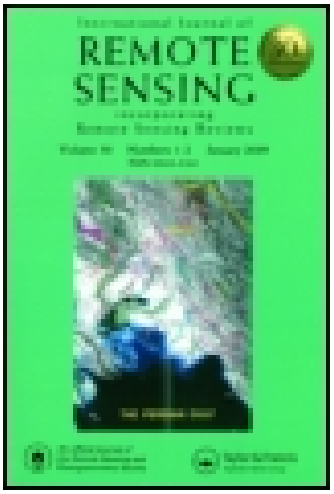

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The spectral responses of algal chlorophyll in water with varying levels of suspended sediment

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The spectral responses of algal chlorophyll in water with varying levels of suspended sediment

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Abstract. The purpose of this paper is to investigate the spectral responses of algal chlorophyll and water, under natural sunlight with varying suspended sediment concentrations (SSC). Twenty levels of SSC with each of two sediment types were generated, ranging from 50 to 1000 mg l^{-1}, in 7510 l of water containing chlorophyll-*a* concentrations of 718 μg l^{-1} and 295 μg l^{-1}. Results indicate that suspended sediments do not eliminate the prominent spectral patterns of algal chlorophyll, even as SSC reached 1000 mg l^{-1}. Between 400 and 900 nm, the relation between reflectance and SSC satisfies the expression: $d^2R(\lambda)/dS^2 < 0$. The effects of varying SSC on the positions and magnitudes of pronounced chlorophyll features were investigated. The ratio between the NIR and red wavelengths was totally independent of SSC. Thus, our finding supports using it as an index for measuring chlorophyll in natural surface water containing suspended sediments.

1. Introduction

Algal chlorophyll and suspended sediments are two of the major optically active factors affecting surface water quality (Ritchie *et al.* 1990). Chlorophyll-*a*, the master pigment in blue-green and eukaryote photosynthesis (Cole 1988), is measurable and quantifiable in a laboratory by extracting and analysing the plant pigments in the cells themselves (Nusch 1980). Because the amount of chlorophyll is indicative of the productivity and trophic status of surface waters, it is desirable to monitor it over geographical space and at numerous points in time, both within one growing season and from one year to the next. The spectral signature of chlorophyll in water is well documented and remote sensing is an established technology for assessing the variable spatial and temporal densities of chlorophyll (Johnson 1978, Alföldi and Munday 1978, Lillesand *et al.* 1983, Khorram and Cheshire 1985, and Ritchie *et al.* 1990).

Few studies have addressed the impact of suspended sediments on the signature of algal chlorophyll. Quibell (1991) investigated the additive effects of sediments on the upwelling radiance from pure algal cultures and found that the addition of particulates increased reflectance at wavelengths longer than 550 nm. He suggested that in algae-laden water, the difference between reflectance at 710 nm and 660 nm

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remained roughly constant with increasing sediment loads. Therefore, these spectral locations can be used to estimate chlorophyll concentration despite varying levels of suspended sediment. Goodin *et al.* (1993) found that pure-water effects can be reduced by a first-order derivative and suspended-sediment effects can be removed by a second-order transformation. Furthermore, they found chlorophyll concentration to be highly correlated with the difference between the second derivatives at 660 and 695 nm. The relation seems to hold even in the presence of background turbidity.

It is important to study the impact(s) of suspended particulates on the algal-chlorophyll signal. In the natural world, sediments and algae interact such that the upwelling radiance from a lake or reservoir represents a composite signal corresponding to those (and perhaps other) components. Determining precisely what portion of the signal is attributable to chlorophyll alone is a complex undertaking (Alföldi 1982). We suggest that hyperspectral remote sensing at close range is a logical first step in making an accurate determination.

Therefore, the purpose of our research was to investigate the spectral responses of algal chlorophyll in water when varying levels of suspended sediments were added. The work was based on controlled-experimental procedures undertaken in a relatively large water tank. Data were collected in natural sunlight under a wide range of suspended-sediment concentrations.

