulated data of the non-algal particles

absorption coefficient correlation models of non-algal particles. With those models, an absorption coefficient at one band can be inverted by another absorption coefficient at other band, which reduces the number of unknown parameters in water color remote sensing. In this paper, the model is established with the band 440nm, which is an important parameter in the research of water color remote sensing and many scalars have established the absorption coefficient models of non-algal particles based on it (Wang, 2006; Zeng, 2006; Zhou, 2007). The absorption coefficient at band λ is expressed as followed:

$$a_d(\lambda) = a_d(\lambda_0) \exp(-S(\lambda - \lambda_0)) \quad (6)$$

where, λ_0 is the band 440nm, S is the slope, which is different at different samples and ranges from 0.01014—0.0128. The mean value is 0.0115, the standard deviation is 0.00155. Taking the sample #2, #19 for example, and the absorption coefficient models are as followed:

$$a_d(\lambda) = a_d(440) \exp(-0.0122(\lambda - 440)) \quad (7)$$

$$a_d(\lambda) = a_d(440) \exp(-0.0114(\lambda - 440)) \quad (8)$$

Compared with the report that we have, the value of S in the Three Gorges Dam water is similar with the results that in Zhu River estuary sea area (Cao, 2003), Pacific Ocean and Mediterranean Sea (Bricaud, 1998). It is pointed that the value of S is also consistent with that of CDOM in Zhu River estuary sea

area (Chen, 2002). The results show that the optical properties of non-algal particles in the Three Gorges Dam are not only similar with that in other sea areas, but also consistent with that of CDOM. For Case water, the researches are shown that chlorophyll *a* and the absorption coefficient of nonalgal particle have better correlation, which is considering as the degradation of phytoplankton (Cao, 2003). For the Three Gorges Dam water, the correlations between the chlorophyll *a* concentration, suspended substance concentration and the absorption coefficient of non-algal particle are analyzed. Taking the band 440nm and 675nm for example, on band 440nm, the correlation between $a_d(440)$ and chlorophyll *a* concentration, suspended substance concentration is very weak; at band 675nm, $a_d(675)$ and suspended substance concentration present discretely, while the correlation between $a_d(675)$ and chlorophyll *a* concentration improves obviously (Fig.6). The results show that the absorption characteristics of non-algal particle in the Three Gorges Dam are influenced weakly by terrigenous deposits, and the degradation products of phytoplankton are the main resource of non-algal particles.

3.3 The absorption coefficient analysis of phytoplankton

The absorption spectrum distribution of phytoplankton at

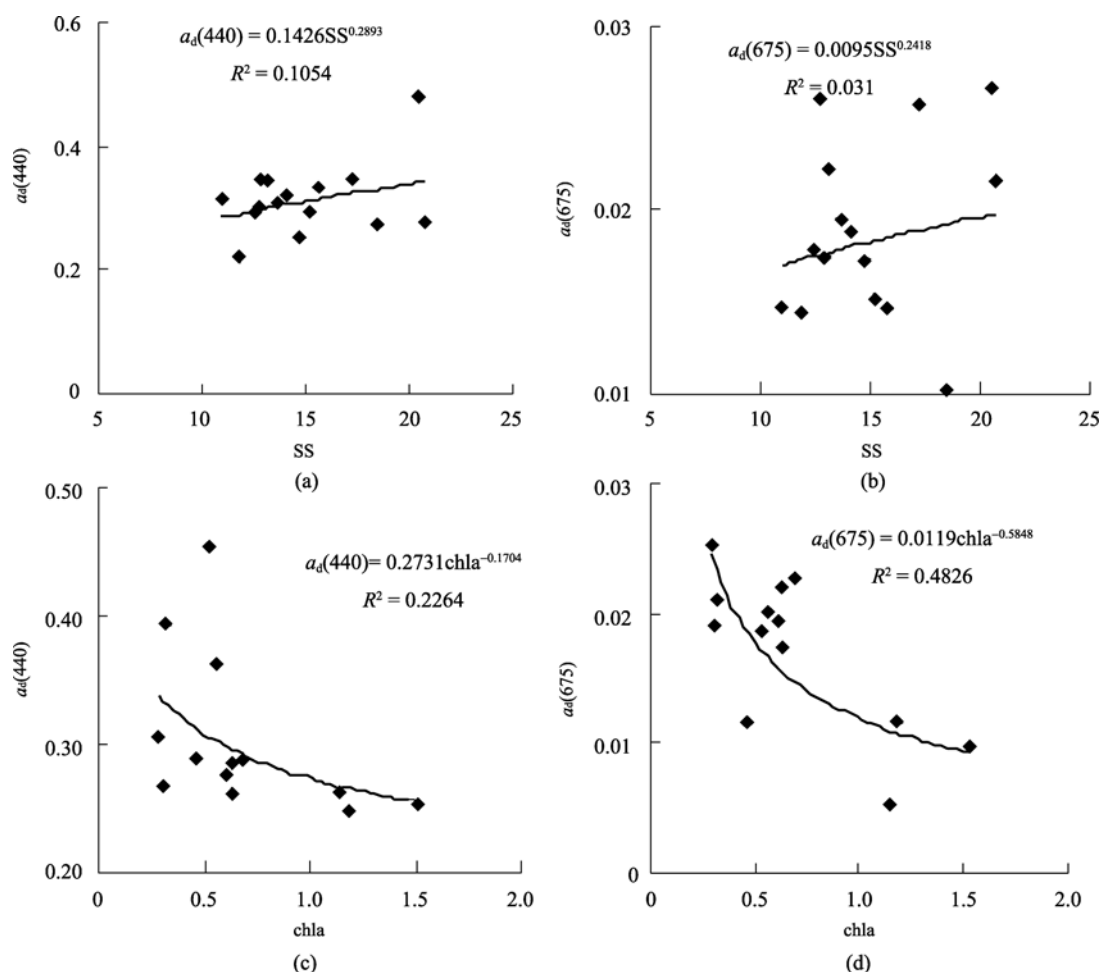


Fig. 6 Correlation between $a_d(440)$ & $a_d(675)$ and chlorophyll *a* & suspended substance concentration

different samples is similar, and the common characteristics are as followed (Fig.2): First, there are absorption peaks at band 443nm and 675nm respectively; second, the absorption coefficient between band 520—650nm does not change obviously; third, the absorption coefficient decreases with the band increasing. The phytoplankton absorption coefficients at different samples have great changes on spectrum range and value, such as $a_{ph}(443)$ ranges from 0.02 to 0.18 m^{-1} ; Corresponding, the chlorophyll a concentration ranges from 0.29 to 2.98 $\mu g/L$. The results in *si-tu* show that the environmental factors, such as ray, nutritive salts, will influence the estate of the phytoplankton, which will influence the absorption spectrum. While, the absorption spectrum difference of phytoplankton is mainly due to the pigment composition and the pack effect. The former determines the spectrum types directly and the latter influences the ray absorption efficiency of pigments (Wu, 2006). At present, most of specific absorptivity models belong to regional statistic ones, which are obtained though relationship between the specific absorptivity and chlorophyll a concentration. The researches show that the correlation between chlorophyll a concentration and the specific absorptivity of total particles and phytoplankton is better in case water; for case water, chlorophyll a concentration and the specific absorptivity of phytoplankton presents correlation (Bricaud, 1995; Cleveland, 1995). Due to the influence of the pigment composition and the pack effect, the relationship between phytoplankton absorption and chlorophyll a concentration is mainly non-linear.

Prieur and Sathyendranath (1981), Bricaud (1995), Cao (2003) described the relationship of the two variables with power function fitting:

$$a_{ph}(\lambda) = A[chla]^B$$

where, λ is band, A and B are the parameters of fitting respectively.

Cleveland (1995) illuminated that with polynomial fitting:

$$a_{ph}(\lambda) = A[chla]^2 + B[chla]$$

Sathyendranath and Platt (1988), Lutz (1996) used rectangle hyperbolic function to illuminate the relationship:

$$a_{ph}(\lambda) = \frac{A[chla]}{B + [chla]}$$

With the research on the water in the Three Gorges Dam, it is discovered that $a_{ph}(\lambda)$ -chla has obvious relationship, even in case water. The results of the relationship between chlorophyll a and phytoplankton absorption coefficient at band 443nm and 675nm are shown in Fig.7. The absorption coefficient is a variable, which has a better relationship with chlorophyll a concentration. For the water in Three Gorges Dam, the polynomial equation can description the relationship well.

$$a_{ph}(443) = -0.1123(chla)^2 + 0.2381chla - 0.0427 \quad (R^2 = 0.7232) \quad (9)$$

$$a_{ph}(675) = -0.0241(chla)^2 + 0.0441chla + 0.0026 \quad (R^2 = 0.8247) \quad (10)$$

$a_{ph}(443)$ and $a_{ph}(675)$ are the absorption coefficient of phytoplankton at band 443nm and 675nm respectively, chla is the chlorophyll a concentration. Compared to the correlation between the absorption coefficient and chla at band 443nm, the correlation at band 675 is better, due to the influence of non-algal particles. For the water in the Three Gorges Dam, the suspend substance concentration is higher than that of the chlorophyll a, while in *situ*, the method we used to measure the absorption coefficient of phytoplankton is pigment extraction, which is calculated the absorption coefficient by the difference between the fore and after of suspend substance absorption coefficient extracted (Zhao, 2006). When the algal pigment is extracted with carbinol, the pigment in non-algal particles is extracted inevitably, which conduces the increase of the algal absorption; while at band 675 nm, the absorption coefficient of non-algal particles is smaller, and the influence of that is also feeble to the phytoplankton absorption coefficient (Cao, 2003; Zhang, 2006).

