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A bio-optical model for the calculation of suspended matter concentration from MODIS data in the Pakri Bay, the Gulf of Finland

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A semi empirical bio-optical model was developed for the Pakri Bay. Model input parameters i.e. particle-specific spectral absorption and scattering coefficients and slope factor of coloured dissolved organic matter were calculated from the field data. The modelled reflectance spectra correspond to typical reflectance spectra with low chlorophyll-*a* concentration. The model is intended for the calculation of suspended matter (SM) concentration maps in the Pakri Bay using the MODIS band 1 reflectance values as input to the model. The linear relationship between the measured reflectance at the MODIS band 1 and the model reflectance was established ($R = 0.76$, $p < 0.01$, $n = 48$), which was used for the correction of the MODIS reflectance values. The spatial distributions of SM concentration in the Pakri Bay were calculated in four ways: (1) using bio-optical model with the MODIS reflectance values with correction; (2) using linear regression between the MODIS reflectance and SM concentration; (3) using bio-optical model with the MODIS reflectance values without correction; (4) using bio-optical model with the MODIS reflectance values with correction, but increasing chlorophyll-*a* concentration by two orders of magnitude as compared with that in cases 2 and 3. The first two cases produced similar results for SM concentrations, while the latter two gave much higher SM concentrations, especially in the sediment plume. It was concluded that the MODIS band 1 (620–670 nm) is the most suitable for the detection of SM concentrations between 0 and 28 mg l^{-1}.

Introduction

Dredging operations in coastal waters affect water quality through an increase in suspended matter (SM) concentrations. The release of SM into a water column usually takes place over a very limited area, while the local hydrodynamic regime results in the spreading and dispersion of particulate matter over a much larger sea area. An adequate knowledge of the distribution of SM is essential for the environmental impact assessment of dredging operations and for taking preventive measures against any possible reduction in water quality below acceptable levels. If dredging operations are performed in sea area with an intensive hydrodynamic regime

and close to biologically sensitive areas, then monitoring of SM distribution with fine temporal and spatial resolution is required. In this case, conventional field measurements of SM concentrations become too costly.

Remote sensing offers a cost-effective method for water quality monitoring in coastal waters. Spectral band ratios are widely used to interpret the remote sensing data, but in Estonian coastal waters, where the spatial distribution of optically active constituents is variable, these ratios seem to have local and regional characteristics (Kutser *et al*. 2001, Sipelgas *et al*. 2004). Miller and McKee (2004) and Sipelgas *et al*. (2006) used MODIS (Moderate Resolution Imaging Spectrometer) band 1 (wavelengths 620–670 nm) reflectance data with spatial resolution of 250 m for the calculation of SM concentrations using linear regression in the Gulf of Mexico and in the Pakri Bay, respectively. According to a study by Reinart and Kutser (2006), MODIS sensor bands with 250 m and 500 m spatial resolution in the near infrared region (NIR) of light spectrum can be efficiently used in the detection of heavy cyanobacteria bloom surface accumulations. During dredging operations, SM is a water quality parameter of major concern but we have to take into account the high variability of chlorophyll content in the water that can also cause high reflectance in NIR region.

Bio-optical reflectance models are more appropriate tools for the interpretation of remote sensing data in multi-componential turbid waters, where the concentrations of different water quality parameters (i.e. coloured dissolved organic matter (CDOM), chlorophyll *a*, and SM) are obtained using inversion algorithms (Kutser 2004, Phinn *et al*. 2005, Giardino *et al*. 2007). Input parameters (site specific absorption and backscattering coefficients) for bio-optical models have recently been the topic of numerous studies (e.g. Babin *et al*. 2003, Gallegos *et al*. 2005, Simis *et al*. 2005, Tilstone *et al*. 2005), highlighting the necessity of bio-optical measurements at a regional scale, which is a crucial step in improving the accuracy of coastal bio-optical models and developing the remote sensing algorithms.

The general aim of this paper is to calculate the spatial distribution of SM concentrations for the relatively small Pakri Bay (Fig. 1a) using the MODIS reflectance data. The aim will be achieved through following steps: (1) the bio-optical model is established for the Pakri Bay using the measured absorption and scattering coefficients; (2) modelled reflectance is compared with MODIS reflectance for the known values of the SM concentrations; (3) the SM concentrations are calculated for the Pakri Bay for one snapshot of MODIS image.

The Pakri Bay is under a heavy anthropogenic stress due to a harbour development. Local currents can reach 50 cm s^{-1} due to water flows through the Pakri Bay and the circulation pattern may change within a couple of days in response to wind variations. As the SM concentrations and distribution patterns depend on dredging amounts and the intensity of wind driven currents, the situation in the Pakri Bay can change considerably within a week (Sipelgas *et al*. 2006). One of the major concerns is to protect the whitefish spawning areas between the Pakri islands from overlapping with SM released into the water column during dredging. Thus it is important to obtain more accurate estimations of the SM concentrations in the sensitive areas of the Pakri Bay.

