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The Relationship Between Suspended Sediment Concentration and Remotely Sensed Spectral Radiance: A Review

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ABSTRACT

CURRAN, P.J. and NOVO, E.M.M., 1988. The relationship between suspended sediment concentration and remotely sensed spectral radiance: A review. *Journal of Coastal Research,* 4(3), 351–368. Charlottesville (Virginia), ISSN 0749-0208.

Information on the concentration of suspended sediments in coastal waters is necessary for the understanding and management of the coastal environment. Traditionally, suspended sediment concentration (SSC) has been measured by time-consuming and costly boat surveys which allow the accurate measurement of SSC for single points in space and time. Remote sensing from airborne and spaceborne sensors has proved to be a useful adjunct to such surveys as it provides an instantaneous and synoptic view of sediments that would otherwise be unavailable. The key to the success of remote sensing in such a role is the strong positive relationship that exists between SSC and remotely sensed spectral radiance ($L_{(\lambda)}$).

This review provides an introduction to this SSC/$L_{(\lambda)}$ relationship; exploring its physical basis, its robustness under a range of environmental conditions and its utility as a tool for estimation. It is concluded that future research on this relationship should concentrate upon the suppression of environmental influences and the optimum sampling of SSC.

ADDITIONAL INDEX WORDS: *Suspended sediment concentration, remote sensing, statistical relationship, environmental effects, estimation.*

INTRODUCTION

The estimation of suspended sediment concentration (SSC) over large areas of water using *in situ* sampling is lengthy, expensive and often inaccurate. Remotely sensed spectral radiant $L_{(\lambda)}$ measured by aircraft or satellite sensors can provide an alternative, synoptic, speedy and economic method for assessing the SSC of reservoirs (RITCHIE *et al.,* 1976); lakes and rivers (GOLDMAN *et al.,* 1974; McKIM *et al.,* 1984) and coastal waters (KHORRAM, 1979; 1981a; 1985; LINDELL *et al.,* 1985; CURRAN and WILKINSON, 1985). Such information is useful for the management of water quality (SCHERZ, 1972; McCAULEY and YARGER, 1975; BNSC, 1986); the monitoring of water pollution (JOHNSON and HARRIS, 1980) and the modelling of sediment distribution in estuarine environments (CATTS *et al.,* 1985) and sediment budgets in coastal zones (MASON, 1985).

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Many studies have reported on the high correlations between SSC and $L_{(\lambda)}$ (HOLYER, 1978; JOHNSON and MUNDAY, 1983; FISCHER, 1985). However, relatively few studies have proceeded to the next stage where $L_{(\lambda)}$ is used to estimate SSC (WHITLOCK *et al.,* 1982; CURRAN *et al.,* 1987). An explanation for this reluctance is to be found in the large spread of points around any regression relationship between SSC and $L_{(\lambda)}$. This has been attributed to many factors including changes in water parameters during the collection of SSC data; changes in atmospheric transmission and acquisition geometry during the collection of $L_{(\lambda)}$ data; inadequate geometric correction of $L_{(\lambda)}$ and a small sample size in relation to the known areal, vertical and temporal variability in SSC (MILLER *et al.,* 1977; CURRAN *et al.,* 1987). In addition, there are statistical problems associated with the sampling of the data and the use of the SSC/$L_{(\lambda)}$ relationship for estimation (MUNDAY and ALFÖLDI, 1979; WHITLOCK *et al.,* 1982; CURRAN and HAY, 1986). The objective of this review is to provide the back-

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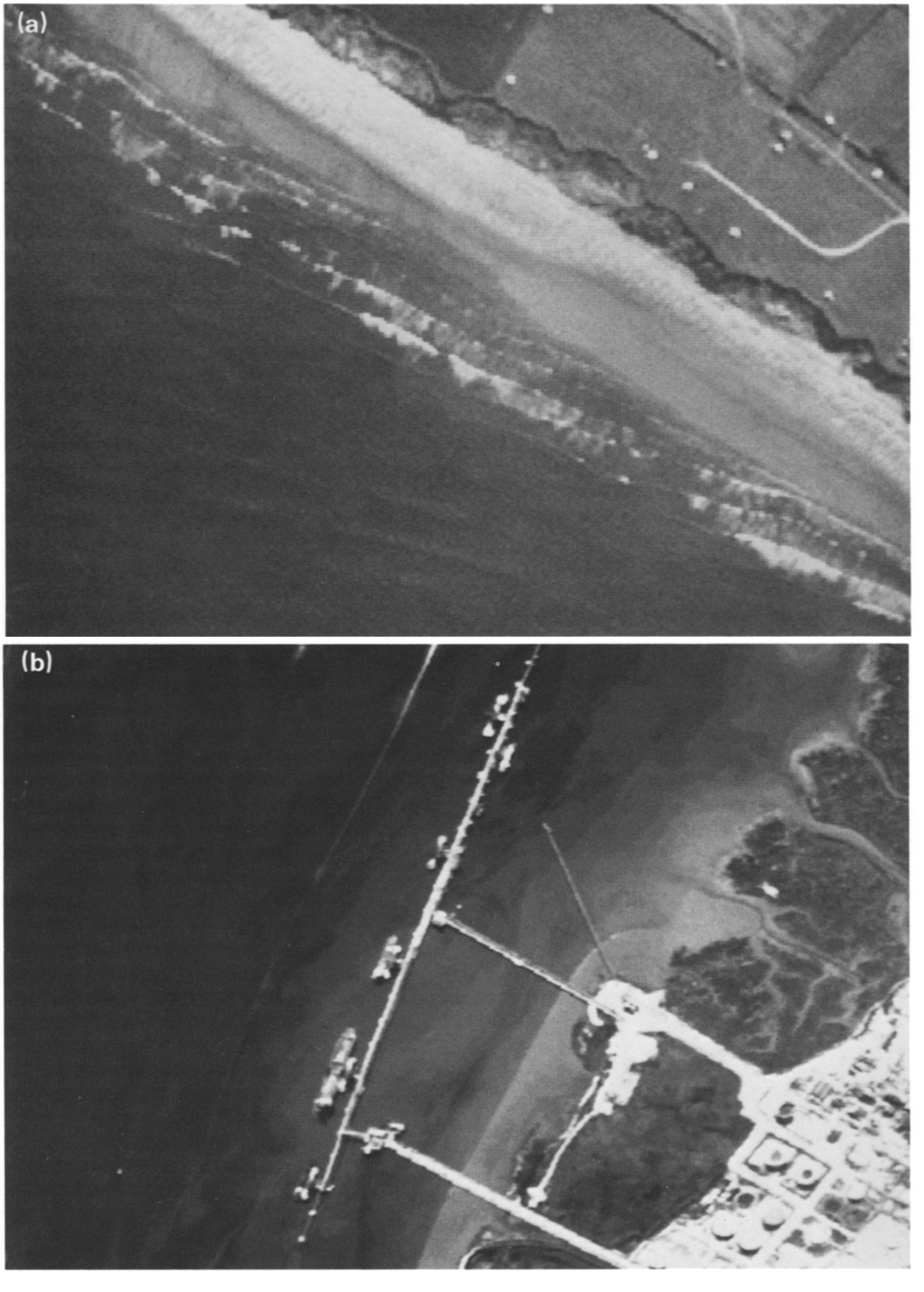

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ground necessary for the use of remote sensing in this particular area of coastal research. Attention will be focused on the fundamental relationship between SSC and $L_{(\lambda)}$, the environmental effects that disturb that relationship and the methodology used to exploit such a relationship for the remote estimation of SSC. The remote sensing hardware used for such studies will not be discussed. For further details on this aspect the reader is referred to CURRAN (1985) and LILLESAND and KIEFER (1987).