2. Experimental design

Our experiments were conducted at the Mead Research and Development Center (96°25′51″ W and 41°10′34″ N), an agricultural station of the University of Nebraska-Lincoln. Data were collected on two occasions, 21 August 1992, and 22 September 1992, both under clear skies (see pertinent conditions in table 1). The times of data collection were 11:18 a.m. to 12:07 p.m. and 12:18 p.m. to 1:20 p.m. local daylight saving time, respectively. Because the measurements were close to solar noon, variability in solar elevation was minimized and solar illumination was maximized (Deering 1989).

A volume of 7510 l of water in a vinyl tank, 366 cm in diameter and 91 cm in depth, was used for both experiments. The walls and bottom were lined with black plastic to eliminate extraneous internal reflectance (McCluney 1976). The tank was located in an open field at the Mead site.

A Spectron Engineering SE-590 spectroradiometer was used to collect radiance upwelling from the water. This instrument acquires data in 256 discrete channels, among which 252 are used for recording radiance with four reserved for file-header

Table 1. Environmental conditions during data collection.

Date	Time	Air temp. (F)	Relative humidity (%)	Wind speed ($m s^{-1}$)	Wind direction	Solar radiation ($W m^{-2}$)
21 August	1100	78·37	76·20	2·48	172·10	712·00
21 August	1200	81·27	73·30	2·66	174·60	791·00
22 September	1200	65·77	41·81	2·41	12·52	700·00
22 September	1300	67·44	39·21	2·36	14·90	711·00

information. The spectral range of the instrument is from 368·4 to 1113·7 nm. For our study, data from 402·1 to 896·4 nm (170 channels) were used because of significant noise in the water signal at wavelengths shorter than 400 nm and longer than 900 nm. The sensor head was attached to a telescoping, truck-mounted boom, which was pointed south. The spectroradiometer was positioned over the centre of the tank at a height of 135 cm. A nadir view angle was selected for use (Novo *et al.* 1989 b). The 15° optic resulted in an instantaneous field of view of 35 cm by 35 cm on the water surface. A microcomputer initiated spectroradiometer scanning and stored the data. A Barium-Sulfate ($BaSO_4$) reference panel (70 cm by 70 cm) served as the calibration standard. Bi-directional reflectance factors ($R(\lambda)$, in per cent) were calculated using the following equation:

$$R(\lambda) = \frac{L(\lambda)}{B(\lambda)} Cal(\lambda) \times 100 \tag{1}$$

where $L(\lambda)$ is the wavelength-specific target radiance, $B(\lambda)$ is the corresponding radiance from the $BaSO_4$ reference panel, and $Cal(\lambda)$ is the calibration factor for the $BaSO_4$ panel. The latter allowed correction both for the non-Lambertian properties of the panel and the slight changes in solar-zenith angle. Two replicate scans were taken for each sample and the mean of the two was used in the analyses.

Algal concentrations were induced by fertilization with a commercial garden product over a period of several weeks prior to the experiment. The dominant algae present was Cyanophyta (blue-green algae). The concentration of chlorophyll-*a*, as analysed in the laboratory using standard chloroform-methanol extraction procedures (Wood 1985), was 718 $\mu g\, l^{-1}$ for the first experiment (21 August 1992) and 295 $\mu g\, l^{-1}$ for the second experiment (22 September 1992).

Two types of silty clay loam soil, with slightly different amounts of fine-grained particulates, were chosen for use as suspended sediment in the experiments because they were available near the research site (table 2). A total of 20 samples was used for each experiment. Samples were dried, sieved, and placed in plastic bottles. Each bottle contained 375 grams of the dry sample, which generated 50 mg l^{-1} of SSC in a volume of 7510 l of water. The soil sediments were kept in suspension by manually stirring at regular intervals. The tank was scanned with the spectroradiometer within 20 s of sediment addition in order to minimize the amount of material settling to the bottom.

Table 2. Description of the soil sediment used.

