Spectral Reflectance with Varying Suspended Sediment Concentrations in Clear and Algae-Laden Waters

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Abstract

The objective of the study was to characterize and compare the relationship between suspended sediment concentration (SSC) and reflectance in clear and algae-laden waters. A controlled experiment was conducted outdoors in a 7510-litre water tank using natural sunlight. A red loam soil was added and suspended in the tank filled with clear and algae-laden waters, respectively. A total of 20 levels of SSC (from 25 to 500 mg l^{-1}) were created for each type of treatment. Reflectance was recorded using an ASD spectroradiometer, and the bi-directional reflectance factor was computed and analyzed. The same amount of suspended sediment generated higher reflectance between 400 and 700 nm in clear water than in algae-laden water due to the blue and red absorption of chlorophyll. The effect of chlorophyll on the SSC-reflectance relationship was minimum at wavelengths between 700 and 900 nm. For both clear and algae-laden waters, the linearity in the SSC-reflectance relationship increased with wavelength between 400 and 900 nm. A near-linear relationship between SSC and reflectance was found between 720 and 900 nm.

Introduction

Soil erosion is a major cause of non-point source pollution in surface water. The degradation of surface water quality is caused by sedimentation, and by contaminants such as nutrients and pesticides that are often attached to soil particles as they are removed from the land surface. In suspension, soil particles affect not only aquatic ecosystems, but also a wide range of activities, including recreation, water storage and purification, navigation, and others (Clark II, 1987).

Several investigators have studied the relationships between suspended sediment concentration (SSC) and spectral reflectance or radiance. Such work constitutes an important part of the fundamental research in remote sensing of water quality. Ritchie *et al.* (1976) found that the best fit from linear regression analyses between SSC and reflectance occurred between 700 and 800 nm. Curran *et al.* (1987) analyzed spectral radiance recorded by an airborne multispectral scanner and found a positive correlation between SSC and radiance. Novo *et al.* (1989) conducted a laboratory study on the effect of sediment type on reflectance. They found that the strength of the relationship was affected by sediment type, with the fine (white) sediment differing from coarse (red) sediment. Bhargava and Mariam (1990) studied the spectral reflectance of turbidity caused by different clay materials. The authors found a linear relationship between turbidity and reflectance for bentonite clay and black cotton soil, but a curvilinear association for kaoline and gray soil. Chen *et al.* (1991) found that the relationship between SSC and reflectance was log-linear at wavelengths of 450 to 700 nm and linear at wavelengths of 700 to 1050 nm. Novo *et al.* (1991) found that, for oxisoil sediment, the relationship between total suspended solids concentration and reflectance was linear and constant from 450 to 900 nm. Chen *et al.* (1992) examined the usage of derivative reflectance spectra in estimating SSC and found a strong correlation under both controlled and uncontrolled experiments. Mantovani and Cabral (1992) studied the optimum depth for the assessment of spectral reflectance from suspended sediment and concluded that the determination of the optimum tank depth depends on the sediment type and concentration. Han and Rundquist (1994) investigated the response of both underwater light field and surface reflectance to varying SSC. The association between SSC and reflectance was linear at low SSC and non-linear at high SSC. Ferrier (1995) found the variation in the SSC-reflectance relationship due to changing viewing angle and different particle shapes. The author demonstrated the effectiveness of using a polarizing filter to remove some of the specular components of reflected radiation. Han and Rundquist (1996) compared the spectral signatures generated from two texture types of clay soil and found that the reflectance from the finer soil increased faster with SSC than that from the coarse soil. The authors also demonstrated the utility of the integral of reflectance for estimating SSC.

Because most of these experiments were conducted in clear water, one must ask about the practical application of the results because, in nature, both suspended sediments and algae co-exist in surface waters (Alföldi, 1982). It is also clear that the spectral interactions occur between suspended sediments and algal chlorophyll (Quibell, 1991; Goodin *et al.*, 1993; Han *et al.*, 1994).

Therefore, the purpose of this research is to examine the SSC-reflectance relationship in clear water versus the same for algae-laden water. The research was based on a controlled experiment conducted outdoors using a large tank and natural sunlight.