At the same time, the relationship between $a_{ph}(\lambda)$ and $a_{ph}(675)$ is fitted with linearity, exponential, logarithm, power function

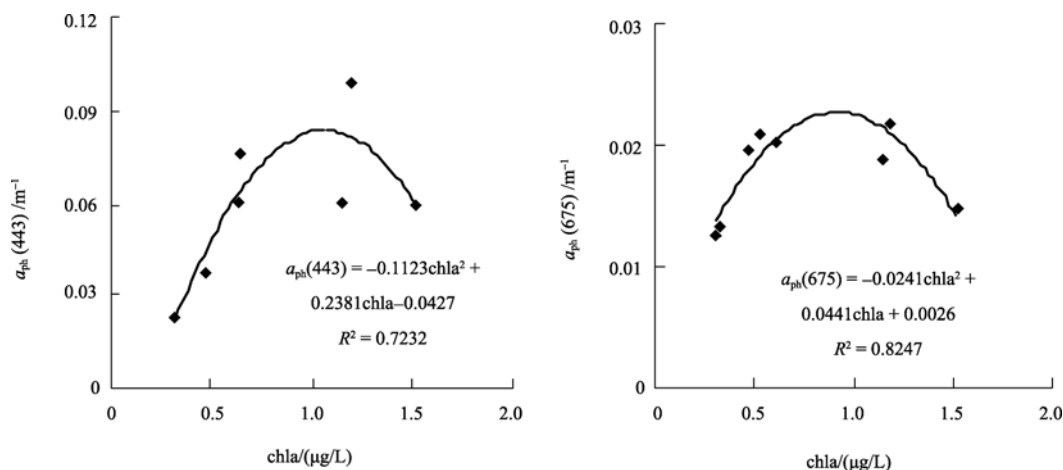


Fig. 7 Correlation between the absorption coefficient of phytoplankton and chlorophyll a

and so on. It is discovered that correlation between them is better. Taking the $a_{ph}(566)$ and $a_{ph}(675)$ for example, power function can describe the relationship well, and the correlation is up to 0.6982 (Fig.8). Based on the research we have done, the relationship between $a_{ph}(\lambda)$ and $a_{ph}(675)$ between 400—700 nm band is fitted with Eq. (11), and established the experimental model between $a_{ph}(\lambda)$ and $a_{ph}(675)$. The coherent parameters at represented band are shown in Table 1.

$$a_{ph}(\lambda) = m a_{ph}(675)^n \quad (11)$$

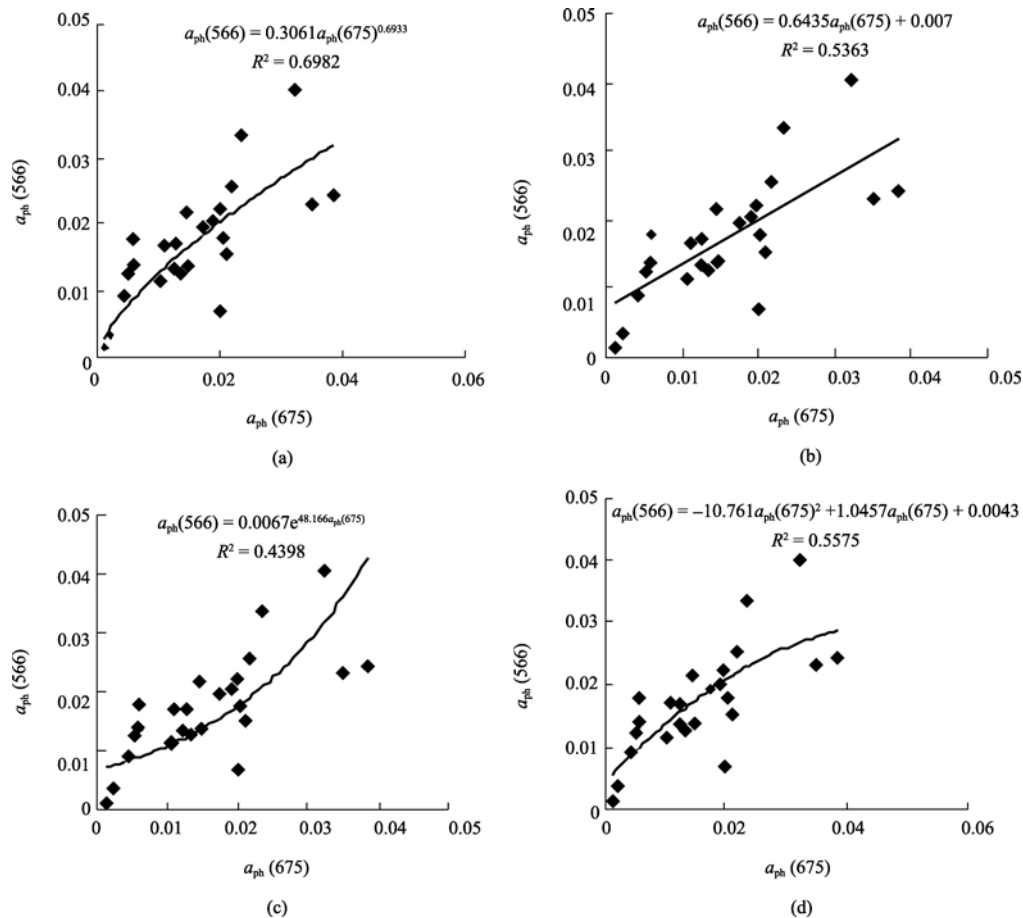


Fig. 8 Comparison with the different fitting methods between $a_{ph}(566)$ & $a_{ph}(675)$

(a) Power; (b) Linear; (c) Exponential; (d) Polynomial

Table 1 The parameter of the power relation between $a_{ph}(\lambda)$ & $a_{ph}(675)$

Band /nm	Coefficient/m	Coefficient/n	Relativity/ R^2
520	0.13	0.3753	0.4149
566	0.3061	0.6933	0.6982
617	0.1689	0.6109	0.5846
652	0.2647	0.7555	0.6655
685	2.9728	1.3252	0.929

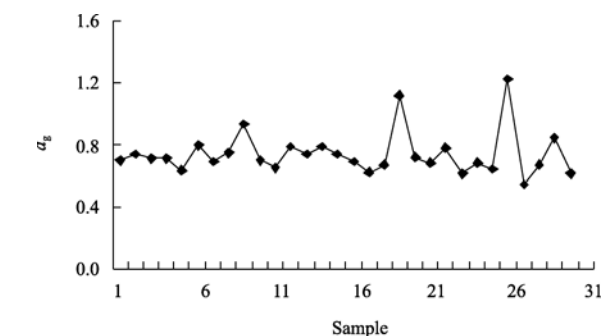


Fig. 9 The absorption coefficient of 400nm at different samples

3.4 The absorption coefficient analysis of CDOM

The spectrum characteristic of CDOM is shown in Fig.2. It is similar with that of non-algal particles, and the absorption coefficient presents as exponential degression with the band increases.

The absorption coefficient of 400nm at different samples is shown in Fig.9. The value ranges from 0.53 to 1.22 m^{-1} ; mean is 0.7378 m^{-1} . Compared to the results of the Dian-shan Lake (Song, 2007), Taihu Lake Mei Liang-wan Bay (Zhang, 2006),

such as $a_g(355)$ ranges from 6.95 to 10.28m^{-1} , and $a_g(440)$ ranges from $1.06\text{—}1.70\text{m}^{-1}$, the CDOM concentration in the Three Gorges Dam is not high. In addition, the concentration distributes homogeneously.

The researches show that the absorption coefficient of CDOM below 500nm present as exponential degression with the band increases. Bricaud (1981) advanced the followed function in 1981.

$$a_g(\lambda) = a_g(\lambda_0) \exp[S(\lambda_0 - \lambda)] \quad (12)$$

$a_g(\lambda)$ is the absorption coefficient of the CDOM, λ is the band, λ_0 is the reference band, and 440nm is often chosen, S is the slope of the exponential function curve, which is related to the constitute of CDOM. In addition, the S value changes when the band ranges change. Generally, the range of 300—500nm is chosen, while the range of 300—700nm is used sometimes. In order to obtain the credible value of S , the absorption coefficient of CDOM is fitted with least-squares procedure in the ranges 300—500 nm, 501—700 nm and 300—700nm in our research.

The results show that the precision in band range 300—500 nm and 300—700 nm is higher (Fig.10), while in band range 501—700nm, it is barely fitted with the Eq. (12). However, the data is fitted with Eq. (13) well, and the precision is shown in Fig.11.

$$a_g(\lambda) = a\lambda^2 + b\lambda + c \quad (13)$$

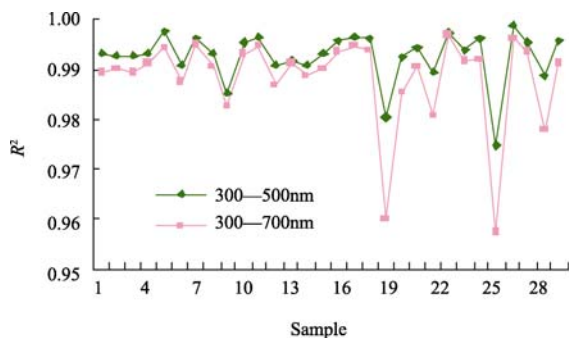


Fig.10 R^2 from exponential fitting in bands 300—500, 300—700nm

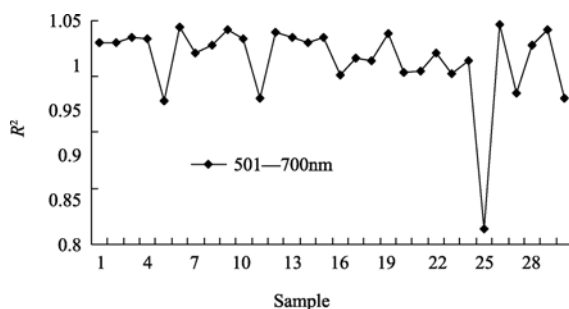


Fig. 11 R^2 from polynomial fitting in band 501—700nm

With the analysis of the results, it is discovered that:

(1) S for the different band range 300—500nm, 300—700nm do not change obviously. The value of that changes between $0.0108\text{—}0.01883\text{ }\mu\text{m}^{-1}$ and $0.01066\text{—}0.01882\text{ }\mu\text{m}^{-1}$ respectively; the mean is $0.015956\text{ }\mu\text{m}^{-1}$ and $0.015933\text{ }\mu\text{m}^{-1}$. However, S of the former range is higher than that of the latter, in other words, the band range can influence the value of S .

(2) R^2 for different samples in band range 300—500nm changes feebly, and approaches to 1. Specifically, the minimum is 0.9749, and the maximum is 0.9988. It is proved that S of this range is reliable and the Eq. (12) can be used to describe the spectrum characteristic of CDOM.

(3) The value of R^2 at different samples in band range 300—700nm changes feebly; the minimum is 0.9749, and the maximum is 0.9988. It is proved that S of this range is also reliable and the Eq. (12) can be used to describe the spectrum characteristic of CDOM in band range 300—700nm.

(4) The spectrum characteristic of CDOM in band range 501—700nm can be fitted with polynomial function well and R^2 is also higher. The minimum is 0.8139, and the maximum is 0.9963. In other words, for the band range 501—700 nm, the Eq. (12) can not applied to describe the relationship between $a_g(\lambda)$ and λ , while polynomial function should be used.