	Percentage sand	Percentage coarse silt	Percentage fine silt	Percentage very fine silt	Percentage clay	Texture class	Colour code
Experiment 1	7·25	24·31	27·49	5·28	35·67	Silty clay loam	10 YR 4/3
Experiment 2	3·12	15·24	37·58	10·29	33·77	Silty clay loam	10 YR 4/2

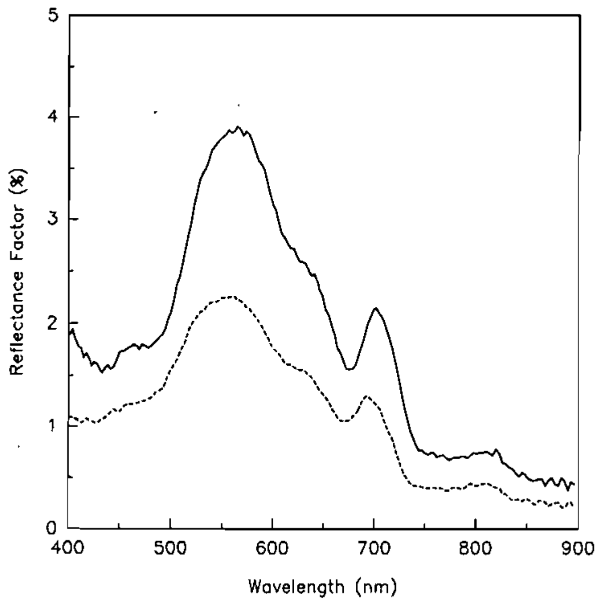

Figure 1. Spectral reflectance of initial algal chlorophyll with pure water. ——, Chl-*a*: 718 $\mu g\,l^{-1}$ (Experiment 1). – – – –, Chl-*a*: 295 $\mu g\,l^{-1}$ (Experiment 2).

3. Results and discussion

Two spectral profiles (figure 1), generated at the start of our experiments, depict algal chlorophyll in pure water. For the chlorophyll densities (295 and 718 $\mu g\,l^{-1}$), the low reflectance between 400 and 500 nm is due to absorption caused by both chlorophyll and dissolved organic matter (Gitelson 1992). The minimum in the red spectrum (centred at 670·2 nm for 295 $\mu g\,l^{-1}$ and 676 nm for 718 $\mu g\,l^{-1}$) is due to chlorophyll absorption by living cells (Cole 1988). The broad reflectance peak in the green spectrum (561·9 nm for 295 $\mu g\,l^{-1}$ and 564 nm for 718 $\mu g\,l^{-1}$) is the result of low absorption of chlorophyll coupled with some backscattering because of particulate concentration (Dekker *et al.* 1991). The cause of the prominent reflectance peak in the near-infrared (NIR) region (693·7 for 295 $\mu g\,l^{-1}$ and 702·5 nm for 718 $\mu g\,l^{-1}$) has been explained by others as: (1) fluorescence of phytoplankton pigments (Carder and Steward 1985, and Hoge and Swift 1987); (2) anomalous scattering caused by absorption minima at 675–680 nm (Morel and Prieur 1977); and (3) a minimum in the combined absorption curves of algae and water (Vos *et al.* 1986, and Gitelson and Kondratyev 1991). In addition to these major features, there is a minor reflectance peak at about 810 nm, which was also documented by Quibell (1991). The 810 nm peak is presumably due to turbidity and the general absorption of near-infrared wavelengths by pure water. Notice that the local minimum and maxima (in green, red, and NIR as discussed above) shifted toward longer wavelengths as the chlorophyll concentration increased from 295 $\mu g\,l^{-1}$ to 718 $\mu g\,l^{-1}$. Similar effects were reported by Gitelson (1992) and Mittenzwey *et al.* (1992).