THE MEASUREMENT OF SSC

Suspended sediments are the inorganic particles kept temporarily in suspension within water. They are measured either directly or indirectly. In the direct method a container is lowered through a fixed vertical distance of water, the collected samples are filtered and the remaining sediment is expressed as a proportion of the original sample in parts per million (ppm) or more usually milligrammes per litre (mg/l) (GRAY, 1973; RODDA *et al.*, 1976). In the indirect method a turbidity meter is used to measure the backscattering of a light beam within the water. The resultant value can be converted via a calibration equation to SSC (mg/l). These techniques have been developed for the accurate measurement of SSC at a few points (GERACI *et al.*, 1981; ALFÖLDI, 1982). However, suspended sediments have great spatial variability (Figure 1) and points often quite close to each other can have very different values of SSC. This spatial variability has severely limited the extrapolation of such point samples over large areas (RITCHIE *et al.*, 1975; CURRAN and WILKINSON, 1985; WILKINSON and CURRAN, 1985). Fortunately, remotely sensed data can put such point measurements in their spatial context (ROBINSON, 1985) and perhaps more importantly can provide a means of estimating SSC that is at least as accurate as the conventional methods discussed above (CATTS *et al.*, 1985). The principle upon which the remote sensing of SSC is based is that the interaction of incident solar radiation with subsurface water material results in an increase in the $L_{(\lambda)}$ returned to the sensor. In practice this is manifest as a light tone on remotely sensed imagery (Figure 1) and a positive relationship between SSC and the $L_{(\lambda)}$ recorded by the sensor (Table 1) (JOHNSON and HARRIS, 1980; McKIM *et al.*, 1984). For instance, during the 1970s a large number of researchers observed correlation coefficients of around 0.9 between SSC and $L_{(\lambda\ red)}$ (KLEMAS *et al.*, 1974; BOWKER and WITTE, 1975a; JOHNSON, 1975; MUNDAY and ALFÖLDI, 1979) and over 0.9 between turbidity and $L_{(\lambda)}$ (ARANUVA-CHAPUN and LeBLONDE, 1981; CARPENTER, 1981; CARPENTER and CARPENTER, 1983; LINDELL *et al.*, 1985; LATHROP and LILLESAND, 1986). Details of fourteen relationships between SSC and $L_{(\lambda)}$ in near coastal environments are given for illustration in Table 1.

Figure 1. Airborne multispectral scanner images of suspended sediments in coastal waters. Both images have a spatial resolution of 5 m and cover an area of approximately 2.5 × 2.0 km. Image (a) of the Holderness coast of N.E. England was recorded on 16.6.84. North is to the right of the image; the colouring is red for the near infrared waveband; green for the red waveband and blue for the green waveband and the concentration of suspended sediment can be seen to decrease regularly from the beach. Data, Courtesy of the Natural Environment Research Council. Image (b) of Southampton Water in Southern England was recorded on 2.7.85. North is to the bottom of the image; the colouring is red for the red waveband, green for the green waveband and blue for the blue waveband and the concentration of suspended sediment can be seen to decrease irregularly from the marsh. Data, Courtesy of the Southern Water Authority/Water Research Centre. (*Facing page*).

THE INTERACTION BETWEEN ELECTROMAGNETIC RADIATION AND WATER

The electromagnetic radiation that reaches the water from the Sun comprises direct solar irradiance (E_{Sun}) and diffuse irradiance (E_{sky}) (Figure 2). This irradiance falls with a zenith angle θ_0 onto the water surface (s) where it is specularly relfected (r θ_0) and also transmitted into the water. The specularly reflected flux undergoes polarisation (TALMAGE and CURRAN, 1986) and the transmitted flux is either absorbed (A) or scattered (S). The upwelling radiance that reaches the sensor is the apparent upwelling radiance, while the upwelling radiance just below the water surface (GORDON, 1974; GORDON, *et al.*, 1975) is the inherent water radiance (Figure 2). The apparent upwelling radiance is usually expressed as the spectral radiance $L_{(\lambda)}$ or if ratioed against irradiance the spectral reflectance ρ (λ).

The fundamental inherent optical properties of water are the volume attenuation function (α) and the volume scattering function (σ). They are inherent in the sense that their magnitudes

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Table 1. *Empirically derived relationships between SSC and L(λ) for near coastal waters. Modified from BENTLEY (1987).*

Form of relationship where: L = radiance, λ = wavelength, SSC = suspended sediment concentration and a, b, c and d are regression constants	SSC range of relationship (mg/l)	n	r	SE (mg/l)	Location	Reference
$SSC = a + b\,L_{(\lambda)}$	0–50	NA	0.89	4.76	James River	JOHNSON (1975)
$L_{(\lambda)} = a + b\,SSC$	0–14	302	0.92	NA	Lower Chesapeake Bay	BOWKER & WITTE (1975b)
$SSC = a + b_1 L_{(\lambda 1)} + b_2 L_{(\lambda 2)} + b_3 L_{(\lambda 3)} + b_4 L_{(\lambda 4)}$	5–200	23	0.60	NA	Various	JOHNSON (1976)
$SSC = a + b_1 L_{(\lambda 1)} + b_2 L_{(\lambda 2)}$	9–48	NA	0.90	5.25	James River	JOHNSON & BAHN (1972)
$SSC = a + b_1 L_{(\lambda 1)} + b_2 L_{(\lambda 2)}$	1–32	NA	0.96	4.11	New York Bight	JOHNSON & HARRIS (1980)
$SSC = a + b_1 L_{(\lambda 1)} + b_2 L_{(\lambda 2)} + b_3 L_{(\lambda 3)}$	8–80	29	0.61	NA	San Francisco Bay	KHORRAM (1981a)
$SSC = a + b_1 (L_{(\lambda 1)}/c_1)^{d1} + b_2 (L_{(\lambda 2)}/c_2)^{d2} + b_3 (L_{(\lambda 3)}/c_3)^{d3}$	NA	29	0.67	NA	San Francisco Bay Delta	KHORRAM (1981b)
$SSC = a + b_1 (L_{(\lambda 1)}{}^{d1}/(L_{(\lambda 2)} L_{(\lambda 3)})$	NA	9	0.94	NA	Lower Chesapeake Bay	BOWKER *et al.* (1983a)
$SSC = a + b_1 L_{(\lambda 1)} + b_2 L_{(\lambda 2)} + b_3 L_{(\lambda 3)} + b_4 L_{(\lambda 4)} + b_5 L_{(\lambda 5)} + b_6 L_{(\lambda 6)}$	1–8	75	0.80	NA	Neuse Estuary	KHORRAM and CHESHIRE (1985)
$\log SSC = a + b_1 L_{(\lambda 1)} + b_2 L_{(\lambda 2)} + b_3 L_{(\lambda 3)} + b_4 L_{(\lambda 4)}$	2–21	29	0.60	0.46	Bristol Channel	COLLINS & PATTIARCHI (1984)
$SSC = a + b_1 \log L_{(\lambda 1)} + b_2 \log L_{(\lambda 2)}$	2–70	72	0.90	NA	San Francisco Bay	KHORRAM (1985)
$\log SSC = a + b\,(L_{(\lambda 1)} - L_{(\lambda 2)})\,(L_{(\lambda 3)}/L_{(\lambda 1)})$	2–15	8	0.83	NA	Adriatic Sea	TASSAN & STURM (1986)
$\log SSC = a + b_1 L_{(\lambda 1)} + b_2 L_{(\lambda 2)}$	5–200	23	0.60	NA	Holderness Coast	CURRAN *et al.* (1987)
$\log SSC = a + b_1 L_{(\lambda 1)} + b_2 L_{(\lambda 2)} + b_3 L_{(\lambda 3)}$	2–21	31	0.89	NA	Bristol Channel	RIMMER *et al.* (1987)

NA = Not available

for each wavelength depend only on the substances comprising the water mass and not the geometric structure of the various light fields that may pervade it (PREISENDORFER, 1976).

