Estimate Model of Suspended Sediments in Yangtze River

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Abstract: Traditional estimate of suspended sediments relied on the discrete sample data collected in river, which takes a lot of time or manpower and works out approximately. Because of these characters, it is difficult to measure suspended sediments of the whole river at the same time, and analyze the distributing status of suspended sediments. Estimating suspended sediments using satellite data, however, is a quick and effective way for measuring and analyzing in the whole river. In this research, an estimation model of suspended sediments in Yangtze River was built using spectral analysis based on correlative researches. Firstly, an attempt to fit the relation curve between concentration of suspended sediments and reflectance of river was based on three classical models used widely. Land spectral experiment, which simulated the situation of Yangtze River, was carried out to estimate the parameters of model. And then, we analyzed the Landsat TM data using the models and compared the results with the hydrological data for error quantitative analysis. And the errors are calculated to be almost 20%, for that we did the experiment indoor, and the satellite image data is obtained outdoors. The traditional estimate of suspended sediments relied on the discrete sample data collected in Yichang area, while results of models listed here are average values of river in Yichang area. For the reasons stated before, we think the models are effective to estimate suspended sediments concentration. During the experiment, we didn't consider the depth and the color of the river, which may also, influenced the precision of the results. In order to calculate the parameters more accurately, field experiment, in which other aspects such as the depth and the color would be taken into account, is going to put in practice.

Keywords: Estimate Model, Suspended Sediments, Spectral Analysis

1. Introduction

On account of the reasons, such as the space and the people, the traditional measurement of suspended sediments always can't response the information in lager area in real time, whereas remote sensing technology can make up the shortage for its characteristic of large-scale and continuous observation and multi-spectral, multi-resolution. The main purpose of the research is to find a suited remote sensing estimate model of suspended sediments concentration in Yangtze River. This paper reports an investigation of models literature applied to suspended sediments estimation using satellite data. Results show that nonlinear models give higher correlation coefficients than a linear model. Also, tests of models were carried out to validate the precision of the models. Finally, reasons of error were discussed to give the future direction of our research.

2. General Basis

In this part, the relation curve between concentration of suspended sediments and reflectance of water was analyzed firstly. It is the theory base to build an effective estimate model of suspended sediments using satellite data, and then three kinds of classical estimate models were introduced.

2.1 Optical Characteristic

Suspended sediment estimation using satellite data is based on back scattering theory of suspended particle in physics. The response of each satellite sensor band to up-welling radiance over water can be expressed [2]:

$$L = L_p + \frac{E_{ad}}{\pi} \bullet R \bullet T \qquad (1)$$

Here, L is apparent radiance, L_p is atmospheric path radiance, T is atmospheric transmission, E_{ad} is down-welling irradiance at the water surface, and R is the water reflectance. While E_{ad} is composed of

$$E_{ad} = E_s T^{\sec\theta} \cos\theta + E_k \qquad (2)$$

Where E_s is solar irradiance (the solar constant) above the atmosphere, θ is the angle subtended at the target between sun and nadir, and E_k is sky irradiance at the target. L_p, T and E_{ad} are always looked as constant with same imaging condition.

The most important thing is that the choice of a relationship between R and S, suspended sediments concentration. Based on large members of experiments [5, 8], relation curve between concentration of suspended sediments and reflectance of water can be showed as Fig.1:

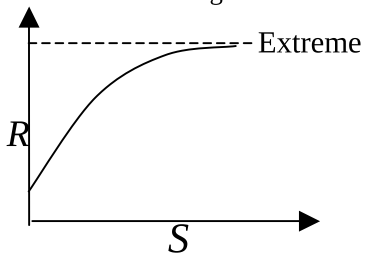


Fig.1 Relation curve between concentration of suspended sediments and reflectance of water
The cross axle here displays the concentration of suspended sediments, and the vertical axis means reflectance of water.

