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The effect of sediment type on the relationship between reflectance and suspended sediment concentration

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Abstract. The use of remotely-sensed optical data to estimate the suspended sediment concentration (SSC) of water is dependent upon the correlation between SSC and reflectance. The *strength* of this relationship was hypothesized to vary with sediment type, as it is known that sediments, when dry, differ in their particle size distributions, colour and therefore reflectance properties. To test this, the reflectance of pure water with four concentrations of white clay and red silt were measured in the laboratory using a spectroradiometer. The correlation between SSC and reflectance varied with wavelength and sediment type. For white clay the correlations were very high ($r \simeq 0{\cdot}98$) in visible and near-infrared wavelengths but for the red silt it was lower ($r \simeq 0{\cdot}8$) in blue wavelengths increasing to much higher levels ($r \simeq 0{\cdot}98$) in blue/green and longer wavelengths. It was concluded that sediment type can affect the strength of the correlation between SSC and reflectance and that this will be most noticeable at shorter wavelengths.

1. Introduction

Several attempts have been made to estimate suspended sediment concentration (SSC) from the remotely-sensed reflectance of water (Ritchie *et al.* 1976, Holyer 1978, Munday and Alföldi 1979, Khorram 1981, Whitlock *et al.* 1982, Catts *et al.* 1985, Curran *et al.* 1987, Rimmer *et al.* 1987, Tassan 1987). However, little agreement has emerged on the strength, form or even the optimum wavelengths to be used in the relationship between SSC and remotely-sensed reflectance (reviewed in Curran and Novo 1988). It seems likely that this lack of agreement is the result of variation in the following factors: (i) the range of SSC (Rouse and Coleman 1976, McCauley and Yarger 1975, Moore 1977, Sydor 1980, Bukata *et al.* 1981 b) (ii) the particle size distribution (Sturm 1980, Whitlock *et al.* 1982), (iii) the particle shape (Bukata *et al.* 1981 a), (iv) the particle mineralogy (Witte *et al.* 1982), (v) the presence of covarying water substances such as chlorophyll and organic acids (Tassan and Sturm 1986), (vi) the geometry of measurement (Whitlock *et al.* 1981) and (vii) the areal, vertical and temporal variability of SSC (Curran *et al.* 1987, Bentley 1987).

It is clear that isolation and quantification of some or all of the above factors would enhance greatly the utility of remote sensing for water quality monitoring. The objective of this Letter is to examine the effect of sediment type (notably that of

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particle size and mineral colour) on the relationship between water reflectance and SSC in a controlled laboratory environment.

2. Theoretical background

The determination of SSC from water reflectance is based on the relationship between the absorption and scattering properties of water and its constitutents (Maul 1985). Thus, the absorption and scattering properties of sediment affect the overall water reflectance.

The spectral behaviour of sediments, however, is dependent on particle size distribution and mineral composition (Maul 1985, Bricaud and Sathyendranath 1981, Querry *et al.* 1977, Gordon 1974). The reflectance of dry sediment increases with a decrease in particle size (Myers and Allen 1968) and the same trend has been reported for sediment suspended in water (Moore 1977, Holyer 1978). For any given concentration, fine-grained material contains more particles and thus scatters more than would an equal weight of coarse-grained material. The effect of sediment spectra on water spectra is affected by both particle size and concentration, with large suspended particles at high concentrations producing a marked increase in water reflectance at visible wavelengths (Moore 1977). Some experimental results (Whitlock *et al.* 1978, Witte *et al.* 1982, McKim *et al.* 1987) suggest that distinctive water reflectance spectra are produced for high concentrations of different minerals as a result of sediment colour. Consequently, sediment colour may be expected to affect the relationship between SSC and reflectance.

On the basis of this theoretical background it was hypothesized that the strength of the correlation between SSC and reflectance is dependent upon sediment type.

3. Method

Variations in SSC were simulated in the laboratory by adding known amounts of sediment to 12 litres of pure water in a 0·5 m deep, black laboratory vessel. Two sediment types were used; a white industrial clay with a particle size distribution of 1–20 μm and a red natural silt from the Holderness coast of the U.K. (Mason 1985) with a particle size distribution of 7–37 μm.

Reflectance was recorded using a Geophysical Environmental Research Incorporated (GER), Mark IV Infrared Intelligent Spectroradiometer (IRIS) (GER 1987). This recorded over the wavelength range of 0·35–3·0 μm with a spectral resolution of 2 nm over the range 0·35–1·0 μm; 4 nm over the range 1·0–1·8 μm and 5 nm over the range 1·8–3·0 μm (Horsefall 1987). Of importance in this study was its ability to provide simultaneous measurements of both the water and a barium sulphate reference panel, with a 12-bit quantization, in just under a minute.

