Remote sensing reflectance of Pomeranian lakes and the Baltic*

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Abstract

The remote sensing reflectance R_{rs}, concentrations of chlorophyll *a* and other pigments C_i, suspended particulate matter concentrations C_{SPM} and coloured

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dissolved organic matter absorption coefficient $a_{\rm CDOM}(\lambda)$ were measured in the euphotic zones of 15 Pomeranian lakes in 2007–2010. On the basis of 235 sets of data points obtained from simultaneous estimates of these quantities, we classified the lake waters into three types. The first one, with the lowest $a_{\rm CDOM}$(440 nm) (usually between 0.1 and 1.3 $\rm m^{-1}$ and chlorophyll a concentrations $1.3 < C_a < 33$ mg $\rm m^{-3}$), displays a broad peak on the reflectance spectrum at 560–580 nm and resembles the shape of the remote sensing reflectance spectra usually observed in the Baltic Proper. A set of $R_{\rm rs}$ spectra from the Baltic Proper is given for comparison. The second lake water type has a very high CDOM absorption coefficient (usually $a_{\rm CDOM}$(440 nm) > 10 $\rm m^{-1}$, up to 17.4 $\rm m^{-1}$ in Lake Pyszne; it has a relatively low reflectance ($R_{\rm rs} < 0.001$ $\rm sr^{-1}$) over the entire spectral range, and two visible reflectance spectra peaks at ca 650 and 690–710 nm. The third type of lake water represents waters with a lower CDOM absorption coefficient (usually $a_{\rm CDOM}$(440 nm)< 5 $\rm m^{-1}$) and a high chlorophyll a concentration (usually $C_a > 4$ mg $\rm m^{-3}$, up to 336 mg $\rm m^{-3}$ in Lake Gardno). The remote sensing reflectance spectra in these waters always exhibit three peaks ($R_{\rm rs} > 0.005$ $\rm sr^{-1}$): a broad one at 560–580 nm, a smaller one at ca 650 nm and a well-pronounced one at 690–720 nm. These $R_{\rm rs}(\lambda)$ peaks correspond to the relatively low absorption of light by the various optically active components of the lake water and the considerable scattering (over the entire spectral range investigated) due to the high SPM concentrations there. The remote sensing maximum at $\lambda \approx 690$–720 nm is higher still as a result of the natural fluorescence of chlorophyll a. Empirical relationships between the spectral reflectance band ratios at selected wavelengths and the various optically active components for these lake waters are also established: for example, the chlorophyll a concentration in surface water layer $C_a = 6.432\ {\rm e}^{4.556X}$, where $X = [\max R_{\rm rs}(695 \le \lambda \le 720) - R_{\rm rs}(\lambda = 670)]/ \max R_{\rm rs}(695 \le \lambda \le 720)$, and the coefficient of determination $\rm R^2 = 0.95$.

1. Introduction

The Pomeranian Lake District is situated in northern Poland and borders on the southern Baltic coastline. The undulating topography of this region with its numerous lakes was formed by the Scandinavian ice-sheet and the subsequent actions of the Baltic Sea. There are 3381 lakes with an area of more than 1 ha; their total area is 104 197.3 ha (Choiński 2007). Since the bio-optical properties of these lakes had been poorly investigated, a comprehensive study of 15 lakes in central Pomerania was undertaken in 2007–2010. Some of the results of this investigation, namely, the remote sensing reflectance $R_{\rm rs}(\lambda)$ spectra of the lake waters, are the subject of this paper.

The waters of these lakes are highly diverse and, like sea waters, contain groups of optically active components (OACs) such as phytoplankton pigments (including chlorophyll a), organic and mineral suspended particulate matter (SPM), and coloured dissolved organic matter (CDOM). But the range of differentiation of their concentrations far exceeds that normally recorded in the open waters of the Baltic and other seas. A very much more precise definition of how each of these groups of substances modifies the reflectance spectra $R_{\rm rs}(\lambda)$ is possible from a study of these lake waters than of sea waters. The aim of the present work was therefore to define this influence, i.e. to interpret the shapes of the reflectance spectra $R_{\rm rs}(\lambda)$ and to establish correlations between the spectral reflectance band ratio and the chlorophyll a concentration, the SPM concentration $C_{\rm SPM}$, and the index of CDOM concentration in the water, i.e. the coefficient of light absorption $a_{\rm CDOM}$ in the blue waveband (440 nm). For comparison the reflectance spectra of the Baltic Sea are also presented.