The *volume attenuation function* (α) is a measure of the loss of radiant flux at a given wavelength due to scattering (with or without a change in wavelength) and absorption (equation 1),

$$\alpha = -\frac{1}{r}\log_e \mathrm{Tr} \qquad (1)$$

where, r is the distance travelled by the radiant flux and T_r is the flux transmitted at distance r (JERLOV, 1976). From equation 1 it can be seen that the flux decreases exponentially with depth.

The *volume scattering function* (σ) is the radiant intensity from a volume of water, in a given direction per unit of irradiance on that volume (JERLOV, 1976).

The two functions of α and σ carry information on the material within a body of water. For example, the absorption coefficient which is low and wavelength dependent in distilled water is higher and relatively independent in 'natural' water (Table 2). In distilled water scattering is due to molecular interaction. This follows the fourth power law of the wavelength (JERLOV, 1976) which results in a scattering maximum at shorter wavelengths. In 'natural' water it is the SSC that is an important determinant of scattering, as is discussed in the following section.

The combined effect of absorption and scattering reduces the amount of energy that can pass through a water body (Table 2). This is measured by the attenuation coefficient which is at a minimum in blue/green wavelengths and rises rapidly with wavelength.

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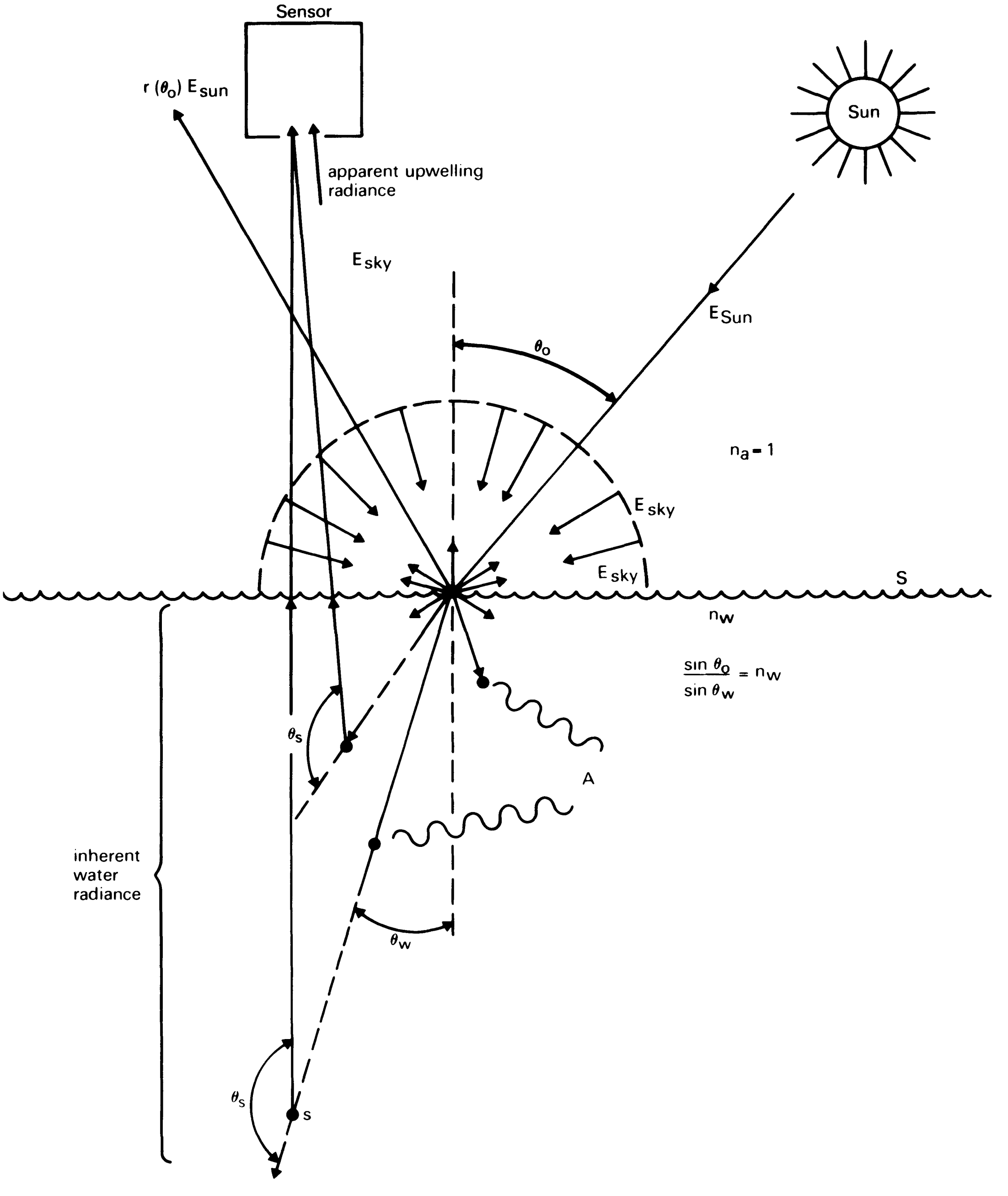

Figure 2. The interaction of electromagnetic radiation with water. Where E_{Sun} is solar irradiance; E_{sky} is sky radiance. θ_o is the solar zenith angle; s is the water surface; $r\theta_o$ is the specular reflection angle; θ_w is the refractive angle; θ_s is the scattering angle; A is absorption; na is the refractive index for air and n_w is the refractive index for water. Modified from STURM (1980).

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Table 2. *The absorption, scattering and attenuation coefficients for distilled and 'natural' water from Chesapeake Bay, USA. Modified from PREISENDORFER (1976).*

Wavelength μm	Absorption coefficient		Scattering coefficient		Attenuation coefficent	
	Distilled water	'Natural' water	Distilled water	'Natural' water	Distilled water	'Natural' water
0.40	0.042	—	0.038	—	0.080	—
0.42	0.031	0.625	0.030	0.175	0.061	0.800
0.44	0.021	0.488	0.025	0.180	0.046	0.628
0.48	0.020	0.267	0.017	0.180	0.037	0.447
0.52	0.028	0.171	0.013	0.180	0.040	0.351
0.56	0.044	0.143	0.009	0.180	0.053	0.323
0.60	0.190	0.249	0.007	0.180	0.197	0.429
0.64	0.287	0.320	0.005	0.180	0.292	0.500
0.68	0.402	0.409	0.004	0.180	0.406	0.589
0.70	0.572	0.560	0.004	0.180	0.576	0.740

THE REMOTELY SENSED RADIANCE OF WATER

The apparent upwelling radiance (Figure 1) measured by a sensor above the water (MILLER *et al.*, 1977; HOLYER, 1979; WHITLOCK *et al.*, 1982) is expressed by equation 2,

$$L_{(\lambda)} = Ta_{(\lambda)} \{\rho\mu_{(\lambda)} [L_{so\,(\lambda)}] + L_{Rd\,(\lambda)} + L_{Rs\,(\lambda)}\} L_{a(\lambda)} \quad (2)$$

where, λ is wavelength, L is apparent upwelling radiance; Ta is atmospheric transmission; $\rho\mu$ is upwelling reflectance at the water surface; L_{SO} is upwelling radiance from a 100% diffuse reflector, L_{Rd} is upwelling radiance from a specular reflector of diffuse skylight; L_{Rs} is upwelling radiance from a specular reflector of direct sunlight and L_a is upwelling radiance from the atmosphere.