Methods

Field measurements in the Pakri Bay were performed on 6 October 2002 and 11 November 2002. Water samples for laboratory analysis were collected from 27 stations (Fig. 1b) on both dates.

Laboratory analysis

The concentration of chlorophyll *a* (C_{chl}, mg m^{-3}) was determined by filtering the water samples through Whatman GF/C glass microfibre filters (pore size 1.2 μm, diameter 47 mm, Whatman International Ltd. Maidstone, England), extracting the pigments with hot ethanol (90%, 75 °C) and measuring the absorption at the wavelength of 665 nm and 750 nm. The values of C_{chl} were calculated using the Lorenzen (1967) formula.

To determine the SM concentrations in

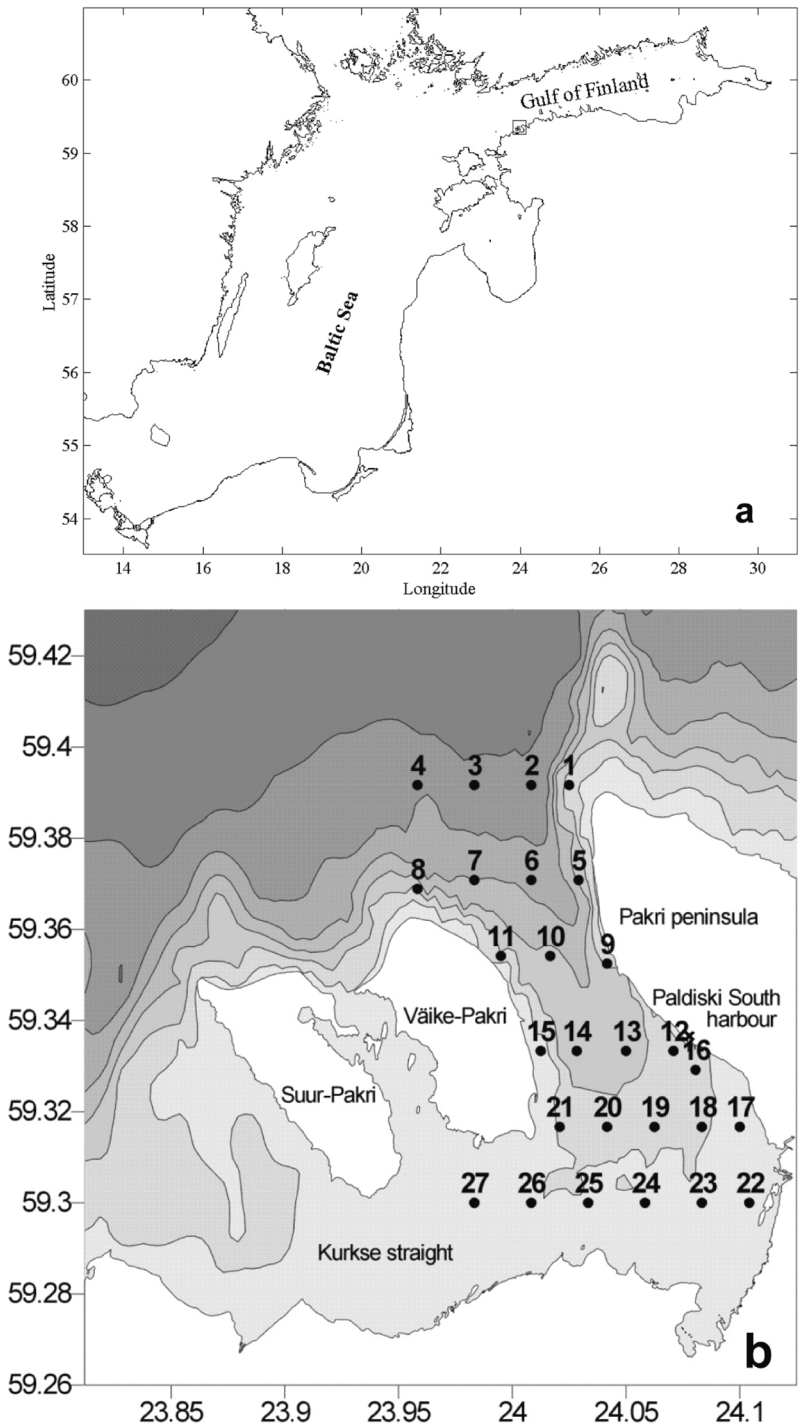

Fig. 1. (**a**) Study site, (**b**) sampling stations

the water, samples were filtered through pre-weighed Millipore membrane filters (pore size 0.45 μm, diameter 47 mm, Millipore Corporation, Bedford, MA), and the filters were dried to a constant weight at a fixed temperature (103–105 °C). The increase in filter weight indicates the SM concentration in the water sample (Lindell *et al*. 1999).