The figure can be characterized as follow:

(1) R increases as S gets bigger:

$$\frac{dR}{dS} > 0 \qquad (3)$$

(2) Change ratio $\frac{dR}{dS}$ decreases as S gets smaller:

$$\frac{d^2R}{dS^2} < 0 \qquad (4)$$

(3) As S gets bigger, R gets closer quickly to an extreme less than 1:

$$\lim_{S\to+\infty} R(S) = R(\infty) < 1 \qquad (5)$$

2.2 Classical Estimate Models

1) Linear Model A linear relationship between R and S has often been used, as seen in the literature, for apparently practical reasons but without theoretical justification. It may be formed as a special case of a model by Prieur (Morel and Prieur, 1977) [8], who used a successive diffuse reflectance R. He obtained the expression:

$$R = 0.33 \times \left(\frac{b'}{a}\right) \times (1+\Delta) \qquad (6)$$

Where the corrective term Δ depends on the radiance distribution and on the volume scattering function, and where a and b' by definition (see Maul and Gordon, 1975) are the absorption and backscattering coefficients, $a = a_w + a_p + a_y$ and $b' = b'_w + b'_p + b'_y$, for water (w), particles (p) and yellow substance (y). The term Δ did not exceed 5% in Prieur's investigation of ocean water. To obtain a linear model, we must assume $\Delta = 0$, $a_p = 0$ and b'_p proportional to suspended solids concentration S. From these assumptions, we obtain

$$R = A + BS \qquad (7)$$

Where A and B are collected constants.

2) Logarithmic Model A nonlinear alternative, which has been found to improve the correlation between satellite radiance and suspended sediments concentration, is a simple logarithmic model [8].

$$R = A + B\ln S \quad (B > 0) \qquad (8)$$

Here A and B are collected constants.

3) Negative Index Equation A different theoretical framework has developed for considering uneven vertical optical characteristic of suspended sediments [2]. The equation was obtained as:

$$R = A + B(1 - e^{-D \bullet S}) \quad (A, B > 0) \qquad (9)$$

Where A and B are collected constants, and D is composed of

$$D = \frac{kh_0}{d} \qquad (10)$$

Here, h_0 means perspective depth of bands. According to Whitlock [2], h_0 changes little when S is larger than $0.01 kg/m^3$. In this study, suspended sediments concentration of Yangtze River obviously transcends the scale, so h_0 is looked as a constant. d means diameter of suspended particle, and is measured as $0.02mm$. That is to say, D is also a constant bigger than zero.

3. Estimate Model

In order to select the most suitable model for suspended sediments estimation of Yangtze River, three models were compared with each other and parameters were calculated by land experiment. After that, the results of tests using Landsat data were compared with hydrological data to analyze the error quantificationally.

3.1 Land Experiment and Parameters Estimation

To simulate real situation of Yangtze River, suspended sediments were taken from low reaches of the river, and then put into a glass flume (like Fig.2) with the size of $10m \times 50cm \times 60cm$. In order to avoid up-welling radiance of the flume bottom, we covered it with black paint and polished to decrease the reflectance near zero. Velocity of flow keeps almost the same with the river in whole process. And the concentration changed gradually from $0kg/m^3$ to $1.5kg/m^3$, which included average suspended sediments concentration of Yangtze River ($0.55kg/m^3$).

Fig.2 Photos of indoor experiments

Spectral reflectance of suspended sediments was measured in the room with a spectrometer (Field Spec FR). Light source used here is a halogen lamp. Field Spec FR is composed of three separate spectrometers covering the spectral range $350nm - 2500nm$, while the spectral resolution is $10nm$. After measuring spectral for a sample and a standard white board one by one, reflectance for each concentration was calculated from raw spectral digital numbers of the sample divided by those of the standard white board. To obtain high precise data, reflectance of same concentration was measured at three different places of flume and mean was calculated. Thus, we may get the spectral response curve as follow:

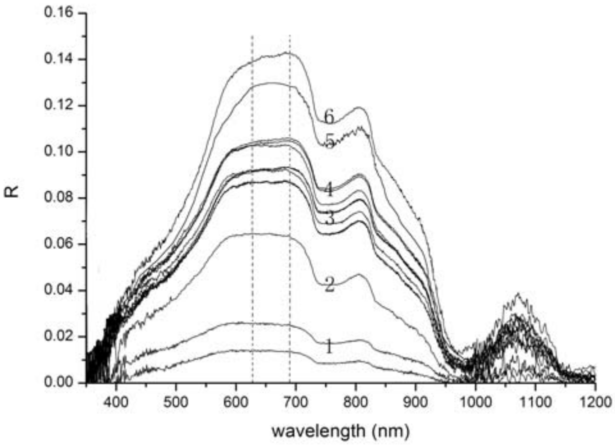
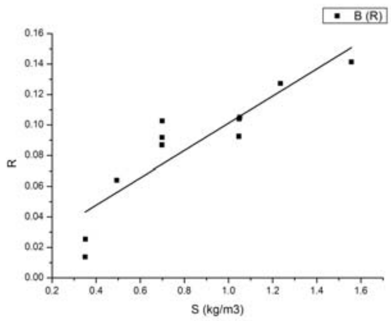