Results from experiments 1 and 2, involving the addition of the two sediments (table 2) to a chlorophyll solution, are summarized in figures 2 and 3. As suspended-sediment concentrations (SSC) increased from 0 to 300 $mg\,l^{-1}$, reflectance increased

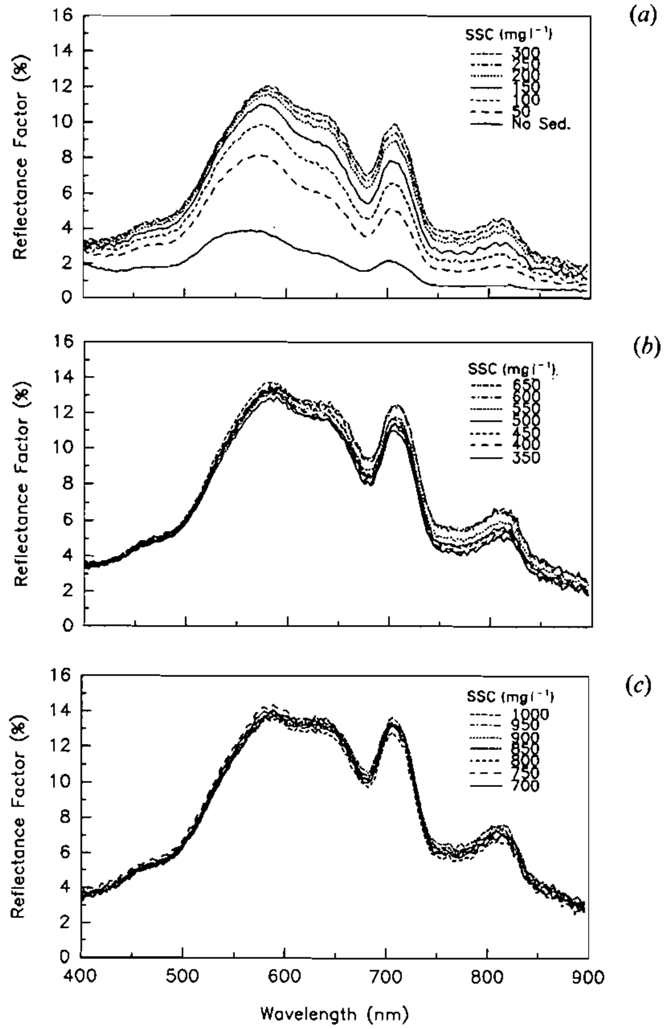

Figure 2. Spectral reflectance during experiment 1 (Chl-*a*: 718 $\mu g l^{-1}$).

relatively uniformly at most wavelengths between 400 and 900 nm (figures 2 (*a*) and 3 (*a*)). However, at sediment levels between 350 and 650 $mg l^{-1}$ (figures 2 (*b*) and 3 (*b*)), the pattern of reflectivity increase was less clear, and at sediment concentrations above 700 $mg l^{-1}$ (figures 2 (*c*) and 3 (*c*)), the spectral curves were virtually indistinguishable. These findings are in agreement with our previous work involving sediment additions to pure water, but without the presence of algae (Han and Rundquist 1993).

Comparing spectral reflectances of the two current experiments, we found that the second sample, which contains more fine-grained materials, increased reflectance faster (as SSC increased) than the first (see figures 2 and 3). This result can be attributed to fine material containing more particles than coarse material, which scatters more light than would an equal amount of coarse-grained (Novo *et al.* 1989 a). In regard to the spectral residual from the algal-chlorophyll signal, notice

