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Estimating Suspended Sediment Concentration in Turbid Water Using Remotely Sensed Data

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ABSTRACT

Remote sensing is proved to be a useful tool to provide an instantaneous and synoptic view of suspended sediments in rivers & estuaries. Turbidity is not a uniform parameter, either spatially or temporally. The objective of the research study is to estimate suspended sediments in turbid sediment-dominated waters from high spatial resolution remotely sensed data. In this study, laboratory experiments and simulated Landsat 7 ETM data is used to establish relationship between the hyperspectral remote sensing reflectance signal and suspended sediment concentration (SSC). The indoor spectral reflectance was measured 1m above the water surface using hyperspectral Field SpecPro FR Spectroradiometer in the electromagnetic spectrum region of 400 nm to 900 nm. The experiments were performed under controlled condition keeping all environmental parameters constant. Model was developed to quantify the suspended sediment concentration. The techniques used were band ratioing and regression modeling. Results from the study indicate that strong correlation exists between the suspended sediment concentration and ETM bands 3 & 4. Variations of quantity and characteristics of suspended sediment affect the reflectance signal and limit the accuracy of suspended sediment measurement. However, remotely sensed data makes it possible to efficiently monitor the seasonal distribution and concentration of suspended sediment in the water bodies.

Keywords: Remotely sensed data, Suspended sediment, Optimum range

1. Introduction

Sustainable development demands a deeper knowledge of the interaction among economy, society and water resources. Monitoring of Suspended Sediment Concentration (SSC), in reservoirs, rivers, coastal waters and estuaries is imperative for proper water resources and environmental management. Sediments, which fill lakes, reservoirs, and dams, are one of the most important environmental problems throughout the world. Most of the sediment which is eroded from the land surface is in the form of fine particles which are transported in water courses as a suspended load. High concentrations of suspended sediment in water is a critical element in the economic feasibility of a project and could shorten the useful life of many reservoirs & dams. The design and sizing of many hydraulics structures require a pre-determined knowledge of the quality and quantity of suspended sediments. This necessitates a comprehensive study of suspended sediments, quantitative relation of sediment to the flow of water, sediment carrying capacity of rivers, and the quantity of total sediment deposited in reservoirs.

The most often cited estimates of the global suspended sediment discharge to the ocean range between $15\times10^9\ t\cdot yr^{-1}$ to $20\times10^9\ t\cdot yr^{-1}$ where the best estimate may be about $20\times\times10^9\ t\cdot yr^{-1}$ [1], of which over 25% is considered to be trapped by dam reservoirs [2].

Remote sensing holds potential for monitoring and estimating suspended sediments in surface water. Several studies have been conducted to address the impact of suspended sediments on the spectral profile of surface waters. Most of these studies focus on the relationships between spectral reflectance and suspended sediment concentrations in surface waters. Few studies actually address how different sediment types and size affect spectral reflectance [3] [4] [5]. The strength of remote sensing techniques lies in their ability to provide both spatial and temporal views of surface water quality parameters that is typically not possible from in situ measurements.

It is imperative to determine the quantity, distribution, type of suspended sediments, and optimal wavelength to enhance the reliability and applicability of remotely sensed data for water quality monitoring. Current water quality techniques involve in-situ measurements and/or the collection of water samples for subsequent laboratory analyses. Remote sensing makes it possible to monitor the water bodies effectively & efficiently and, identifying areas with significant water quality problems. Remote sensing (hyperspectral, satellite and airborne platforms) is a tool that addresses problems of a regional or global nature. It is an economical way to monitor spatial or temporal change in terrestrial areas and water bodies, because it can monitor large areas in a short time on a repetitive basis. It is most successfully used as part of a multidisciplinary approach to addressing natural resource questions.