To assess the contribution of SSC to remotely sensed $L_{(\lambda)}$ it is necessary to quantify each of these variables. Atmospheric transmission $Ta_{(\lambda)}$, is multiplicative and affects all of the reflected energy leaving the water while upwelling radiance from the atmosphere $L_{a(\lambda)}$, is additive (SLATER, 1980). Both are dependent upon sensor altitude, the ratio of diffuse and direct irradiance and the viewing geometry of the sensor. The relative contributions of $L_{SO(\lambda)}$, $L_{Rd(\lambda)}$ and $L_{Rs(\lambda)}$ to remotely sensed $L_{(\lambda)}$ are dependent upon the characteristics of the atmosphere/water boundary and these change with wind speed (McKIM *et al.*, 1984; MILLER *et al.*, 1977). The critical term $\rho\mu$ (λ) refers to the water volume reflectance as a whole and for the study of SSC it is useful to define its two components (equation 3),

$$\rho\mu_{(\lambda)} = \rho w_{(\lambda)} + \rho s_{(\lambda)} \quad (3)$$

where, $\rho w_{(\lambda)}$ is inherent upwelling reflectance from background water and $\rho s_{(\lambda)}$ is the upwelling reflectance from suspended sediments. Both are complex terms; $\rho w_{(\lambda)}$ includes such factors as the contribution by other types of particulate and bottom scattering and $\rho s_{(\lambda)}$ is dependent upon the concentration and grain size distribution of the sediment (SATHYDENDRANATH and MOREL, 1983).

ENVIRONMENTAL INFLUENCES ON THE REMOTELY SENSED RADIANCE OF WATER

As has been outlined, the influence of SSC on $L_{(\lambda)}$ is dependent upon many environmental factors. For convenience these can be grouped into those relating to the atmosphere, sensing geometry, water/atmosphere boundary, water components, water depth and the concentration of suspended sediment.

Atmosphere

The atmosphere affects the upwelling radiance by changing the amount and quality of energy available at the water surface and sensor (EGAN and FISCHBEIN, 1975). The factors of importance can be divided into meteorological parameters and optical parameters (BOWKER *et al.*, 1985). The meteorological parameters include relative humidity, cloud cover and surface pressure. Relative humidity determines the strength of the water absorption bands within the electromagnetic spectrum and the type and amount of aerosol; unresolved cloud alters upwelling radiance independently of conditions at the water surface (DUGGIN,

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1985) and surface pressure can effect the amount of molecular scattering. The most important optical parameters are aerosol content and skylight (BOWKER *et al.*, 1985). The amount of aerosol in the atmosphere can be expressed by the aerosol optical thickness which measures the aerosol transmissivity in a vertical path. However, a rough estimation of aerosol amount can be obtained by measuring the visual range in the horizontal (BOWKER *et al.*, 1985). The interrelationships between such a measure of aerosol content, wavelength and reflectance are given in Figure 3. Recently an algorithm for suppressing the effects of aerosol content on the radiance of dark water surfaces, especially in blue/green wavelengths, has been developed by BOWKER *et al.* (1983b). This algorithm is based on radiative transfer equations and enables the calculation of multiple scattering and absorption by the atmosphere. However, like other similar algorithms it does not account for aerosol colour which can be an important consideration, especially for dark water surfaces.

Skylight, or the reflectance of radiation by the atmosphere, is the largest single component of $L_{(\lambda)}$. For example, it has been reported that on clear days the radiance received by the sensor could be around four to five times higher than the radiance from the volume of water in California coastal waters (AUSTIN, 1974). This effect being particularly severe at shorter wavelengths (Figure 4).

The atmosphere is more of a problem for the remote sensing of SSC than it is for many other areas of remote sensing. There are two reasons for this: first, the water surface has such a low reflectance that atmospheric scattering can account for over 95% of the signal received by a spaceborne sensor when recording over clear deep water (MOORE, 1977) and second, the blue/green wavelengths that are ideal for the remote sensing of SSC are those most affected by atmospheric scattering. To use remotely

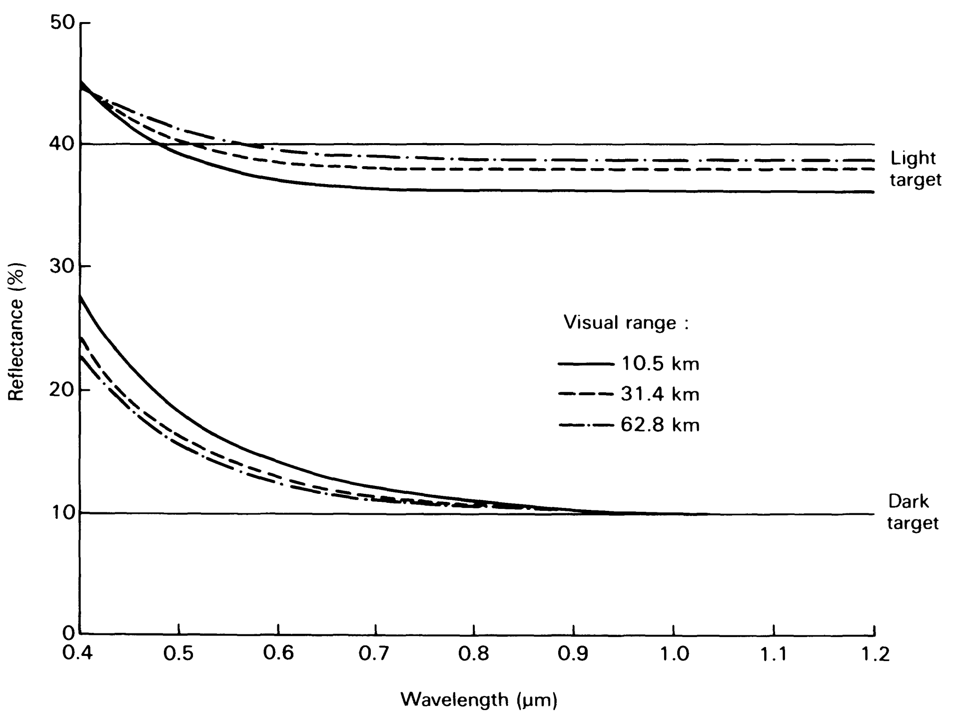

Figure 3. The effect of atmospheric aerosol content (recorded by visual range) on the reflectance properties of a light toned (40% reflectance) and a dark toned (10% reflectance) target. The targets were recorded vertically with a solar zenith angle of 20°. Modified from BOWKER *et al.* (1985).

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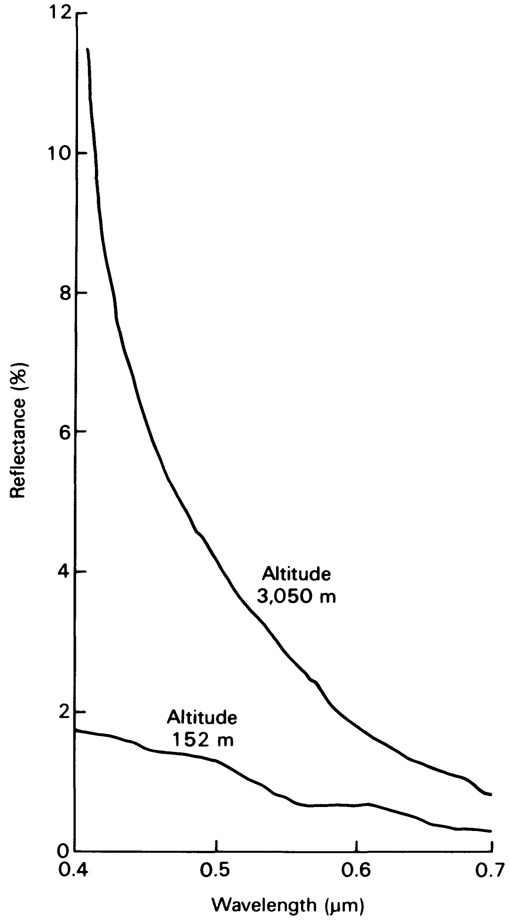

Figure 4. The effect of sensor altitude on the recorded reflectance of a water body. Modified from CLARKE and EWING (1974).

