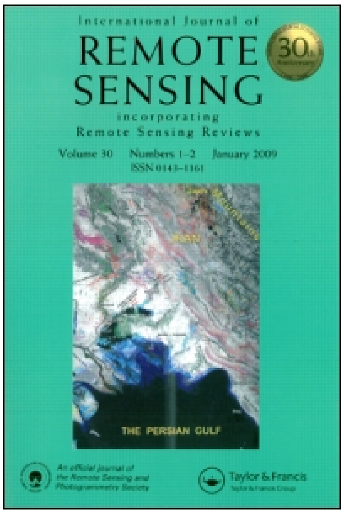

International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713722504

Spectral irradiance profiles of suspended marine clay for the estimation of suspended sediment concentration in tropical waters

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To cite this Article Gin, K. Y. -H. , Koh, S. T. andLin, I. -I.(2003) 'Spectral irradiance profiles of suspended marine clay for the estimation of suspended sediment concentration in tropical waters', International Journal of Remote Sensing, 24: 16, 3235 — 3245

To link to this Article: DOI: 10.1080/01431160110114934

URL: http://dx.doi.org/10.1080/01431160110114934

INT. J. REMOTE SENSING, 2003, VOL. 24, NO. 16, 3235–3245

Spectral irradiance profiles of suspended marine clay for the estimation of suspended sediment concentration in tropical waters

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(*Received 23 August 1999; in final form 2 August 2001*)

Abstract. Reflectance spectra of water containing varying concentrations of organic and inorganic sediments isolated from the coastal waters of Singapore were measured using a portable spectroradiometer under controlled experimental conditions and natural sunlight. The effect of different sizes of sediments on the spectral profile of water was also investigated. In the presence of organic sediments, maximum reflectance of water was observed over a broad band between 440–580 nm, with a peak reflectance at about 550 nm, followed by two smaller peaks at 600–645 nm and 665–690 nm. In contrast, inorganic sediments produced a distinct band peak between 595 and 690 nm. For both sediment types, characteristic features in the infra-red region include a reflectance trough at 754 nm and peak at 814 nm. The empirical colour ratios, OD550/OD754 and OD 595/OD754, were used to estimate the organic and inorganic sediment concentrations respectively. In the case of organic sediments, a power function was found to fit the data well ($R^2=0.89$–0.98), whereas a linear fit was found for inorganic sediments ($R^2=0.53$–0.86). In general, decreases in particle size resulted in overall increases in spectral reflectance.

1. Introduction

With increasing coastal developments, there is a pressing need for robust and effective means of monitoring large areas of coastal waters. Satellites with ocean colour sensors provide such a tool for monitoring seawater as they have the advantage of providing synoptic views of algal and suspended matter distributions, thus allowing an assessment of the overall trophic state of the water body. From the remote sensing perspective, waters can be generally divided into two classes: Case 1 and Case 2. Case 1 waters refer to phytoplankton dominating water (e.g. open oceans) whereas Case 2 waters refer to coastal waters which contain resuspended

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2003 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160110114934

sediments, terrigenous particles from river and glacial runoff, dissolved organic matter (yellow substances) and anthropogenic substances (Nichol 1993). Human activities such as treated effluent discharges from sewage treatment plants, land reclamation activities, fish farms, and erosion generally affect Case 2 waters.

Algal chlorophyll, suspended sediments and dissolved organic substances are the three optically active factors that affect water quality. While many studies have been carried out for temperate waters (Ritchie *et al.* 1990, Ann Gallie and Murtha 1992, Gitelson 1993, Arenz *et al.* 1996, Thiemann and Kaufmann 2000), there are fewer studies for tropical coastal waters where the interaction of different factors may be at work. In particular, the effect of suspended sediments (including different sediment composition and type) on the spectral signatures of tropical water bodies needs to be explored further. Suspended sediments can have a significant effect on primary production in several ways: (1) they increase the attenuation of light, therefore reducing the light availability for photosynthesis by plants; and (2) they may sorb selected nutrients (e.g. phosphate) in the water column, rendering them less available for algal uptake. Several studies have been conducted to address the impact of suspended sediments on the spectral profile of surface waters (Doerffer *et al.* 1989, Ritchie *et al.* 1990, Goodin *et al.* 1993, Han and Rundquist 1994). One study indicated that the addition of particulates generally increases reflectance at wavelengths longer than 550 nm (Quibell 1992). Another study showed that an increase in suspended sediments increases the overall reflectance of algal-laden waters relatively uniformly between wavelengths of 400 nm and 900 nm; however, for higher concentrations of sediments (i.e. between 350 and 650 mg l^{-1}), the pattern of surface reflectance increase was less clear, especially for concentrations greater than 700 mg l^{-1} (Han *et al.* 1994). 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 (Lodhi *et al.* 1997, Bhargava and Mariam 1990, 1991).

