Modelling of remote sensing reflectance spectra for suspended matter concentration detection in coastal waters

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ABSTRACT

Application of optical remote sensing in coastal waters is hindered by lack of understanding of the relationship between reflectance spectrum and suspended matter concentration. Interpretation is usually based on statistical relations between suspended matter concentrations derived from filtered water samples and remotely measured radiances. As a consequence water bodies have to be sampled at the time of satellite (or aircraft) passage to validate functional relationships for every image, sensor and water region. This procedure restrains the use of remote sensing for monitoring purposes.

In this study an analytical reflectance model is proposed based on inherent optical properties (IOP's) of Dutch coastal waters. In these waters a survey of optical and conventional in-situ measurements is carried out along a transect with a large gradient (1-42 g m^{-3}) of suspended matter concentration. These measurements are used to set some parameters of IOP spectra of silt and yellow substance and to validate the model.

Beam attenuation is proportional to the suspended matter concentration and is a suitable input parameter for the reflectance model. Therefore, it is concluded that transmissometers are ideal field instruments for remote sensing calibration, if used in conjunction with an analytical model based on IOP's of this area.

Reflectance spectra of suspended matter concentrations exceeding concentrations measured during the calibration survey are simulated. This allows simulation of NOAA/AVHRR band 1 response from 0-100 g m^{-3} suspended matter. An almost linear response is found for silt concentrations lower than 30 g m^{-3}, at higher concentrations the NOAA response starts to saturate.

1. INTRODUCTION

Operational use of remote sensing is seen as an important part of (future) monitoring networks that form the basis of water policy management (Stokkom et al., 1993). Also remote sensing of 'water quality' parameters - such as total suspended matter (TSM) or silt concentration - can provide relevant information on a regular basis. At present, however, quantitative interpretation of remote sensing images is only achieved for single images, after substantial statistical analysis (e.g. Gitelson et al., 1993; Dekker, 1993).

New generation satellite sensors e.g. SeaWiFS, MERIS and airborne sensors such as CASI, ROSIS raise new questions on their value for operational use in monitoring networks (Lyon, 1993). To be able to judge the capabilities of these sensors in providing relevant quantitative information, it is both necessary to measure optical characteristics of the specific area and to understand mechanisms behind the observed phenomena (Stokkom et al., 1993; Dekker, 1993). For remote sensing of suspended matter this implies knowledge of light reflectance mechanisms and inherent optical properties such as absorption and beam attenuation of suspended matter (Gordon, 1994).

Quantitative interpretation of remote sensing data is, in most studies, based on statistical relationships between an image and in-situ measurements from the moment that the image was taken (e.g. Gitelson et al., 1993; Dekker, 1993). This interpretation procedure needs to be repeated for every single image. For a proper calibration it is prerequisite that in-situ measurements match in time to remote sensing data collection. Also several calibration points, at locations showing enough variation to allow regression analysis are necessary for a reliable statistical interpretation.

In-situ measurements carried out by field instruments play an important role in the calibration of remote sensing data. Transmissometers, which measure the attenuation of a light beam, are used to estimate the TSM concentration in situ (Mara, 1994). Such instruments can easily be deployed at many locations and allow estimation of spatial and temporal variability. This information can improve quality control of extrapolation of results from analysed samples to a large water volume as detected by a remote sensor (Zaneveld, 1994).

In this study an analytical reflectance model based on IOP's (Gordon, 1975) is calibrated with optical and conventional in-situ measurements. Beam attenuation measurements are applied as input parameter for the model to investigate the value for remote sensing quantification. As transmissometers can be deployed on unattended measuring platforms (moorings, oil platforms), it is foreseen that these instruments can form the basis for remote sensing quantification within monitoring networks.