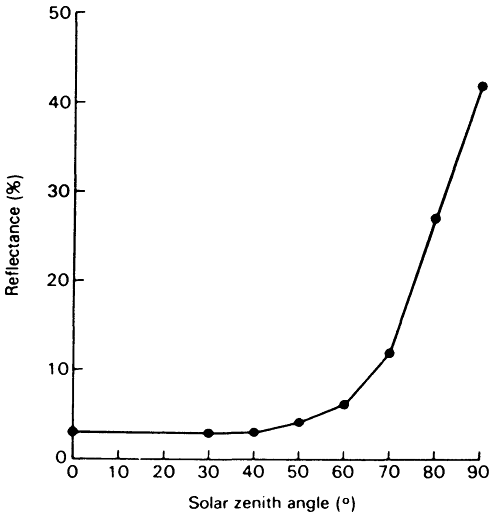

Figure 5. The reflectance of a flat water surface in visible wavelengths (0.4-0.7μm) at a range of solar zenith angles. Drawn from data in JERLOV (1976).

sensed data for the operational estimation of SSC the atmospheric effects must be suppressed (CONEY and SALZMAN, 1979). Attempts to achieve this are well discussed in TURNER *et al.* (1971); DANA (1975); AHERN *et al.* (1977); GORDON (1978a); PLASS *et al.* (1981) and MacFARLANE and ROBINSON (1984).

Sensing Geometry

The angle at which the radiation reaches the water and sensor determines the degree of correlation between SSC and $L_{(\lambda)}$. The most important angle is that of solar zenith angle (θ_0) (Figure 2) which is often strongly and positively related to radiance in flat water bodies (LIST, 1971; JERLOV, 1976). This is because once the Sun is lower than around 50° in the sky, water surface radiance starts to make a significant contribution to the total signal detected by the sensor (Figure 5). This angle also determines the proportion of direct to diffuse radiation reaching the water surface (PLASS *et al.*, 1981) with low solar zenith angles being associated with higher depths of radiation penetration and a lower $L_{(\lambda)}$ (EGAN, 1972). However, both of these effects are reduced at shorter wavelengths due to the effect of atmospheric scattering (Figure 6).

When water surfaces are not flat then Sun glint (or glitter) can be a problem at solar zenith angles of less than approximately 40° (JERLOV, 1976; CONEY and SALZMAN, 1979). For this reason solar zenith angles around 40–50° are often chosen in studies of the SSC/$L_{(\lambda)}$ relationship.

The relative azimuth angle between the Sun and sensor although generally not as important as the solar zenith angle can be critical at certain angles. These are when the sensor is looking towards the Sun and an increasing amount of radiation is being reflected specularly into the sensor (CLARKE and EWING, 1974), or away from the Sun when an increasing amount

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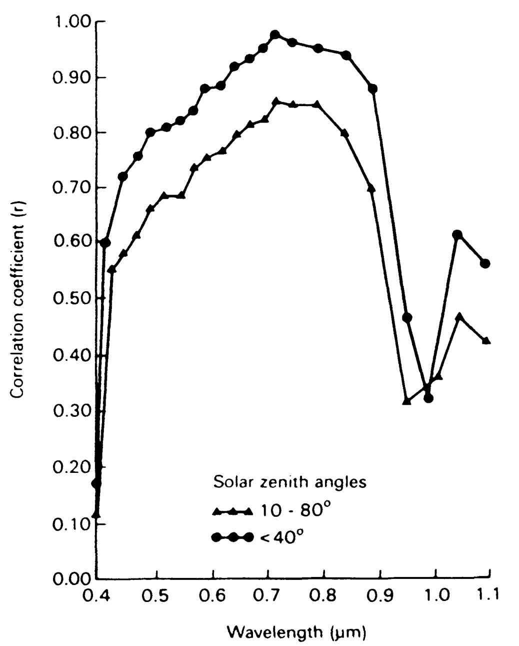

Figure 6. The correlation between SSC and L(λ) at a range of wavelengths and two groups of solar zenith angles. Modified from RICHIE *et al.* (1976).

of radiation is being backscattered from material in the water (PREISENDORFER, 1976).

Water/Atmospheric Boundary

The water/atmosphere boundary determines the amount and character of the radiation that enters and leaves the water. As radiation enters the water it is refracted according to Snell's Law (PREISENDORFER, 1976) which results in a compression of radiation within a subsurface cone of vertically decreasing radius. The vast proportion of $L_{(\lambda)}$ therefore comes from the wider portion of this cone which is just below the water surface.

The roughness of the water/atmosphere boundary determines its influence on $L_{(\lambda)}$. If backscattering is important then an increase in surface roughness will decrease surface penetration and thereby $L_{(\lambda)}$ (PREISENDORFER, 1976). By contrast if Sun glint or whitecaps are important then increased surface roughness will increase their effect and thereby $L_{(\lambda)}$ (COX and MUNK, 1955; GORDON and JACOBS, 1977; GORDON, 1978b; MONOHAN and O'MUIRHEATAIGH, 1986). As was noted earlier Sun glint increases $L_{(\lambda)}$ at low solar angles (KATAWAR and HUMPHREYS, 1976) a relationship that is all the stronger when the waves are orthogonal to the look-direction of the sensor (AHERN *et al.*, 1977).

The atmosphere/water boundary has an undoubted influence on the SSC/$L_{(\lambda)}$ relationship. However, several workers have noted that for practical purposes if the roughness is spatially consistent and the sensor is viewing vertically then the influence of this boundary is minimal (RITCHIE *et al.*, 1976; AHERN *et al.*, 1977).

Water Components

Accompanying suspended sediments can be live phytoplankton, byproducts of phytoplankton and dissolved organic matter (BRICAUD and SATHYENDRANATH, 1981; TASSAN, 1981). The first two categories covary and result in a decrease in reflectance, which is especially noticeable if the phytoplankton diameter is large and if measurements are made in the chlorophyll absorption wavebands of blue and red (Figure 7). The visual effect of an increase in these first two categories is dramatic; in clear waters red light is absorbed within 15 m of the water surface while blue and to a lesser extent green light, are scattered giving the water a blue to blue/green colour. As the chlorophyll concentration increases and blue light is absorbed the region of maximum scattering shifts to green wavelengths (CLARK *et al.*, 1970). Many algorithms are available for calculating the effect of these first two components on the remotely sensed signal, although as they are all empirically based they lack general utility (CLARKE and EWING, 1974; MILLER *et al.*, 1977; ARANUVACHAPUN and PERRY, 1981).

Dissolved organic matter is yellow in colour, absorbs blue radiation strongly (ROBINSON, 1985) and is associated with land runoff in near coastal environments (ROBINSON, 1983). Like chlorophyll it affects the SSC/$L_{(\lambda)}$ relationship but without at least a few *in situ* measurements a correction for its influence has not been possible.