Fig.3 Spectral response curve of each concentration

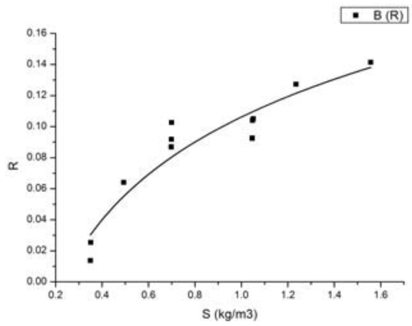
Concentrations of suspended sediments are $0.351kg/m^3$, $0.493kg/m^3$, $0.698kg/m^3$, $1.047kg/m^3$, $1.235kg/m^3$ **and** $1.557kg/m^3$ **respectively (from 1 to 6)**

The cross axle means the wavelength from 350nm to 1200nm, and the vertical axis means reflectance.

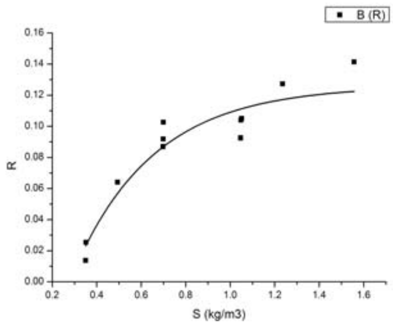
It is known that water has strong absorbency in near-infrared area, while yellow material has strong absorbency in shortwave area and has little absorbency when wavelength is bigger than $0.6\mu m$. Therefore, the most suitable wavelength of suspended sediments remote sensing is $0.6-0.8\mu m$ [2]. And the peak value of water reflectance moved to long wave area with S increased. Based on the suspended sediments concentration of Yangtze River and the satellite sensor used, Landsat TM3 ($0.63-0.69\mu m$) is chose as optimal band (showed in Fig.3). Average reflectance of this area was calculated and fitted relation curve using function 7, 8 and 9.



(a)



(b)



(c)

Fig.4 Relation curve of liner model (a), logarithmic model (b) and negative index equation (c) using the results of indoor experiments

The cross axle means the concentration of suspended sediments, and the vertical axis means reflectance of water, while the dark point here shows the results of indoor experiments

Compared with each other, it is easy to known that negative index equation curve-fits radiance and suspended sediments concentration better than others, especially when concentration is smaller than $1.0 kg/m^3$. The results were showed in Table1.

Table1. The results of fitting relation curve:

Wavelength	Function	A	B	D	Correlation	COD(r^2)
$0.63-0.69\mu m$	$R = A + BS$	0.016	0.084		0.891	0.794
$0.63-0.69\mu m$	$R = A + B\ln S$	0.011	0.072		0.940	0.883
$0.63-0.69\mu m$	$R = A + B(1-e^{-D \bullet S})$	-0.145	0.272	2.768	0.944	0.891

Table1 shows that the nonlinear model curve-fits radiance and suspended sediments data better than a linear model for Yangtze River concentration range. And correlation of negative index equation is higher than that of logarithmic model, for logarithmic model was set up in an even vertical optical condition. And because of uneven vertical distribution of suspended sediments, vertical optical characteristic of water never can be even in reality. Based on these results, tests of nonlinear models were done and discussed using satellite data (Landsat TM).

3.2 Tests and Results Discussions

In order to compare the results with hydrological data provided by committee of Yangtze River and reduce the calculation, Landsat data of August 24th for Yichang area was chosen. Band 3 of Landsat TM, which had a spatial resolution of $30m$, was selected correspond to the land experiments.

At first, water area was extract using Eq. (11).

$$Water = \frac{TM3 - TM7}{TM3 + TM7} \qquad (11)$$

Compared with extraction image and satellite image, DN value of water area is easy to know.