The spectrometric attenuation coefficient of filtered water, $c_f^*(\lambda)$, can be used to describe the content of coloured dissolved organic matter (Højerslev 1980). Water samples were filtered through Millipore membrane filters (pore size 0.45 μm, diameter 47 mm, Millipore Corporation, Bedford, MA) and the corresponding attenuation spectra were determined for filtered water using a spectrophotometer Hitachi U1000. We measured the spectra of $c_f^*(\lambda)$ in the range 350–700 nm and recorded data with wavelength increments of 10 nm. To obtain the absorption coefficient $a_{CDOM}(\lambda)$, spectra of $c_f^*(\lambda)$ were corrected for scattering errors caused by small residual particles and colloids that are not retained on the filter, using the following relationship:

$$a_{CDOM}(\lambda) = c^*_f(\lambda) + c^*_f(\lambda_R)(\lambda_R/\lambda)^g, \quad (1)$$

where $c^*_f(\lambda)$ is the measured value of attenuation coefficient of filtered water and λ_R is the reference wavelength in the red region of the spectrum, where it was assumed that $a_{CDOM}(\lambda_R) = 0$. In our case it was taken as 700 nm and exponent g was taken as 1 (Davies-Colley and Vant 1987).

In situ measurements of inherent optical properties of water

The inherent optical properties (absorption and scattering coefficients) of water were measured using a flow-through system from the moving vessel. The system is based on an ac-9 instrument (attenuation and absorption meter manufactured by WetLabs Inc.) and allows continuous measurements of attenuation (c) and absorption (a) at 9 wavelengths (412, 448, 488, 510, 555, 630, 650, 676, and 750 nm). The water to measurement line was pumped below the surface layer (0.5–1.0 m depth) with a special flow-through system that removes air bubbles from a sample and makes the water flow to the instrument constant and independent of vessel's velocity. In addition to optical parameters, the system records temperature and position with a GPS system. During the data processing, time-lag caused by water lines and a pump is corrected and optical properties are averaged with one-second interval. The construction of the system is described in detail in Lindfors and Rasmus (2000). The system was calibrated based on the WetLabs user manual. The absorption values were corrected for temperature and light scattering. Scattering coefficient (b) was calculated by subtracting the absorption form attenuation. The measurements were made on transects between the sampling stations when the ship moved from one station to the other. In that way, the Pakri Bay was covered on both measurement days. The order of sampling stations was irregular and different in both days.

Bio optical model

Several bio-optical models (Dekker 1993, Kutser *et al*. 2001, Pierson and Strömbeck 2001, Herlevi 2002, Magnusson *et al*. 2004, Morel *et al*. 2006) have been developed for different waters based on the study by Gordon *et al*. (1975) showing that irradiance reflectance just beneath the water surface is the function of absorption and backscattering coefficients:

$$R(\lambda,0) = C_{\mu_0}\frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)}, \quad (2)$$

where $b_b(\lambda)$ is the total backscattering coefficient, $a(\lambda)$ is the total absorption coefficient and C_{μ_0} is the function of solar altitude:

$$C_{\mu_0} = -0.629\mu_0 + 0.975, \quad (3)$$

where μ_0 is the cosine of the zenith angle of the refracted photons (Monte-Carlo by Kirk 1984). Instead of irradiance reflectance beneath the water surface, the reflectance just above the surface is measured by remote sensing instruments. Equation 2 allows for calculating the subsurface irradiance reflectance, but to obtain the reflectance just above the surface Austin (1980) proposes a factor of 0.544 for the conversion of the irradiance reflectance just beneath the water surface to the reflectance just above the water surface:

$$r(\lambda) = 0.544\left(-0.629\mu_0 + 0.975\right) \times \frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)}. \quad (4)$$

The total spectral absorption coefficient is the sum of the optically active water constituents.

We assume that there are three optically active components in water and the total absorption can be described by the following formula:

$$a(\lambda) = a_w(\lambda) + a^*_{ph}(\lambda)C_{chl} + a^*_t(\lambda)C_t, \quad (5)$$

where $a_w(\lambda)$ is the spectral absorption coefficient of pure water; $a_{CDOM}(\lambda)$ is the spectral absorption coefficient of coloured dissolved organic matter; $a^*_{ph}(\lambda)$ is the chlorophyll-specific spectral absorption coefficient of phytoplankton; and $a^*_t(\lambda)$ is the particle-specific spectral absorption coefficient of non-chlorophyllous particles, i.e. tripton. C_{chl} and C_t are concentrations of chlorophyll *a* and tripton, respectively. The total spectral backscattering coefficient can be described by the formula:

$$b^*_b(\mathrm{l}) = 0.5b_w(\lambda) + b^*_{bph}(\lambda)C_{chl} + b^*_{bt}(\lambda)C_t, \quad (6)$$

where $b_w(\lambda)$ is the spectral scattering coefficient of pure water, $b^*_{bph}(\lambda)$ is the chlorophyll-specific spectral backscattering coefficient of phytoplankton and $b^*_{bt}(\lambda)$ is the specific spectral backscattering coefficient of non-chlorophyllous particles.