As a way around the problems caused by areally, vertically and temporally variable chlorphyll and organic matter, some studies

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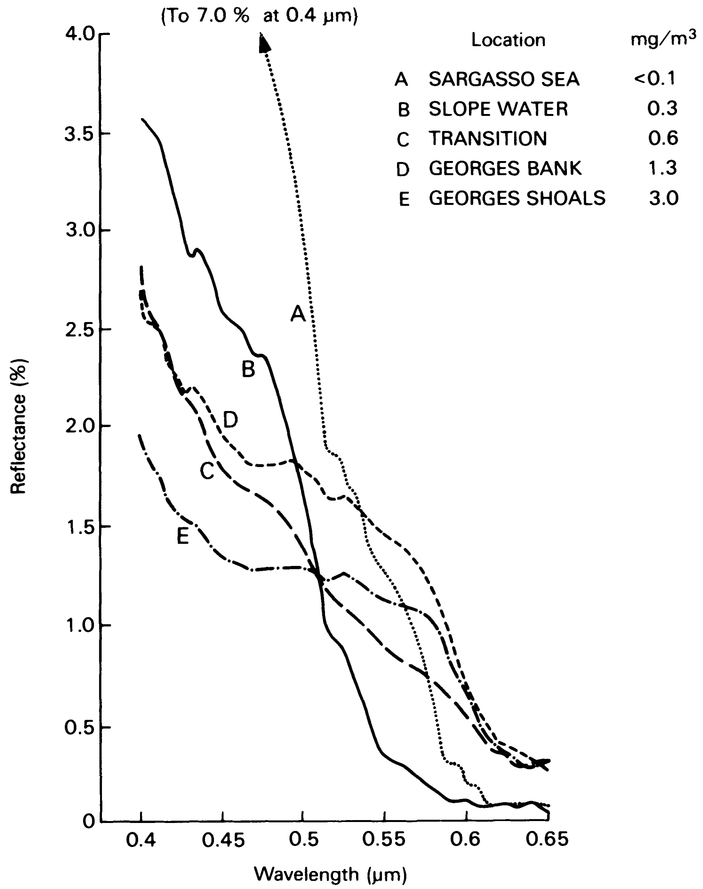

Figure 7. The effect of chlorophyll concentration (in mg/m^3) on the reflectance properties of water. Modified from CLARK *et al.* (1970).

have been limited to areas where both water constituents have been at low concentration. Where this is not a practical option water bodies have been pre-stratified into broad chlorophyll or dissolved organic matter classes (PRIEUR and SATHYENDRANATH, 1981; KHORRAM, 1981a; 1985) (Figure 8) and SSC has been estimated within each class.

Water Depth

The effect of water depth on the SSC/$L_{(\lambda)}$ relationship will vary with bottom material and the type of suspended sediment (GORDON and McLUNEY, 1975; LYZENGA, 1981). However, it is only in very clear and shallow waters (*e.g.* tropical lagoons) that the bottom material makes a significant contribution to the reflectance properties at the water surface. For northern temperate near-coastal waters with a sediment load of around 100 mg/l $L_{(\lambda)}$ is unaffected by bottom reflectance in water depths greater than 20–30 m (BARTOLUCCI *et al.*, 1977; SØRENSON, 1980; SPITZER and DIRKS, 1987).

Concentration of Suspended Sediment

The concentration range of suspended sediments determines the sensitivity of $L_{(\lambda)}$ to SSC. This is because $L_{(\lambda)}$ is not linearly related to SSC but increases to an environmentally determined asymptote that is controlled by many factors including the sediment properties of

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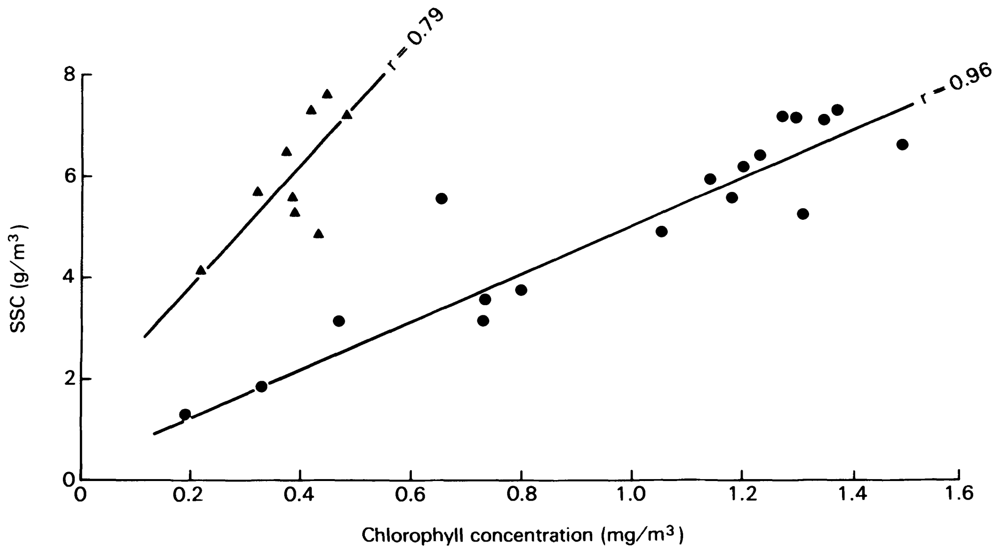

Figure 8. The relationship between chlorophyll concentration and SSC for two classes of water in the Adriatic Sea. Class A are waters with a small range of chlorophyll concentration (line on left) and class B are waters with a large range of chlorophyll concentration (line on right). Modified from TASSAN and STURM (1986).

size, mineralogy and colour (HOLYER, 1978; RIMMER *et al.*, 1987).

In an early laboratory study (Figure 9) bottom reflectance influenced $L_{(\lambda)}$ up to SSCs of around 10 mg/l; above that level $L_{(\lambda)}$ increased linearly up to an asymptote at an SSC of around 1,000 mg/l (SCHERZ and VAN DOMELEN, 1975). In recent years the form of this relation-

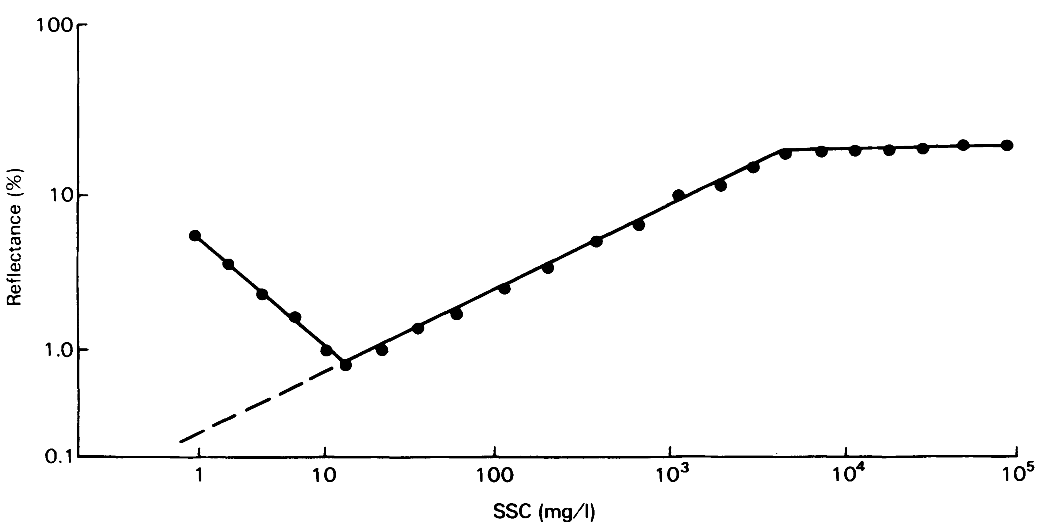

Figure 9. Results of a laboratory study on the effect of SSC on the reflectance of red light. Modified from SCHERZ (1972).