Methods

Two experiments involving varying levels of SSC were conducted. One was based on a background of clear well water and the other was algae-laden water (chlorophyll concentration: 302 μg l^{-1}). A vinyl tank with a total volume of 8543 litres (3.66 m in diameter and 0.91 m in depth) was used as the water container. The tank was filled with water to 0.8 m,

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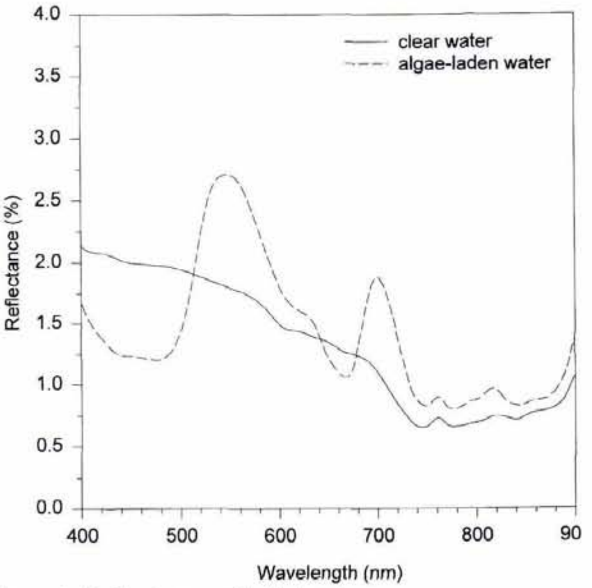

Figure 1. Reflectance of initial waters.

so that the total volume for the experiments was 7510 litres. The water tank was located in an open field. To eliminate extraneous internal reflectance, the wall and bottom of the tank were covered with a custom-made flat-black liner constructed from a heavy vinyl material (McCluney, 1976; Bhargava and Mariam, 1991; Han and Rundquist, 1994).

The two experiments were conducted at 11:57AM to 1:56 PM central daylight saving time on 7 July and 11:43AM to 2:00 PM on 10 July 1995. During these two periods, the skies were clear and wind was calm (wind speed ranged from 3.18 to 5.62 $m\ s^{-1}$). Because an interval of ±2 hours of solar noon was chosen for data collection, the variation in solar illumination was minimized and solar illumination was maximized (Deering, 1989).

The soil sediment applied in the experiments was a red (2.5YR 4/6) loam soil, which was obtained in west-central Alabama. The soil was dried and sifted through a standard screen sieve with a mesh size of 0.5 mm, so that the texture components remaining in the soil were fine sand (35 percent), silt (43 percent), and clay (22 percent). The samples were placed in the plastic jugs with each jug containing 188 grams of dry soil, which generates 25 mg l^{-1} of SSC in a volume of 7510 litres of water. A total of 20 such samples were prepared for each experiment in order to increase SSC from 25 to 500 mg l^{-1}. The sediments were kept in suspension by a mechanical pump-driven device, consisting of a five-horsepower water pump, connecting hoses, and a "diffuser" (Tolk *et al.*, in preparation). The stirring device operated continuously throughout the experiment.

Spectral data were collected using an ASD FieldSpec UV/VNIR (Analytical Devices, Inc., Boulder, Colorado) spectroradiometer. Through a fiber-optic input, this instrument acquired a continuous spectrum in 512 channels ranging from 348 to 1073 nm simultaneously. The fiber-optic was positioned at nadir over the center of the tank at a height of 0.95 m. With a 10 degree field-of-view (FOV) tube, the instantaneous field of view was 0.15 m by 0.15 m on the water surface. The reference panel was Spectralon (Labsphere, Inc., North Sutton, New Hampshire). The fiber and the reference panel were mounted on two specially designed tripods. A fixed geometry among the sensor, the reference panel, and the FOV on the water surface was maintained throughout the data collection (Milton, 1987). Five spectra were taken over both the reference panel and the water surface at each level of SSC. Each measurement took less than one minute to accomplish, with an integration time of 273 milliseconds for each.