In this model, the absorption and scattering spectra of pure water, $a_w(\lambda)$ and $b_w(\lambda)$, were taken from Pope and Fry (1992).

The absorption by CDOM can be expressed as a function of the absorption coefficient of dissolved material at a wavelength of 380 nm and a slope factor by the following formula:

$$a_{CDOM}(\lambda) = a_{CDOM}(380)\exp[-S_{CDOM}(\lambda - 380)], \quad (7)$$

where $a_{CDOM}(380)$ is the absorption coefficient of dissolved matter at 380 nm of 1.84 m^{-1} and S_{CDOM} is the slope factor. The slope value was calculated from experimental data obtained from the Pakri Bay. The exponential function was used to describe the spectra of $a_{CDOM}(\lambda)$. From 100 analyzed spectra, the average slope value for the Pakri Bay was –0.013.

The spectral chlorophyll-specific absorption coefficient of phytoplankton is calculated using the following power function recommended by Bricaud *et al*. (1995):

$$a^*_{ph}(\lambda) = A(\lambda)C_{chl}^{-B(\lambda)}, \quad (8)$$

where $A(\lambda)$ and $B(\lambda)$ are positive wavelength dependent parameters. The spectral chlorophyll-specific backscattering coefficient for phytoplankton was taken from Dekker *et al*. (1993).

The particle-specific spectral absorption and backscattering coefficients for tripton can vary greatly in different water bodies. No such data is available for the Pakri Bay. We used Eq. 5 to calculate the particle-specific absorption coefficient for tripton as follows:

$$a^*_t(\lambda) = \frac{a(\lambda) - a_{CDOM}(\lambda) - a_w(\lambda) - a^*_{ph}(\lambda)C_{chl}}{C_t}. \quad (9)$$

The total spectral scattering coefficient is the sum of scattering coefficients:

$$b(\lambda) = b_w(\lambda) + b^*_{ph}(\lambda)C_{chl} + b^*_t(\lambda)C_t, \quad (10)$$

where $b_w(\lambda)$ is the spectral scattering coefficient of pure water; $b^*_{ph}(\lambda)$ is the chlorophyll-specific spectral scattering coefficient of phytoplankton; and $b^*_t(\lambda)$ is the particle-specific spectral scattering coefficient of non-chlorophyllous particles, i.e. tripton.

The particle-specific spectral scattering coefficient of tripton was calculated from Eq. 10 as follows:

$$b^*_t(\lambda) = \frac{b(\lambda) - b_w(\lambda) - b^*_{ph}C_{chl}}{C_t}. \quad (11)$$

The spectra of total absorption and scattering coefficients were measured by ac-9 and concentrations of optically active substances were determined from water samples. The concentration of tripton was calculated using the following equation developed by Hoogenboom and Dekker (1997):

$$C_t = C_{sm} - 0.07C_{chl}, \quad (12)$$

where C_{SM} is concentration of SM. The absorption of CDOM and specific absorption of phytoplankton was calculated from Eqs. 7 and 8, respectively. The spectral specific scattering coefficient of phytoplankton was taken from Dekker *et al*. (1993) and for pure water from Pope and Fry (1992).

In the model we need backscattering instead of scattering. To obtain particle-specific backscattering spectra, the particle-specific scatter-

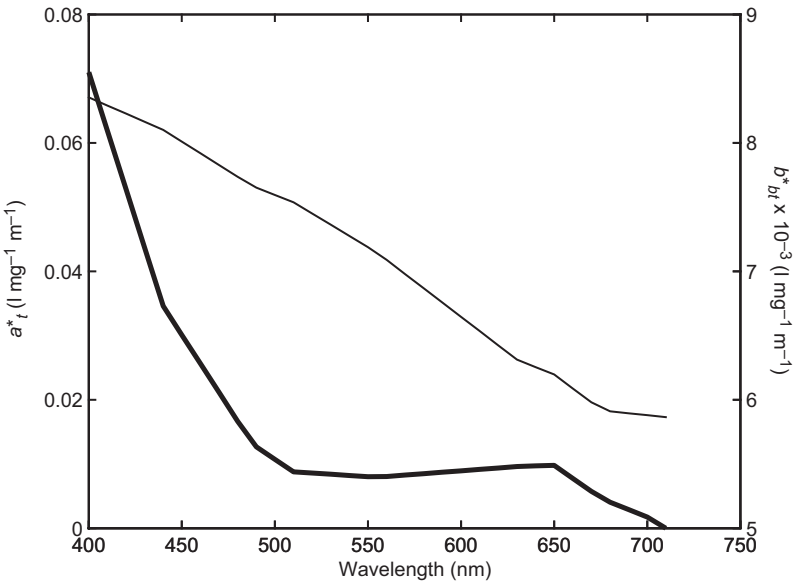

Fig. 2. Particle-specific spectral absorption [a^*_t ($lm^{-1}mg^{-1}$), thick line] and backscattering [b^*_{bt} (lm^{-1} mg^{-1}), thin line] coefficients for the Pakri Bay bio-optical model.

ing spectra were multiplied by the backscattering probability value of 0.019. Herlevi (2002) showed that the backscattering probability varies from 0.016 to 0.022 in Nordic waters. The average spectra obtained, of $a^*_t(\lambda)$ and $b^*_{bt}(\lambda)$ (Fig. 2), were implemented in the model.