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ship has been confirmed in the laboratory and field (AMOS and TOPLIS, 1985). However, in the field the asymptotes have been reached at much lower levels of SSC (Figure 10) (KLOOSTER and SCHERZ, 1974; ROUSE and COLEMAN, 1976; WHITLOCK *et al.*, 1982) and have had a less marked transition as the asymptote is reached. Because of this several workers have concluded that the SSC/$L_{(\lambda)}$ relationship is best considered as logarithmic (MUNDAY and ALFÖLDI, 1979; KHORRAM, 1985; CURRAN *et al.*, 1987). Clearly such a relationship means that the sensitivity of $L_{(\lambda)}$ to changing SSC will decrease with increasing SSC. This however is wavelength dependent, being less of an influence in longer wavelengths of red and near infrared where shallower water penetration enhances the sensitivity of $L_{(\lambda)}$ to higher SSCs (PREISENDORFER, 1976; HOLYER, 1978; NOVO *et al.*, 1988) (Figure 11). To take advantage of the complementary attributes of deep water penetration and sensitivity to high values of SSC many workers have employed a mix of short and long wavelengths in their estimation of SSC (McCAULEY and YARGER, 1975; MUNDAY and ALFÖLDI, 1979).

SUPPRESSION OF ENVIRONMENTAL INFLUENCES ON THE REMOTELY SENSED RADIANCE OF WATER

Many workers have tried to identify the set of environmental conditions that would maximise the degree of correlation between SSC and $L_{(\lambda)}$. The consensus would indicate that such conditions are clear skies, low windspeed (<10 knots), around solar noon and at a time of moderate solar zenith angle (30–60°) (GOLDMAN *et al.*, 1974; RITCHIE *et al.*, 1975). In addition the sensor should be looking off-vertical and away from the plane of the Sun to avoid Sun glint and SSC should be spatially and temporally stable (WITTE, 1975; CURRAN *et al.*, 1987). The effects of not achieving such an ideal mix of environmental conditions can be minimised either at the time of the experiment, for example, by the use of a polarising filter to reduce the effect of specular reflectance

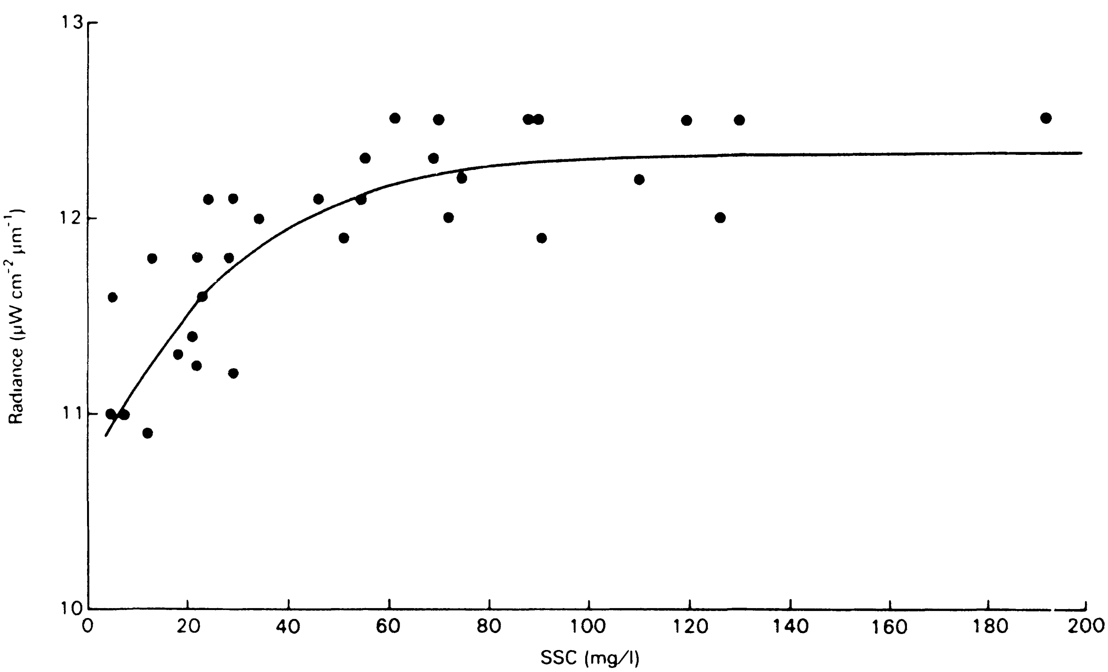

Figure 10. Relationship between SSC and $L_{(\lambda green)}$, recorded from an airborne sensor, for near coastal waters. Modified from BENTLEY (1987).

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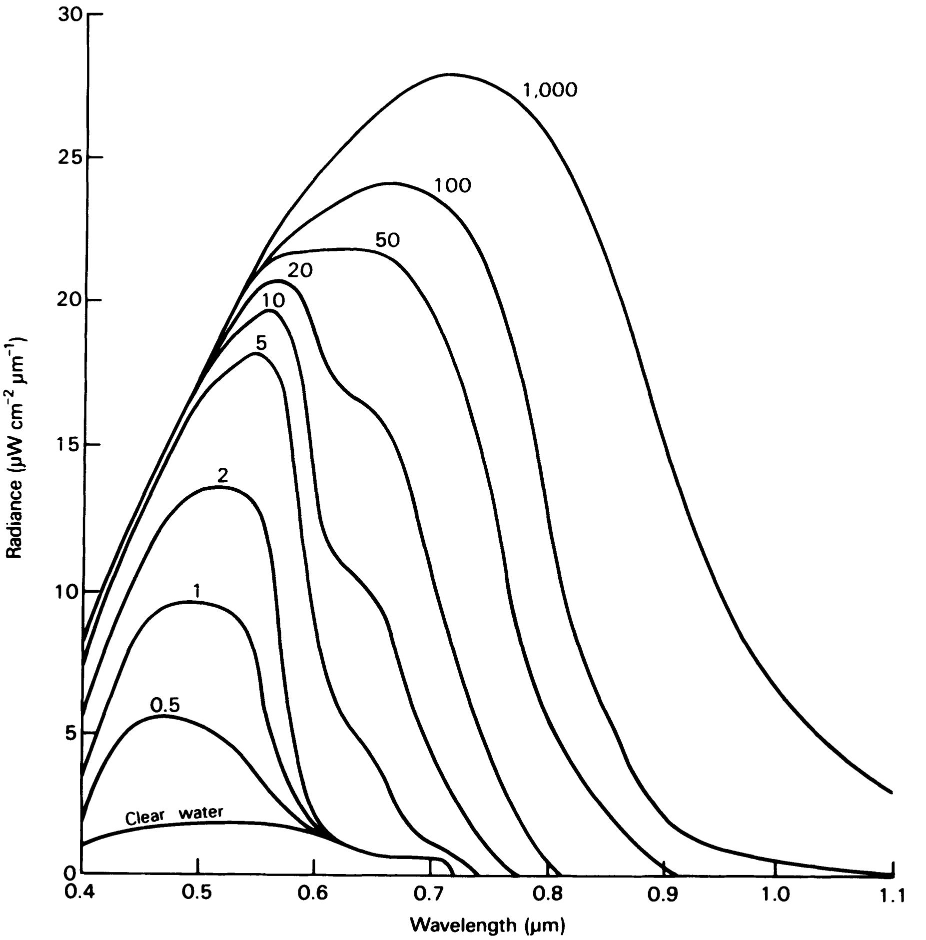

Figure 11. Relationship between radiance and wavelength for ten levels of SSC (in μmg/1). Modified from MOORE (1977).

(McKIM *et al.,* 1984) or more usually at the stage of data processing. The most common corrections are normalisation to a standard solar angle (MUNDAY and ALFÖLDI, 1979); standardisation to a spectrally stable area within the image (JOHNSON and HARRIS, 1980); application of radiative transfer models to the raw data (CONEY and SALZMAN, 1979) and the use of waveband to waveband ratios (McCAULEY and YARGER, 1975) to suppress the effect of the solar angle and atmosphere.