(5) The difference of RMSE(residual mean standard error) is shown in Fig.12. It does not change obviously between the two band range 300—500nm and 300—700nm. For the mean value, the former is 0.08831, the latter is 0.08958. While, the RMSE of band range 501—700nm is smaller, the mean value is only 0.006. So, with piecewise function can express the absorption coefficient characteristics of CDOM and increase the precision of S .

In addition, the relationship between DOC concentration and the absorption coefficient of CDOM is fitted with linearity, exponential, logarithm, power function and so on. It is discovered that relativity between them is feeble. Considering the absorption ability of the ray, DOC is divided to colored and

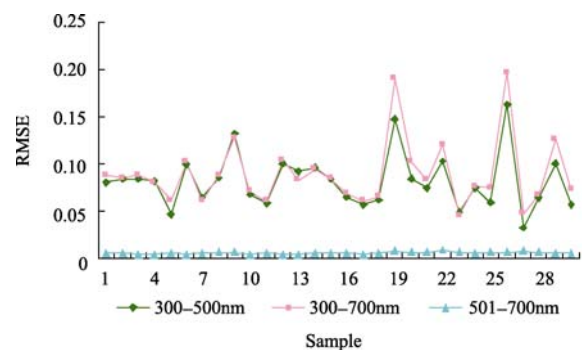


Fig. 12 RMSE of the fitting between different bands

colorless ones, and the proportion of them is different in different regions. Analyzing the reasons, it is considering that the DOC carried by river flow has more color DOC, while the DOC that the phytoplankton degrades products more colorless ones (Kirk, 1994). CDOM is the color ones in dissolvability substances. In our research, the experiment was done when the phytoplankton began to decay and degrade. It is induced that the correlation between DOC concentration and absorption coefficient of CDOM is feeble.

4 CONCLUSION

For water color remote sensing, total particles, non-algal particles, phytoplankton, CDOM, are the main water constitutes. The measurement and analysis of them are the groundwork to the water color remote sensing. This paper analyses the absorption coefficient characteristics for particle matter, phytoplankton and CDOM, using absorption coefficient of water color constituents we measured at the Three Gorges Dam *in situ* on April, 2007. The results show that, for the Three Gorges Dam water:

(1) The absorption spectrum of non-algal is similar with that of total particle matter;

(2) The absorption coefficient of non-algal decreases power exponentially from short to long wavelength, and the absorption coefficients in different bands have a definite relationship;

(3) The absorption coefficient of phytoplankton has a better polynomial relationship with chlorophyll a concentration in the Three Gorges Dam water;

(4) Piecewise function can express the absorption coefficient characteristics of CDOM. The absorption spectrum below 500nm decreases power exponentially from short to long wavelength, and the precision of the fitting R^2 approaches to 1; the absorption spectrum between 501 and 700nm fits well using polynomial relationship, and the precision R^2 is above 95%.

In addition, for the water of the Three Gorges Dam, it is different from ocean, lake and river. With the researches we have done, it is discovered that after the reservoir storage, the absorption characteristics of non-algal particles in the Three Gorges Dam water are influenced weakly by terrigenous deposits, and the degradation products of phytoplankton are the main resource of non-algal particles.

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REFERENCES

Bricaud A, Babin M, Morel A and Prieur L. 1995. Variability in the chlorophyll-specific absorption coefficients of natural phyto-

plankton: analysis and parameterization. *Journal of Geophysical Research*, **100**: 13321—13332

Bricaud A, Morel A, Babin M and Prieur L. 1998. Variations of light absorption by suspended particles with chlorophyll a concentration in oceanic (case I) waters: analysis and implication for bio-optical models. *Journal of Geophysical Research*, **103**: 31033—31044

Bricaud A, Morel A and 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

Bricaud A and Stramski D. 1990. Spectral absorption coefficients of living phytoplankton and nonalgal biogenous matter: a comparison between the Peru upwelling area and the Sargasso Sea. *Limnology and Oceanography*, **35**(3): 562—582

Cao W X, Yang Y Z, Xu X Q, Huang L M and Zhang J L. 2003. Regional patterns of phytoplankton spectral absorption in the Pearl River Estuary. *Chinese Science Bulletin*, **48**(17): 1876—1882

Chen C Q, Shi P, Yin H D and Pan Z L. 2002. Absorption coefficient of yellow substance in the Pearl River estuary. *SPIE* **4892**: 215—221

Cleveland J S. 1995. Regional models for phytoplankton absorption as a function of chlorophyll a concentration. *Journal of Geophysical Research*, **100**(C7): 13333—13344

Dong G X. 2006. Hyperspectral Remote sensing Inversion of the Inland Water Quality Components In Three Gorges Reservoir Chinese Academy of Surveying and Mapping

Kirk J T O. 1994. Light and Photosynthesis in Aquatic Ecosystem. Cambridge, Britain: Cambridge University Press

Konovalov B V and Bekasova O D. 1959. Method for determining the pigment content of marine phytoplankton without extraction. *Limnology and Oceanography*, **9**: 883—892

Li T J, Zhu J H and Cheng Q L. 2006. semi-empirical analysis bio-algorithm research of Yellow-East Sea in Spring. *Ocean Technology*, **25**(1): 82—88

Lutz V A, Sathyendranath S and Head E J H. 1996. Absorption coefficient of phytoplankton: regional variations in the North Atlantic. *Mar Ecol Prog Ser*, **135**: 197—213

Prieur L and Sathyendranath S. 1981. An optical classification of coastal and oceanic waters based on the specific spectral absorption curves of phytoplankton pigments, dissolved organic matter, and other particulate materials. *Limnology and Oceanography*, **26**: 671—689

Sathyendranath S and Platt T. 1988. The spectral irradiance field at the surface and in the interior of the ocean model for application in oceanography and remote sensing. *Journal of Geophysical Research*, **93**: 9270—9280

- Song L L, Qiu Y L, Zhang H E, Liu D G, Han Z H and Zhao J F . 2007. On the light absorption characteristics of colored dissolved organic matter in Lake Dianshan. *Journal of Lake Sciences*, **19**(3): 250—254
- Wang X M, Tang J W, Song Q J, Ding J and Ma C F. 2006. The statistic inversion algorithms and spectral relations of total absorption coefficients for the Huanghai Sea and The East China Sea. *Oceanologia et Limnologia Sinica*, **37**(2): 256—262
- Wu J Y, Shang S L, Hong H S and Li Y. 2006. Advances in the studies on light absorption properties of phytoplankton. *Marine Science*, **30**(6): 77—81
- Xu X Q, Cao W X and Yang Y Z. 2004. Relationships between spectral absorption coefficient of particulates and salinity and chlorophyll a concentration in Zhujiang River Mouth. *Journal of Tropical Oceanography*, **23**(5): 63—71
- Yang J K and Chen C Q. 2007. An optical algorithm for retrieval of chlorophyll, suspended sediments and gelbstoff of case II waters in Zhujiang River Estuary. *Journal of Tropical Oceanography*, **26**(5): 15—20
- Yu H and Cai Q M. 1998. Optical properties of waters in Taihu and parameterizing schemes in ecological and environmental studies of Taihu Lake . Beijing: Metrology Press
- Zeng Y D, Shang S L, Wu J Y , Hu C M and Li Y. 2006. A comparison of different fitting methods for non-pigment absorption spectra. *Journal of Xia'men University(Natural Science)*, **45**(3): 388—392
- Zhang Y L, Qin B Q and Yang L Y. 2006. Spectral absorption coefficient of particulate matter and Chromophoric dissolved organic matter in Meiliang Bay of Lake Taihu. *Acta Ecologica Sinica*, **26**(12): 3969—3979
- Zhao Q H, Zhang Y L and Qin B Q. 2006. Spatial variations of spectral absorption of medium in the Meiliang Bay of Lake Taihu. *Journal of Lake Sciences*, **18**(40): 627—634
- Zhou H L, Han B, Li T J and Zhu J H. 2007. Variations in the light absorption coefficient of de-pigment in South Yellow Sea and Zhujiang Kou of china. *Ocean Technology*, **26**(3): 114—117

三峡坝区水体吸收系数的特征研究

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摘要: 利用 2007 年 11 月在三峡坝区现场实测的水色要素吸收系数数据, 对总颗粒物、浮游植物、CDOM 的吸收系数特征进行了分析和研究。结果表明, 对于三峡坝区区域的水体: (1) 总颗粒物吸收光谱分布与非藻类的吸收光谱相似; (2) 非藻类颗粒物的吸收系数随波长的变化分布接近指数衰减规律, 且不同波段的吸收系数之间存在一定的关系; (3) 多项式关系能较好的表达浮游植物吸收系数与叶绿素 a 浓度之间的关系; (4) 分段函数能很好的表达 CDOM 的吸收系数特性, 对 500 nm 以下光谱的吸收呈现负指数衰减的规律, 不同采样点拟合精度 R^2 接近 1; 501—700nm 波段范围的光谱曲线采用多项式能进行很好的拟和, 且拟合精度 R^2 达到 95% 以上。

关键词: 三峡坝区, 吸收系数, 颗粒物, 浮游植物, CDOM

中图分类号: TP79

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1 引言

水体的光学特性与它的成分有关, 如果不考虑水体本身的气泡、湍流效应等因素, 叶绿素、悬浮物和有色可溶性有机物(color dissolved organic matter: CDOM)通常所称的“水色三要素”, 是影响二类水体光学性质的 4 类物质中的 3 种, 另外一种纯水分子(杨锦坤 & 陈楚群, 2007)。水体的固有光学特性(吸收系数、散射系数、衰减系数等)可以看成是这些成分特性的迭加(李铜基等, 2006)。其中纯水对光的衰减是所有水体共有的, 因而不同类型、不同区域水体的光学特性主要取决于非藻类颗粒物、浮游藻类和 CDOM 的浓度及组成。非藻类颗粒物、浮游藻类和 CDOM 的固有光学特性, 是水色遥感的生物-光学模式、光辐射传输、初级生产力估算和生态过程模拟的基本参数(Kirk, 1994)。近年来, 利用遥感资料监测水色, 对水体光学特性作量化研究已受到关注。海洋里以及国外内陆水体关于这 3 类物质的吸收光谱研究较多, 但国内对内陆水体的研究还相对较少。曹文熙等(2003)对珠江口悬浮颗粒的吸