In general, it appears that there is no standard algorithm for the estimation of suspended sediments in Case 2 coastal waters due to the complex nature and compositions of suspended sediments. Suspended sediments can be divided broadly into organic and inorganic sediments: organic sediments are derived mainly from decomposition of dead organisms in the water, while inorganic sediments (tripton) originate from the erosion of mineral rocks. Different sizes and compositions of organic and inorganic sediments will have varying optical effects on the spectral characteristics of surface waters. For the tropical coastal waters around Singapore, fine marine clays play an important role in the suspended sediments. In order to investigate the effects of varying concentrations and composition of marine sediments on the spectral signature of surface waters, a controlled experiment was set up in which reflectance spectra were measured and used to derive colour ratios for estimating concentrations of suspended sediments in the tropical coastal waters of Singapore.

2. Methods

Marine sediments (predominantly marine clay) were collected from the seabed near the southern tip of Singapore (1°12′ N, 103°18′ E). The sediments were classified as organic and inorganic according to the following treatments. For the organic sediments, water was added to form a slurry, which was then wet-sieved using 63 μm (steel), 20 μm (nylon) and 10 μm (nylon) meshes, respectively. For the inorganic sediments, the organic fraction was removed by burning the sediments in a furnace at 550°C for 24 hours until all the sediments solidified giving an orange-brown appearance (APHA 1995). The solidified sediments were then pounded and blended into powder form using an electric blender. Water was then added and mixed with the powdered inorganic sediments, followed by the wet-sieving procedure mentioned earlier.

Different amounts of sediments were poured into a fiber glass tank (1.2 m × 1.2 m × 1.2 m) filled with water to a depth of 1 m (figure 1). The inner walls of the tank were painted black to minimize 'bottom' effects and reflectance of light off the walls. A portable spectroradiometer (GER 1500) was mounted on a steel bar across the tank. The spectroradiometer covers the ultra-violet (UV), visible and near-infrared (NIR) wavelengths from 350 nm to 1050 nm and uses a diffraction grating with a silicon diode array to read 512 spectral bands. The spectroradiometer was mounted in such a way (perpendicular to the horizontal bar) to achieve nadir view angle. The effects of atmospheric dispersion and absorption of light were considered negligible as the distance of the spectroradiometer from the water surface was fixed at 0.5 m. Incident radiance from the sun was measured by taking readings off a Teflon diffusing screen (Labsphere Spectralon reflective target) which was specially designed and calibrated to reflect natural white light with minimum absorption. Since Singapore has significant cloud cover, the effects of differences in the intensity of light were reduced by taking the percentage reflectance, R, defined as:

$$R = T/L \times 100 \tag{1}$$

where T is the wavelength specific target radiance and L is the corresponding radiance off the Labsphere Spectralon reflective target.

The experiment was conducted between 1300 hours to 1400 hours. Initial reflectance readings were taken for the water tank prior to the addition of any suspended sediments and subsequently after sediments were mixed into the tank. Water samples were then collected for measurement of suspended matter and filtered

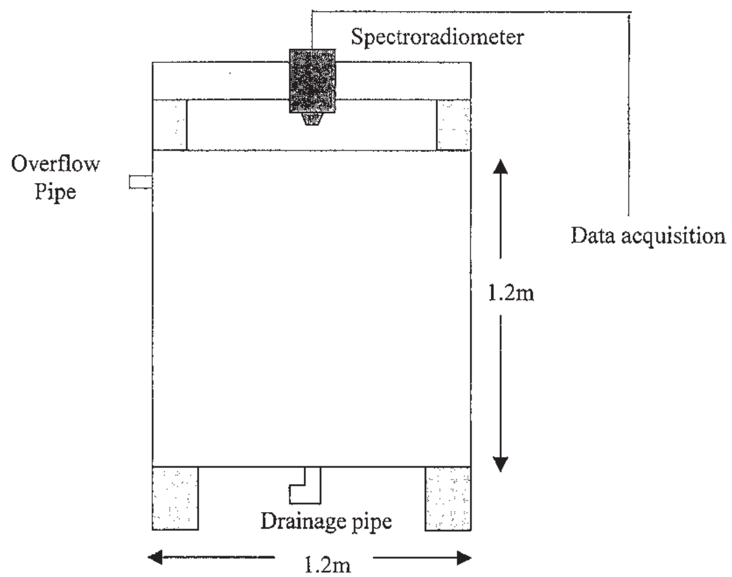


Figure 1. Experimental set up for the study of the spectral profile of suspended sediment.

through 0.7 μm Whatman GF/F filter papers. The filters were dried at 105°C in an oven for 2 hours and left in a dessicator overnight. This process was repeated until a constant reading was achieved. The concentration of suspended sediments was calculated using the formula below:

$$\text{Suspended sediments (mg l}^{-1}) = (M_s - M_0)/\text{volume of sample } (L) \qquad (2)$$

where M_s is the dry mass of sample (mg) and M_0 is the dry mass of blank filter paper (mg).