Results

The spectra of the surface reflectance for different SM concentrations were modelled using Eq. 4 and the model parameters described in the previous section. The concentration of chlorophyll *a* was kept fixed at 4 μg l^{-1}. For $a_{CDOM}(380)$ the value 1.84 m^{-1} was selected, which corresponds to the average measured value for the Pakri Bay. The S_{CDOM} was taken to be equal to –0.013 and μ_0 to 0.45. The values of C_t for different C_{SM} were calculated with Eq. 12.

The modelled surface reflectance data with varying SM concentration reveals that surface reflectance increases in the whole visible range of the spectrum with increasing SM concentration in water (Fig. 3). The spectra correspond to typical spectra with low chlorophyll-*a* concentration (Giardino *et al*. 2007). The maximum is near 570 nm for low SM concentration and shifts to lower wavelength with increasing SM concentration. The reflectance value increases at 700 nm and local minimum becomes more pronounced at 650 nm with higher SM concentration. Increasing chlorophyll-*a* concentration considerably will shift local reflectance minima to 670 nm. Local minima at 630 nm caused by pychocyanin absorption (Reinart and Kutser 2006) is absent in the reflectance spectra, which is caused by the model setup, since we used the averaged specific absorption spectra for phytoplankton.

The modelled reflectance was also tested against the reflectance values measured by the MODIS instrument at band 1 (the wavelength range of 620–670 nm) in the Pakri Bay for the cells where SM concentration was determined in laboratory analyses. The linear regression between the measured reflectance at band 1 and the modelled reflectance was

$$r = 0.4082 r_{MODIS} + 0.014, \qquad (13)$$

($R = 0.76$, $p < 0.01$, $n = 48$), where r is the modelled reflectance and r_{MODIS} is the MODIS band 1 reflectance (Fig. 4).

To calculate the SM concentration from the MODIS band 1 data using the bio-optical model, the tripton concentration can be obtained from Eqs. 4, 5 and 6 as follows:

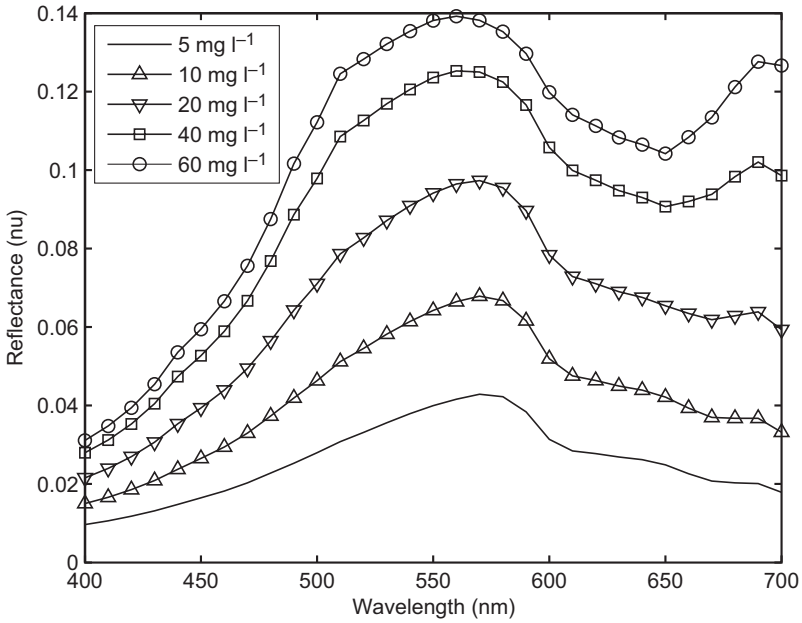

Fig. 3. Modelled surface reflectances with varying C_{SM} (mg l^{-1}) concentrations.

$$C_t = \frac{k\left(0.5b_w + b^*_{bph}C_{chl}\right)}{r\left(a^*_t + b^*_{bt}\right) - kb^*_{bt}} - \frac{r\left[a_w + 0.5b_w + \left(a^*_{ph} + b^*_{bph}\right)C_{chl} + a_{CDOM}\right]}{r\left(a^*_t + b^*_{bt}\right) - kb^*_{bt}}, \quad (14)$$

where

$$k = 0.554(-0.629\mu_0 + 0.975). \quad (15)$$

The values for the coefficients are given in Table 1. The calculated SM concentrations (the tripton concentrations were converted to SM concentrations using Eq. 12) using the reflectance values for the pixels where SM concentrations were determined in laboratory analyses (Fig. 5).