The bi-directional reflectance factor (in percent) was calculated using the following equation:

$$R_{\text{water}}(\lambda) = \frac{\text{DN}_{\text{water}}(\lambda)}{\text{DN}_{\text{panel}}(\lambda)} * R_{\text{panel}}(\lambda)$$

where $R_{\text{water}}(\lambda)$ is the bi-directional reflectance factor of the water, DN_{water} is the mean (of five spectra) raw digital number measured over the water, DN_{panel} is the mean raw digital number measured over the reference panel, R_{panel} is the bi-directional reflectance factor of the reference panel, and λ is the wavelength. Due to an observed low signal-to-noise ratio at wavelengths shorter than 400 nm and longer than 900 nm, the analysis focused on $R_{\text{water}}(\lambda)$ calculated for the range between 400 and 900 nm.

Results and Discussion

Spectral reflectance for the two treatments is illustrated in Figure 1. The reflectance of clear water was around 2 percent between 400 and 500 nm and dropped to less than 1 percent at wavelengths beyond 710 nm. The reflectance of clear water was, no doubt, reduced by the black bottom and the physical nature of the liner. For algae-laden water, four pronounced scattering/absorption features of chlorophyll were found: the low reflectance between 400 and 500 nm (blue absorption) and the conspicuous reflectance minimum around 670 nm (red absorption) due to chlorophyll (Cole, 1988; Gitelson, 1992), the broad reflectance maximum around 550 nm (green peak) caused by low absorption of algae (Gitelson, 1992), and the prominent reflectance maximum around 700 nm (NIR peak) caused by an interaction of algal cell scattering and a minimum combined effect of pigment and water absorption (Rundquist *et al.*, 1995). In addition, for both treatments, there were two minor peaks at 760 and 815 nm, respectively. It appears that the former was caused by the reflection of the liner used inside the tank and the latter was due to low water absorption.

Figure 2 depicts the background reflectance itself. When

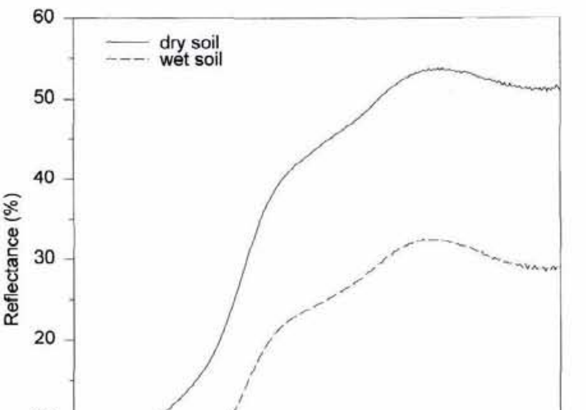

Figure 2. Reflectance of red loam.

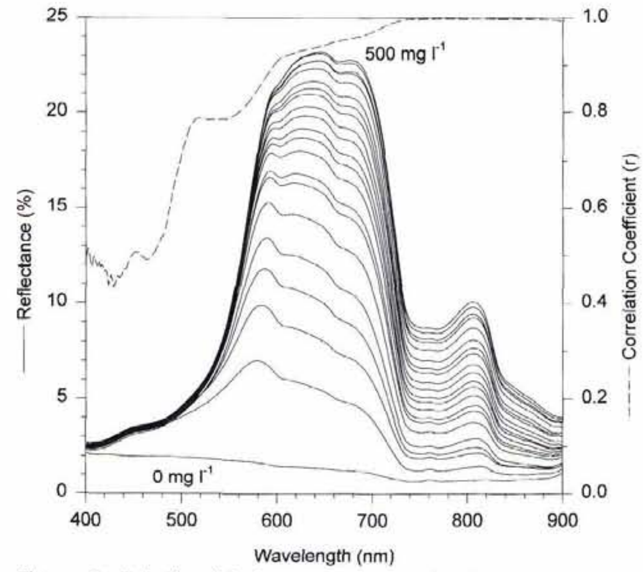

Figure 3. Relationship between SSC and reflectance (clear water).