2. Material and methods

The reflectance was calculated as the ratio of the water-leaving upward radiance $L_{\rm u}(0^+,\ \lambda)$ and the downward irradiance $E_{\rm d}(0^+,\ \lambda)$ just above the water surface: $R_{\rm rs}(\lambda) = L_{\rm u}(0^+,\ \lambda)/E_{\rm d}(0^+,\ \lambda)$. The downward irradiance $E_{\rm d}(0^+,\ \lambda)$ was measured above the water; the upward radiance in the water was measured every 10 cm depth from 0.1–2 m, extrapolated to the water surface $L_{\rm u}(0^-,\ \lambda)$ and to the water-leaving radiance as $L_{\rm u}(0^+,\ \lambda) = 0.544\, L_{\rm u}(0^-,\ \lambda)$ (see Mueller & Austin 1995, Darecki et al. 2005). The irradiance and radiance were measured with a Satlantic Hyper Spectral Radiometer HyperPro in 136 channels in the 350–800 nm spectral range. The absorption spectra $a_{\rm CDOM}(\lambda)$ and the chlorophyll a concentrations C_a were estimated from spectrophotometric measurements using a Hitachi U 2810 UV-VIS Spectrophotometer. Phytoplankton pigment concentrations were estimated using high performance liquid chromatography (HPLC). SPM concentrations ($C_{\rm SPM}$) were determined as the particulate dry mass collected on Whatman GF/F glass filters from known volumes of water.

Optical measurements were carried out in situ and water samples were collected for analysis from boats adapted for such purposes, usually once a month, except when the lakes were covered with ice. The measurement stations were located over the deepest point in the main basin of each lake, as far distant as possible from sources that could accidentally alter the water's properties, i.e. far from river mouths, canals joining the lake with the sea, etc. The results given below refer to the euphotic zones of the largest, representative parts of each of the investigated lakes. 235 sets of empirical data points obtained from the simultaneous measurement of the reflectance spectra $R_{\rm rs}(\lambda)$, chlorophyll concentrations C_a, suspended particulate matter concentrations $C_{\rm SPM}$ and absorption spectra $a_{\rm CDOM}(\lambda)$ were collected for the analysis and interpretation of the remote sensing reflectance spectra $R_{\rm rs}(\lambda)$.

3. Results and discussion

Typical (average) spectra of the remote sensing reflectance $R_{rs}(\lambda)$ recorded in each lake and in Baltic coastal waters (off the Sopot area) are shown in Figure 1. The broad diversity of these spectra is evident,

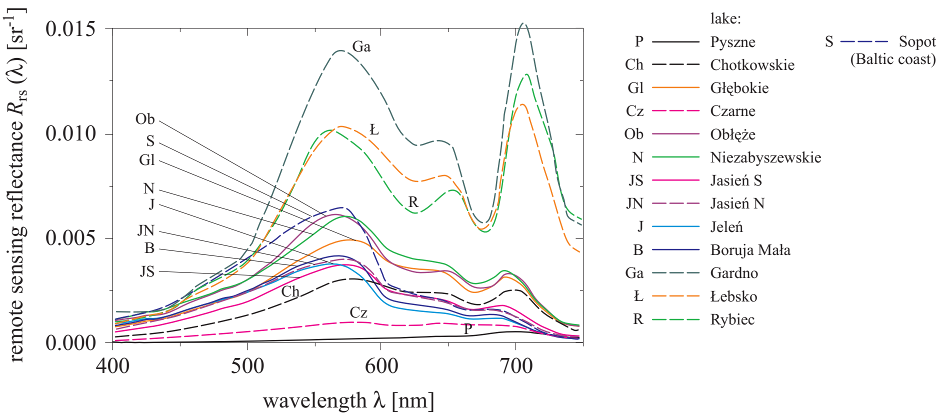

Figure 1. Typical spectra of the remote sensing reflectance $R_{rs}(\lambda)$ recorded in lakes of central Pomerania in the vicinity of the southern Baltic in Poland