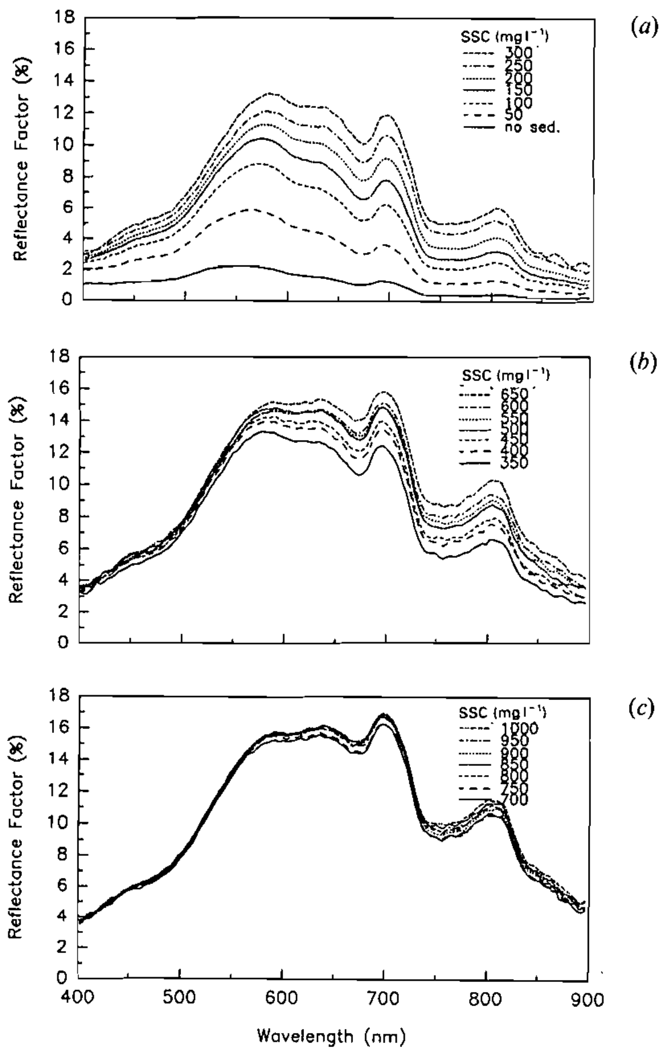

Figure 3. Spectral reflectance during experiment 2 (Chl-a: 295 $\mu g\,l^{-1}$).

that the addition of both types of sediments did not eliminate the primary spectral characteristics of chlorophyll in water; i.e., the NIR peak near 700 nm and the red absorption near 675 nm remained intact despite SSC ranging from 50 $mg\,l^{-1}$ to 1000 $mg\,l^{-1}$.

The patterns shown in figures 2 and 3 can be described quantitatively. Suppose the rate of change in reflectance with SSC is expressed in derivative form as:

$$\frac{dR(\lambda)}{dS} \tag{2}$$

Where: R = reflectance

S = suspended sediment concentration

λ = each of the 170 spectroradiometer channels, 400 to 900 nm.

Thus, as S increases, $dR(\lambda)/dS$ decreases. Therefore, the relation between R and S satisfies the expression:

$$\frac{d^2R(\lambda)}{dS^2}<0 \tag{3}$$

Therefore, it appears that the relation between R and S is non-linear.

A total of 170 correlation coefficients (r) between reflectance and SSC were computed for each experiment (figure 4). For experiment 1, the values of r ranged from 0·69 (at 559 nm) to 0·98 (at 864·7 nm). Spectral reflectance was highly correlated ($r>0{\cdot}9$) with SSC at wavelengths longer than 661·4 nm ($r>0{\cdot}9$), except between 699·6 and 711·5 nm. Another spectral region of lower correlation centred at about 559 nm.

The lowest r(0·79) of experiment 2 was found at both 527·9 and 541·9 nm and the highest r (0·99) was at 883·7 nm (figure 4). High correlations ($r>0{\cdot}9$) between reflectance and SSC occurred at wavelengths longer than 649·6 nm, lower is appearing between 684·9 and 705·5 nm. Like experiment 1, experiment 2 showed a low correlation region at around 541·9 nm. Thus, our findings imply that green and NIR reflectance peaks are not totally reliable in regression models for estimating SSC in the presence of algae.