3. Results and discussion

In the absence of particulate material, the spectral reflectance of water in the tank ranges from 0.2% to about 1.3% (figure 2). The low reflectance is mainly due to the black inner walls of the tank, which absorb much of the incident light. Maximum reflectance is recorded in the visible range from about 440 nm to 580 nm, with secondary peaks at 654 nm and 690 nm. High absorption is observed beyond 740 nm in the near infra-red band. Considerable fluctuations in the profile are observed below 340 nm and above 930 nm due to noise interference. The addition of organic sediments generally causes the overall reflectance of water to increase (figure 3). As with water alone, maximum reflectance is observed as a broad band between 440 nm and 580 nm. Subsequent increases in suspended sediment load generally lead to a shift in the reflectance spectral profile upwards. This observation agrees with Han *et al.* (1994) who observed a uniform increase at most wavelengths between 400 nm and 900 nm as sediment concentrations increased from 0 to 300 mg l^{-1}. However, in our study, the broad maximum peak tends to become narrower and more prominent as sediments are added (peak at ~550 nm). In the infra-red region, relatively high absorption is observed in the 740–780 nm wave band. This is followed by a small reflectance peak at about 814 nm.

To investigate the effects of smaller sized particles, suspensions of organic sediments less than 20 μm and less than 10 μm were also measured (figure 3*b*, *c*). Small sized particles play an important role in the coastal waters of Singapore as particles less than 10 μm often comprise more than 85% of total particle counts (data not

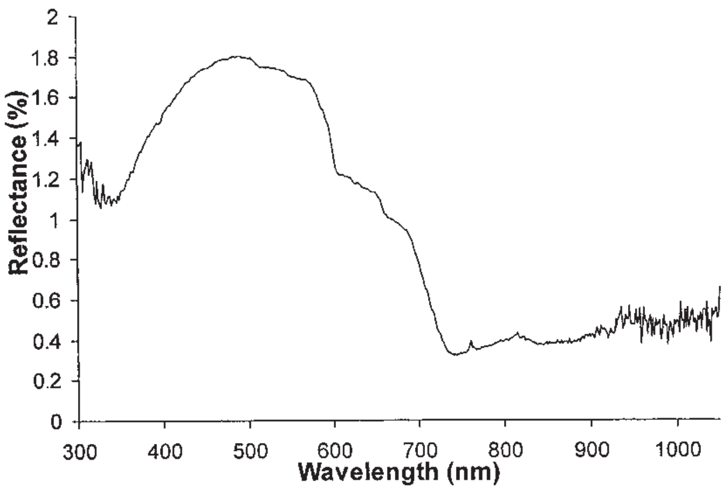


Figure 2. A typical spectral profile for water free of sediments.