To calculate reflectance a_i (i is band number), which included atmospheric effect, we used the following formula:

$$a_i = \frac{I_i}{(\frac{Ew}{\pi})} \qquad (12)$$

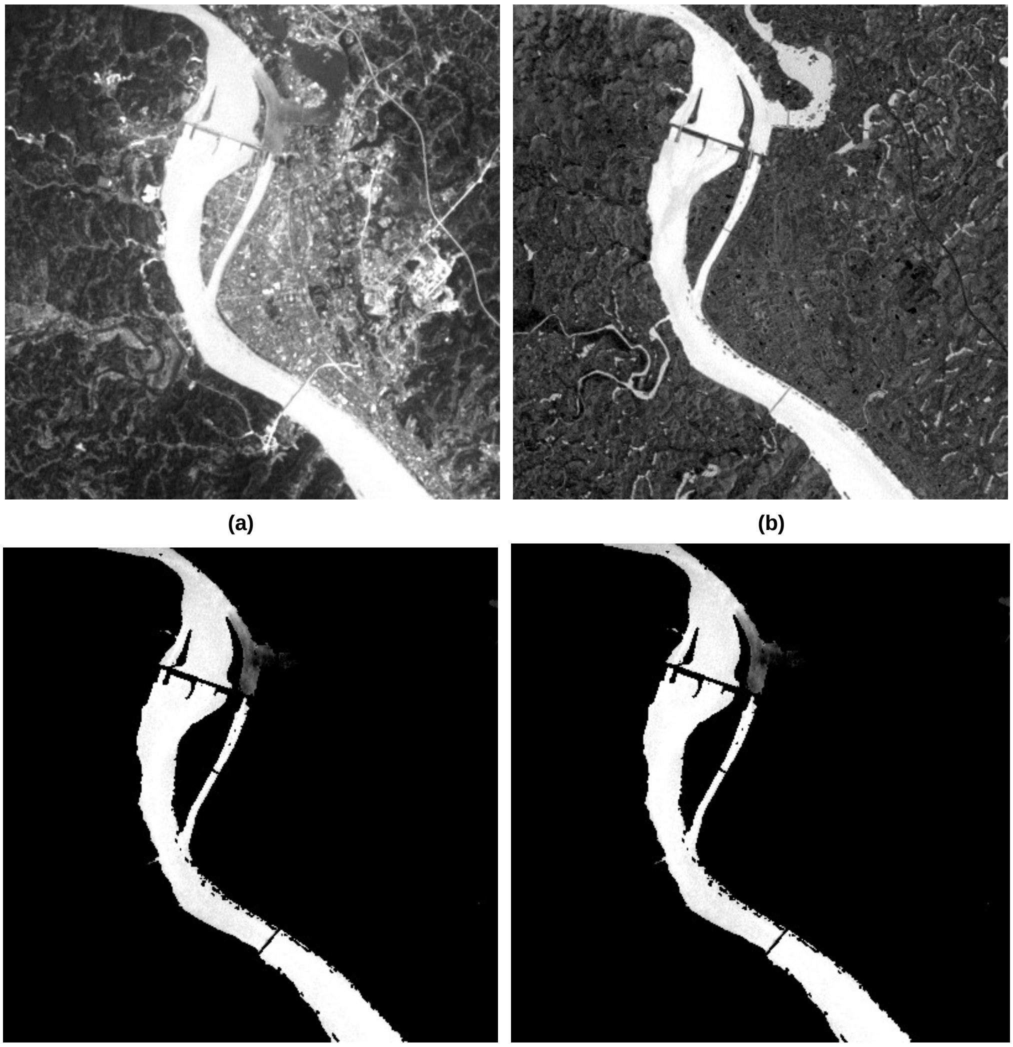
In this formula, I_i is band i 's radiance of land cover; can be calculated by Eq. (13).

$$I_i = (DN - RadianceOffset) \times RadianceScale \qquad (13)$$

And E_w is the value of solar irradiance. Moreover, E_w can be calculated with:

$$Ew = \frac{Es \times \cos\theta}{d} \qquad (14)$$

Here, θ is solar zenith, d is distance from earth to sun in astronomical unit, and E_s is a constant of different bands. While reflectance of land cover is observed by satellite, path irradiance caused by the atmosphere is included at the same time. The main process leading to path radiance is Rayleigh scattering, which was calculated as 0.021 by 6S code. Fig.5 shows the preprocessing of Landsat image.