The wavelengths of the maximum green reflectance from chlorophyll were plotted against SSC (figure 5). As SSC increased, the positions of the green maximum in both experiments showed a trend of shifting toward slightly longer wavelengths. For experiment 1, the green maximum shifted from 564 nm with no sediment in the tank (SSC $=0\,\mathrm{mg\,l^{-1}}$) to 585 nm with heavy sediment (SSC $=1000\,\mathrm{mg\,l^{-1}}$). For experiment 2, the green maximum shifted from 561·9 to

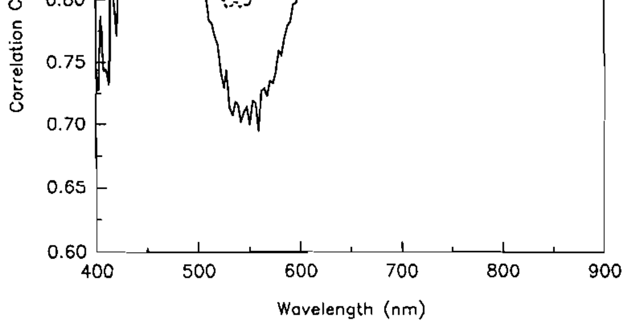

Figure 4. Correlation coefficients, between reflectance and SSC, shown by wavelength. ——, Experiment 1, – – – –, Experiment 2.

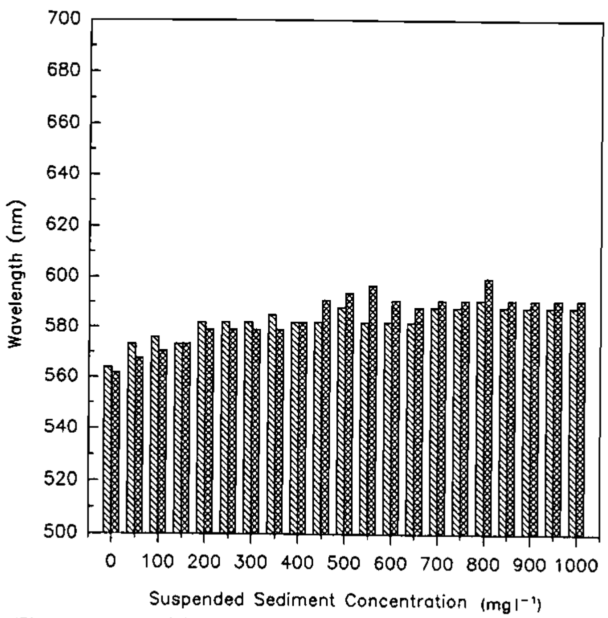

Figure 5. Positions of green maximum with varying SSC.

599·7 nm as SSC increased from 0 to 1000 mg l^{-1}, with minor anomalies in the pattern. In general, then, increasing SSC causes the green maximum to shift to longer wavelengths, a fact documented by numerous other authors (e.g., Quibell 1991). Notice that the fine-grained sediment produced even greater spectral shifts than coarse-grained (figure 5).

In contrast to the behaviour of the green maximum, additions of SSC seemed to have little or no effect on the position of the red-dependent chlorophyll absorption (figure 6). During experiment 1, the red minimum shifted only from 676 nm to 681·9 as SSC increased from 0 mg l^{-1} to 100 mg l. From 150 to 1000 mg l^{-1}, the red minimum stayed between 679 and 681·9 nm. Similarly, no clear trend was found for the red minimum during experiment 2 (figure 6).

Much like the red, the NIR reflection maximum showed little or no effect from suspended sediments (figure 7). Therefore, we assume the positions of the red minimum and NIR maximum to be primarily dependent upon concentrations of algal chlorophyll in water, and not SSC.

The documented evidence concerning the relation between red and NIR reflection with variable chlorophyll concentration suggests that the red is inversely related to chlorophyll concentration while the NIR is directly related (Gitelson and Kondratyev 1991, and Dekker *et al.* 1991). Therefore, a simple ratio (NIR/red) and difference (NIR-red) were tested for predicting chlorophyll concentration (similar to Mittenzwey *et al.* 1992, Quibell 1991).