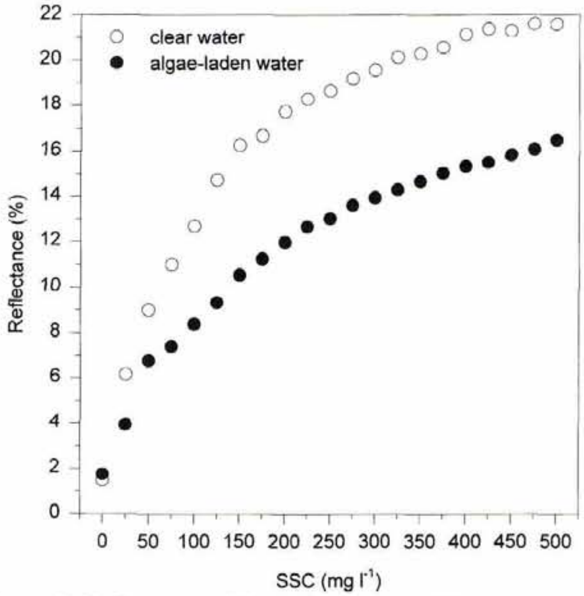

Figure 5. Reflectance with varying SSC at 602 nm.

dry, the red loam increased from 6 percent at 400 nm to 54 percent at about 765 nm, while the reflectance of the wet red loam increased from 3 percent to 33 percent over the same wavelength range. Although the two spectral curves remained similar in shape, the absorption of water associated with the wet red loam increased the separation of the two curves as wavelength increased.

Results involving the addition of the sediment to clear and algae-laden waters are summarized in Figures 3 and 4. For clear water, as SSC increased, reflectance increased at all wavelengths between 500 and 900 nm, and the correlation coefficients (r) between SSC and reflectance were greater than 0.7 beyond 500 nm (Figure 3). The correlation coefficients of 0.99 or greater were observed at wavelengths between 722 and 900 nm, which indicated a near-linear relationship between SSC and reflectance. The highest r (0.9983) occurred at 827, 830, and 847 nm. The correlation between SSC and reflectance was not significant at wavelengths between 400 and 500 nm, with r ranging from 0.43 to 0.70. This was due to the stronger absorption of the visible spectrum by coarser particles, which produced low and insignificant correlation in the blue region (Novo *et al.*, 1989).

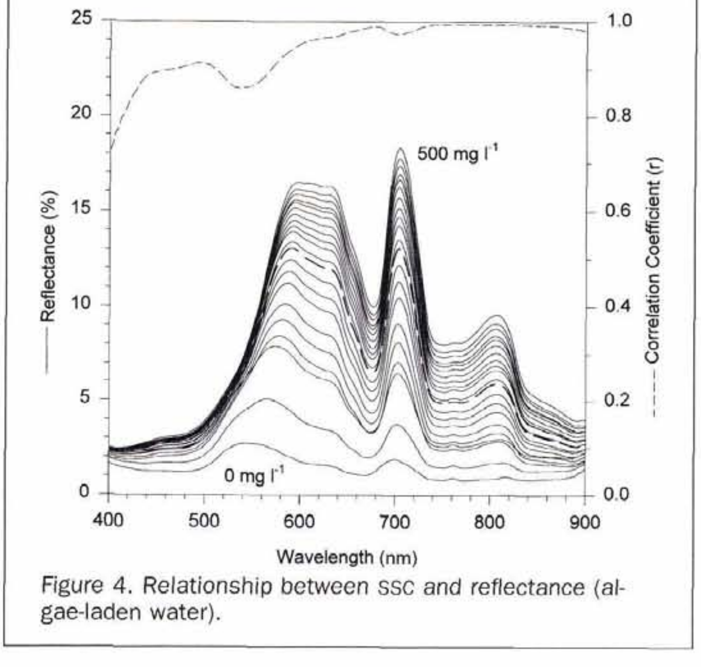

Figure 4. Relationship between SSC and reflectance (algae-laden water).