2. INSTRUMENTATION AND METHODS

2.1 Study area and period

Within the *PMNS* project a survey with *r.v. Pelagia* is carried out in the southern North Sea near the Belgian and Dutch coast on 30 September 1993. This area is characterised by the presence of large tidal flows and the outflow of the Scheldt estuary (Otto et al., 1990). At this time of year no large algal blooms are expected (Reid et al., 1990). During the survey eight stations are sampled during day time for chlorophyll-a and TSM and optical in-situ measurements are made simultaneously. Samples are analysed on chlorophyll-a by standard HPLC techniques. Wind speed did not exceed force 3 and the sky was partly overcast. The first stations (SWA1, SWA2 and SWA3) are situated about 5 km off shore and 10 km apart. The other stations are at increasing distances from the Walcheren coast up to 30 km (SWA8). The last stations are situated in the area influenced by oceanic water entering from the Channel (Otto et al., 1990).

2.2 Optical measurements

Measurements are carried out to determine the subsurface and above water reflectance spectrum and spectral beam attenuation. The above water and subsurface reflectance measurements are combined to calculate a high spectral resolution subsurface spectrum. Therefore, following instruments are used:

The *PR650* (PHOTO RESEARCH®) multi-spectral radiometer, that measures the spectrum of optical radiation from 380-780 nm simultaneously at 4 nm intervals (FWHM 8 nm). Two of these instruments are used to collect data; one measures waterleaving radiance, and the second, fitted with a cosine collector, measures the downwelling irradiance.

Subsurface irradiance reflectance spectra are measured using the Advanced Spectral Irradiance Meter *(ASIR)* developed at NIOZ by Wernand & Spitzer (1984). This instrument simultaneously detects up- and downwelling irradiance in 22 bands between 399-717 nm. (bandwidth 12 nm) using a filter wheel configuration. A single scan is performed in ± 2 minutes, therefore, while performing the measurement, variations in downwelling irradiance are monitored so that if large variations (10%) are encountered the measurement is rejected.

The subsurface reflectance spectra *R(0-)* with a higher wavelength resolution are calculated from the PR650 observations. Surface reflectance spectra are calculated by dividing the upwelling radiance by the downwelling irradiance. A baseline correction is applied by assuming zero subsurface reflectance at wavelengths larger than 750 nm (assuming water absorption dominant to backscatter reflectance of al water constituents). The corrected PR650 spectra are scaled by ASIR measurements, to obtain real values for R(0-). Two examples of PR650 and ASIR spectra comparisons are depicted in **Fig. 1**. Corrected PR650 reflectance spectra show a non zero reflectance at wavelengths larger than 750 nm. This is not from water leaving radiance, but supposed to be an atmospheric effect.

Spectral beam attenuation is measured by the Transmissometer/Advanced Spectral Irradiance Meter *(TRASIR)* developed at NIOZ by Wernand. This instrument uses a pulsating light source and measures the beam attenuation from 0.1-10 m-1 over a path length of 40 cm for 22 bands comparable to ASIR wavelengths. One scan takes approximately 2 minutes.

3. MODELLING OF REFLECTANCE SPECTRA

The reflectance of light scattered back by water and its constituents as detected by a remote sensor, does not only depend on properties of the medium but also on characteristics of the incoming light field. Hence light reflectance