Percentage reflectance at the NIR maximum (702·5–708·5 nm for experiment 1 and 693·7–699·6 nm for experiment 2), and the red absorption feature (676–681·9 nm for experiment 1 and 670·2–676 nm for experiment 2), were plotted against variable

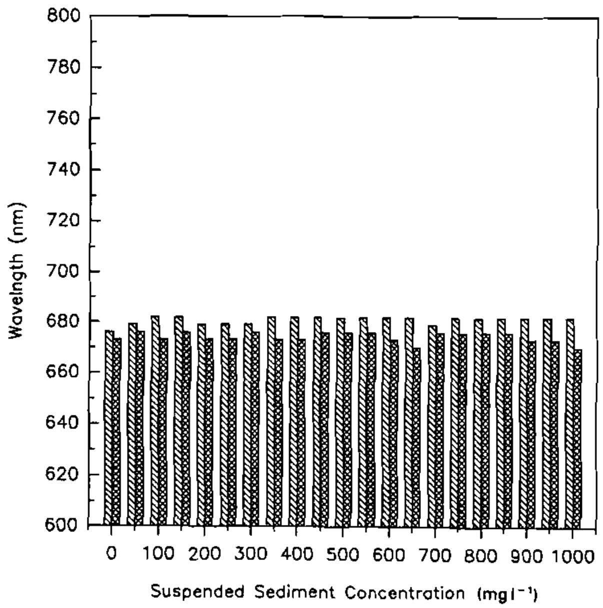

Figure 6. Positions of red minimum with varying SSC.

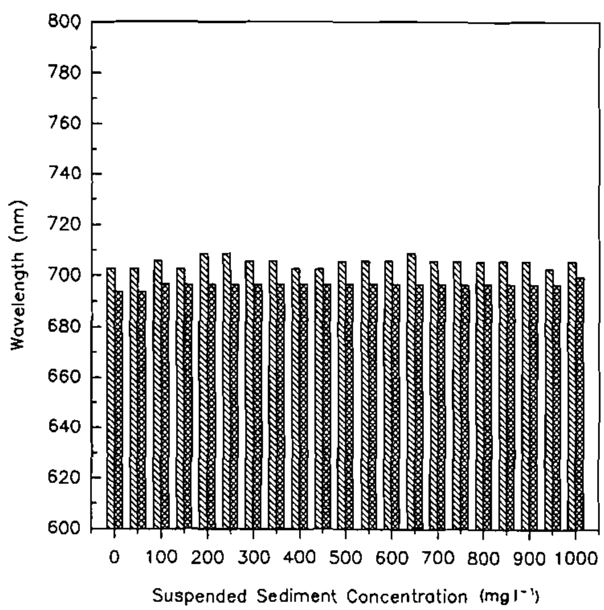

Figure 7. Positions of NIR maximum with varying SSC.