For algae-laden water, as SSC increased, reflectance increased at all wavelengths between 400 and 900 nm (Figure 4). Compared to clear water, a much stronger association between SSC and reflectance was found between 400 and 500 nm (r ranging from 0.73 to 0.91). Correlation coefficients of 0.99 or greater were observed at wavelengths beyond 727 nm, with the highest coefficient (0.9944) occurring at 767, 769, and 770 nm. With respect to the green and near-infrared (NIR) reflectance peaks, it was observed that, below 225 mg l^{-1} (the thicker dashed line in Figure 4), the green peak was higher than the NIR peak. The two reached the same magnitude (13.09 percent) at 225 mg l^{-1}. Above this level, the NIR peak surpassed the green peak and the difference between the two seemed to increase with SSC.

To illustrate further the SSC-reflectance relationship, reflectivity at 602 nm, the mean position of the peak between 400 and 700 nm, and 807 nm, the mean position of the reflectance maximum between 720 and 900 nm, is plotted against SSC in Figures 5 and 6. At 602 nm, for both treatments, the relationship was non-linear and can be characterized as $d^2R/d\text{SSC}^2 < 0$. That is, the greater the SSC, the smaller the $dR/d\text{SSC}$ (Figure 5). The reflectance of clear water was higher than that of algae-laden water at all levels except 0 mg l^{-1} of SSC. The SSC-reflectance relationship at 807 nm, on the other hand, seemed to be near-linear for both treatments (Figure 6). As SSC increased, reflectance of algae-laden water was higher than that of clear water until the sediment level reached 300 mg l^{-1}. Starting from 325 mg l^{-1}, reflectance of clear water was higher than that of algae-laden water.

To examine the "contribution" of algal chlorophyll to the SSC-reflectance relationship, the simple difference for the SSCs from 25 mg l^{-1} to 500 mg l^{-1} between clear water and algae-laden water was calculated (Figure 7). Between 400 and 698 nm, the reflectance difference was positive for all

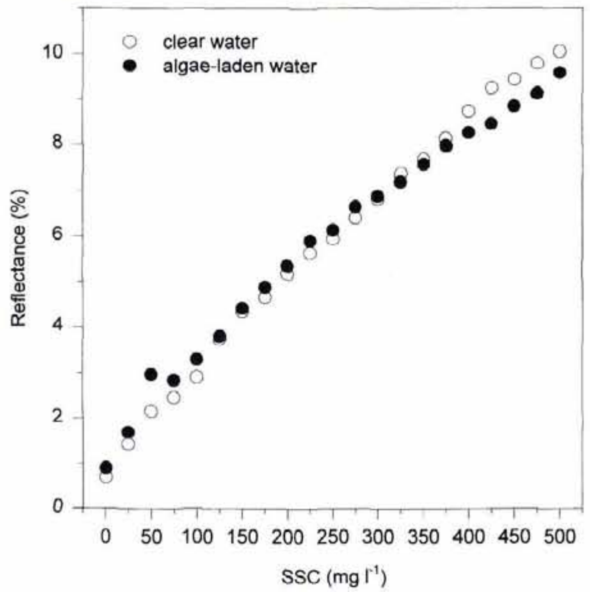

Figure 6. Reflectance with varying SSC at 807 nm.

levels of SSC, which indicated that the same amount of suspended sediment generated higher reflectance in clear water than in algae-laden water. The largest difference was observed at wavelengths between 550 and 700 nm, and centered around 650 nm. The blue absorption and, more importantly, the red absorption of algal chlorophyll seem to be the cause of this. Beyond 700 nm, the reflectance difference appeared to be small, about 1 percent or less. This result implied that the effect of chlorophyll was minimum at the NIR wavelengths. The correlation ($r > 0.7$) between SSC and the reflectance difference was positive at wavelengths longer than 600 nm, meaning that the reflectance difference increased with SSC. The reflectance difference decreased with SSC at wavelengths shorter than 550 nm ($r < -0.7$).