收光谱进行了一些探讨, 但未涉及 CDOM 的吸收光谱; 俞宏、蔡启铭等(1998)在 20 世纪 90 年代中期测定了梅梁湾冬、夏季水体吸收和散射系数, 但未能很好的区分浮游藻类和非藻类颗粒物。对于三峡库区, 目前的研究则更少。董广香(2006)曾就光谱特征方面对三峡库区的水质进行分析, 并建立经验模型反演水色要素, 但未涉及水体的固有光学特性。要想建立三峡库区生物-光学模式的水质遥感监测模型, 目前已有的数据还远远不够, 在现有工作和条件的基础上, 我们对三峡坝区水体的总颗粒物、非藻类颗粒物、浮游植物、CDOM 的吸收系数进行了测量, 并对其结果进行了分析。

2 采样与测量方法

2007-11-07 在三峡坝区距离大坝 3 km 的坝前库区水体共布设 30 个采样点, 考虑到库区中心与库区边缘的水质存在一定的差异, 采样点采取横剖面均匀布点的原则, 水样采集与水体光谱反射率测量同步(图 1)。其中, “+”表示采样点。

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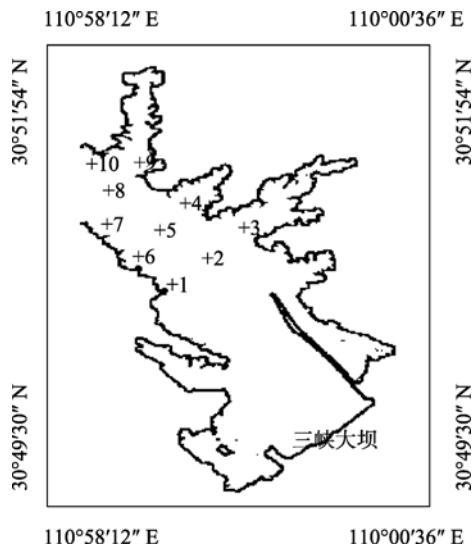


图1 采样点位置示意图

用 Niskin 采样器采集表层水样, 准备两份平行样, 一份用于测定颗粒物的吸收系数, 另外一份用于测量 CDOM 的吸收系数。样品采集后放至荫凉处, 避免日光直射, 采回后 0—4℃ 保存, 采集的水样数据委托中国科学院南京地理与湖泊研究所有关专家检测, 各检测指标分别采用以下方法进行, 2—3d 内测定完毕。

固有光学特性(IOPs)的测量比较困难, 其测量方法主要为光谱仪水下野外测量和对采集水样的实验室内光谱分析。然而, 中国现场测量吸收系数的仪器较少, 尽管可利用实验室分光光度计结合过滤系统进行测量, 但开展这方面工作的实验室很少, 且在水样保存过程中会产生较大的变化, 使得数据应用性较差。测量 IOPs 的野外光谱仪主要有 AC-S、HS-6、AC-9、BB9 等, 用于实验室水质分析测量 IOPs 的仪器主要为各类分光光度计, 它们对定标有严格的要求。本次实验采用岛津 UV-2401PC 分光光度计获取水体组分的吸收系数, 并对获得的数据进行后处理和分析。

2.1 颗粒物、非藻类颗粒物及浮游植物吸收系数的测定

由于三峡坝区附近水体中颗粒物浓度较低, 各种物质的光谱特征相互叠加, 直接、定量测定各种物质的吸收有相当的难度。Konovalov 和 Bekasova 等(1959)首次提出用甲醇萃取滤膜将颗粒物吸收分成浮游植物和碎屑吸收; 后来 Mitchell 把这种方法称为定量滤膜(quantitative filter techniques, QFT)技术, 该方法经过多人的改进, 并被 SeaWiFS 光学观测规范推荐使用。步骤如下:

(1) 用直径 47mm 的 GF/F 滤膜过滤 50—200ml 水样, 用同样湿润程度的空白滤膜做残臂, 用 UV-2401PC 型分光光度计在 350—700nm 间隔 1nm 测定一个吸光度, 用各波段的吸光度减去 750nm 波长处的吸光度, 采用式(1)进行放大因子校正

$$OD_s = 0.378OD_f + 0.523 OD_f^2 \quad OD_f \leq 0.4 \quad (1)$$

式中, OD_s 为校正后滤膜上颗粒物吸光度; OD_f 为直接在仪器上测定的滤膜上颗粒物吸光度。

滤膜上悬浮颗粒物的光谱吸收系数按照式(2)进行计算得到:

$$a_p(\lambda) = 2.303 \times \frac{S}{V} OD_s(\lambda) \quad (2)$$

式中, V 为被过滤水样的体积, 单位为 L, S 为沉积在滤膜上的颗粒物的有效面积, 单位为 cm^2 。

(2) 用 90% 的甲醇溶液浸泡滤膜及上面的总颗粒物 30—180 min, 把可用甲醇萃取的色素从滤纸上的非藻类颗粒物分离出来, 使滤纸上只留下不能用甲醇萃取的碎屑颗粒, 用分光光度计直接测量沉积在滤膜上的非藻类颗粒物光学密度 $OD_p(\lambda)$, 经过类似第(1)步的处理后计算得到非藻类颗粒物光谱吸收系数 $a_d(\lambda)$ 。

(3) 由总颗粒物的光谱吸收系数 $a_p(\lambda)$ 和非藻类颗粒物光谱吸收系数 $a_d(\lambda)$ 计算叶绿素 a 的吸收系数:

$$a_{ph}(\lambda) = a_p(\lambda) - a_d(\lambda) \quad (3)$$

2.2 CDOM 吸收系数的测定

有色可溶性有机物(colored dissolved organic matter, CDOM), 又称黄色物质, 由腐殖酸、芳烃聚合物等一系列物质组成, 主要是土壤和水生植物降解的产物, 存在于所有水体中, 它是溶解性有机物质的重要组成部分(Kirk, 1994)。光学特性较为单一, 主要表现为吸收, 且在紫外和蓝光波段随着波长的增加呈指数下降, 由于其在蓝光波段的吸收与叶绿素 a 吸收重叠(Bricaud 等, 1981), 会干扰水色遥感, 导致水色遥感中叶绿素 a 浓度被高估, 影响水体的遥感反射比。

CDOM 的光谱吸收系数测定采用通过 GF/F 滤膜过滤的水样在 UV2401 分光光度计下测定其吸光度, 然后根据式(4)进行计算得到各波长的吸收系数。

$$a'_g(\lambda) = 2.303 \frac{OD_g(\lambda)}{r} \quad (4)$$

由于过滤清液可能残留细小颗粒会引起 散射, 为此需要作散射效应订正(Bricaud 等, 1981):

$$a_g(\lambda) = a'_g(\lambda) - a'_g(700) \times \frac{\lambda}{700} \quad (5)$$

式中, $a'_g(\lambda)$ 为波长 λ 未校正的吸收系数, r 为光程路

径(m), $a_g(\lambda)$ 为波长 λ 的吸收系数。

3 数据结果及分析

3.1 总颗粒物吸收系数结果分析

图 2 为三峡坝区附近水体 30 个采样点总颗粒物、非藻类颗粒物、浮游植物的光谱吸收系数曲线。除在个别采样点由于人文因素(渔业养殖、船只停泊等)影响外,不同采样点的总颗粒物、CDOM 吸收系数变化不大,如 $a_p(440)$ 的变化范围为 $0.22 \sim 0.43 \text{ m}^{-1}$ 。

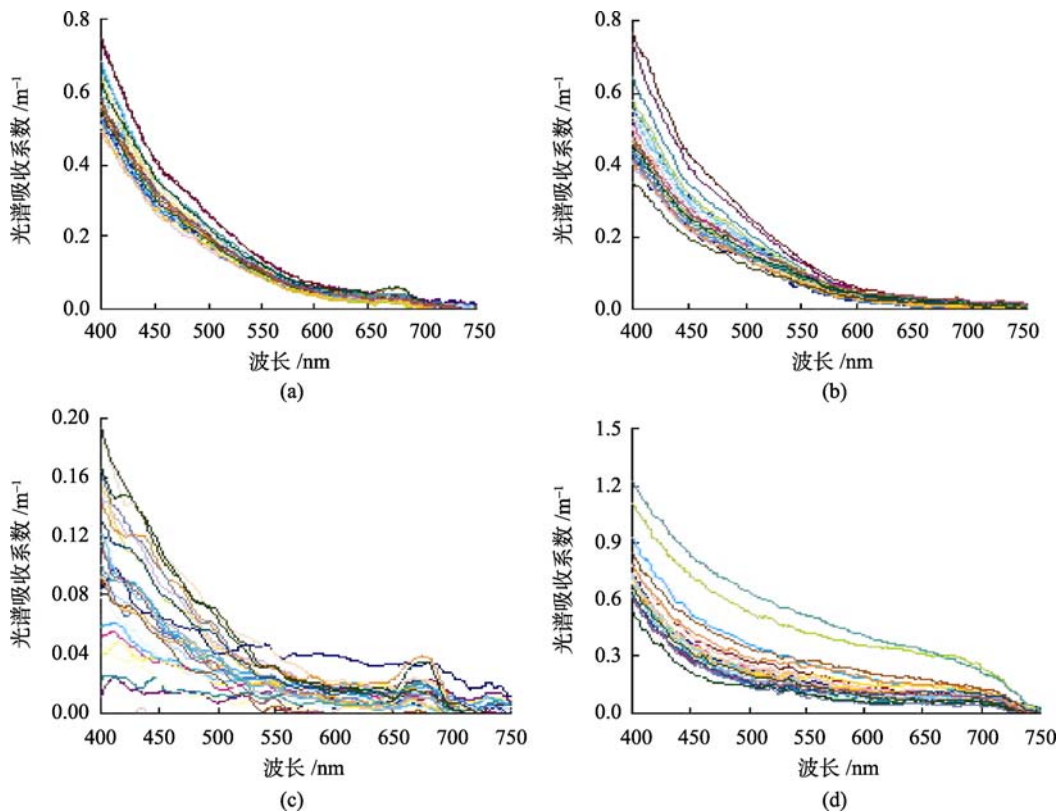


图 2 总颗粒物(a)、非藻类颗粒物(b)、浮游植物(c)、CDOM(d)的吸收系数

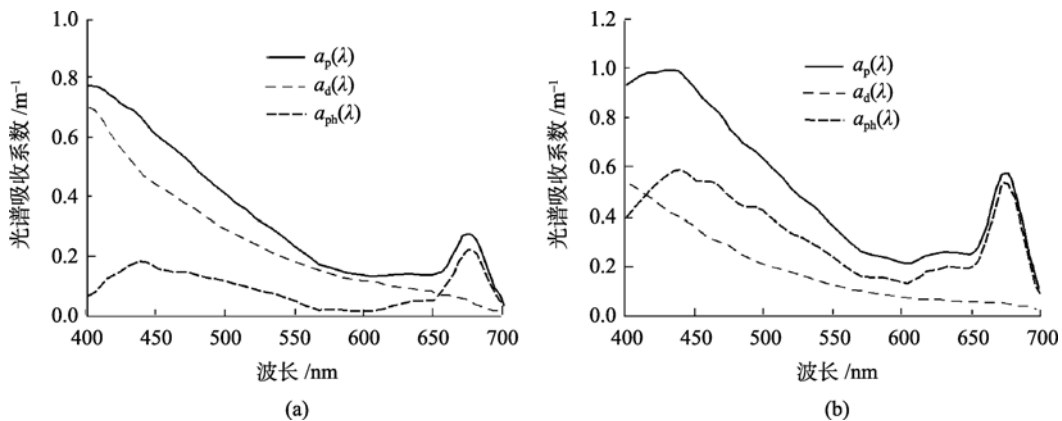


图 3 两种典型的总颗粒物吸收光谱(引自曹文熙(2003))