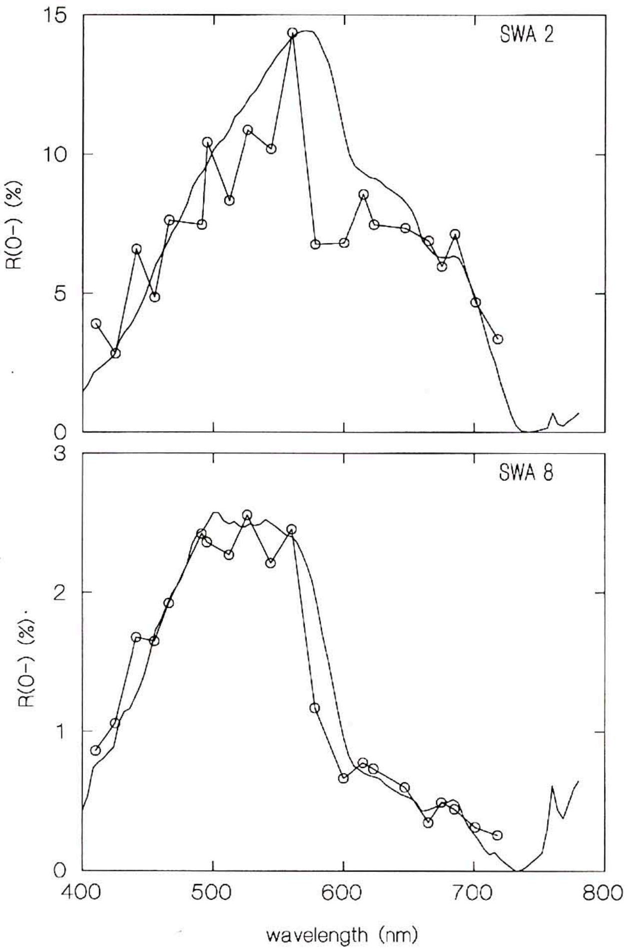

Figure 1 - Two examples of the comparison between measured subsurface irradiance reflectance R(0-) (connected symbols) and adapted PR650 measurements (solid line).

is referred to as an apparent optical property (AOP) (Gordon, 1994). Beam attenuation and absorption of water or suspended particles, however, do not vary with a changing light field and consequently these are termed inherent optical properties (IOP's). IOP's are proportionally related to the concentration of water constituents. This means that for quantification of remote sensing data the AOP reflectance must be related to IOP's of individual water constituents. If no knowledge of the incoming light field is involved, this relation remains an approximation (e.g. Aas, 1987).

In this study modelling of reflectance spectra is based on equations developed by Gordon et al. (1975) and Aas (1987) pretending a zenith sun and no diffuse light component (see Tab. 2). It is assumed that the reflectance characteristics detected in our area are mainly determined by inorganic suspended particles (silt) and (dissolved) yellow substance. Assumptions about their IOP's are summarised in **Tab. 2**. The IOP's of individual components are summed to give the total absorption and backscatter values used in the reflectance equation.

By only changing model parameters TSM attenuation at 380 nm, $c^s(380)$ and yellow substance absorbance at 380 nm, $a^y(380)$ - representing respectively TSM and yellow substance concentration - a reflectance spectrum is calculated. For this it is assumed that silt IOP's, determined by the model parameters rs, $a^s(380)/b^s(380)$ and n^s, are the same for every station. Values of these parameters (see Tab. 2) are concluded after optimal reproduction of measured reflectance and attenuation spectra of all 8 stations is gained. To enable a comparison between model calculations and measurements a baseline correction is applied to the modelled spectra. A constant background reflectance equal to the modelled reflectance at 750 nm is subtracted.

4. RESULTS

The results of the laboratory analysis show that there was a large gradient in TSM concentration from 1-42 g m^{-3} along the transect (see Tab. 1). The algal concentration (measured as chlorophyll-a (CHL) concentration) was, at the time of the survey, low and rather constant for the first 6 stations, only stations SWA7 and SWA8 showed a significantly lower algal concentration.

The relation between the beam attenuation and the particle concentration is depicted in **Fig. 2**. Because no stratification layers is evident from temperature and salinity depth profiles (data not shown), surface and 5 m samples are regarded as duplicate measurements. Variations of suspended matter loads at the station are supposed to be a consequence of subsampling. In **Tab. 1** averaged values of the two depth sampling is presented.