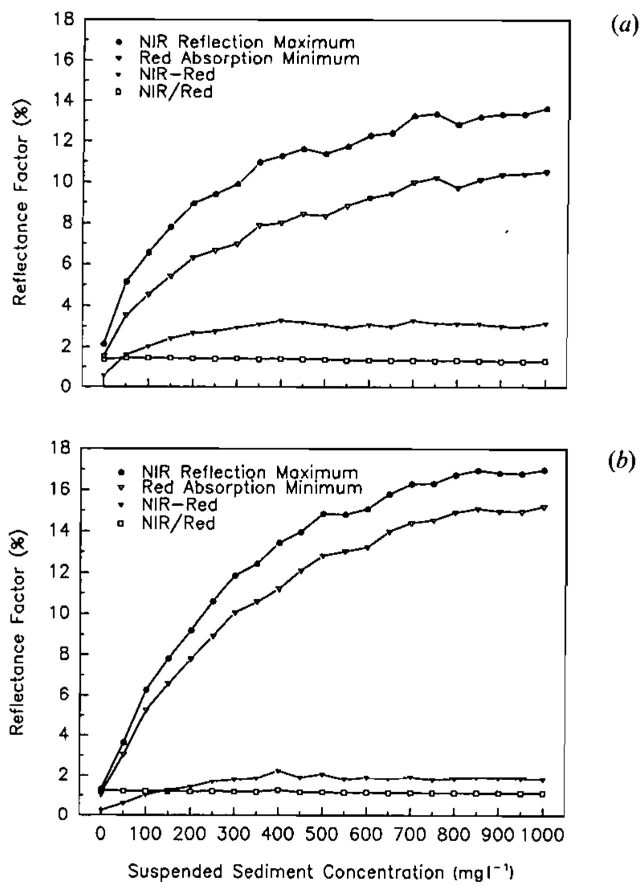

Figure 8. Magnitudes of NIR, red, NIR-red, and NIR/red with varying SSC: (*a*) experiment 1, and (*b*) experiment 2.

SSC concentration for both experiments (figure 8). First, for experiment 1, notice that reflectivity for both NIR and red tended to increase with increasing amounts of SSC (figure 8(*a*)). More specifically, at SSC densities of less then $350\,\mathrm{mg\,l^{-1}}$, the slope of the line summarizing NIR reflectance was slightly steeper than that for red reflectivity. At concentrations of more than $350\,\mathrm{mg\,l^{-1}}$, however, the rate of increased reflectance is approximately the same for both spectral regions. Experiment 2 displayed a similar pattern (figure 8(*b*)). Our findings seem to contradict Quibell (1991) who stated that 'sediments appeared to have equal additive effect at both the red and infrared wavelengths'.

Figures 8(*a*) and (*b*) also were used to compare the results of the two commonly used approaches, NIR/red and NIR-red. Notice that the plots for NIR minus red showed a slight positive relationship to concentrations of SSC, while the lines for NIR/red seemed totally independent of SSC. The Coefficient of Variation (CV), which allows comparison of variables measured in different units and different scales, indicated NIR/red (0·04 and 0·03 for experiments 1 and 2, respectively) to be less variable than NIR-red (0·23 and 0·29 for experiments 1 and 2). The mean of NIR/red values in experiment 1 was 1·36 while the mean of the ratios between NIR and red was 1·16 for experiment 2. The latter result was consistent with the documented trend showing a positive correlation between chlorophyll concentration and the ratio of the reflectance between NIR and red spectra (Mittenzwey *et al.* 1992).

4. Summary and conclusions

The research summarized in this paper highlights the importance of examining the effects of suspended sediments on algal chlorophyll in water. The intention is to precisely measure chlorophyll concentration in surface waters using remote sensing. The analysis of twenty levels of SSC, ranging from 50 to $1000\,\mathrm{mg\,l^{-1}}$ and two types of sediment applied to two different concentrations of algal chlorophyll in water, lead us to conclude: (1) the additive effects of SSC on per cent reflectance from algal-laden water occur at all wavelengths between 400 and 900 nm; (2) the relationship between reflectivity and SSC satisfies the expression: $d^2R(\lambda)/dS^2 < 0$; (3) the characteristic spectral signals from algal chlorophyll, the green, red and NIR, are not eliminated even as SSC reaches $1000\,\mathrm{mg\,l^{-1}}$; (4) the higher correlation ($r > 0{\cdot}9$) between mixed sediment-chlorophyll-water reflectance and SSC occurs at wavelengths longer than about 650 nm and the local lower correlations include the green and NIR reflectance maxima for chlorophyll; (5) positions of the green peak are shifted toward longer wavelengths with varying SSC; (6) the red minimum and NIR maximum show little or no impact from increased SSC, which provides a potential for use of red and NIR spectra in establishing indices for measuring chlorophyll when sediments exist; and (7) with the additive effects from SSC on the red and NIR being unequal, NIR/red seems to be totally independent of SSC, whereas NIR-red is not. Finally, we realize that further observations of the spectral responses at other chlorophyll concentrations are still required.

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