In our previous study (Sipelgas *et al*. 2006), the following linear regression model between MODIS reflectance and SM concentration was developed:

$$C_{SM} = 110.3r_{MODIS} + 1.99, \quad (16)$$

($R = 0.76$, $p < 0.01$, $n = 48$) and was applied to obtain SM distribution maps for the Pakri Bay during dredging activities. The SM concentration calculated from Eq. 16 using the same MODIS reflectance data are shown in Fig. 5. The differences between SM concentrations calculated with the different methods are negligible.

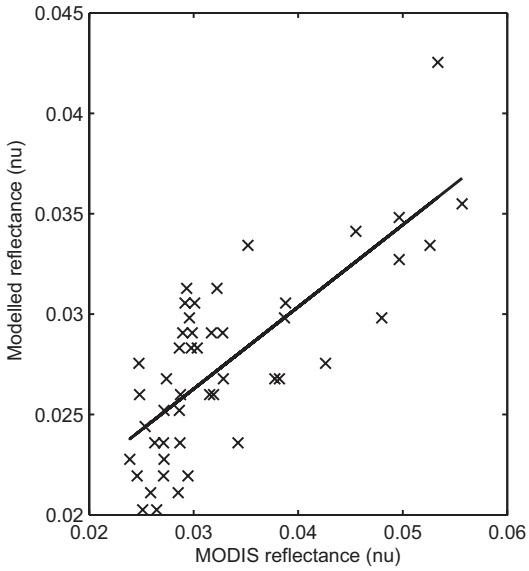

Fig. 4. Modelled remote sensing reflectance *vs.* the reflectance measured at MODIS band 1 calculated for the cells.

We calculated the SM distribution in the Pakri Bay from the MODIS reflectance at band 1 on 11 May 2003 using the linear regression (Eq. 16) and the bio-optical model (Eqs. 13, 14, 15 and

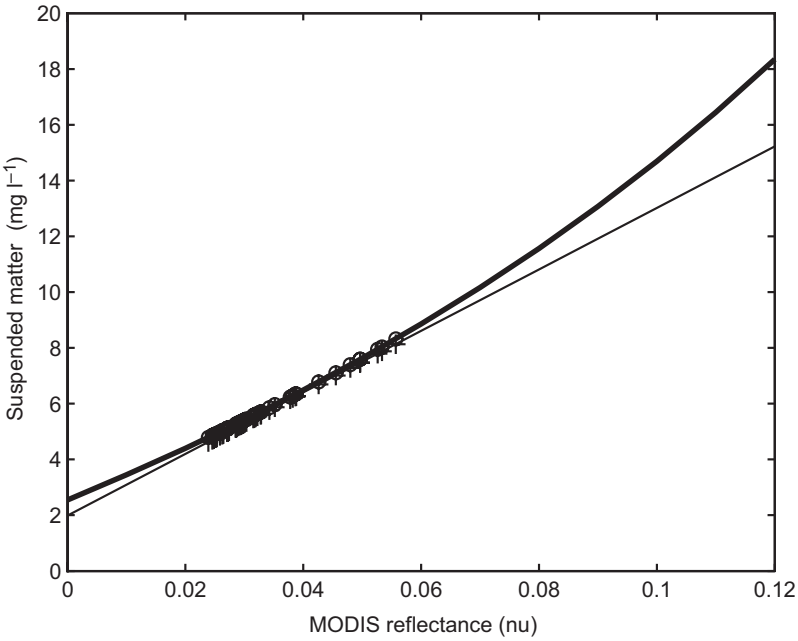

Fig. 5. Suspended matter concentrations (mg l^{-1}) as a function of MODIS reflectance calculated using bio-optical model (thick line and 'o') and linear regression (thin line and 'x').

12). In the bio-optical model the chlorophyll-*a* concentration used was 4 μg l^{-1}, which was the average measured value on that day. Both models gave similar distribution patterns of SM (Fig. 6a and b). High SM concentrations of 6.5–8.5 mg l^{-1} were obtained at the dredging site. Background concentrations in the bay and over the coastal sea area were 4.5–5 mg l^{-1}.

A comparative SM distribution map was created assuming that the model reflectance is equal to the MODIS reflectance, i.e. $r = r_{MODIS}$ instead of to reflectance calculated with Eq. 13. In this case, the SM concentrations increased over the entire area (Fig. 6c). The increase was smallest over the coastal sea where the SM concentration increased from 4.5–5 mg l^{-1} to 5–5.5 mg l^{-1} (the background values). The increase was greatest at the dredging site, where maximum value of 8–9 mg l^{-1} rose to 15–16 mg l^{-1}.

The sensitivity of the bio-optical model with respect to the "errors" in chlorophyll-*a* concentration was checked by calculating SM distribution map for chlorophyll *a* equal to 200 μg l^{-1}. This value corresponds to cyanobacteria accumulations on the water surface during the bloom (Reinart and Kutser 2006). No model parameters were adjusted to the new chlorophyll-*a* concentration. The maximum SM concentration increased to 19–20 mg l^{-1} instead of 8.5 mg l^{-1} and the difference between the concentration of the sediment plume and background concentration became larger (Fig. 6d).

