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Estimation of Suspended Sediment Concentration in Water Using Integrated Surface Reflectance

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Abstract

The reflectance spectra of suspended sediments derived from a silty soil were analyzed in an effort to measure suspended sediment concentration (SSC) in surface waters. Twenty levels of SSC (50 to 1000 mg/l) were created in a large tank filled with 7510 liters of clear water. Reflectance measurements were made using a high resolution spectroradiometer. The spectroradiometer data were integrated into the band widths of Landsat-TM. The simulated TM bands were then used to develop regression models for estimating SSC. We found that the spectroradiometer data, integrated into the band width of Landsat-TM 4, when used in second-order regression models, is the best estimator of SSC.

Introduction

The presence of suspended sediments in surface waters affects its quality and suitability for drinking, recreational, and industrial purposes. The transported sediment serves as a carrier and storage agent for pesticides, adsorbed phosphorus, nitrogen, and organic compounds. Thus, sediment load can be an indicator of pollution potential in surface waters (Julien, 1995).

Sediments also have an impact on aquatic ecosystems (Ritchie, 1972). They impede the transmission of solar radiation and reduce photosynthesis in submerged aquatic vegetation and near-bottom phytoplankton. Large quantities of suspended sediments can cover entire benthic communities, and gravel necessary for spawning some types of fish (Klapper, 1991; Goldman and Home, 1994).

In addition, the high concentration of suspended sediments in lakes and reservoirs accelerates the situation process and thus shortens their useful life and efficiency. The loss of storage capacity in reservoirs in the United States costs $100 million annually in dredging and related mitigation efforts (Julien, 1995). For the above reasons, monitoring suspended sediments in surface waters is important. Traditional methods of data collection and analysis, including water sampling, filtering, and measuring dry weight, are time consuming, labor intensive, and provide only point data. Multiple measurements on one or more lakes are generally necessary.

Remote sensing, one alternative to *in-situ* measurement, is a useful tool for monitoring suspended sediments in surface waters for a variety of reasons, including the multi spectral nature, large-area coverage, timeliness, and repetitive nature of satellite imaging. Several investigators have analyzed surface waters by means of satellite remote sensing and demonstrated empirical relationships between reflectance and amounts of suspended sediments (e.g., Alfoldi and Munday, 1978; Amos and Alfoldi, 1979; Amos and Toplis, 1985; Ritchie and Schiebe, 1986; Curran *et al.*, 1987; Aranuvachapun and Walling, 1988; Curran and Novo, 1988; Lyon *et al.* 1988; Doerffer *et al.*, 1989; Ritchie *et al.*, 1990; Harrington *et al.*, 1989, 1992; Schiebe *et al.*, 1992; Mayo *et al.*, 1993).

A major problem in evaluating the utility of satellite data for measuring suspended sediments in surface waters is obtaining the "ground truth." From a logistical standpoint, it is difficult to make acceptable *in-situ* measurements that are coincident with the satellite pass and provide representative spatial coverage of the water body. In addition, the task of registering the sampling (*in-situ* measurement) locations with the satellite data requires expertise in both Global Positioning Satellite (GPS) technology and image processing. Atmospheric scattering and the vagaries of weather at the time of imaging are other problems that must be overcome.

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One can assess the value of the satellite data for measuring suspended-sediment concentration (SSC) in surface waters by integrating high resolution spectroradiometer data into the optical band widths of an orbital sensor. The proximity of the spectroradiometer to the water surface negates atmospheric effects and one can make close-range measurements at any time when weather conditions are favorable. In this case, spectral-sampling locations are tied precisely to water-sampling locations, however a negative aspect of such an approach is that the spatial coverage of the satellite sensor cannot be simulated.

The objectives of our study were to: 1) determine whether spectroradiometer data, integrated to the optical bands of Landsat Thematic Mapper (TM) sensor, can be used to measure precisely the amounts of sediment suspended in water; and 2) determine which of the integrated optical bands are most appropriate for this purpose. Our literature search located only one similar work; that by Ritchie *et al.* (1976) who demonstrated a linear correlation (R=0.85) between integrated spectroradiometer reflectance (700-800 nm) and amounts of SSC in Mississippi reservoirs.