(a)第 1 种类型; (b)第 2 种类型

总颗粒物的吸收系数的光谱分布主要有 2 种类型,图 3 代表性的给出了这 2 种类型的总颗粒物吸收光谱与浮游植物及非藻类颗粒物吸收光谱的比较。对于第 1 种类型,除 670nm 附近具有叶绿素吸收峰的红光波段外,非藻类的吸收系数大于浮游植物色素吸收系数。总颗粒物吸收光谱分布与非藻类的吸收光谱相似(图 3(a)),吸收系数随波长增大而减小,浮游植物的吸收光谱淹没在非藻类的吸收光谱中,相反地,对于第 2 种类型,在大部分波段,浮游植物色素的吸收系数大于非藻类的吸收系数,总颗粒物的吸收光谱与藻类的吸收光谱形状相似(图 3(b))。初步分析表明,第 1 种光谱类型的站点主要

分布在盐度介于 15—27 之间, 咸淡水强烈混合的内河口。光谱类型沿河口逐渐过渡, 到近海逐步变为第 2 种类型(曹文熙等, 2003)。

分析三峡大坝附近水体的总颗粒物吸收系数, 基本符合第 1 种类型的吸收光谱曲线特征, 即总颗粒物吸收光谱分布与非藻类的吸收光谱相似。一方面, 水体不同采样点总颗粒物吸收系数随波长的增大而减小, 且按幂指数规律衰减, 这与许晓强、曹文熙等(2004)在珠江试验得出的结论相同; 另一方面, 水体总颗粒物吸收系数曲线在三峡坝区附近水体呈现图 3(a)中的吸收光谱型, 这与采样点周围的水环境是分不开的。三峡水库建成后, 由于水流的情况和过去长江的水流情况发生了很大的变化, 原来是一条急流, 现在变成了一个水库, 河流上游带来的大量陆源性颗粒物使得非藻类颗粒物吸收非常强烈, 而非悬浮颗粒的吸收是河口内总颗粒物吸收系数的主导因素(许晓强等, 2004), 其控制着总颗粒物吸收系数的大小和变化。另外, 670nm 波段是浮游植物的吸收峰, 其主导了该波长总吸收系数的变化, 图 2 中描述的所有采样点的总颗粒物的吸收系数中, 大部分采样点吸收系数基本为随波长增加呈负指数形式衰减, 只有 #22、#27 两个采样点在 675nm 波段表现出较弱的吸收峰; 结合实地试验的记录, #22、#27 两个采样点处分别位于支流的交汇处和养殖区, 受外界环境影响较大, 因此我们可以肯定的说, 在三峡坝区附近水域中, 总颗粒物的光谱吸收表现为非藻类颗粒物的吸收特点, 与海洋中悬浮颗粒物的吸收特性(Bricaud & Stramski, 1990)有着较明显的不同。

为了进一步分析三峡坝区非藻类颗粒物、浮游植物对水体总颗粒物吸收系数的贡献程度, 我们做了更深一步的分析。取不同采样点的总颗粒物吸收系数、非藻类颗粒物吸收系数、浮游植物吸收系数进行统计分析(图 4)。统计结果再一次证明了在三峡坝区附近水域, 非藻类颗粒物基本上是总颗粒物吸收特性的主要决定者, 这也从侧面印证了上面分析的正确性。

另外, 通过分析发现, 在不同波段浮游植物和非藻类颗粒物对总颗粒物吸收系数的贡献不仅是不同的, 且所占比例均不是一个常数, 而是与波长有关的变量。具体来讲, 非藻类颗粒物在短波端的贡献要大于在长波端的贡献, 且随波长的增加贡献率而降低; 浮游植物在长波端的贡献要大于短波端的贡献且随波长的增加贡献率增大, 因此即使在叶绿素浓度不高的三峡坝区水体中, 也能在水体总颗粒

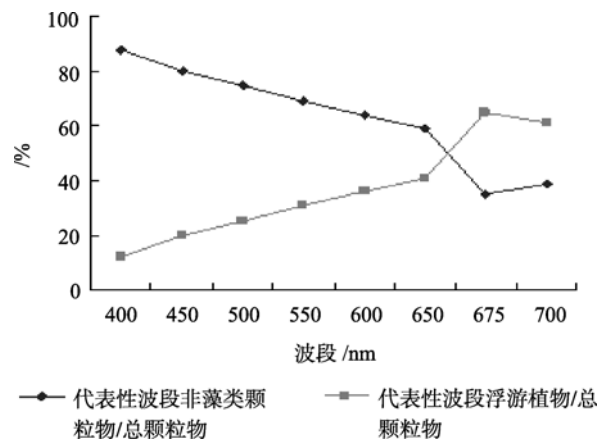


图 4 非藻类颗粒物、浮游植物吸收系数在总颗粒物吸收系数中的百分比

物吸收系数曲线中见到浮游植物在 675nm 波长处的吸收峰。

3.2 非藻类颗粒物的吸收系数结果分析

非藻类颗粒物包括浮游植物的分解残体、底泥和土壤中输送腐殖质、无机颗粒物, 所有样品的非藻类颗粒物吸收光谱分布是十分相似的, 即吸收系数随波长的增大而减小(图 2)。对实测数据曲线的模拟结果表明, 非藻类颗粒物的吸收系数随波长的变化分布十分接近指数衰减规律, 且不同波段的吸收系数之间存在一定的关系(图 5)。建立三峡坝区附近水域中非藻类颗粒物的吸收系数关系模型, 可以从一个已知波段的吸收系数反演出任何另外一个波段的吸收系数, 这在水色反演中大大减少了未知因子的个数。这里我们在建立模型过程中选择波段 440nm 作为基础来建立模型。波段 440nm 的吸收系数是水色研究的重要参数之一, 许多学者已经建立了基于 440nm 波段的非藻类颗粒物吸收系数模型(王晓梅等, 2006; 曾银东等, 2006; 张运林等, 2006; 周虹丽等, 2007)。波长 λ 处的吸收系数可以用下式表示:

$$a_d(\lambda) = a_d(\lambda_0) \exp(-S(\lambda - \lambda_0)) \quad (6)$$

式中, λ_0 为 440nm 波段, S 为斜率, 不同样品的 S 值有一定差别, 变化范围为 0.01014—0.0128, 平均值为 0.0115, 标准偏差为 0.00155。以 #2、#19 采样点为例, 其非藻类颗粒物吸收系数模型分别为:

$$a_d(\lambda) = a_d(440) \exp(-0.0122(\lambda - 440)) \quad (7)$$

$$a_d(\lambda) = a_d(440) \exp(-0.0114(\lambda - 440)) \quad (8)$$

与现有的报道相比可知, 三峡坝区水域的 S 值与曹文熙等(2003)报道的珠江口海域的 S 值、Bricaud 等(1998)报道的赤道太平洋及东地中海的 S

值都很接近;与陈楚群等(2002)报道的珠江口海区的溶解有机物(CDOM)的 S 值也很接近。这一结果说明,三峡坝区水域的非藻类颗粒吸收物质,不仅有与其他海区非藻类颗粒吸收物质相似的光学性质,而且有与溶解性有机物(CDOM)相似的光学性质。

对于一类水体,已有较多的研究表明,非藻类颗粒物的吸收系数与叶绿素 a 浓度逐渐存在较好的相关关系,并认为一类水体的非藻类颗粒物主要来

源于浮游植物的降解(曹文熙等, 2003)。对于三峡坝区附近的水体,我们也对非藻类颗粒物的吸收系数与叶绿素 a 浓度、悬浮物浓度的相关性进行了分析。以特征波段 440nm、675nm 波段为例,在 440nm 波段, $a_d(440)$ 与叶绿素 a 浓度、悬浮物浓度均存在弱非线性关系;而在 675nm 波段, $a_d(675)$ 与悬浮物浓度几乎不相关,呈现离散性,而与叶绿素 a 浓度的相关性则明显提高(图 6),说明在三峡库区蓄水后,陆

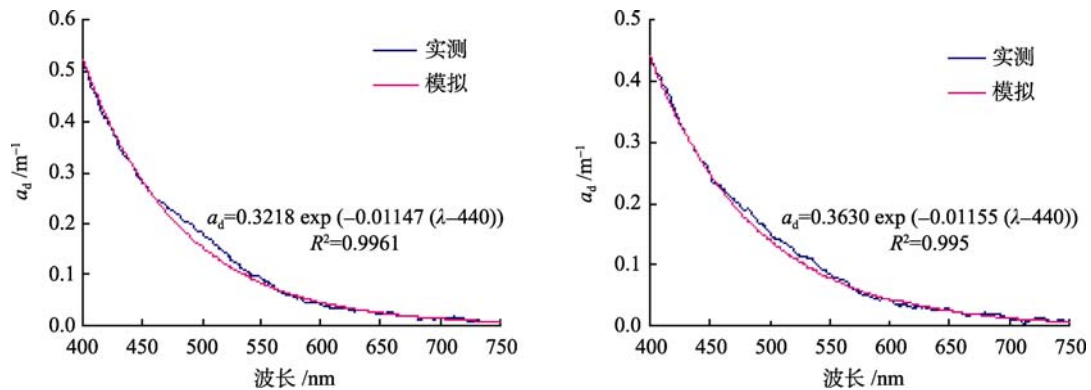


图 5 非藻类颗粒物吸收光谱实测结果与模拟结果的比较(以#2、#19 为例)