Table 1 - Water characteristics measured at the Walcheren stations on 30 September 1993

station	c(550) (m^{-1})	TSM (mg/l)	CHL (µg/l)
SWA1	> 10	42	5.9
SWA2	8.8	35	5.5
SWA3	4.3	17	5.2
SWA4	2.8	10	5.0
SWA5	1.6	10	4.4
SWA6	0.6	9	4.2
SWA7	0.4	3	1.6
SWA8	0.3	1	1.2

Table 2 - Parameters and relations used to model subsurface irradiance reflectance R(0-). Inherent optical properties are spectra of attenuation c, absorption a and total scattering b (in m^{-1}). Superscripts w, s and y symbolize specific parameters of the water itself, silt and yellow substance respectively. The superscript * is used to indicate a spectrum that is tabulated in literature. b_b is the total scattering in backward directions (scatter angle larger than 90°). r is used for the b_b to b ratio, n^s varies between 0 and 1 (Morel & Prieur 1977) and introduces wavelength dependence of silt scattering. λ is used for the wavelength of the light (in nm)

reflectance equation	$R(0\text{-}) = \frac{1}{3} \frac{b_b}{a + b_b}$	Gordon et al. 1994 Aas 1987 Krijgsman 1994
inherent optical properties	$c = a + b$ $a = a^w + a^s + a^y$ $b = b^w + b^s$ $b_b = r^w b^w + r^s b^s$	Kirk 1983 Jerlov 1976
water properties	$a^w = a^{*w}$ $b^w = b^{*w}$ $r^w = 0.5$	Buiteveld 1994
silt properties	$c^s = a^s + b^s$ $a^s = a^s(380) \cdot a^{*s}$ $b^s = b^s(380) \cdot (\frac{380}{\lambda})^{n^s}$ $r^s = constant$	Kirk 1983 Morel & Prieur 1977 Prieur & Sathyendranath 1981 Whitlock 1981
	$n^s = 0.5$ $r^s = 0.02$ $\frac{a^s(380)}{b^s(380)} = 0.16$	This study
yellow substance properties	$a^y = a^y(380) \cdot e^{-0.014(\lambda - 380)}$	Prieur & Sathyendranath 1981 Krijgsman 1994

In **Fig. 3** the subsurface reflectance spectra of the eight stations are plotted. An increase in the TSM concentration generates an increase in the amount of reflected light, but also the spectral signature is changed. The maximum reflectance at 570 nm becomes more pronounced at higher concentrations. The reflectance at this and lower wavelengths become saturated at TSM values larger than 30 g m^{-3}.

The spectra of Fig. 3 are modelled as explained above. The model input parameters and modelled attenuation at 550 nm and reflectances at 550 nm and 650 nm are shown for all stations in **Tab. 3**. For comparison the corresponding measured values are given. Two examples (SWA2 and SWA8) of modelled and measured attenuation and reflectance spectra are given in **Fig. 4**. All model results (above

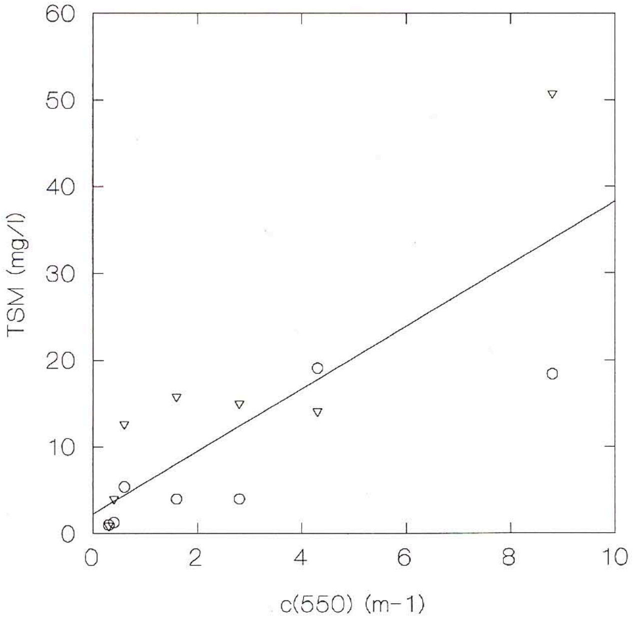

Figure 2 - Comparison of beam attenuation c(550) and TSM concentration. O and ∇ represent samples taken at the surface and 5 m depth. The calculated linear regression is: $Y = 3.2 + 3.6X$ ($n = 14, r^2 = 0.64$)