Different channels have their own properties and show different spectral characteristics. Rational feature selection is imperative for analysis and information extraction of hyperspectral data. Research on processing, analysis and information extraction of hyperspectral data should be strengthened to determine more useful information, make full use of the advantage and potential of hyperspectral remote sensing technology and promote the development of new and important technology [6]. In order to investigate the effects of varying concentrations and composition of suspended sediments on the spectral signature of surface waters, series of controlled experiments were conducted. In the present research work the hyperspectral data of different suspended sediments, spectral characteristics, and correlation between different bands is comprehensively analyzed. On the basis of analysis, optimum band selection and feature extraction from hyperspectral remote sensing data was proposed.

2. Methods

The experiments were conducted indoor in a black painted room at Kochi University of Technology, Japan and Center for Advanced Land Management Information Technologies (CALMIT), University of Nebraska- Lincoln, USA. A hyperspectral Field SpecPro FR Spectroradiometer (Analytical Devices, Inc., Boulder, CO) was used to collect the upwelling radiance from the water surface.

In the present research work three types of soils were taken into account to serve as suspended sediments for the experiments. The first was silty red soil collected from the central area of Okinawa Island (coordinates: 26º23´N and 127º73´E) which contained about 60 percent of silt and only 10 percent sand while the second type Kaolin was readily available from the market. The third type silty red soil (50%) and kaolin (50%) was prepared at the laboratory to elucidate the effect of colour and texture of soil on the spectral reflectance. The silty red soil sample was air dried and manually sieved to ensure a uniform sediment size. The sieved soil samples were weighted to produce fifty concentrations of suspended sediments in each case ranging from 20 to 1000 mg/l. Initial reflectance readings were taken for the water tank prior to the addition of any suspended sediments and sediments were added systematically to the water-filled tank to enable spectra to be collected for a range of SSC. To study the SSC and reflectance relationship, the mean of ten scans was used for analysis.

The soil sediments were kept in suspension by manually stirring at regular intervals. The depth of water column was 60 am and was kept constant for all experiments The water tank was scanned within 15 seconds of addition of sediments in order to minimize settling of input sediments. The sensor of spectroradiometer was positioned perpendicular at the center of the tank to achieve nadir view. The distance of the sensor from the water surface was kept fixed at the height of 1 meter above the sample, yielding an instantaneous field of view (FOV) 1.75 cm. For this study, data from 400 to 900 nm was used because noise was pronounced at wavelength shorter that 400 nm and longer than 900 nm. Two 500 watt tungsten halogen lamps uniformly illuminated from 1 meter above water surface with a beam inclination of 30^o was the sources of illumination during the experiment. The inner walls of the water tank were painted black to minimize ‘bottom’ effects and extraneous reflectance. Radiation input to the ASD FieldSpec FR spectrometers is through a fiber optic bundle, 5 meters in length. The fiber optic cable provides the ability to quickly and easily point the spectrometer field of view at different targets, especially when using the pistol grip. Measurements pertaining to the underwater irradiance at certain depth with varying sediment loads were made using four Li-192SA underwater quantum sensors.

Reflectance was calculated as a simple ratio between target and reference panel using following equation.

$$\% R(\lambda) = \frac{L(\lambda)}{S(\lambda)} \times Cal\ (\lambda)$$

Where L (λ) is the radiance measured from the water surface, S (λ) is the radiance from the reference panel measured under the same illumination conditions and Cal (λ) is the calibration factor for the reference panel. The reference plaque was a Labsphere white Spectralon of dimensions 12.5cm x 12.5cm which was specially designed and calibrated to reflect natural white light with minimum absorption. Using this method, all parameters that are multiplicative in nature, such as the spectral irradiance of the illumination source and the optical throughput of the field spectrometer, and present in both the spectral response of a reference sample and the target material, are mathematically eliminated.

In addition to study the response of spectral reflectance, irradiance and extinction coefficient with various types and concentration of suspended sediments, the relationship between the SSC and simulated Landsat ETM bands were also examined.