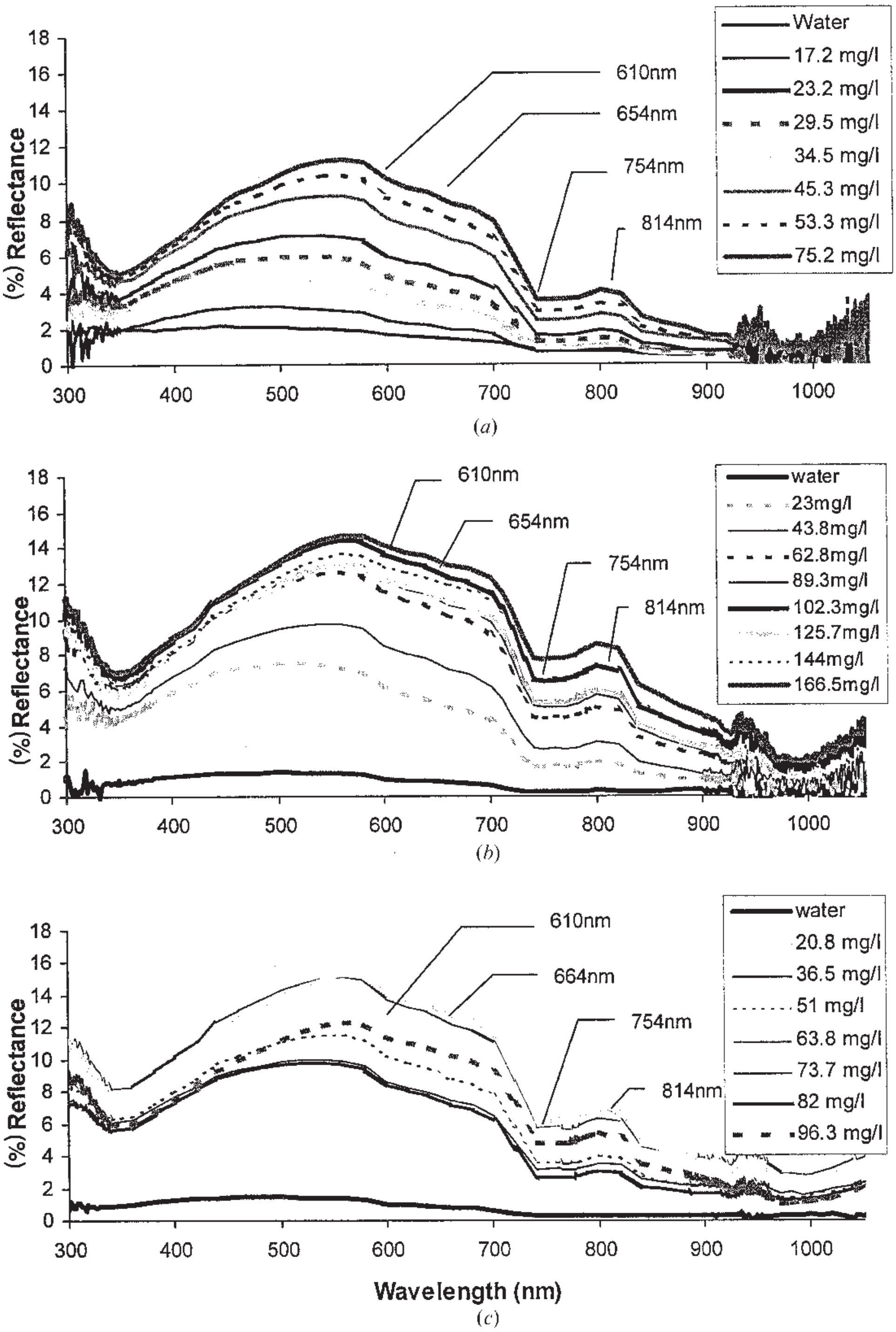


Figure 3. Spectral profiles for water with varying concentrations of organic sediments (*a*) less than 63 μm, (*b*) less than 20 μm, and (*c*) less than 10 μm. Salient points of absorption and reflectance wavelengths are indicated.

shown). A comparison of the three graphs in figure 3 shows that the optical signature trends are generally similar. However, in some cases an increase in suspended sediments added did not necessarily result in an increase in overall reflectance (figure 3*b*, *c*). This is probably due to changes in cloud cover and ambient light intensity since the measurements for the different size fractions were carried out on different days. This discrepancy can be avoided if colour ratios are used (see below). In addition, for similar suspended sediment content, the smaller sized sediments generally gave a higher percentage spectral reflectance, e.g. for sediments less than 63 μm, a suspended sediment concentration of 75 mg l^{-1} gave a maximum reflectance of about 11% at 570 nm, whereas for sediments less than 10 μm at a suspended sediment concentration of 64 mg l^{-1}, a maximum reflectance of about 15% was observed at the same wavelength.

In the case of inorganic sediments (i.e. burnt sediments), the reflectance spectra generally show greater absorption between 368 nm to 568 nm in the visible band as compared to organic sediments (figure 4). In addition, the reflectance peak is phase-shifted to 590–690 nm compared to 530–570 nm for the organic sediments. This is more clearly illustrated in figure 5 where the spectral profiles of organic and inorganic sediments (with comparable suspended sediment concentrations) are presented.

The suspended marine sediments found off the coast of Singapore appear to give different spectral reflectance characteristics in the 400–700 nm waveband, depending on whether organic matter is present in the sediments. Lodhi *et al.* (1997) found that suspended dark clayey soil and light silty soil could be distinguished in the waveband from 580–690 nm, with clays giving a more prominent reflectance peak at about 680 nm whereas silty soil gave a broad band peak from 570–680 nm. However, these differences only became apparent for high levels of suspended solids, from 300 mg l^{-1} to 1000 mg l^{-1}. In the coastal waters of Singapore, typical suspended solids range from about 2 to 100 mg l^{-1} (Gin *et al.* 2000), therefore the suspended sediment concentrations conducted in this study were typically less than 100 mg l^{-1}. Nevertheless, it is noted that the spectral reflectance profiles (especially for inorganic sediments $<20\,\mu$m) found in our study are similar to those of the silty soil in the study by Lodhi *et al.* (1997). In both cases of organic and inorganic sediments, particles of smaller size generally exhibit a higher overall reflectance due to the greater surface area available for scattering of light, consistent with the study by Bhargava and Mariam (1991).

One of the main differences between the spectral reflectance profiles for organic and inorganic sediments in our study is the shift in the reflectance peak to lower wavelengths ($\sim$550 nm) for organic sediments. While dissolved organic matter in water generally increases absorption in the blue and UV wavelengths (Mobley 1994, Jorgenson 1999), the presence of organic matter bound to the sediments actually appears to give greater reflectance in the blue compared to inorganic sediments of comparable size (figure 5). In addition, relatively greater absorption in the red is observed compared to the inorganic sediments. In contrast, Arenz *et al.* (1996) showed an enrichment of the spectrum in the red spectral range for waters containing both tripton and dissolved organic matter. This discrepancy could be due to the different compositions of organic matter and the way in which they bind to the sediments.