The sensor head was set to record vertically from a height of around 1 m. This ensured a reasonably sized target area of 20 cm × 5 cm for both the water and the reference panel. Illumination was provided by a 1000 W photoflood lamp adjusted to give a spatially uniform beam from a zenith angle of 60°.

Three spectra were recorded for the water and the reference panel for each sediment type and for each of the four levels of SSC (25, 50, 75 and 100 mg l^{-1}). For these spectra the dark-level current was subtracted; band numbers were linked to wavelength; gain was normalized with respect to wavelength; detector spectral response curves were standardized; reflectance of the water spectra was determined with respect to the barium sulphate reference panel and reflectance spectra of each sediment type and concentration was expressed as a mean of three spectra (Milton and Rollin 1987).

4. Results

4.1. *Reflectance spectra of pure water and dry sediment*

The reflectance spectra of pure water and two sediments were significantly different at the 99 per cent level of confidence (figure 1). The reflectance of pure water decreased from around 5 per cent in blue to less than 1 per cent in near-infrared wavelengths. Over the same spectral region the reflectance of white clay increased from around 60 per cent to over 80 per cent and the reflectance of red silt increased from under 10 per cent to a maximum of 40 per cent.

4.2. *Reflectance spectra of SSCs*

The relationship between reflectance and SSC depends on the joint effect of the water and sediment on the scattering/attenuation ratio. The contribution of SSC to this relationship can be extracted via a difference spectrum which represents the difference between the pure water reflectance and the reflectance of turbid water.

Difference spectra for SSCs of 25, 50, 75 and 100 mg l^{-1} are shown in figure 2 for both sediment types. At the lower concentrations the spectra for the white clay showed no discernable trends and remained fairly constant with wavelength except in the near-infrared where they declined sharply. The two higher concentrations showed similar peak and plateau reflectance differences in green before declining sharply in near-infrared wavelengths. The red silt difference spectrum was quite distinct from that of the white clay. From low reflectance differences in blue the maximum was achieved in red, with a slow decrease towards near-infrared wavelengths. In the whole spectral range, the reflectance difference of the red silt was much smaller than that of the white clay. For the higher concentrations (75 mg l^{-1} and 100 mg l^{-1}), the curves of the two sediment types were significantly different at the 99 per cent level of

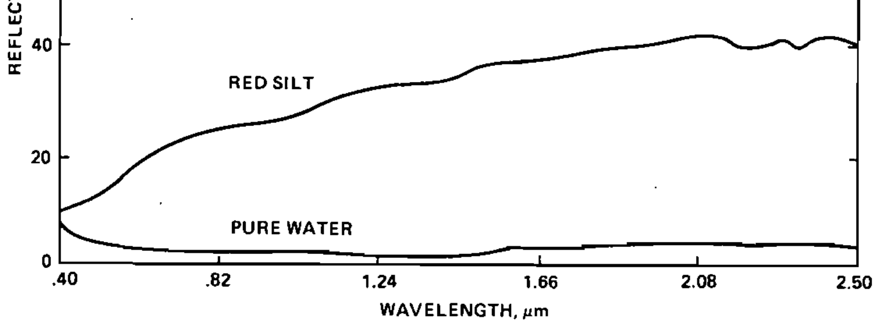

Figure 1. Spectral curves of dry white clay, dry red silt and pure water obtained using the IRIS Mark IV spectroradiometer.

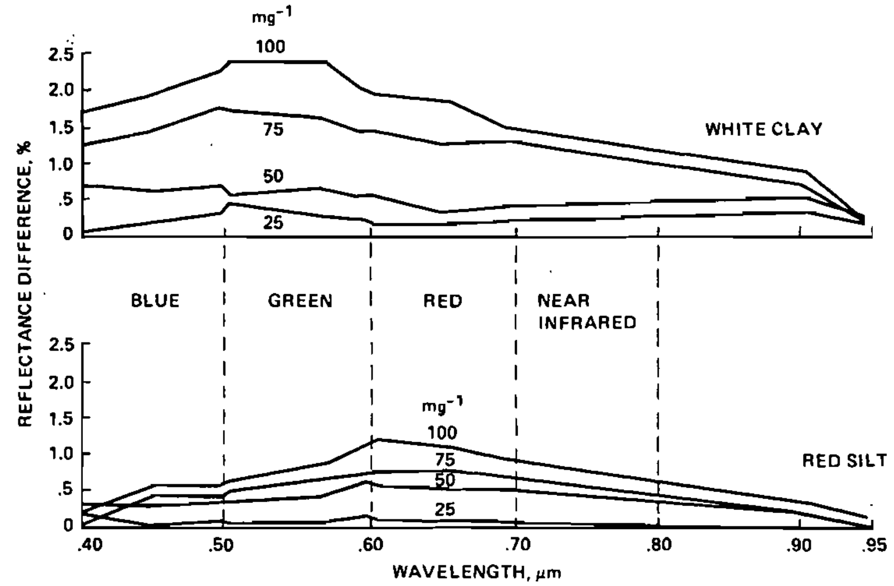

Figure 2. Difference reflectance spectra between SSC and pure water for the white clay and red silt sediments.

confidence. At lower SSCs the differences were less due to the increased contribution of water over sediment reflectance.