3. Results and discussion

3.1 Response of Reflectance, Irradiance and Extinction coefficient with Suspended Sediments

Suspended sediments can be divided broadly into organic and inorganic sediments. Inorganic sediments (tripton) originate from soil erosion and land slides in the upstream catchments. There is no standard algorithm for the estimation of suspended sediments due to the complex nature and composition of the suspended sediments. The spectral reflectance of water with different types and concentration of suspended sediments is shown in figure 1. The reflectances tend to increase with the increase in SSC, with a few minor exceptions. At wavelengths shorter than 500 nm, visual separation of spectral curves is more difficult in case of silty red soil as compared to Kaolin. At levels of 600 mg/l SSC and above, the spectral profile becomes somewhat irregular in all cases, suggesting that the relationship between reflectance and SSC was found to be nonlinear.

Maximum reflectance was observed in the visible domain (Band 1, 2, and 3 of Landsat TM) and high absorption is in the NIR (Band 4 of Landsat TM). With the increase in the suspended sediments spectral reflectance increase and peak reflectance shifts towards longer wavelengths. The qualitative nature of the spectral curves are similar in all cases, however, there is considerable variance in the magnitude of spectral reflectance.

The optical properties of water are functions of underwater irradiance, such as the vertical attenuation coefficient for downward irradiance or irradiance reflectance. The quantum sensors were placed first at the depth of 30 cm and then 60 cm from the water surface, with one facing upward to measure the downwelling irradiance (E_{do}) beneath the surface and the other facing downward to measure the upwelling irradiance (E_u). The quantum instrument record amounts of photosynthetically active radiation (PAR-400 to 700 nm) in the water, measure photosynthetic photon flux density (PPFD) in micromoles per second per meter squared ($\mu mols^{-1}m^2$).

The measurements E_{do}, underwater downwelling irradiance at depth (E_d) , upwelling irradiance from the tank bottom and water column (E_u) and PAR reflectance form the water surface R, in conjunction with variable SSC, allowed us to examine the energy budget for PAR in the water. The effect of depth and SSC on upwelling irradiance (figure 1.2) was also examined. E_u is a complex parameter because it should be dependent on the total radiation incident to the surface, SSC in the water column and any reflective effect of the bottom itself [7]. When