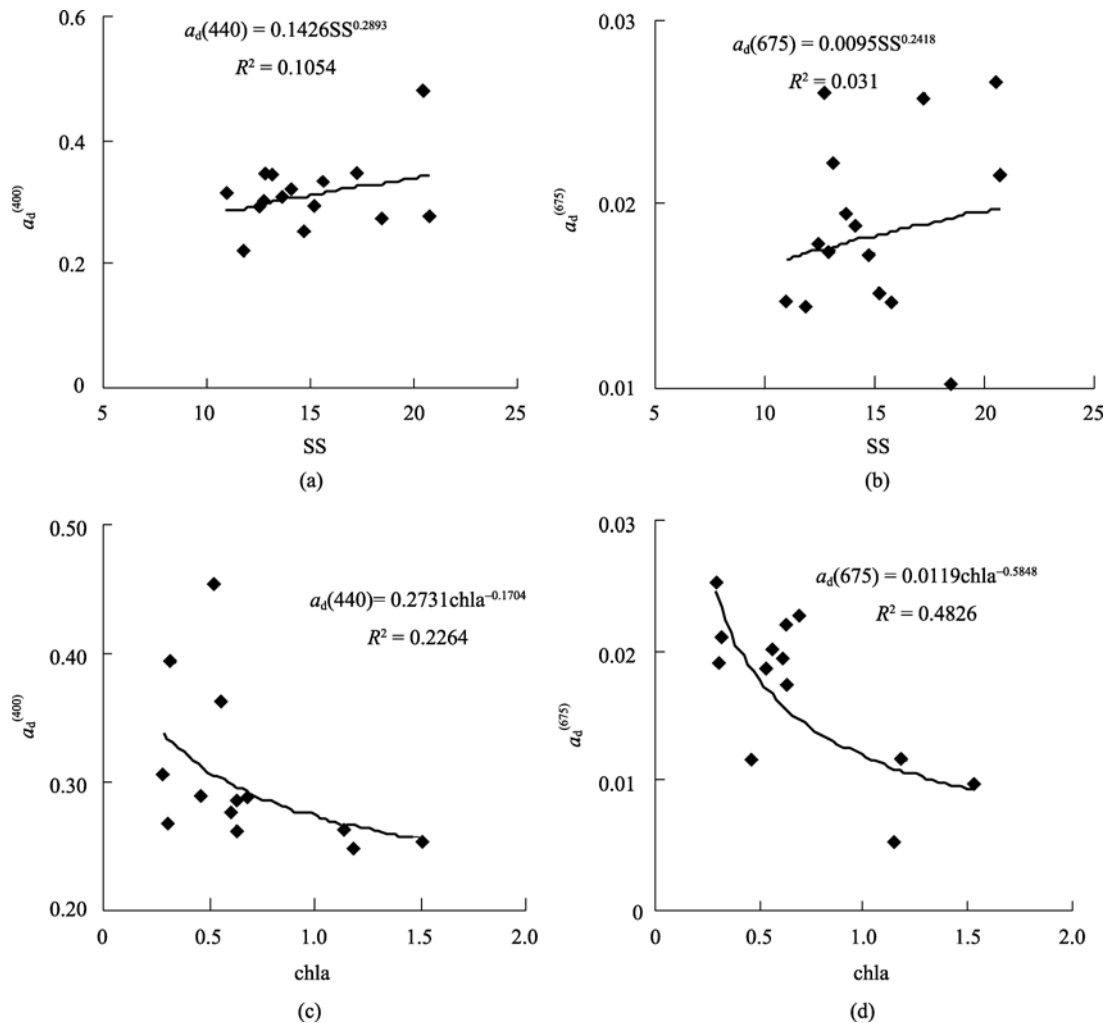


图 6 三峡坝区水体 $a_d(440)$ 、 $a_d(675)$ 与叶绿素 a 浓度、悬浮物浓度的相关性

源性的输入对三峡坝区水体中非藻类颗粒物的吸收影响不大, 而浮游植物的降解才是水中非藻类颗粒物的主要来源。

3.3 浮游植物的吸收系数结果分析

不同采样点的浮游植物色素的吸收光谱分布比较相似, 均表现出以下共同的特点(图 2): 其一, 有两个明显的吸收峰, 分别位于 443nm 和 675nm 附近; 其二, 在 520—650nm 之间, 其间的吸收系数变化不大; 其三, 随波长的进一步增大, 其吸收系数却基本上在持续减小。不同采样点浮游植物吸收在光谱和大小上均存在很大的变动, 如 $a_{ph}(443)$ 的变化范围为 0.02—0.18 m^{-1} , 相应的叶绿素 a 浓度变化范围为 0.29—2.98 $\mu g/L$ 。大量的观测结果表明, 环境因素如光线、营养盐等会影响藻类细胞的状态而最终影响吸收光谱, 不同的藻类则明显存异。但浮游植物的吸收光谱最终可归因于色素组成及打包效应的差异: 色素组成直接决定光谱谱型, 打包效应影响色素对光的吸收效率(吴璟瑜等, 2006)。目前建立的浮游植物的比吸收系数光谱模型大多属于区域性的统计模型, 且大多通过分析浮游植物的比吸收系数和叶绿素 a 浓度的关系得到。许多研究结果(Bricaud 等, 1995; Cleveland, 1995)表明, 对于一类水体, 总颗粒物、浮游植物的比吸收系数与叶绿素 a 浓度有较好的相关性; 对于二类水体, 只有浮游植物比吸收系数与叶绿素 a 浓度之间存在相关性。受色素组成和打包效应的影响, 浮游植物吸收与叶绿素 a 浓度的关系多数为非线性的。

Prieur 和 Sathyendranath(1981)、Bricaud 等(1995)、曹文熙等(2003)用幂函数拟和二者的关系:

$$a_{ph}(\lambda) = A[chla]^B$$

式中, λ 表示波长, A 、 B 为两个拟和参数。Cleveland

等(1995)采用多项式拟合:

$$a_{ph}(\lambda) = A[chla]^2 + B[chla]$$

Sathyendranath 和 Platt(1988)、Lutz 等(1996)采用直角双曲线函数:

$$a_{ph}(\lambda) = \frac{A[chla]}{B + [chla]}$$

本文对于三峡坝区附近水体的研究表明, 即使在三峡坝区这样复杂的二类水体, $a_{ph}(\lambda)$ -chla 也存在明显的关系。图 7 给出了 443nm 和 675nm 波长浮游植物吸收系数随水体叶绿素 a 浓度变化的统计分析结果。从中可以看出, 浮游植物吸收系数不是一个常数, 而是与叶绿素 a 浓度之间存在较好的非线性关系的生物学变量。就三峡坝区附近水体, 多项式关系能较好的描述两者之间的关系。其统计关系为:

$$a_{ph}(443) = -0.1123(chla)^2 + 0.2381chla - 0.0427 \quad (9)$$

$$(R^2 = 0.7232)$$

$$a_{ph}(675) = -0.0241(chla)^2 + 0.0441chla + 0.0026 \quad (10)$$

$$(R^2 = 0.8247)$$

式中, $a_{ph}(443)$ 和 $a_{ph}(675)$ 分别为 443nm 和 675nm 波长浮游植物吸收系数, chla 为叶绿素 a 浓度。相比而言, 675nm 处的相关性要好于 443nm, 主要是由于 443nm 浮游藻类吸收系数会受非藻类颗粒物的影响, 因为在三峡坝区, 悬浮物浓度远远高于叶绿素浓度, 而在测量浮游藻类吸收系数时, 我们选用的是色素提取法, 该方法通过颗粒物吸收系数在提取色素前后的不同来确定藻类吸收系数(赵巧华等, 2006), 在用甲醇提取活体藻类色素的同时, 不可避免的提取了非藻类颗粒物中的色素, 从而导致在 500nm 以下波段浮游藻类吸收人为增加, 降低了吸收系数与叶绿素 a 浓度的相关性; 而在 675nm 非藻类颗粒物的吸收系数很小, 其对浮游藻类吸收系数的干扰要小

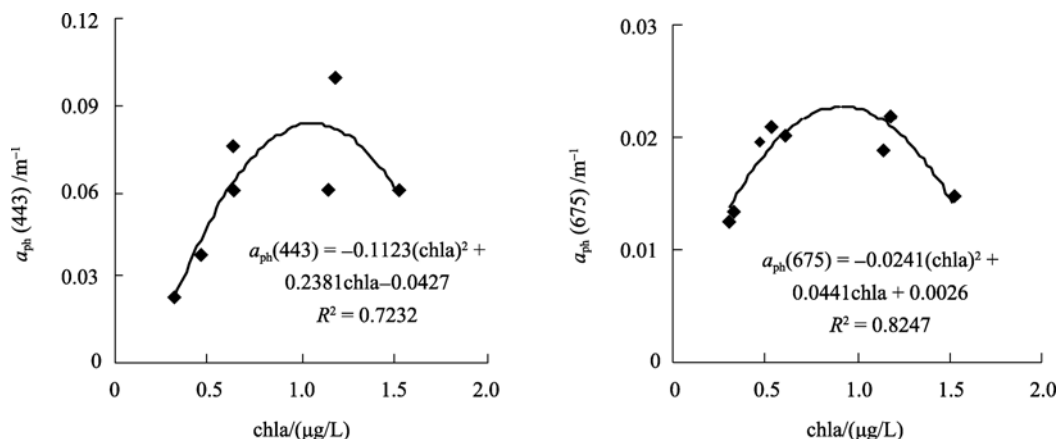
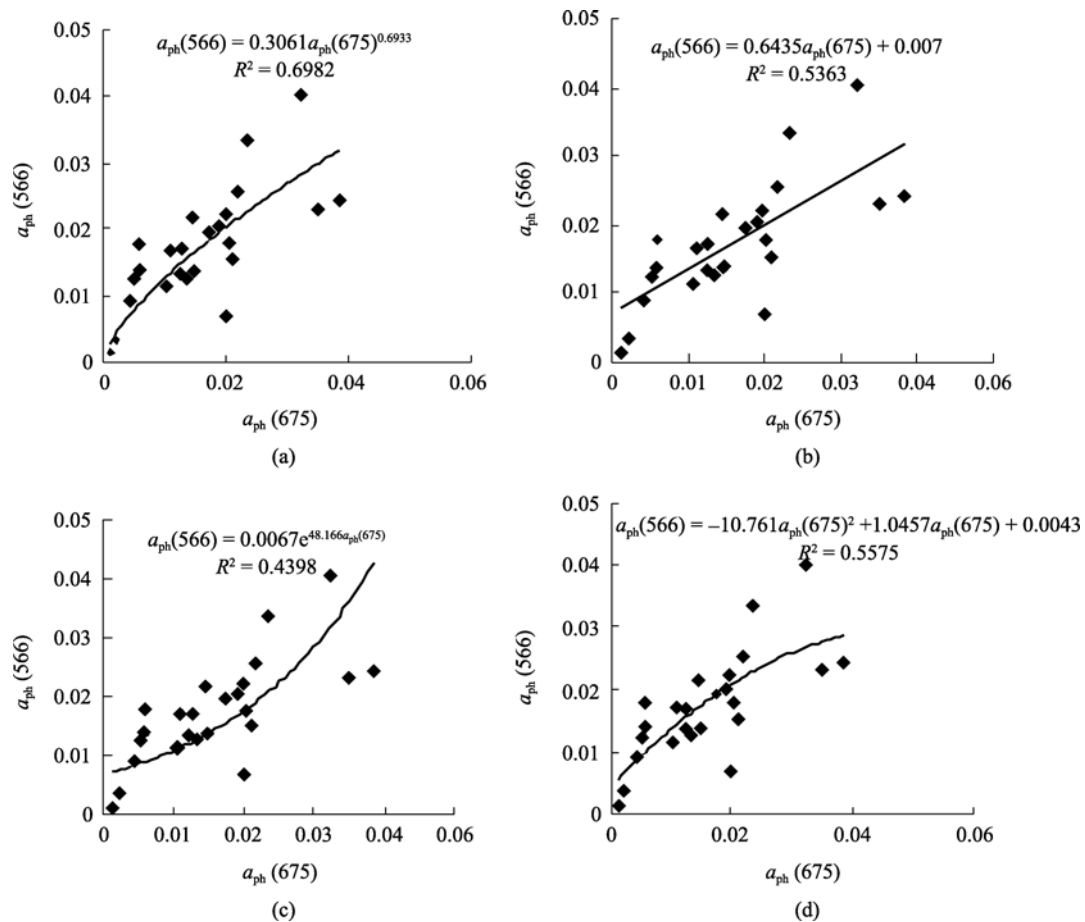