due to the differences in concentrations and compositions of the various groups of OACs in the waters of these lakes (i.e. SPM, chlorophyll *a* and other pigments, CDOM). So, for example, the lowest chlorophyll *a* levels dropped to ca 1 mg m^{-3} (in Lake Jasień Północny), whereas the highest value of 336 mg m^{-3} was recorded in Lake Gardno. The overall effect of the concentration of this group of components on the reflectance spectra $R_{rs}(\lambda)$ is shown in Figure 2: this presents practically all the reflectance spectra in comparison with the triangular plot of the relative OAC concentrations in these waters. A glance at this figure shows straight away that the reflectances $R_{rs}(\lambda)$ over the whole spectral range are the highest in waters with a high chlorophyll *a* concentration, i.e. a high concentration of phytoplankton and a high overall mass of SPM. Reflectances thus increase distinctly over the entire VIS spectral range as a result of the enhanced scattering of light from suspended particles; the spectra of this reflectance are simultaneously modified as a result of the selective absorption of light according to the well-known relationship $R_{rs}(\lambda) \sim b_b(\lambda)/(a(\lambda) + b_b(\lambda))$, where b_b and a are the respective coefficients of backscattering and absorption (see e.g. Gordon & Morel 1983, Gordon et al. 1988). This figure also shows that waters with a high CDOM concentration have the lowest reflectance; the index of this concentration is

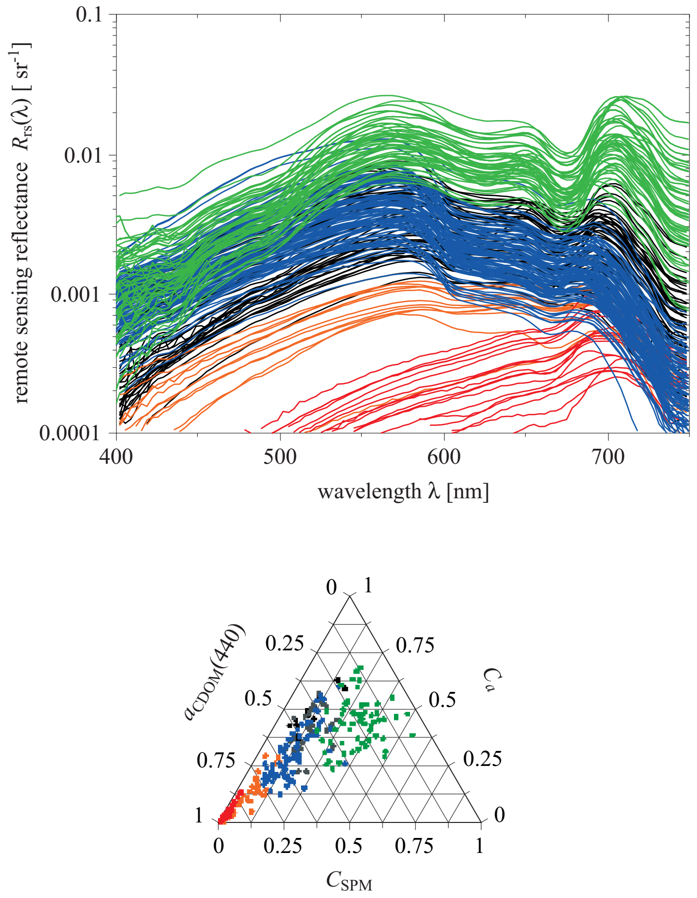

Figure 2. Spectra of the remote sensing reflectance $R_{rs}(\lambda)$ for the waters of the investigated lakes, compared with the triangular plot of the relative concentrations of optically active components (OAC) in these waters

the coefficient of light absorption a_{CDOM}(440 nm) and is practically non-measurable in the short-wave region of the VIS spectrum, which CDOM absorbs very strongly (e.g. Woźniak & Dera 2007).

In comparison with the plot of reflectance spectra $R_{rs}(\lambda)$, the triangular plot in Figure 2 clearly demonstrates a strong rise in spectral values of R_{rs} with high chlorophyll *a* concentration, and their sharp drop due to the high concentration of CDOM (high values of a_{CDOM}(440)). The distinct increase in reflectance with rising levels of chlorophyll *a* and total SPM for similar CDOM concentrations (strictly speaking, the index of these concentrations a_{CDOM}(440 nm)) is shown in Figure 3.

The selective absorption of light by the various pigments and CDOM contained in the water complicates the reflectance spectra considerably.