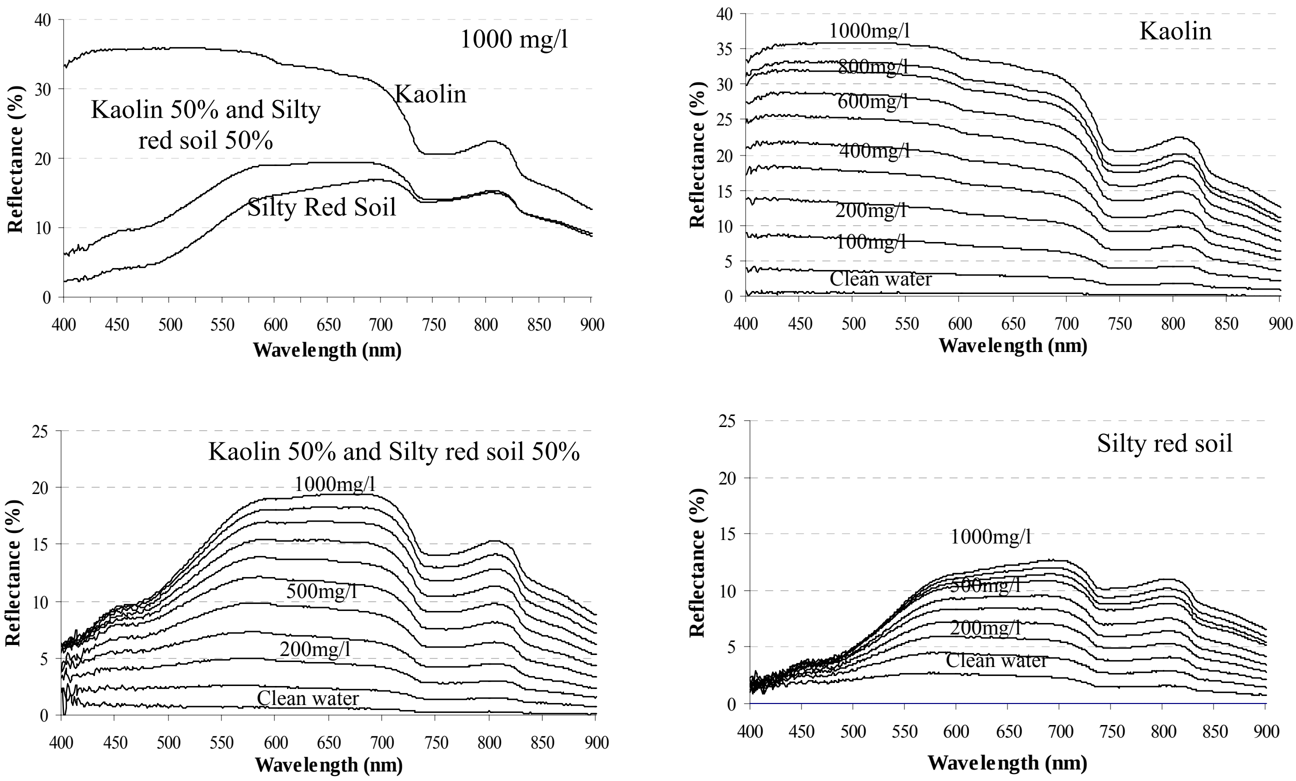

Figure 1: Spectral reflectance of water with different types and concentration of suspended sediments

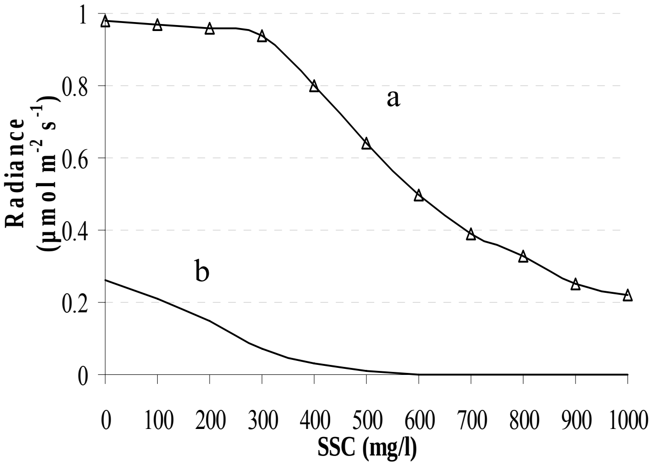

Figure 1.2: Upwelling irradiance (Eu) at 30 cm (a) & 60 cm (b) depth from water surface with varying SSC

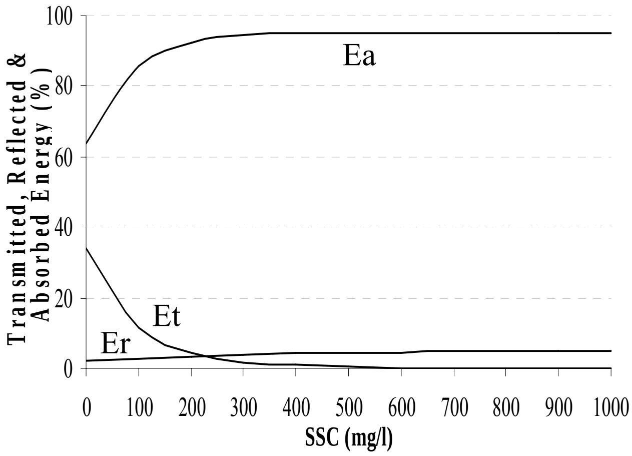

Figure 1.3: PAR Budget with varying SSC

electromagnetic energy reaches the surface water body, it may be reflected, absorbed, or transmitted. The interrelationship among these three processes can be expressed as

$$Ei = Ea + Et + Er$$

Where Ei is the incident energy; Ea is absorbed energy (100-Et-Er); Et is transmitted energy (E_d/E_{do}); and Er is reflected enegery (R- E_u/E_{do}). The interrelationship involving PAR transmittance, reflectance, and absorption (in percent) with varying SSC is shown in figure 1.3. Both the downwelling and upwelling irradiance below the water surface decreased with increasing SSC.