For the infra-red region (above 740 nm), both the spectral profiles of organic and inorganic sediments follow similar trends, with high absorption between 745–760 nm, and reflectance peaks at about 814 nm. These characteristics are similar to those

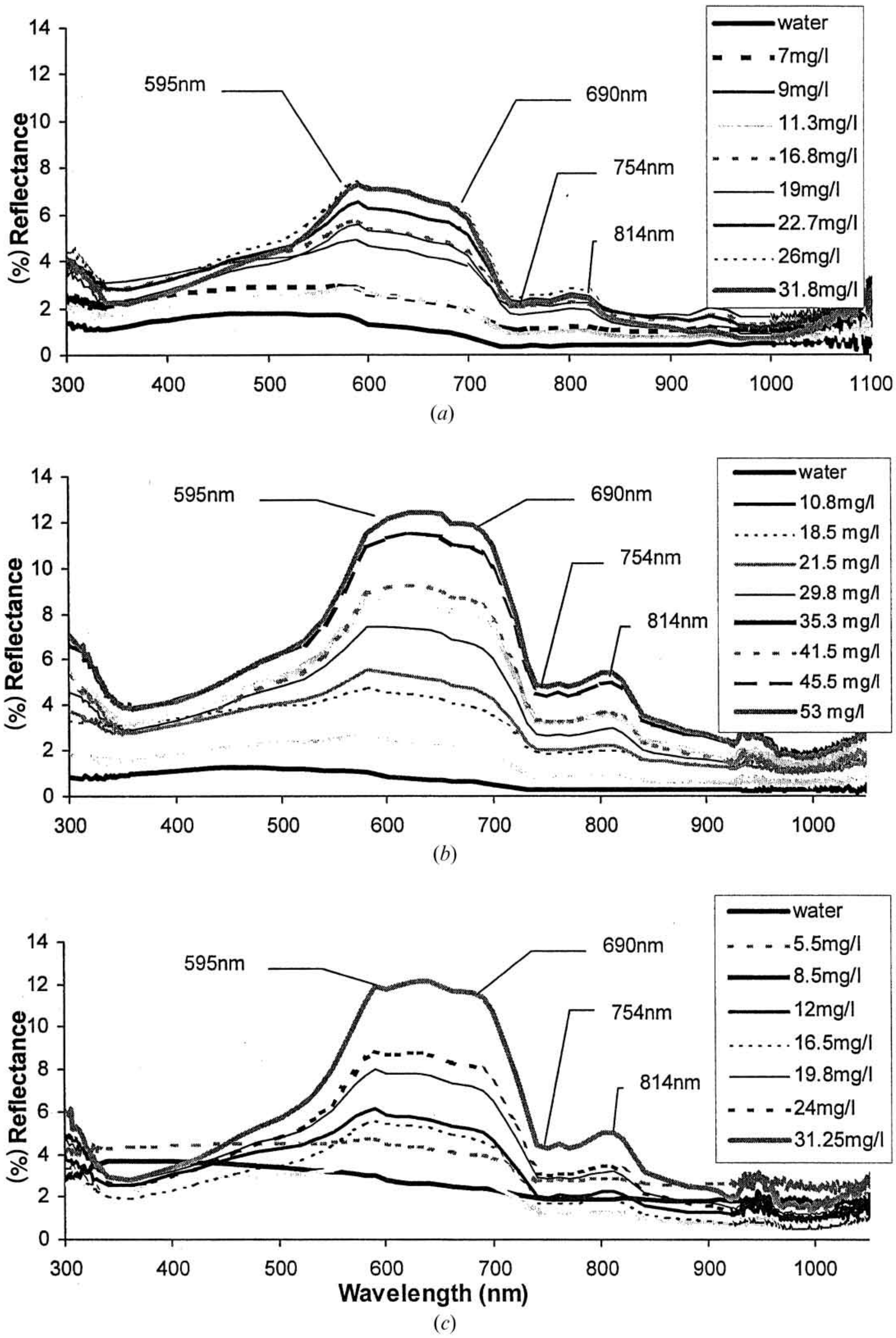


Figure 4. Spectral profiles for water with varying concentrations of inorganic sediments (*a*) less than 63 μm, (*b*) less than 20 μm, and (*c*) less than 10 μm. Salient points of absorption and reflectance wavelengths are indicated.