ESTIMATING SSC FROM REMOTELY SENSED MEASUREMENTS OF WATER

The estimation of SSC from remotely sensed $L_{(\lambda)}$ has followed all or, more usually, some of the following five stages (CURRAN *et al.,* 1987; TASSAN, 1987).

1. Simultaneous measurement of SSC and $L_{(\lambda)}$.
2. Correct, as far as possible, for environmental influences on (1).
3. Derive an empirical relationship between corrected SSC and $L_{(\lambda)}$ on a training set of data.
4. Use corrected $L_{(\lambda)}$ and the relationship in (3) to estimate SSC.
5. Determine the accuracy of SSC estimation using a testing set of corrected SSC data.

The majority of studies in the literature terminate at stage (3) on the assumption that a statistically significant correlation between

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SSC and $L_{(\lambda)}$ is the basis for an accurate estimation (HOLYER, 1978; McFARLANE and ROBINSON, 1984; LODWICK and HARRINGTON, 1985). However, as ALFÖLDI (1982) notes it is the spread of points around the relationship not the significance of the relationship that is critical.

An increasing number of workers have progressed to stage (4), and produced maps of SSC or estimates of mean SSC for particular regions of water (KLEMAS *et al.*, 1974; JOHNSON, 1975; 1976; AMOS and ALFÖLDI, 1979; KHORRAM, 1981a; 1985; KHORRAM and CHESHIRE, 1985; RIMMER *et al.*, 1987). Unfortunately, the vast majority of workers have simply inverted a SSC/$L_{(\lambda)}$ regression relationship which violates three assumptions upon which such regression is based: (1) SSC on $L_{(\lambda)}$ is the same as $L_{(\lambda)}$ on SSC; (2) there is no error in the measurement of SSC and (3) the error in $L_{(\lambda)}$ is unrelated to SSC (CURRAN and HAY, 1986). Therefore, the conclusions drawn from such studies are of limited utility.

A few authors have proceeded to stage (4) and have attempted to determine the accuracy of their estimated SSC (DOERFFER, 1979; AMOS and ALFÖLDI, 1979; CURRAN *et al.*, 1987). Given the small sample size in each case their conclusions were necessarily tentative. At the moment the single largest limitation to the successful implementation of these five stages is the problem of sampling areally, vertically and temporally varying SSC synchronously with $L_{(\lambda)}$. The majority of studies have taken an inadequate number of random samples to try and characterise areal variability. Increasing evidence now points to the need for a two level systematic sampling scheme; level one at the scale of the image and level two at the scale of the image pixel (CURRAN and WILLIAMSON, 1985; 1986; CURRAN, 1988).

The depth at which SSC is measured should be related to the extinction coefficient of the sensing wavelength. In practice it is usually as near to the surface as is practically possible.

The problem of temporal variability in SSC is severe in studies where due to tides, weather and river flow the water body is in constant motion. Typically, samples are taken as near as possible to the recording of $L_{(\lambda)}$. In coastal waters this is rarely adequate and recently workers have been readjusting the location of their sample points to their approximate location at the time $L_{(\lambda)}$ was recorded (CURRAN and WILKINSON, 1985; CURRAN, 1987).

As this review shows advances are now being made in both theory and methodology that should enable the use of the SSC/$L_{(\lambda)}$ relationship for the remote measurement, mapping and monitoring of SSC.

SUMMARY

Suspended sediments are readily visible on optical remotely sensed imagery of coastal waters. However, the manifestation of the well documented SSC/$L_{(\lambda)}$ relationship is difficult to both quantify and utilise. It is difficult to quantify because of the many environmental factors that disturb the relationship. These include the atmosphere, sensing geometry, water/atmosphere boundary, water components and concentration of suspended sediments. It is difficult to utilise because of the problems associated with sampling the SSC that is necessary to both train and test any estimation procedure.

It is recommended that future work on the SSC/$L_{(\lambda)}$ relationship should concentrate upon the suppression of environmental influences and the optimum sampling of SSC.

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□ RESUMEN □

La informaci6n sobre la concentraci6n de sedimentos en suspensi6n en las aguas costeras es necesaria para la comprensi6n y la gesti6n de las áreas costeras. Tradicionalmente, la concentraci6n de sedimento en suspensi6n (SSC) se ha medido mediante costosas y largas campañas con embarcaci6n que permiten una ajustada medida de la SSC en puntos simples del espacio y tiempo. El muestreo remoto mediante sensores en vehiculos aéreos o espaciales han demostrado ser un útil apoyo a las campañas de barco y aportan una visi6n instantánea y sin6ptica de los sedimentos, que de otra manera no seria posible obtener. La clave del éxito del muestreo remoto en este caso es la estrecha relaci6n que existe entre la SSC y la radiaci6n espectral muestreada a distancia (L). Esta reseña provee una introducción a esta relación SSC/L, explorando sus bases fisicas, su robustez bajo un rango de condiciones ambientales y su utilidad como herramienta para la estimaci6n. Se concluye que las futuras investigaciones sobre esta correlaci6n deberian concentrarse sobre todo en la supresi6n de las influencias ambientales y en le muestreo 6ptimo de la SSC.—*Department of Water Sciences, University of Santander, Santander, Spain.*

□ ZUSAMMENFASSUNG □

Kenntnisse über die Konzentration der Schwebfracht in Küstengewässern its notwendig für das Verständnis und das Management der Küstengebiete. Die bisher übliche Messung der Schwebfractkonzentration (SSC) durch Boote, die eine exakte Feststellung der SSC für einzelne Punkte erlaubte, war zeit- und kostintensiv. Es hat sich gezeigt, daß flugzeug- und satellitengestützte Fernerkundung eine nützliche Ergänzung der Bootsmessungen darstellt, weil hierdurch eine ständige und synoptische Erfassung der Sedimente ermöglicht wird. Der Schlüseel für den Erfolg der Fernerkundung ist in diesem Fall die starke positive Relation, die zwischen der SSC und der aufgezeichneten Spektralstrahlung ($Lat_{(\lambda)}$) existiert. Dieser Überblicksartikel liefert eine Einführung in diese SSC/$L_{(\lambda)}$ Beziehung, untersucht seien physikalische Basis, seine Tauglichkeit unter verschiedenen Umweltbedingungen und seine Nützlichkeit als ein Werkzeug zur Abschätzung der Schwebfracht. Eine wichtige Konsequenz des Artikels ist, daß zukünftige Forschung zur oben genannten Beziehung sich auf die Begrenzung der Umwelteinflüsse und die optimale Probennahme für die Schwebfracht konzentrieren sollte.—*Ulrich Radtke, Geographisches Institut, Universität Düsseldorf, F.R.G.*

□ RESÚMÉ □

Des Données sur la concentration de sédiments en suspension dans les eaux littorales sont néssaires pour comprendre et aménager l'environnement côtier. Traditionnellement, la concentration de sédiments en suspension (SSC) est mesurée par des relevés en bateau qui sont longs et coûteux. La télédétection, à partir d'aéronefs et d'engins spatiaux, s'est avérée être un outil utile pour ce genre d'étude car elle donne de ces sédiments une vision instantanée et synoptique qu'il est impossible d'obtenir autrement. La clé du succès de la télédétection en la matière est la très nette corrélation positive qui existe entre la SSC et le spectre de réflectance (L).

Cette mise au point constitue une introduction à la relation SSC/L, en essayant de préciser sa base physique, sa validité dans différents environnements et son utilité comme outil d'évaluation. On conclut que les futures recherches sur cette relation devraient porter sur la suppression des effets de l'environnement et sur le meilleur échantillonnage de la SSC.—*Roland Paskoff, Université Lumière de Lyon, France.*

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