The extinction coefficient (k) is derived from the Beer-Bouger Law and can be calculated using the following equation.

$$k = [\ln (E_{do} - E_d)] / d$$

Where E_{do} is the irradiance at the surface, E_d is the irradiance at depth and d is the distance between the sensor at depth and the sensor at the surface.

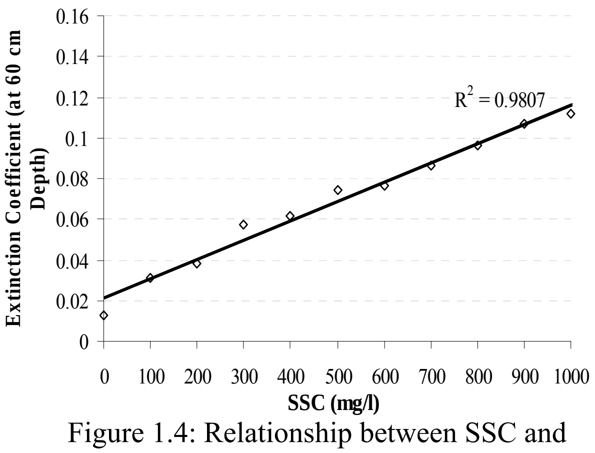

Figure 1.4: Relationship between SSC and extinction coefficient

The vertical extinction coefficient k quantifies the “quenching” of light as it passes from the water surface to the quantum sensor at the depth of 60 cm. The relationship between SSC and k is important because the level of turbidity of a water body can be measured by means of computing k, instead of measuring SSC. The results of relationship between SSC and k are summarized graphically as figure 1.4. Suspended sediment concentrations can be estimated by extension coefficients using a linear regression model of the form

$$k = 9E\text{-}05\ (SSC) + 0.021$$

3.2 Correlation between simulated ETM Bands and SSC

Numerous researchers have analyzed the relationship between SSC and remotely sensed data, especially Landsat multispeatral scanner (MSS) and Thematic Mapper (TM). In order to investigate the applicability of satellite data to measure precisely the SSC, the spectroradimeter data between 400 to 900 nm were integrated to spectral width of Landsat ETM Band 1 (450 to 520 nm), Band 2 (520 to 600 nm), band 3 (630 to 690 nm) and Band 4 (760 to 900 nm). The integration to the satellite bands was approximated by the following summation:

$$\text{Band averaged reflectance (\%)} = \Sigma Ri / n$$

Where Ri is the reflectance in the ith spectral band of the spectroradiometer and n is the number of spectroradiometer bands integrated per satellite band width.

The simulated ETM bands, individually and in combination, was used with regression techniques to examine the relationship between reflectance and SSC to provide solution for the field application of remotely sensed data for assessment of suspended sediments. The correlation coefficients (R^2) were computed between SSC and simulated ETM band (Table 1).