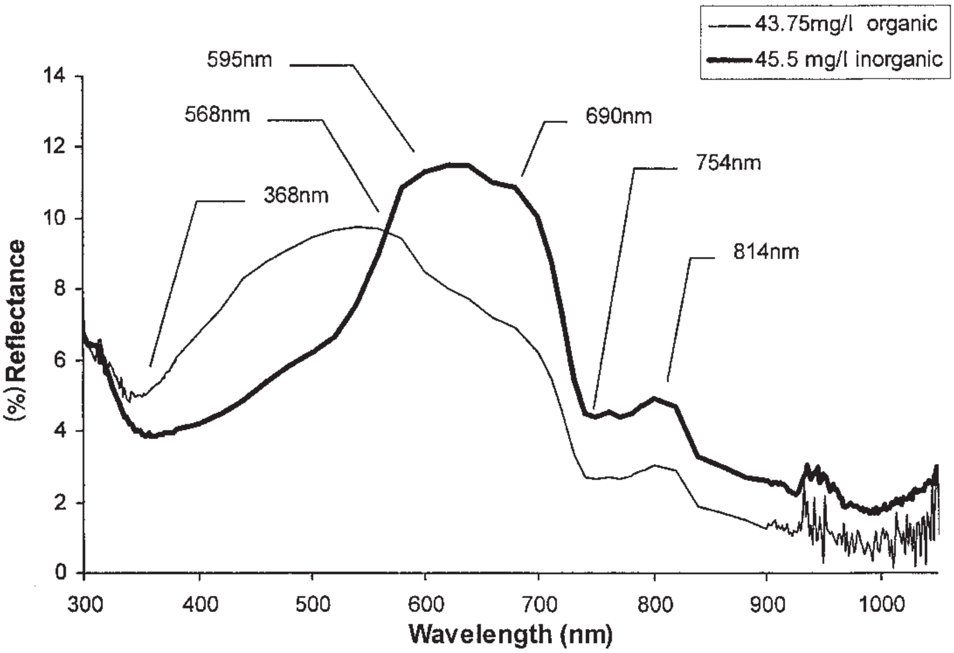
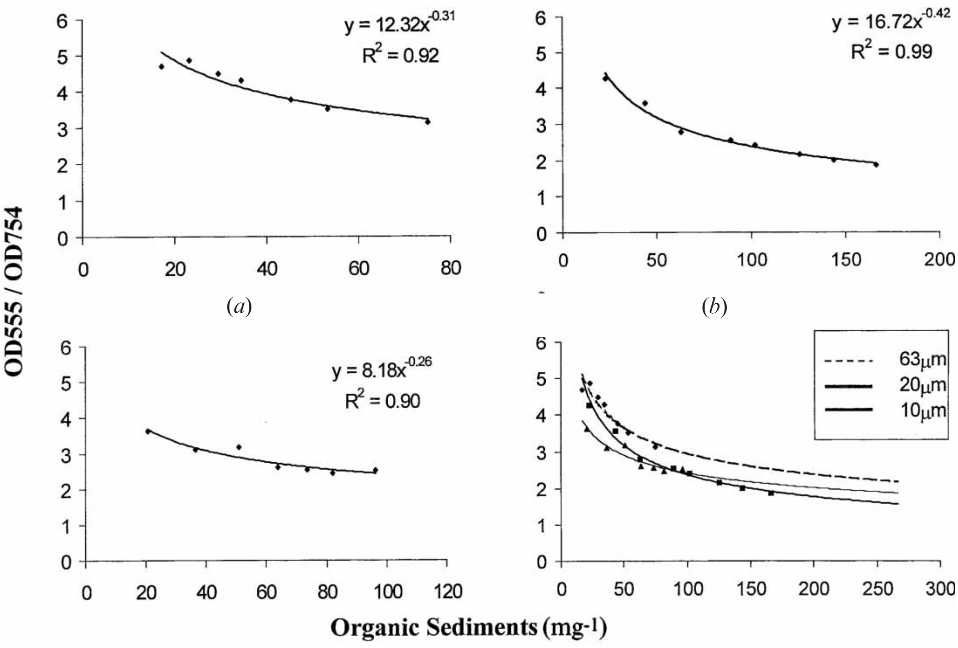


Figure 5. Comparison of spectral profiles of organic and inorganic sediments less than 20 μm. Salient points of absorption and reflectance wavelengths are indicated.

found in other studies of suspended sediments in surface waters and wavelengths in this region have been recommended for determining the concentrations of suspended sediments in waters (Lodhi *et al.* 1997, Arenz *et al.* 1996, Han and Rundquist 1994). Using data from the spectral profiles in this study, colour ratios were derived for estimating the concentrations of suspended organic and inorganic sediments. Colour ratios normally involve two wavelengths: one corresponding to high reflectance and the other to high absorption (Gordon *et al.* 1980). For organic sediments, maximum reflectance is observed over a wide band from 415 to 610 nm for low concentrations of organic sediments but this band narrows to between 500 and 610 nm for higher concentrations. Maximum absorption at 754 nm in the infra-red band is found to be consistent regardless of the size and concentration of particles. Thus, a colour ratio of OD555/OD754 was chosen for correlation with suspended sediment concentrations (figure 6). In general, a power function, $Y = AX^{-b}$ (where Y = sediment concentrations; X = colour ratio OD555/OD754; A and b are constants) gives the best fit, with an R^2 of 0.90 to 0.98. As the concentration of organic sediments is increased, the colour ratio OD555/OD754 decreases until it appears to reach a constant value. This observation complies with that made by Han *et al.* (1994), who found that at high sediment levels between 300 and 600 mg l^{-1}, the pattern of reflectance increase becomes less clear. Extrapolations of the three power functions to 300 mg l^{-1} show that the curves tend to an OD555/OD754 ratio of about two.