Table 1. Coefficient values.

Coefficient	Average value at 620–670 nm
a_w (m^{-1})	0.335067
b_w (m^{-1})	0.00075
a^*_{ph} (m^2 mg C_{chl}^{-1})	0.00844
b^*_{bph} (m^2 mg C_{chl}^{-1})	0.00065
a^*_t (lm^{-1} mg^{-1})	0.008654
b^*_{bt} (lm^{-1} mg^{-1})	0.006209
a_{CDOM} (m^{-1})	0.06016

Discussion

In this study we focused on the wavelength range of 620–670 nm, which corresponds to the MODIS band 1 with a spatial resolution of 250 m. The reflectance depends on the concentrations of optically active substances of water. The sensitivity of reflectance at different wavelength is not uniform. Sensitivity analysis based on the first derivative approach has shown that the variations of the first derivative of reflectance

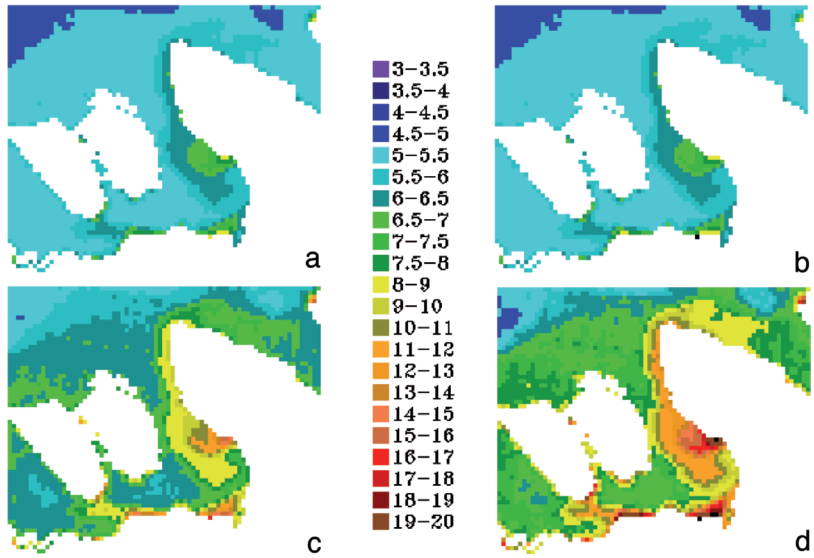

Fig. 6. Suspended matter concentration calculated from the MODIS band 1 data from the Pakri Bay 11 May 2003: (**a**) using the linear regression relationship, (**b**) using the bio-optical model with C_{chl} 4 µg l^{-1}, (**c**) using the bio-optical model, but assuming that model reflectance is equal to MODIS reflectance, and (**d**) using the bio-optical model with C_{chl} 200 µg l^{-1}.

for CDOM and chlorophyll-*a* concentrations are negligible at the wavelengths of band 1 (Giardino *et al*. 2007). In that respect the changes in chlorophyll-*a* and CDOM concentrations should not affect the reflectance values significantly at the MODIS band 1. With respect to the SM concentrations, the modelled reflectance at the MODIS band 1 increases faster with increasing SM concentration when the concentrations are low (Fig. 7). The saturation reflectance for tripton is expressed as:

$$\lim_{C_t \to \infty} r = 0.544\left(-0.629\mu_0 + 0.975\right)\frac{b_{bt}^*}{b_{bt}^* + a_t^*}. \quad (17)$$

According to the selected model parameters (Table 1) and assuming that chlorophyll-*a* concentration is constant, the saturation reflectance is 0.16 and half saturation reflectance is reached at the SM concentration of 28 mg l^{-1}. In the range of SM concentrations below that value the change of reflectance is more than 10^{-3} (mg l^{-1})$^{-1}$. The observed surface concentrations of SM during dredging operations in the Pakri Bay have remained smaller than that value (Sipelgas *et al*. 2006) except in close proximity to dredging platforms. Also Jørgensen and Edelvang (2000) reported SM concentration in sediment plume in the range of 1–30 mg l^{-1} during dredging operations related to the construction of the Øresund Link. Thus, we may say that resolution of reflectance values is suitable for the detection of SM concentrations at the MODIS band 1.

Comparing the MODIS reflectance and modelled reflectance for the known SM concentration showed statistically significant correlation. The correlation coefficient reveals that reasonable results for the detection of the SM distribution can be obtained, although no atmospheric correction was done for the MODIS data. The obtained linear regression (Eq. 13) was used for the correction of MODIS reflectance values in the calculation of the SM concentrations in the model. Conversion of MODIS reflectance values calculated with Eq. 13 resulted in increase/decrease of reflectance for low/high MODIS reflectance. The equilibrium point is at 0.024. Thus, the effect of using the linear relationship for MODIS reflectance data (Eq. 13) will reduce the range of reflectance values in the model. When this conversion is not applied the range of reflectance values is wider and the contrast between SM concentrations is larger (Fig. 6a and b).