图 7 浮游植物色素吸收系数与叶绿素 a 浓度的关系

图8 $a_{ph}(566)$ 与 $a_{ph}(675)$ 之间不同拟和方法的比较

(a)乘幂关系; (b)线性关系; (c)指数关系; (d)多项式关系

得多,因而相关性会提高,这在一些同类研究中也
有相同的结论(曹文熙等, 2003; 张运林等, 2006)。

与此同时,我们对 $a_{ph}(\lambda)$ 与 $a_{ph}(675)$ 进行了线性、指数、对数以及幂函数等关系的拟和,发现二者之间存在较好的相关性,以 $a_{ph}(566)$ 与 $a_{ph}(675)$ 为例,如图8。通过比较,我们发现,几种拟合方法中,乘幂关系最能较好的表达 $a_{ph}(566)$ 与 $a_{ph}(675)$ 之间的关系,其相关性最好,达到0.6982。在这个基础上,我们对400—700nm波段范围的 $a_{ph}(\lambda)$ 与 $a_{ph}(675)$ 用乘幂关系式(11)进行了拟和,建立了 $a_{ph}(\lambda)$ 与 $a_{ph}(675)$ 之间的经验关系模型。代表性波段的拟和关系的相关参数如表1。

$$a_{ph}(\lambda) = m a_{ph}(675)^n \quad (11)$$

表1 $a_{ph}(\lambda)$ 与 $a_{ph}(675)$ 之间的乘幂关系参数

波长/nm	系数/m	系数/n	相关性/ R^2
520	0.13	0.3753	0.4149
566	0.3061	0.6933	0.6982
617	0.1689	0.6109	0.5846
652	0.2647	0.7555	0.6655
685	2.9728	1.3252	0.929

3.4 CDOM 吸收系数结果分析

图2给出了各采样点CDOM的光谱吸收曲线,由图可知,CDOM的光谱吸收曲线变化与非藻类颗粒物相似,各采样点的吸收系数曲线表现出高度的一致性,随波长增加按指数规律递减,在紫外波段吸光度比较大,在可见光和红外波段吸光度明显变小,在700nm附近的近红外波段吸光度趋向于0。

图9是30个采样点的水样在400nm波长处的吸收系数,其取值范围在0.53—1.22 m^{-1} 之间,平均值为0.7378 m^{-1} ,相对于淀山湖(宋玲玲等, 2007) $a_g(355)$ 的6.95—10.28 m^{-1} ,太湖梅梁湾(张运林等, 2006) $a_g(440)$ 的1.06—1.70 m^{-1} ,可知三峡坝区附近水域的CDOM浓度并不高。另外,根据图9吸收系数的大小,除在#9、#19、#26号采样点吸收系数较大以外,其他采样点吸收系数分布相差不大,说明三峡坝区附近水体CDOM浓度分布比较均一。

很多研究表明,CDOM对500nm以下光谱的吸收基本上呈现负指数衰减的规律, Bricaud等在1981年提出如下的公式:

$$a_g(\lambda) = a_g(\lambda_0) \exp[S(\lambda_0 - \lambda)] \quad (12)$$

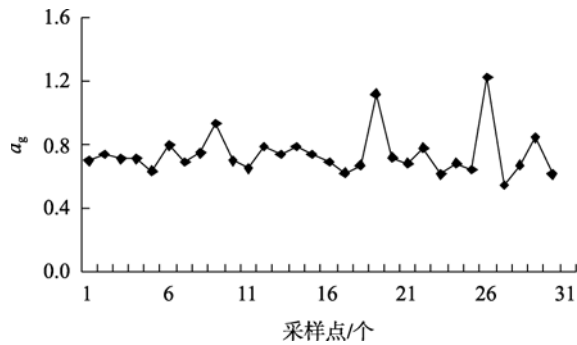


图9 不同采样点在 400nm 波段处的吸收系数

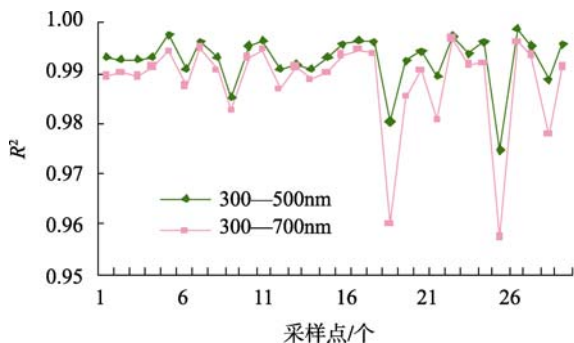
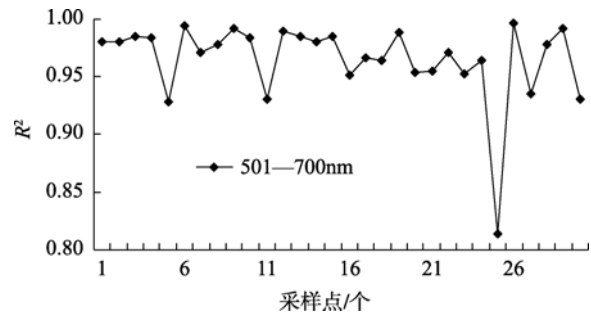
式中, $a_g(\lambda)$ 是 CDOM 的吸收系数(nm), λ 是波长(nm), λ_0 是参照波长(nm), 一般取 440nm, S 是指数函数曲线斜率函数, 与有色可溶性有机物浓度无关, 而与有色可溶性有机物的组成有关。此外, 采用波段范围不同得到的 S 值不同, 通常采用最多的波段范围是 300—500nm, 也有采用 300—700nm 更宽范围的。为了得到更加可靠的 S 值, 本文研究了在 300—500nm、501—700nm 和 300—700nm 3 个不同波段利用最小二乘法进行曲线拟合的 S 值。

将测定的 300—700nm、300—500nm、501—700nm 波段范围的 CDOM 的吸收系数按式(12)进行拟和, 发现 300—500nm、300—700nm 波段范围的拟和精度较高(图 10), 而 501—700nm 几乎不能按照上式进行拟和, 不过我们按照式(13)进行拟和, 得到了很好的拟和效果, 精度如图 11。

$$a_g(\lambda) = a\lambda^2 + b\lambda + c \quad (13)$$

通过对不同波段范围的 CDOM 吸收系数的拟和结果分析, 发现:

(1) 300—500nm、300—700nm 2 个波长范围内拟合得到的 S 值差别不是很大, 300—500nm 范围内 S 值变化范围为 $0.0108—0.01883\mu\text{m}^{-1}$, 平均值为 $0.015956\mu\text{m}^{-1}$; 300—700nm 范围内 S 值变化范围为 $0.01066—0.01882\mu\text{m}^{-1}$, 平均值为 $0.015933\mu\text{m}^{-1}$, 但低波段范围的 S 值还是高于全波段范围的 S 值, 这说明在对 CDOM 吸收系数进行拟合时, 扩大波段范围会影响 S 值的变化。

图10 300—500nm、300—700nm 波段指数拟和的 R^2 图11 501—700nm 波段多项式拟和的 R^2

(2) 300—500nm 波段范围的不同采样点的 R^2 差别很小, 接近于 1, 其中最小值仅为 0.9749, 最大值为 0.9988, 说明在此波段范围内的 S 值具有很好的可靠性, 在此波段范围内可以用式(12)描述 CDOM 的吸收光谱曲线;

(3) 300—700nm 波段范围内不同采样点之间的 R^2 差别也不大, 其最小值为 0.9575, 最大值为 0.9971, 拟和精度较高, 说明在整个波段范围内的 S 值也具有较好的可靠性, 受 501—700nm 范围内的吸收系数影响较小, 也可以利用式(12)描述 CDOM 的吸收光谱曲线;

(4) 501—700nm 波段范围的光谱曲线采用多项式能进行很好的拟和, R^2 较高, 最小值为 0.8139, 最大值为 0.9963, 只在极个别采样点波动较大, 这也说明在 501—700nm 波段范围内不能用式(12)描述 CDOM 的吸收光谱曲线, 而应该用多项式方程描述。

(5) 标准偏差 RMSE(residual mean standard error)的差别如图 12, 300—500nm 与 300—700nm 2 个范围的 RMSE 差别不是很大, 平均值前者为 0.08821, 后者为 0.08958, 但总体趋势还是 300—500nm 的 RMSE 值较小, 说明 300—500nm 波段采用式(12)进行拟和, 其 S 值的误差要小于利用 300—700nm 波段范围拟和的误差; 另外, 501—700nm 波段范围的 RMSE 值很小, 平均值仅为 0.006, 误差很小, 说明