For inorganic sediments, maximum absorption is observed to be the same as that of the organic sediments (i.e.754 nm) while maximum reflectance is obtained from 595–690 nm (average 643 nm). Using a colour ratio of OD595/OD754, linear regressions are obtained with R^2 values of 0.53, 0.86 and 0.72 for sediment sizes less than 63 μm, 20 μm and 10 μm, respectively (figure 7). The reason for a lower R^2 value



(c) (d)

Figure 6. Correlations between the colour ratio OD555/OD754 and organic sediment concentration for (*a*) less than 63 μm, (*b*) less than 20 μm, (*c*) less than 10 μm, and (*d*) the three graphs (*a*, *b*, *c*) have been extrapolated to higher sediment concentration using the power functions derived from the experimental data points.

in the case of sediments less than 63 μm is likely due to the settling of larger particles according to Stoke's Law. Furthermore, with the removal of the organic fraction, the density of inorganic sediments is generally greater than that of organic sediments and this also has the effect of increasing the settling velocity. For smaller sediments with lower settling velocity, the correlation between OD595/OD754 and sediment concentration generally gave a better fit, with R^2 of 0.86 and 0.72 for sediments less than 20 μm and 10 μm, respectively (figure 7*b*, *c*). In both cases of inorganic and organic sediments, the regression slope is negative, implying relatively greater absorption at the green wavelengths but higher reflectance in the infra-red region for higher sediment concentrations.

The implication of these results is that the spectral bands corresponding to OD595, OD555 and OD754 are sensitive wavelengths for the estimation of suspended sediment concentrations in the coastal waters of Singapore. With the launch of new, high-resolution ocean colour sensors, remote sensing can be used for this purpose. This is particularly important for monitoring tropical coastal waters in South East Asia where most of the suspended sediments are dominated by marine clay.

4. Conclusions

By studying the reflectance spectra of inorganic marine sediments suspended in water, it was found that the dominant reflectance peak lay between 595 and 690 nm, compared to a broader maximum, ranging from 440 to 580 nm (peak at about 555 nm) for organic sediments. For both organic and inorganic sediments, similar

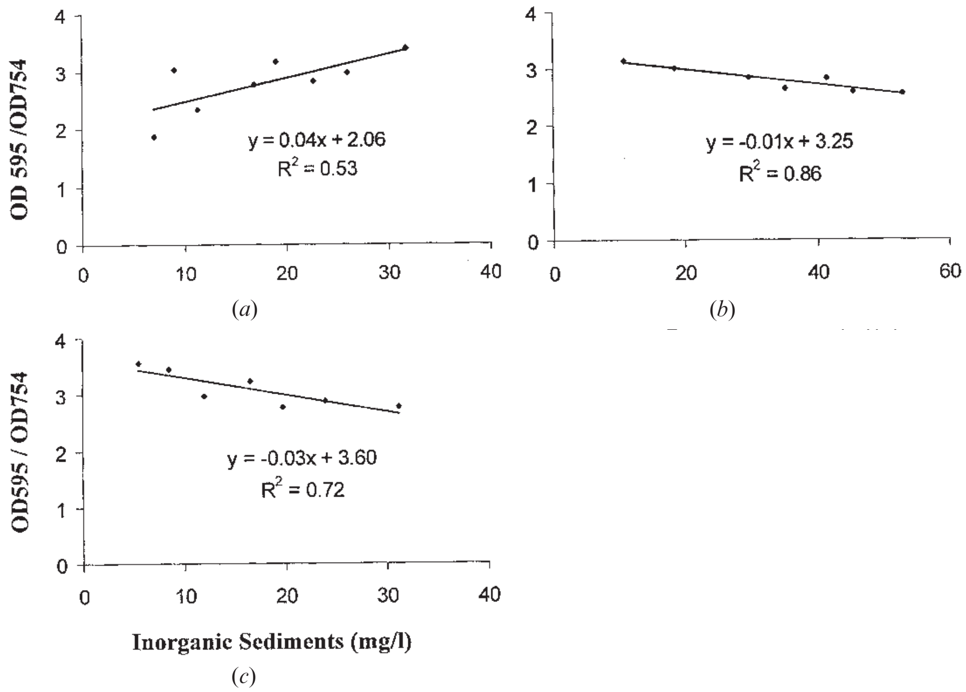


Figure 7. Linear regression showing relationships between OD595/OD754 and inorganic sediment concentration (*a*) less than 63 μm, (*b*) less than 20 μm, and (*c*) less than 10 μm.

characteristic features were found in the infra-red region of the reflectance spectra, with a distinct trough at about 754 nm and peak at 814 nm. Smaller sized particles led to greater scattering, and therefore an overall increase in spectral reflectance.