A comparison of SM concentrations calculated using a linear regression (Sipelgas *et al*. 2006) directly relating MODIS reflectance and SM concentration and the bio-optical model showed that the differences in SM concentrations were negligible. That is explained due to the low range of variations of reflectance values meas-

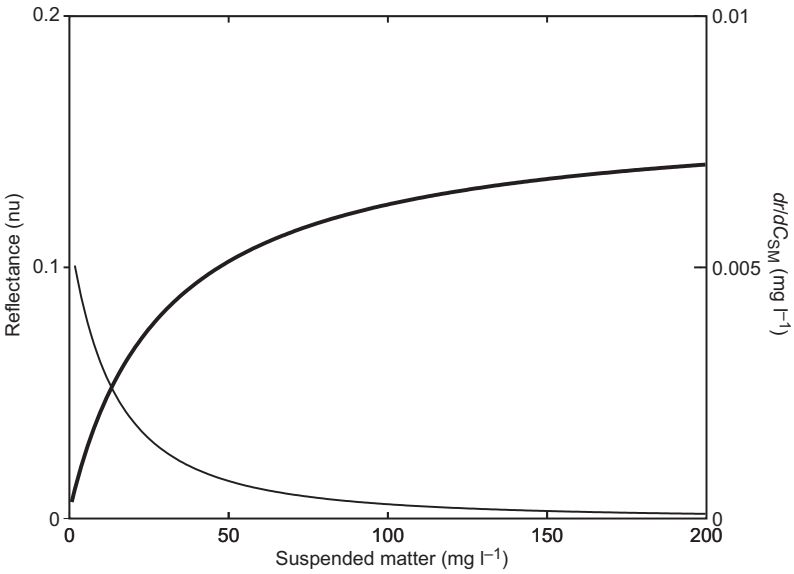

Fig. 7. Modelled reflectance (thick line) and the first derivative of modelled reflectance with respect to SM concentration (mg l^{-1}) (thin line) at band 620–670 nm as function of SM concentration.

ured in the Pakri Bay by the MODIS instrument. Extending the range of the reflectance values and calculating the corresponding SM concentrations by the two methods shows that the two curves start to depart at a higher reflectance range than was actually measured in the Pakri Bay (Fig. 5). The SM concentrations calculated by the model become higher than the values obtained from the linear relationship. If the range of measured reflectance and corresponding SM concentrations is not wide then a linear relationship that is fitted to the data may provide reasonable results. Even predicted results can be good if the variation of reflectance does not extend significantly beyond the range that is used for the establishment of the regression relationship. Thus, when the range of reflectance values by MODIS is narrow then linear function approximates to more general linear fractional function rather well.

According to the sensitivity analyses, the variations of chlorophyll-*a* concentration do not affect modelled reflectance at MODIS band 1 significantly. But if the chlorophyll *a* concentration is strongly underestimated and model parameters are not recalculated according to actual chlorophyll-*a* concentration, then the estimated SM concentrations become too high. The latter was shown when the chlorophyll-*a* concentration that corresponds to phytoplankton bloom was selected. According to Eq. 14, the change in tripton concentration is proportional to the change in chlorophyll *a* concentration with the proportionality factor equal to $b^*_{bph}(k - r)$. Following application of Eq. 12 for calculation of SM from tripton, this has only an additive effect. Still, the latter shows that the current model should not be applied during a phytoplankton bloom without redefining the model parameters.

Conclusions

A bio-optical model based on the formulation by Gordon *et al* (1975) was established for the Pakri Bay, the southern Gulf of Finland. The model parameters, the absorption spectra by CDOM, spectral chlorophyll-specific absorption coefficient and mainly particle-specific spectral absorption and scattering coefficients, were determined from the laboratory analyses of water samples and from *in situ* measurements of the inherent optical water properties.

The modelled reflectance spectra correspond to typical reflectance spectra with the low chlorophyll-*a* concentration.

The linear relationship between the MODIS reflectance and the model reflectance was established and used for the conversion of MODIS reflectance values to the reflectance values used in the model for the calculation of SM concentrations. The conversion relationship reduces the range of the MODIS reflectance values and the

contrasts between the SM concentrations consequently.

A comparison of SM concentrations calculated using a linear regression (Sipelgas *et al.* 2006) directly relating MODIS reflectance and SM concentration and bio-optical model showed that the differences in SM concentrations were negligible. That was explained due to the low range of variations of reflectance values measured in the Pakri Bay by the MODIS instrument.

Sensitivity analyses reveal that the resolution of reflectance values on the wavelength range of the MODIS band 1 (620–670 nm) is the most suitable for the detection of SM concentrations between 0 and 28 mg l^{-1}, which covers the range of SM concentrations during dredging operations. The current model should not be applied during a phytoplankton bloom without redefining the model parameters.

The current study suggests that the presented bio-optical model should be tested with more field data in the Pakri Bay and the other areas. A more general relationship for conversion of MODIS reflectance values to model reflectance should be sought.

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