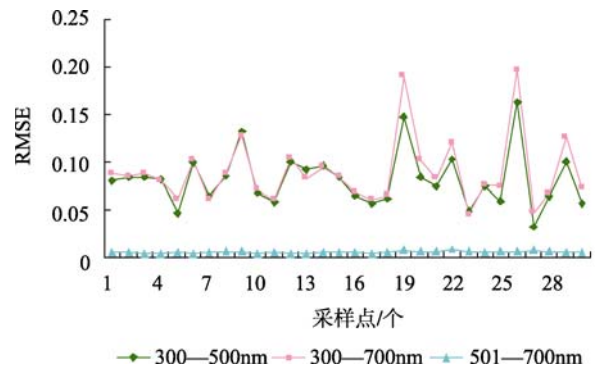


图12 不同波段拟和的 RMSE

采用分波段对三峡坝区水体的 CDOM 吸收系数进行拟和能够提高拟和的精度, 降低 S 值的误差。

另外, 还对 CDOM 的吸收系数与 DOC 浓度进行了线性、指数、对数以及幂函数等关系的拟和, 发现二者之间相关性比较弱。从光吸收能力角度, DOC 一般可以分为有色的和无色的, 两者占总 DOC 的比例随不同地区和来源存在很大差异。分析其原因, 一般来讲, 来自河流携带的陆源 DOC 含有更多的有色 DOC, 而浮游藻类自身降解产生的 DOC 中含有更多的无色 DOC(Kirk, 1994)。CDOM 代表了溶解性物质中有颜色的部分, 三峡坝区试验时正值夏末, 浮游植物生长后腐烂降解, 产生大量无色的溶解性有机碳, 造成了 CDOM 吸收系数和 DOC 浓度之间不存在显著的相关性。

4 结 论

在水色遥感监测中, 水体水色要素(总颗粒物、非藻类颗粒物、浮游植物、CDOM)吸收系数的测定和分析是进行水体光学遥感监测的基础, 具有非常重要的意义。本文以三峡坝区附近水体为研究对象, 在野外实测水色要素(总颗粒物、非藻类颗粒物、浮游植物、CDOM)吸收系数的基础上, 对获取的吸收系数数据分别进行了分析。结果表明, 对于三峡坝区区域的水体:

(1) 总颗粒物吸收光谱分布与非藻类的吸收光谱相似;

(2) 非藻类颗粒物的吸收系数随波长的变化分布十分接近指数衰减规律, 且不同波段的吸收系数之间存在一定的关系;

(3) 多项式关系能较好的表达浮游植物吸收系数与叶绿素 a 浓度之间的关系;

(4) 分段函数能很好的表达 CDOM 的吸收系数特性, 对 500nm 以下光谱的吸收呈现负指数衰减的规律, 不同采样点拟合精度 R^2 接近于 1; 501—700nm 波段范围的光谱曲线采用多项式能进行很好的拟和, 且拟合精度 R^2 达到 95% 以上。

另外, 需要指数的是, 对于三峡库区蓄水后的水体, 它既不同于海洋, 也不同于内陆的湖泊、河流。通过本文的研究发现, 三峡库区蓄水后, 陆源性的输入对三峡坝区水体中非藻类颗粒物的吸收影响不大, 而浮游植物的降解才是水中非藻类颗粒物的主要来源。

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REFERENCES

- Bricaud A, Babin M, Morel A and Prieur L. 1995. Variability in the chlorophyll-specific absorption coefficients of natural phytoplankton: analysis and parameterization. *Journal of Geophysical Research*, **100**: 13321—13332
- Bricaud A, Morel A, Babin M and Prieur L. 1998. Variations of light absorption by suspended particles with chlorophyll a concentration in oceanic (case I) waters: analysis and implication for bio-optical models. *Journal of Geophysical Research*, **103**: 31033—31044
- Bricaud A, Morel A and 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
- Bricaud A and Stramski D. 1990. Spectral absorption coefficients of living phytoplankton and nonalgal biogenous matter: a comparison between the Peru upwelling area and the Sargasso Sea. *Limnology and Oceanography*, **35**(3): 562—582
- Cao W X, Yang Y Z, Xu X Q, Huang L M and Zhang J L. 2003. Regional patterns of phytoplankton spectral absorption in the Pearl River Estuary. *Chinese Science Bulletin*, **48**(17): 1876—1882
- Chen C Q, Shi P, Yin H D and Pan Z L. 2002. Absorption coefficient of yellow substance in the Pearl River estuary. *SPIE*, **4892**: 215—221
- Cleveland J S. 1995. Regional models for phytoplankton absorption as a function of chlorophyll a concentration. *Journal of Geophysical Research*, **100**(C7): 13333—13344
- Dong G X. 2006. Hyperspectral Remote sensing Inversion of the Inland Water Quality Components In Three Gorges Reservoir Chinese Academy of Surveying and Mapping
- Kirk J T O. 1994. Light and Photosynthesis in Aquatic Ecosystem. Cambridge, Britain: Cambridge University Press
- Konovalov B V and Bekasova O D. 1959. Method for determining the pigment content of marine phytoplankton without extraction. *Limnology and Oceanography*, **9**: 883—892
- Li T J, Zhu J H and Cheng Q L. 2006. semi-empirical analysis bio-algorithm research of Yellow-East Sea in Spring. *Ocean Technology*, **25**(1): 82—88
- Lutz V A, Sathyendranath S and Head E J H. 1996. Absorption coefficient of phytoplankton: regional variations in the North Atlantic. *Mar Ecol Prog Ser*, **135**: 197—213
- Prieur L and Sathyendranath S. 1981. An optical classification of coastal and oceanic waters based on the specific spectral absorption curves of phytoplankton pigments, dissolved organic matter, and other particulate materials. *Limnology and Oceanography*, **26**: 671—689
- Sathyendranath S and Platt T. 1988. The spectral irradiance field at the surface and in the interior of the ocean model for application in oceanography and remote sensing. *Journal of Geophysical Research*, **93**: 9270—9280
- Song L L, Qiu Y L, Zhang H E, Liu D G, Han Z H and Zhao J F.

2007. On the light absorption characteristics of colored dissolved organic matter in Lake Dianshan. *Journal of Lake Sciences*, **19**(3): 250—254
- Wang X M, Tang J W, Song Q J, Ding J and Ma C F. 2006. The statistic inversion algorithms and spectral relations of total absorption coefficients for the Huanghai Sea and The East China Sea. *Oceanologia et Limnologia Sinica*, **37**(2): 256—262
- Wu J Y, Shang S L, Hong H S and Li Y. 2006. Advances in the studies on light absorption properties of phytoplankton. *Marine Science*, **30**(6): 77—81
- Xu X Q, Cao W X and Yang Y Z. 2004. Relationships between spectral absorption coefficient of particulates and salinity and chlorophyll a concentration in Zhujiang River Mouth. *Journal of Tropical Oceanography*, **23**(5): 63—71
- Yang J K and Chen C Q. 2007. An optical algorithm for retrieval of chlorophyll, suspended sediments and gelbstoff of case II waters in Zhujiang River Estuary. *Journal of Tropical Oceanography*, **26**(5): 15—20
- Yu H and Cai Q M. 1998. Optical properties of waters in Taihu and parameterizing schemes in ecological and environmental studies of Taihu Lake. Beijing: Metrology Press
- Zeng Y D, Shang S L, Wu J Y, Hu C M and Li Y. 2006. A comparison of different fitting methods for non-pigment absorption spectra. *Journal of Xia'men University(Natural Science)*, **45**(3): 388—392
- Zhang Y L, Qin B Q and Yang L Y. 2006. Spectral absorption coefficient of particulate matter and Chromophoric dissolved organic matter in Meiliang Bay of Lake Taihu. *Acta Ecologica Sinica*, **26**(12): 3969—3979
- Zhao Q H, Zhang Y L and Qin B Q. 2006. Spatial variations of spectral absorption of medium in the Meiliang Bay of Lake Taihu. *Journal of Lake Sciences*, **18**(40): 627—634
- Zhou H L, Han B, Li T J and Zhu J H. 2007. Variations in the light absorption coefficient of de-pigment in South Yellow Sea and Zhujiang Kou of China. *Ocean Technology*, **26**(3): 114—117

附中文参考文献

- 曹文熙, 杨跃忠, 许晓强, 黄良民, 张建新. 2003. 珠江口悬浮物的吸收光谱及其区域模式. *科学通报*, **48**(17): 1876—1882
- 董广香. 2006. 三峡库区高光谱水质参数反演数据处理及分析研究. 中国测绘科学研究院
- 李铜基, 朱建华, 陈清莲. 2006. 黄东海海区春季半经验分析生物-光学算法研究. *海洋技术*, **25**(1): 83—88
- 宋玲玲, 仇雁翎, 张洪恩, 刘登国, 韩中豪, 赵建夫. 2007. 淀山湖有色可溶性有机物的光谱吸收特性. *湖泊科学*, **19**(3): 250—254
- 王晓梅, 唐军武, 宋庆君, 丁静, 马超飞. 2006. 黄海、东海水体总吸收系数光谱特性及其统计反演模式研究. *海洋与湖沼*, **37**(3): 256—262
- 吴璟瑜, 商少凌, 洪华生, 李炎. 2006. 浮游植物光吸收特性研究. *海洋科学*, **30**(6): 77—81
- 许晓强, 曹文熙, 杨跃忠. 2004. 珠江口颗粒物吸收系数与盐度及叶绿素 a 浓度的关系. *热带海洋学报*, **23**(5): 63—71
- 杨锦坤, 陈楚群. 2007. 珠江口二类水体水色三要素的优化反演. *热带海洋学报*, **26**(5): 15—20
- 俞宏, 蔡启铭. 1998. 太湖水体的光学特性及其参数化方案. 太湖环境生态研究(一). 北京: 气象出版社
- 曾银东, 商少凌, 吴璟瑜, 胡传民, 李炎. 2006. 非色素物质吸收光谱拟合方法比较. *厦门大学学报(自然科学版)*, **45**(3): 388—392
- 张运林, 秦伯强, 杨龙元. 2006. 太湖梅梁湾水体悬浮颗粒物和 CDOM 的吸收特性. *生态学报*, **26**(12): 3969—3979
- 赵巧华, 张运林, 秦伯强. 2006. 太湖梅梁湾水体悬浮颗粒物吸收系数的分离. *湖泊科学*, **18**(40): 627—634
- 周虹丽, 韩冰, 李铜基, 朱建华. 2007. 南黄海和珠江口海区非色素颗粒物光谱吸收特性. *海洋技术*, **26**(3): 114—117