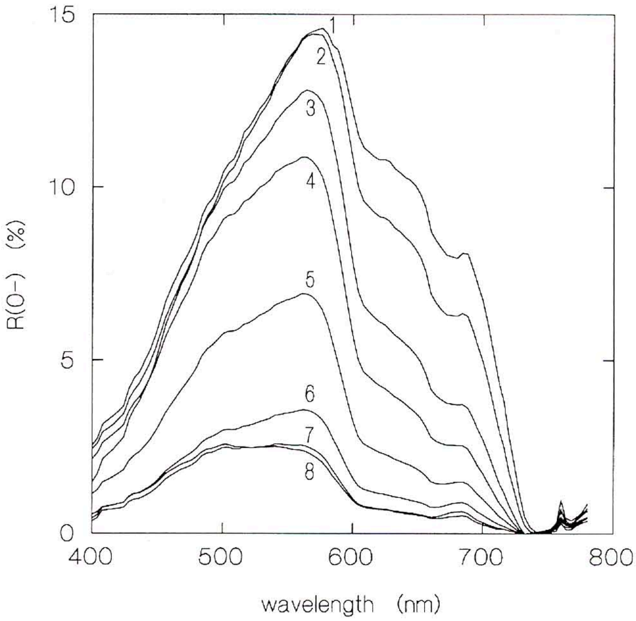

Figure 3 - Subsurface irradiance reflectance spectra measured at 8 Walcheren stations. Spectra are derived from PR650 measurements

500 nm) correspond to measurements within 20% and in most cases within 10%.

Model calculations assuming a constant yellow substance concentration ($a^y(380) = 0.18$ m^{-1}) are presented too. In cases where these reflectance calculations differ from calculations using a more realistic concentrations they are mentioned in **Tab. 2**.

Table 3 - Input and results of model calculations compared with subsurface measurements. Also model results are presented assuming a constant yellow substance contribution ($a^y(380)$ =0.18m^{-1})

	model input		model results			measurements		
station	$c^s(380)$ m^{-1}	$a^y(380)$ m^{-1}	R(550) %	R(650) %	c(550) m^{-1}	R(550) %	R(650) %	c(550) m^{-1}
SWA1	17	0.18	13.8	10.2	12.4	13.6	10.0	>10
SWA2	12	0.18	13.5	8.5	8.8	13.3	8.0	8.8
SWA3	6	0.18	11.9	5.4	4.4	12.3	5.2	4.3
SWA4	3.7	0.18	10.1	3.7	2.8	10.6	3.5	2.8
SWA5	2.0	0.38 (0.18)	6.5 (7.5)	2.1	1.5	6.7	1.9	1.6
SWA6	0.8	0.46 (0.18)	3.2 (4.2)	0.9	0.7	3.5	0.9	0.6
SWA7	0.5	0.36 (0.18)	2.4 (2.9)	0.6	0.45 (0.44)	2.6	0.6	0.4
SWA8	0.43	0.29 (0.18)	2.3 (2.6)	0.5	0.36	2.5	0.5	0.3