Our study differs from previous works in the following ways: a) we simulated Landsat-TM bands by integrating high resolution ("hyperspectral") data, whereas most previous studies utilized measurements made in wide spectral intervals; b) we conducted our experiment by creating a suspension of known sediment concentration in a large tank while in previous studies, the spectral data were collected on natural water bodies with the usual problems of water sampling and measurement (described above); c) we collected hyperspectral data from water containing very low amount of suspended sediment to very high amount. Thus, the range of SSC in our study was very large; and d) we tested both linear and second-order regression equations to optimize the fit while in earlier studies, linear models were commonly used.

The use of natural sun light, selection of very large tank to contain the water, and creation of uniform suspension of sediment, has allowed us to achieve a more realistic or "closer to nature" conditions during the data collection phase. Thus our study explains more accurately, the nature of relationship between the spectral reflectance and the varying concentration of suspended sediment in surface waters.

Research Methodology

The experiment for this research was conducted at the Agricultural Research and Development Center-Ithaca, University of Nebraska-Lincoln. Data were collected when the sky was clear, and to minimize the angular variability in solar position, the reflectance measurements were made within two hours of solar noon (Deering, 1989).

A light-colored silty soil, dark yellowish brown when moist (1OYR 4/4), and brown when dry (1OYR 5/3) was used as the suspended sediment. The soil sample was collected from Czechland Lake Watershed in Saunders County, Eastern Nebraska. Particle size analysis revealed 6% fine sand, 66% silt, and 28% clay.

The soil sample was air-dried, pulverized, and sieved through U.S. Standard sieve # 230 (62 μm). The sieved material was weighed and then mixed with a known volume of water. Twenty containers, each containing 375 grams of soil material in 3.785 liters of water were prepared; then added, one by one, to a large (90 cm deep and 366 cm wide) tank containing 7,510 liters of clear water. The addition of the first bottle produced a suspended sediment concentration of 50 mg/l, and the addition of the last bottle produced an SSC of 1000 mg/l. During the experiment, sediments were kept in suspension by manual stirring. To reduce extraneous reflectance, the tank bottom and side walls were enclosed in a black plastic liner (McCluney, 1975; Bhargava and Mariam, 1990, 1991; Han and Rundquist, 1994).

Reflectance data were acquired using a Spectron Engineering SE-590 spectroradiometer from a height of 165 cm above the water surface (Figure 1). The measurements were made in 252 discrete spectral bands in a wavelength region between 368 and 1114 nm (visible through near-infrared). A gray card with 18% reflectance (cross-referenced to a $BaSO_4$ panel) was used for the calibration of the spectroradiometer. Reflectance factors (%) were calculated as a simple ratio between the target and the panel using the following equation (Markham and Barker, 1986, Han and Rundquist, 1994):

$$R(\lambda) = {}^{L(\lambda)}/_{S(\lambda)} \times Cal(\lambda) \times 100 \qquad \text{(I)}$$

where $R(\lambda)$ is the wavelength-specific target radiance, $S(\lambda)$ is the radiance from the $BaSO_4$ panel, and $Cal(\lambda)$ is the calibration factor.

Integration of Spectroradiometer Reflectance to Satellite Band Widths

To simulate satellite bands, the spectroradiometer data between 400 and 900 nm were integrated to spectral band