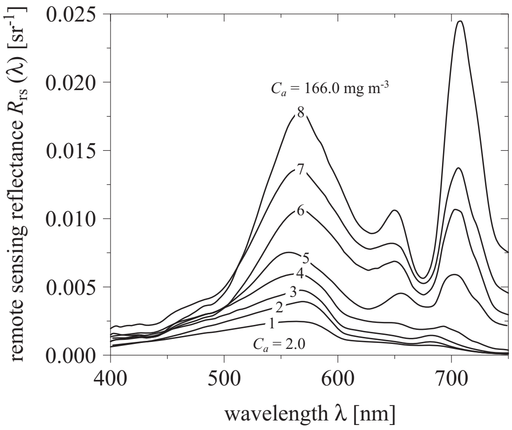

Figure 3. Reflectance spectra in the investigated lake waters with increasing concentrations of chlorophyll a and total SPM for similar CDOM concentration indices. The successive spectra correspond to increasing concentrations:

1 – $C_a = 2.0$ mg m^{-3}, $C_{\text{SPM}} = 1.4$ g m^{-3}, $a_{\text{CDOM}}(440) = 0.35$ m^{-1};
2 – $C_a = 3.8$ mg m^{-3}, $C_{\text{SPM}} = 1.0$ g m^{-3}, $a_{\text{CDOM}}(440) = 0.67$ m^{-1};
3 – $C_a = 5.2$ mg m^{-3}, $C_{\text{SPM}} = 1.7$ g m^{-3}, $a_{\text{CDOM}}(440) = 0.28$ m^{-1};
4 – $C_a = 11.2$ mg m^{-3}, $C_{\text{SPM}} = 2.1$ g m^{-3}, $a_{\text{CDOM}}(440) = 0.35$ m^{-1};
5 – $C_a = 27.6$ mg m^{-3}, $C_{\text{SPM}} = 5.9$ g m^{-3}, $a_{\text{CDOM}}(440) = 0.92$ m^{-1};
6 – $C_a = 74.2$ mg m^{-3}, $C_{\text{SPM}} = 38.0$ g m^{-3}, $a_{\text{CDOM}}(440) = 1.54$ m^{-1};
7 – $C_a = 96.6$ mg m^{-3}, $C_{\text{SPM}} = 50.0$ g m^{-3}, $a_{\text{CDOM}}(440) = 1.24$ m^{-1};
8 – $C_a = 166.0$ mg m^{-3}, $C_{\text{SPM}} = 52.0$ g m^{-3}, $a_{\text{CDOM}}(440) = 0.81$ m^{-1}

Its maxima lie in the wavelength intervals less strongly absorbed than the wavelengths in adjacent intervals, and the minima coincide with the absorption bands of particular OACs, both dissolved and suspended in the water. There are many absorption bands, but their detailed analysis would exceed the scope of this article (see e.g. Woźniak & Dera 2007).

Figure 4 illustrates the three types of remote sensing reflectance spectra $R_{\text{rs}}(\lambda)$ that we distinguished in Pomeranian lakes. The first type of lake water, with the lowest $a_{\text{CDOM}}(440$ nm) (mostly between 0.1 and 1.3 m^{-1}, and chlorophyll a concentrations $1.3 < C_a < 33$ mg m^{-3} – both values similar to those recorded in the Baltic – see Figure 5, Darecki et al. 2008, Kowalczuk et al. 2010), displays a broad peak on the reflectance spectrum at 560–580 nm and resembles the shape of the remote sensing reflectance spectra usually observed in the Baltic Sea (see e.g. Darecki et al. 2003). The second type has a very high CDOM absorption coefficient (usually $a_{\text{CDOM}}(440$ nm) > 10 m^{-1}, up to 17.4 m^{-1}) in Lake Pyszne; they have a relatively low reflectance ($R_{\text{rs}} < 0.001$ sr^{-1}) over the entire spectral range, and two visible reflectance spectra peaks at ca 650 and 690–710 nm.

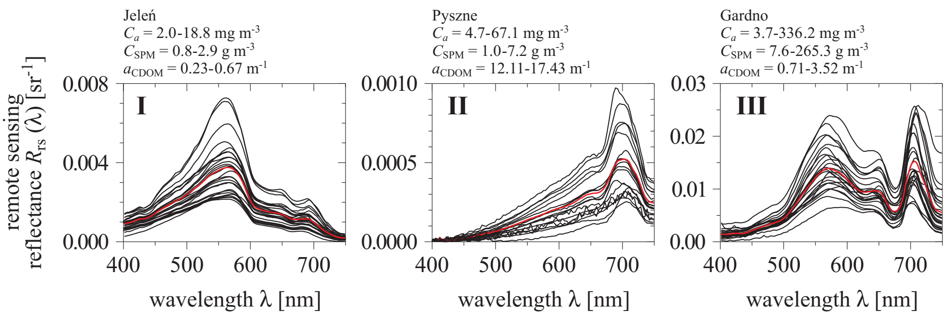

Figure 4. Three types of remote sensing reflectance spectra distinguished in Pomeranian lakes. The red line is the average value calculated from all the values of $R_{\rm rs}$ recorded in a given lake (Note the differences in the scale of $R_{\rm rs}$ for these three different types of spectra)