The strength of the relationship between SSC and reflectance was investigated by calculating Pearson correlation coefficients for blocks of visible and near-visible wavelengths (figure 3). The relationships between SSC and reflectance were strong, positive and significant at the 99 per cent level of confidence, with the exception of red silt in blue wavelengths.

5. Discussion

The spectral curves for both dry sediments were in agreement with work elsewhere which shows that fine sediments have higher reflectances than coarser sediments at all wavelengths (e.g., Myers and Allen 1968). Similarly, there were strong relationships between SSC and reflectance as has been noted by Curran *et al.* (1987) (figure 2). Since the reflectance of pure water was relatively low, the reflectance difference between turbid water and pure water (figure 2) was a useful tool in identifying differences in the reflectance contributions of the two sediment types. The white clay displayed higher reflectivity than the red silt and this is in agreement with Holyer (1978) who showed that SSC reflectance increased as particle size decreased. However, as figure 2 indicates, this effect was much less important in the longer wavelengths as reflectance dropped rapidly in the near-infrared in spite of high SSC and sediment reflectivity. The coarser red silts had low reflectance in the shorter wavelengths, probably due to increased absorption by coarse particles and as a result, the SSC reflectance was not substantially different from that of pure water.

The uniform reflectance of the fine SSCs across the visible range was supported by consistently high correlations between SSC and reflectance (figure 3) suggesting that

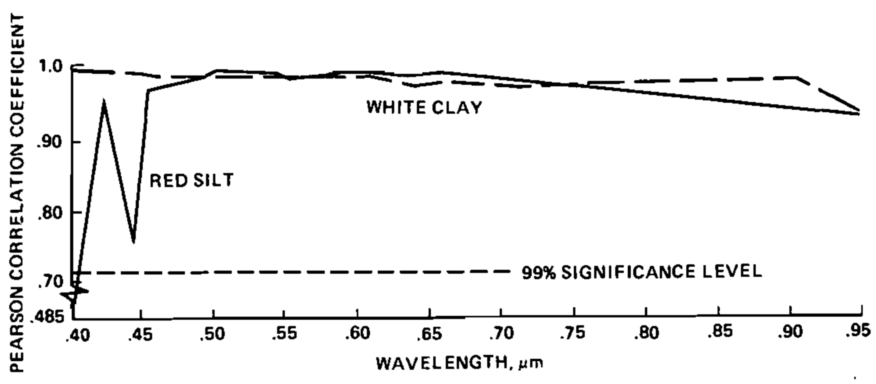

Figure 3. Correlation between SSC and water reflectance for the white clay and red silt sediments. The results are significant at the 99 per cent level of confidence, except in the blue region for red silt.

these fine particles behave primarily as scatterers. However, the coarser particles absorb more strongly in the visible wavelengths and this produces low and insignificant correlations in the blue region. The strength of the relationships is primarily dependent on the reflectance differences between pure water and SSC. For example, the difference spectra for red silt (figure 2) had low and declining values (0·25 per cent) in blue wavelengths. Dry red silt (figure 1) had low reflectance in the blue which contrasts with a relatively high reflectance from pure water in this wavelength region (e.g., Jerlov 1976). So, in these wavelengths, the SSC reflectance measured by the sensor are related principally to pure water reflectance, and thus correlations between reflectance and SSC will necessarily be low. As the water scatter decreases towards the red region and the red silt reflectance increases to a peak, the correlation coefficients climb rapidly to that of the white clay. As a result of scattering, the correlation coefficients for the white clay are high across all the wavelengths and not only in the red wavelengths as suggested for fine sediments by McCluney (1976) and Holyer (1978).

6. Conclusions

The strength of the relationship between SSC and water reflectance was affected by sediment type, with the fine white sediment showing significant differences from the coarse red sediment.

The low reflectivity of coarse red silt (<10 per cent) and the relatively high reflectance of pure water renders turbid water reflectance in the blue region insensive to the SSC of coarse red silt. The effect of sediment type may, therefore, be to define the spectral region where the highest correlation and reflectance difference between SSC and water reflectance should be expected.

Fine-grained sediments may result in a spectrally more uniform strength of correlation between SSC and reflectance in visible wavelengths since they behave mainly as scattering particles rather than absorbing particles.

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