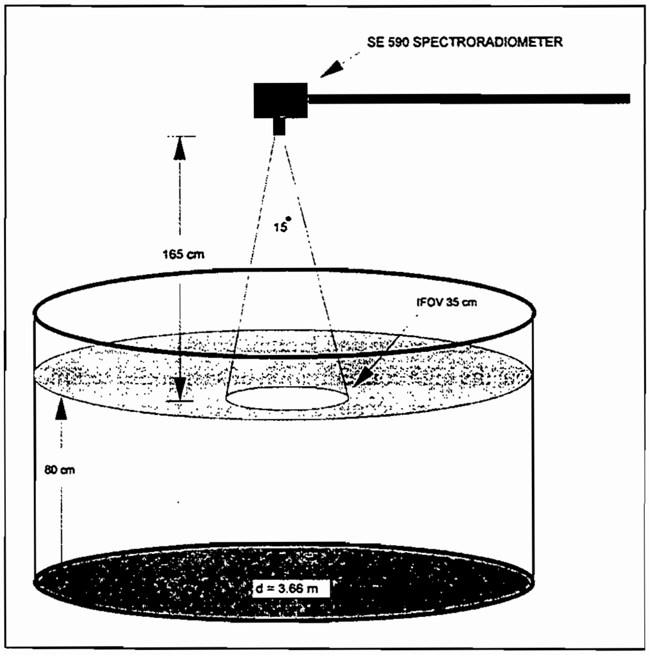

Figure 1 Experimental design

widths of Landsat-TM Band-1 (0.45 to 0.52 µm), Band-2 (0.520.60 µm), Band-3 (0.63-0.69 µm), and Band-4 (0.76-0.90 µm). The integration to the satellite bands was approximated by the following summation:

$$\textit{Band-averaged reflectance } (\%) = \sum \rho_{(I)} / n \qquad \text{(II)}$$

where '$\rho_{(I)}$' is the reflectance in the ith spectral band of the spectroradiometer and 'n' is the number of spectroradiometer bands integrated per satellite band width.

Statistical Analysis

The simulated TM bands, individually and in combination, were used with regression techniques to examine the relationship between reflectance and SSC. First, correlation coefficients (R) between SSC and simulated TM bands were computed and compared. Second, a step-wise regression, with a forward-selection procedure (Draper and Smith, 1981; SAS, 1985), was applied to find the best linear regression model for the estimation of SSC. In the forward-selection procedure, the variables (bands) are inserted in the model sequentially until the prediction model is satisfactory, as indicated by the coefficient of determination (R^2) and an F-value.

Results and Discussion

The spectral reflectance, in the wavelength region between 400 and 900 nm (visible through NIR), as a function of changing levels of SSC in water is shown in Figure 2. A progressive increase in reflectance can be seen in the visible region until the sediment concentration approached 600 mg/l; above this level, the spectral response changes little with further increases in SSC. Note that within the visible region, longer wavelengths seem more affected by SSC than shorter wavelengths. Between 700 and 900 nm (NIR) the reflectance increases more uniformly with increased SSC than was true in the 400 to 700 region (visible). Thus, the NIR region seems more useful than the visible for measuring SSC in water, a finding which is similar to Han and Rundquist, 1994.

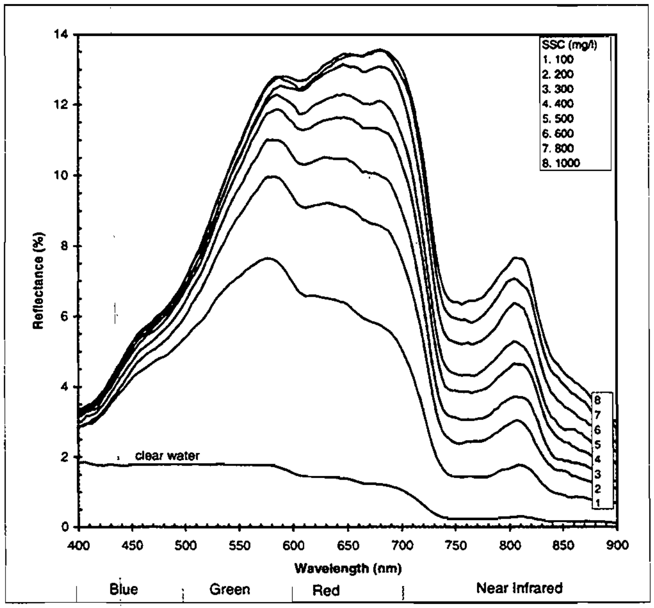

Figure 2 Spectral reflectance of water with varying levels of suspended sediment concentration (only selected levels are shown)