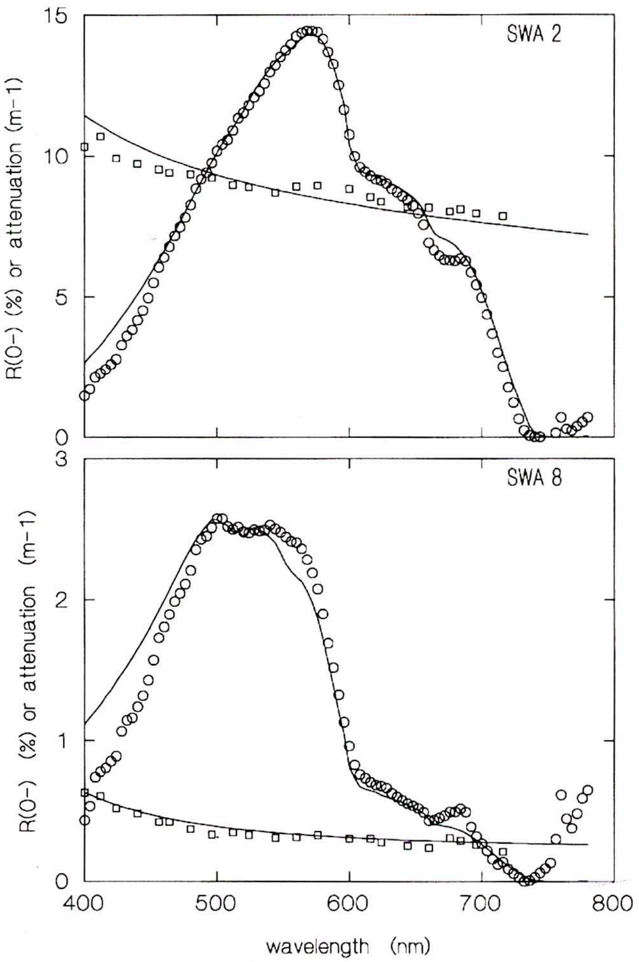

Figure 4 - Two examples of modelled results compared to measurements. Symbols O *and* □ *represent measured subsurface irradiance reflectance and transmission spectra, respectively. Solid lines represent model results*

The model allows a simulation of subsurface reflectance spectra as a function of beam attenuation, assuming a constant yellow substance absorption. In **Fig. 5** the simulated reflectances at 550, 650 nm and the averaged reflectance of band 1 of the NOAA-AVHRR satellite sensor (570-670 nm) are calculated and extrapolated to high attenuation values. The reflectance at 550 nm is saturated near 5 m^{-1} beam attenuation, while NOAA and 650 nm reflectance still display a significant increase at beam attenuations larger than 20 m^{-1} (roughly corresponding to 80 g m^{-3} TSM). These differences in saturation concentration for different wavelengths find there origin in the water absorption spectrum. If water does not significantly contribute to the total absorption, increase of TSM has no effect on the reflectance. The influence of yellow substance concentration is only notable for reflectances at 550 nm (see Fig. 5).

In Fig. 5 the modelled reflectance at 750 nm is also depicted. In all model results this value was subtracted from the reflectance spectrum. From the modelled 750 nm reflectance it is clear that this significantly affects the results of the total reflectance spectra. At 650 nm this results in a subtraction of 20% of the modelled reflectance value if attenuations are larger than 20 m^{-1}. However, for attenuations lower than 5 m-1 corrections at 650 nm do not exceed a 10% decrease. In this context it should also be noted that for NOAA/AVHRR atmospheric correction, water leaving radiance at wavelengths larger than 700 nm are assumed to be zero (Roozekrans & Prangsma, 1988). This justifies a comparison between modelled NOAA band 1 response and 'atmospherically' corrected NOAA imagery.