Using these spectral profiles, colour ratios were derived for the estimation of suspended sediment concentrations. In the case of organic sediments, a colour ratio of OD550/OD754 was found to give the best correlation (R^2 = 0.89–0.98). Power functions of the form $Y = AX^{-b}$ were found to best describe the relationship between colour ratio and suspended organic sediment concentration. In the case of inorganic suspended sediments, the colour ratio OD595/OD754 was found to give linear fits with suspended sediment concentrations (R^2 = 0.53–0.86). Sediments less than 20 μm generally gave better correlations. The implications of these results are that the spectral bands corresponding to OD595, OD555 and OD754 are sensitive wavelengths for the estimation of marine clay suspensions, which are abundant in the tropical coastal waters of South East Asia.

Acknowledgments

The authors would like to acknowledge the Maritime and Port Authority of Singapore for their vessel support; Michael Tan and hydraulic laboratory technicians for their assistance in the collection of marine sediments and last but not least, Victor Khoo, Brian Phan Seow Fong, Adrian Tay Hwang Jian and Kenneth Ang Han Guan for their assistance in taking spectroradiometric readings.

References

Ann Gallie, E., and Murtha, P. A., 1992, Specific absorption and backscattering spectra for suspended minerals and chlorophyll-a in Chilko Lake, British Columbia. *Remote Sensing of Environment*, **39**, 103–118.

Apha, 1995, *Standard Methods for the Examination of Water and Wastewater*, 19th edn (Baltimore, MD: United Book Press Inc.)

Arenz Jr, R. F., Lewis Jr, W. M., and Saunders III, J. F., 1996, Determination of chlorophyll and dissolved organic carbon from reflectance data for Colorado reservoirs. *International Journal of Remote Sensing*, **17**, 1547–1566.

Bhargava, D. S., and Mariam, D. W., 1990, Spectral reflectance relationships to turbidity generated by different clay materials. *Photogrammetric Engineering and Remote Sensing*, **56**, 225–229.

Bhargava, D. S., and Mariam, D. W., 1991, Effects of suspended particle size and concentration on reflectance measurement. *Photogrammetric Engineering and Remote Sensing*, **57**, 519–529.

Doerffer, R., Fisher, J., Stossel, M., and Brockman, C., 1989, Analysis of thematic mapper data for studying the suspended matter distribution in the coastal area of the German Bight (North Sea). *Remote Sensing of Environment*, **28**, 61–73.

Gin, K. Y. H., Lin X., and Zhang, S., 2000, Dynamics and size structure of phytoplankton in the coastal waters of Singapore. *Journal of Plankton Research*, **22**, 1465–1484.

Gitelson, A., 1993, Algorithms for remote sensing of phytoplankton pigments in inland waters. *Advanced Space Research*, **13**, 197–201.

Goodin, D. G., Han, L., Fraser, R. N., Rundquist, D. C., Stebbins, W. A., and Schalles, J. F., 1993, Analysis of suspended solids in water using remotely sensed high resolution derivative spectra. *Photogrammetric Engineering and Remote Sensing,* **59**, 505–510.

Gordon, H. R., Clark, D. K., Mueller, J. L., and Hovis, W. A., 1980, Phytoplankton pigments from the Nimbus-7 Coastal Zone Colour Scanner: comparison with surface measurements. *Science,* **210**, 63–66.

Han, L., and Rundquist, D. C., 1994, The response of both surface reflectance and the underwater light field to various levels of suspended sediments: preliminary results. *Photogrammetric Engineering and Remote Sensing*, **60**, 1463–1471.

Han, L., Rundquist, D. C., Liu, L. L., Fraser, R. N., and Schalles, J. F., 1994, The spectral responses of algal chlorophyll in water with varying levels of suspended sediments. *International Journal of Remote Sensing*, **18**, 3707–3718.

Jorgenson, S. V., 1999, Standard Case 1 algorithms in Danish coastal waters. *International Journal of Remote Sensing*, **20**, 1289–1301.

Lodhi, M. A., Rundquist, D. C., Han, L., and Kuzila, M. S., 1997, The potential for remote sensing of loess soils suspended in surface waters. *Journal of the American Water Resources Association*, **33**, 111–117.

Mobley, C. D., 1994, *Light and Water: Radiative transfer in natural waters*. (San Diego, California: Academic Press) pp. 85–90.

Nichol, J. E., 1993, Remote sensing of water quality in the SingaporeJohor-Riau growth triangle. *Remote Sensing of Environment*, **43**, 139–148.

Quibell, G., 1992, Estimating chlorophyll concentrations using upwelling radiance from different fresh water genera. *International Journal of Remote Sensing*, **13**, 2611–2621.

Ritchie, J. C., Cooper, C. M., and Schiebe, F. R., 1990, The relationship of MSS and TM digital data with suspended sediments, chlorophyll and temperature in Moon Lake, Mississippi. *Remote Sensing of Environment*, **33**, 137–148.

Thiemann, S., and Kaufmann, H., 2000, Determination of chlorophyll content and trophic state of lakes using field spectrometer and IRS-1C satellite data in the Mecklenburg Lake District, Germany. *Remote Sensing of Environment*, **73**, 227–235.