Table 1: Correlation between simulated ETM bands and SSC

TM Bands	R^2
1	0.90
2	0.97
3	0.98
4	0.99

The NIR region (Band 4) seems to be more useful than the visible region for measuring the SSC in water. The spectral reflectance, in the NIR domain (Band 4), as a function of varying SSC in water is shown in figure 1.5. The selection of the best

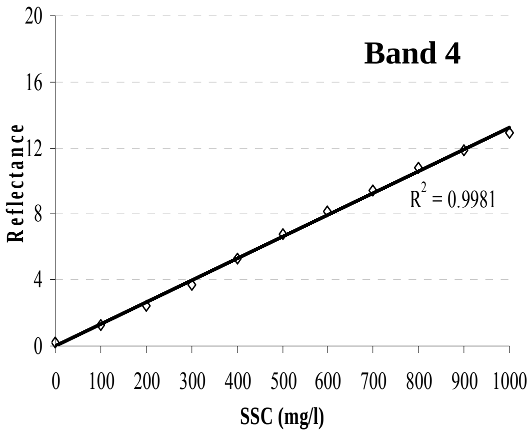

Figure 1.5: Correlation between simulated TM bands and SSC

regression equation for measuring SSC is made by comparing the correlation coefficients. The reflectance of band 4 can be used to develop a linear regression model of the following form for estimation of SSC.

SC (mg/l) = (R (Band 4) – 0.0102)/ 0.0132

3.3 Development of band ratio model

The use of band ratio technique is very common in remote sensing measurements. The advantage of using ratios over absolute values of radiance or reflectance is that they correct some of the effects of measurement geometry and atmosphere. Band ratio model was developed to examine the relationship between suspended sediment and ratio of reflectance. The reflectance in NIR (Band 4) increased with increasing SSC. However, no significant correlation was found between visible (Band 2) and SSC. It was observed that the reflectance ratio was strongly correlated to SSC. This linear relationship is based on reflectance ratio between Band 4 (NIR) and Band 2 (Visible) as

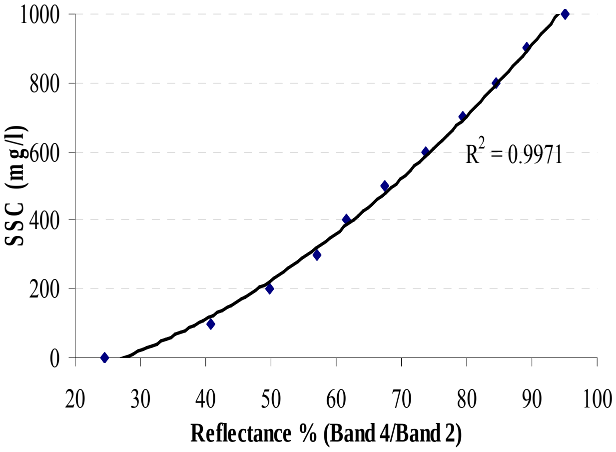

Figure 1.6: Correlation between Band 4/Band 2 and SSC

depicted in the figure 1.6.

$$SSC = 1150\,(Band\ 4 / Band\ 2)^2 + 101.5\,(Band4 / Band2) - 112.9$$

It was observed that in case of Multispectral remotely sensed data (Landsat ETM), the ratios of band 4 & band 2 plotted against SSC will provide solution for the assessment of suspended sediments.

4. Conclusions

The research summarized in this paper leads us to the following useful findings 1) In the visible domain, with increase in SSC, there is small increase in reflected energy compared to a large increase in energy absorbed; 2) Between 700 to 900 nm (NIR) the reflectance increases more uniformly with increased SSC. Thus, the optimum wavelength for measuring SSC is NIR (Band 4 of Landsat ETM). However, visible wavelength (Band 2) is useful for qualitative point of view to characterizing and differentiating suspended sediments. 3) The shape and magnitude of the spectra reflected from water is strongly influenced by type and amount of suspended sediments. 4) The spectroradimeter data, integrated to into the band width of Landsat TM, allow accurate assessment of SSC. Effect of suspended sediments distribution with depth and application of remotely sensed data with different environmental condition needs to be explored for future research. It is further concluded that sustainable water resources management in an organized and coordinated way will be key measures to sustain the economic development. In the future, therefore, it will be important to incorporate sediment assessment as an integral part of water resources and environmental planning, development and management. Without this approach the problems of the water & environmental sector are going to compound in the future.

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