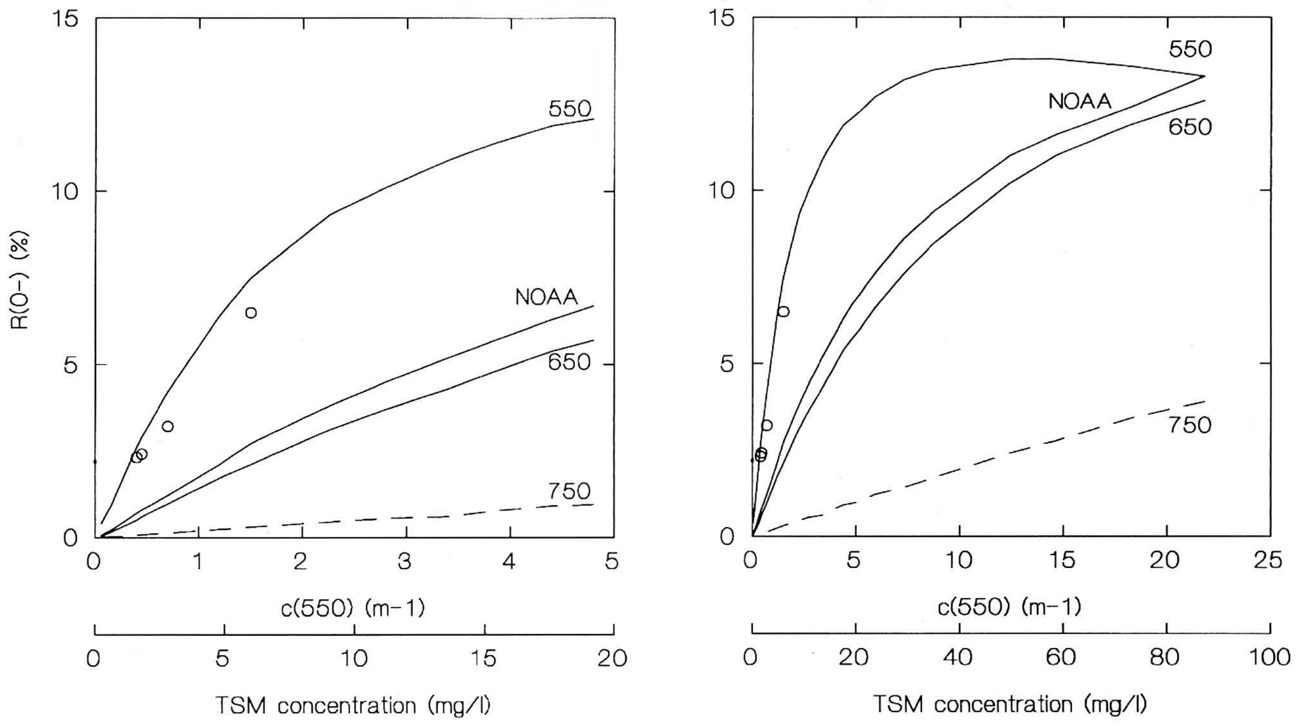

Figure 5 - Model simulations of subsurface irradiance reflectance at 550 nm, 650 nm and the first NOAA/AVHRR band are depicted. The left pannel shows the lower and the right the higher concentration range upto 100 g m⁻³. The 750 nm baseline substracted is depicted by the dashed line. Yellow substance concentration is assumed constant. Symbols indicate more realistic values as listed in table 3

5. CONCLUSIONS AND RECOMMENDATIONS

By applying the Gordon (1975) reflectance model and making assumptions about the optical characteristics of water, silt and yellow substance, we have successfully reconstructed the spectral beam attenuation and spectral reflectance measurements of 8 stations whose TSM concentrations ranged from 1 to 42 g m^{-3}.

This approach allows predictions of reflectance spectra based on single wavelength attenuation observations. Therefore transmissometers are concluded ideal in-situ data for remote sensing quantification, if used in combination with an analytical model and presuming knowledge of IOP's. Every commercially available single wavelength transmissometer (400-800 nm) is suitable for this purpose, because the total attenuation spectrum can be modelled.

The red part of the reflectance spectra (above 570 nm) is dominated by water absorbance characteristics. Below 570 nm the reflectance spectrum is mainly affected by silt absorption and backscatter. This causes a reflectance saturation at silt concentrations of 30 g m^{-3} or larger (larger than 7.5 m^{-1} attenuation at 550 nm). From this it is concluded that remote sensing of inorganic suspended matter concentrations larger than 10 g m^{-3} is only possible in the red part of the spectrum.

With the calibrated model the response of NOAA/AVHRR band 1 with increasing TSM can be simulated. The response of other sensors can also easily be evaluated by this method.

From this study it became clear that for future modelling activities the following aspects should be taken into consideration:

(1) To apply the analytical model more generally IOP's of other locations and other seasons need to be included.

(2) Measured particle absorption and backscatter spectra should be used instead of using standard spectra from other regions. Measurements of the volume scattering function to estimate rs are believed to be less critical in model calibration.

(3) Extension of the modelling by introducing optical properties of algae.

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