The importance of the NIR is also supported by a Pearson (R) of 0.98 between TM-4 and SSC (Table 1). The results obtained from step-wise regression provided further evidence of strong correlation (partial $R^2 = 0.97$) between TM-4 and SSC (Table 2). Therefore Band-4 can be used to develop a linear regression model of the following form for the estimation of SSC:

$$\text{SSC (mg/l)} = b_0 + b_1 x_{\text{(band 4)}} + e(x) \qquad \text{(III)}$$

The assumptions of linear models require that the residuals must be normally distributed and have a mean of zero. A complete analysis of the residuals was performed to validate linear models for our purpose, and it was determined that the means were not zero. We also computed and compared skewness (γ_1) and kurtosis (g_1) to determine the departure from the normality (Table 3). For Band-4, the value of (g_1) is low, both in linear and quadratic models, and does not indicate deviation from the normal distribution. The value of (γ_1), on the other hand, is higher in the linear model indicating a deviation from the assumption of normal distribution. The plots of residuals also indicated a curvilinear trend in the data. Thus, a decision was made to add a second term in the model. The second-order regression model for estimating SSC is:

$$\text{SSC (mg/l)} = b_0 + b_1 x_{\text{(band 4)}} + b_1 x^2_{\text{(band 4)}} + e(x) \qquad \text{(IV)}$$

The selection of the best regression equation is made by comparing the coefficient of determination (R^2), F-value, and the standard error of the estimate. The equation with

Table 1 Correlation between Simulated TM Bands and SSC

TM Band	R
1	0.769
2	0.770
3	0.887
4	0.983

Table 2 Summary of the Step-wise Regression Procedure for SSC

TM Band	Partial R^2	Model R^2	C (p)	F	Prob > F
4	0.9675	0.9675	25.859	535.63	0.0001
3	0.0203	0.9878	1.724	28.253	0.0001
2	0.0005	0.9882	3.129	0.629	0.0001

0.05 Level of Significance

Table 3 Skewness and Kurtosis Coefficients for Test of Normality of the Residuals Obtained from the First and Second-order Linear Regression Equations for Simulated TM Bands

Regression Model	Coefficient	Band 1	Band 2	Band 3	Band 4
Linear	Skewness	0.75	0.68	0.75	0.87
Linear	Kurtosis	-0.88	-0.90	-0.76	0.01
Qiardratoc	Skewness	1.01	1.17	0.76	-0.04
Quadratic	Kurtosis	0.77	0.72	0.19	0.20

highest coefficient of determination, lowest standard error of the estimate, and an F-value higher than the critical value of F at 0.05 *a-level* was selected. Thus, the Band-4 was selected as the best band for developing a model for estimating SSC in surface waters. With the second-order models, the R^2 improved to 0.99 (Table 4). The best model is SSC (mg/l) = 19.516 + 42.65 + 23.16 Band_4^2. It is also evident from Figure 3, that second-order models provide a better fit than simple linear models.

Conclusion

The research findings summarized in this paper lead us to conclude: 1) the wavelength range between 700 and 900 nm (NIR) is best for determining the amount of suspended sediments in surface waters; 2) Spectroradiometer data, integrated into the band width of Landsat-TM 4, allow accurate estimation of SSC; and 3) second-order regression models are better and more appropriate than linear models for such purposes. Future research is needed to compare the findings presented in this study to actual TM spectral data acquired over lakes and reservoirs.