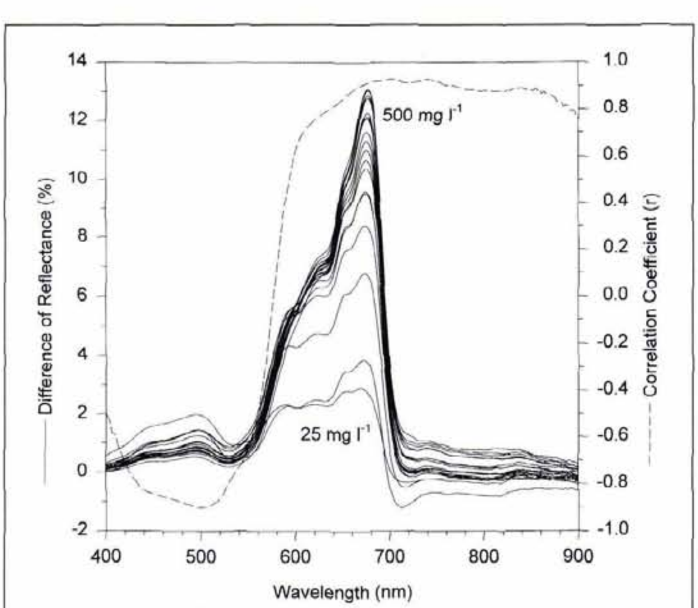

Figure 7. Relationship between SSC and reflectance difference.

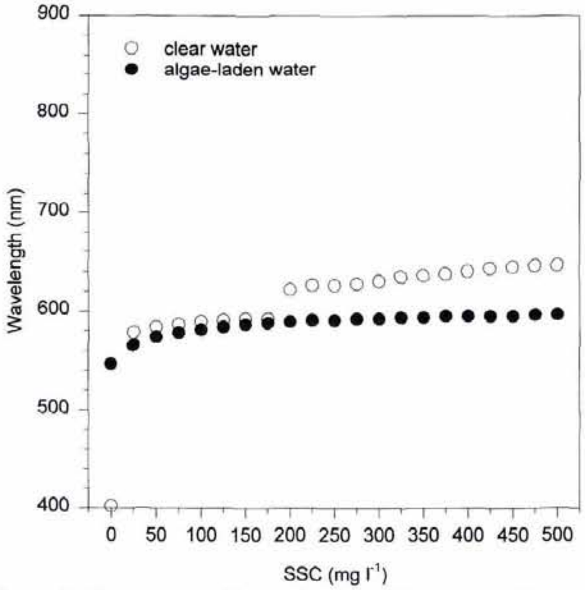

Figure 8. Spectral positions of peak reflectance with varying SSC.

To establish the relationship between SSC and the dominant color in the water, spectral positions of the peak reflectance between 400 and 700 nm with varying SSC were studied (Figure 8). As SSC increased in clear water, the peak reflectance shifted from 578 nm (yellow) at 25 mg l^{-1} to 592 nm (orange) at 175 mg l^{-1}, followed by an abrupt shift from 592 nm to 622 nm (red) when SSC reached 200 mg l^{-1}. Above 200 mg l^{-1}, a uniform pattern of the shift was found. The peak reflectance was spectrally located at 646 nm (red) when SSC reached 500 mg l^{-1}. For algae-laden water, the peak reflectance smoothly shifted from 547 nm (green) at 0 mg l^{-1} to 596 nm (orange) at 500 mg l^{-1}.

Conclusions

The results summarized in this research show that the same amount of suspended sediment generated higher reflectance in clear water than in algae-laden water between 400 and 700 nm, due to the blue and red absorption of algal chlorophyll. The effect of chlorophyll on the SSC-reflectance relationship was minimum at wavelengths between 700 and 900 nm. For both clear and algae-laden waters, the linearity in the SSC-reflectance relationship increased with wavelength between 400 and 900 nm. A near-linear relationship between SSC and reflectance was found between 720 and 900 nm. The best wavelengths for a first-order regression model to estimate SSC using reflectance were 827, 830, and 847 nm for clear water and 767, 769, and 770 nm for algae-laden water. Between 400 and 720 nm, for algae-laden water, the linearity in the SSC-reflectance relationship was higher than that of clear water, especially at wavelengths between 400 and 500 nm. Also in this spectrum, for both treatments, the higher the SSC, the smaller the rate of change between reflectance and SSC. As the red loam increased from 25 to 500 mg l^{-1}, the dominant color of clear water changed in a sequence of yellow, orange, and red, and the change was more abrupt than the case in algae-laden water. When the water contained algae, the dominant color changed from green when no sediment was added to orange when the highest amount of sediment was introduced.

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