(a) (b) (c) (d)

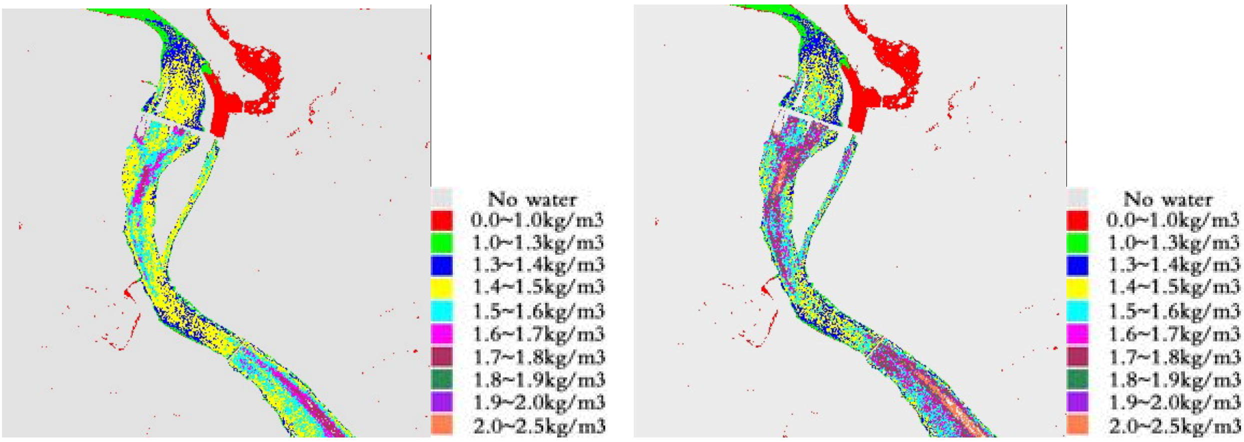
Fig.5 Gray image of band 3 (a);

River extraction using function 11 (b), only the part of river is lighter than other places;

Compared a and b, river extraction image of band 3 could be showed as c;

Atmospheric correction (d)

After that, tests of two models were done (shows in Fig.6), and suspended sediments concentrations in Yichang area using satellite data were listed in Table2.



(a) (b)

Fig.6 Results of Logarithmic Model (a) and Negative Index Equation (b)

Table2. Results of suspended sediments concentrations:

	Hydrological Data	Logarithmic Model	Negative Index Equation
Concentration	$1.26kg/m^3$	$1.46kg/m^3$	$1.48kg/m^3$
Error		15.50%	18.02%

From Table2, errors between results of models and hydrological data are almost 20%, for that we did the experiment indoor, and the satellite image data is obtained outdoors. And traditional estimate of suspended sediments relied on the discrete sample data collected in Yichang area, while results of models listed here are average values of river in Yichang area. For the reasons stated before, we think the models are effective to estimate suspended sediments concentration.

And from the table, it is also known that the result of Logarithmic Model is better than that of Negative Index Equation. In respect that the latter one is more sensitive to optical characteristic of river, and the optical condition of parameter estimation and concentration estimation changed hugely so that precision of the model reduced.

During the experiment, we didn't consider the depth and the color of the river, which may also influenced the precision of the results. In order to calculate the parameters more accurately, field experiment, in which other aspects such as the depth and the color would be taken into account, is going to put in practice.

4. Conclusion

To sum up, we may draw the conclusions as follows:

1. Based on the experiment, we analyzed three classical estimation models of suspended solids concentration, found out that non-linear model fit the relation curve between reflectance and concentration better. And the negative index equation model fitted the relation curve best because of considering uneven vertical optical characteristic of water. However, if the S is small enough, the result of logarithmic model is close to that of negative index equation.
2. As previous statement, the estimation parameters of suspended sediments concentration in Yangtze River were induced by indoors simulated experiment, in which velocity of flow and particle size of the river were taken into account.
3. Landsat TM data was analyzed using nonlinear models; and the results were compared with the hydrological data

to validate the precision of the models. It shows that result of Logarithmic Model is a little better than that of Negative Index Equation.

4. The results indicate that there exist some shortages in estimation model, the spectrum measurement on the spot in Yangtze River is considered to carry out in next step.

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