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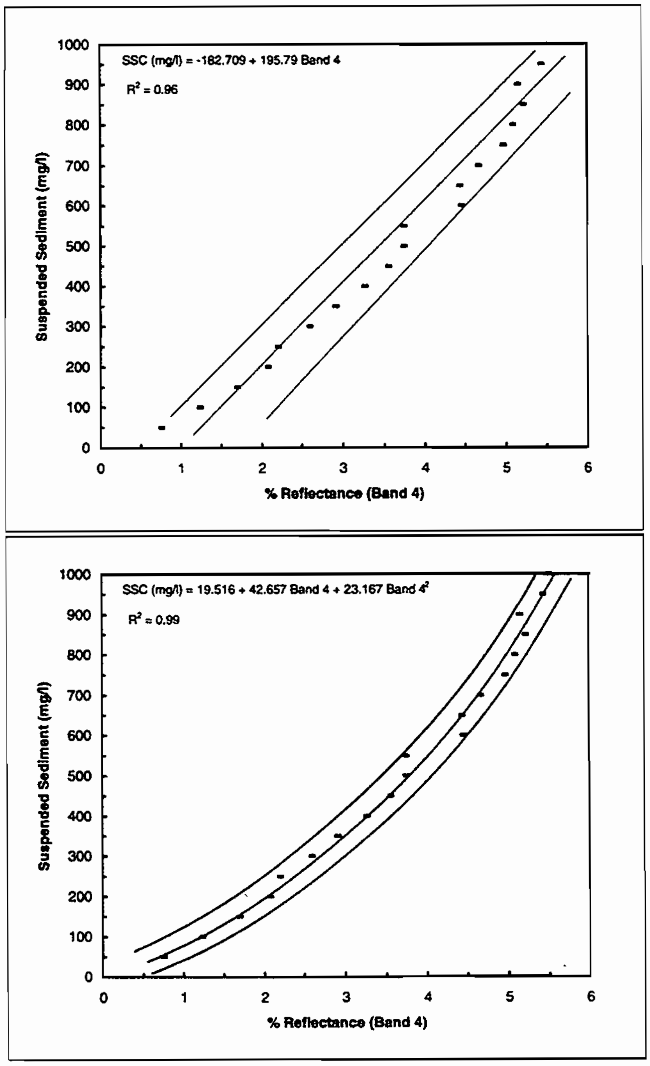

Figure 2 Correlation between suspended sediment concentration and simulated TM Band-4 (a) simple linear model (b) second-order model

Table 4 Statistical parameters for Second-order Regression Equations for Simulated TM Bands

Prediction Equations	R^2	RMSE	F	F_{cr} (0.05)	Prob > F
SSC = 3683.468 - 1653.189 + 184.64 Band^2	0.7300	162.37	23.028	3.59	0.0001
SSC = 1400.86 - 443.00 + 34.632 Band^2	0.7590	153.519	26.770	3.59	0.0001
SSC = 503.988 - 158.18 + 136.64 Band^2	0.9189	89.053	96.358	3.59	0.0001
SSC = 19.516 + 42.65 + 23.16 Band^2	0.9890	31.880	808.94	3.59	0.0001

0.05 Level of Significance

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The 19TH
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16-20 November 1998

Traders Hotel, Manila, Philippines

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1. Objectives

The 19th Asian Conference on Remote Sensing with emphasis on Remote Sensing and GIS will be held at Traders Hotel, Manila, Philippines from the 16th to the 20th November, 1998.

The 19th ACRS is being organized by the National Mapping and Resource Information Authority (NAMRIA) and Asian Association on Remote Sensing (AARS).

The conference will consist of Plenary Sessions, Technical Sessions (Oral), Poster Presentation, Workshops and Commercial Exhibition. The objectives of the conference are:

a) to discuss Asian problems in Remote Sensing and GIS,
b) to exchange academic, application and technical information,
c) to promote regional cooperation amongst the member countries, and
d) to promote operational applications of remote sensing and space technology.

2. Call for papers

All persons interested in contributing a paper for consideration should submit the abstract of the proposed presentation, not **later than July 31, 1998** to Prof. Shunji Murai, General Secretary, Asian Association on Remote Sensing (AARS), Institute of Industrial Science, University of Tokyo, 7-22-1 Roppongi, Minato-ku Tokyo 106-8558, Japan.

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