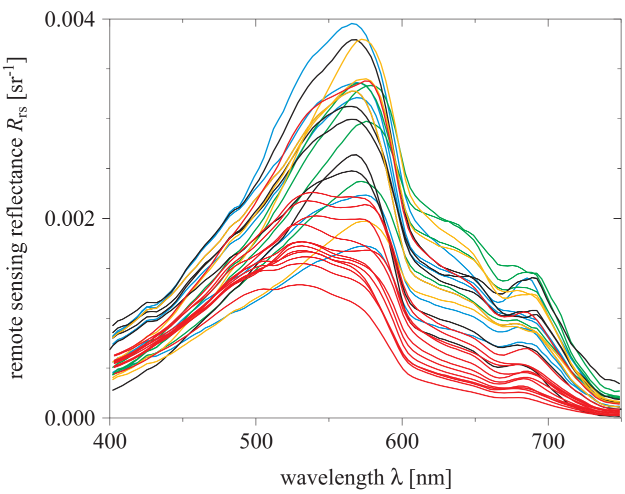

Figure 5. Typical spectra of the remote sensing reflectance in the Baltic Proper (red lines), showing a strong resemblance to the type I spectra of lake waters given in the plot for comparison: Lake Jeleń – black line, Lake Boruja Mała – blue line, Lake Jasień Południowy – green line, Lake Jasień Północny – yellow line. Baltic data measured by M. Darecki in the spring of 2011 (18–28 May) (IO PAS Data Bank)

The third type represents waters with a lower CDOM absorption coefficient (usually $a_{\rm CDOM}(440\ {\rm nm}) < 5\ {\rm m}^{-1}$) and a high chlorophyll a concentration (usually $C_a > 4$ mg m^{-3}, up to 336 mg m^{-3} in Lake Gardno).

The third type of remote sensing reflectance spectra in lake waters always exhibits three peaks ($R_{\rm rs} > 0.005$ sr^{-1}): a broad one at 560–580 nm, a smaller one at ca 650 nm and a well-pronounced one at 690–720 nm.

These $R_{rs}(\lambda)$ peaks correspond to the relatively low absorption of light by the various OACs of the lake water and the considerable scattering due to the high SPM concentrations there. The remote sensing maximum at $\lambda \approx$ 690–720 nm is higher still as a result of the natural fluorescence of chlorophyll *a* (Mitchell & Kiefer 1988). The position of this maximum in the red region shifts distinctly in the direction of the longer waves with increasing

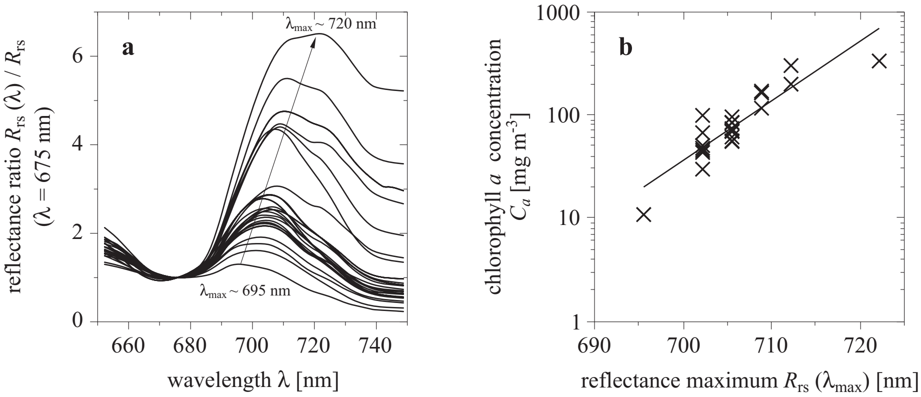

Figure 6. Remote sensing reflectance R_{rs}, normalized to 675 nm, measured in Lake Gardno: a) magnified section of the spectrum in the 700 nm region, b) dependence between the position of the reflectance peak and the chlorophyll *a* concentration

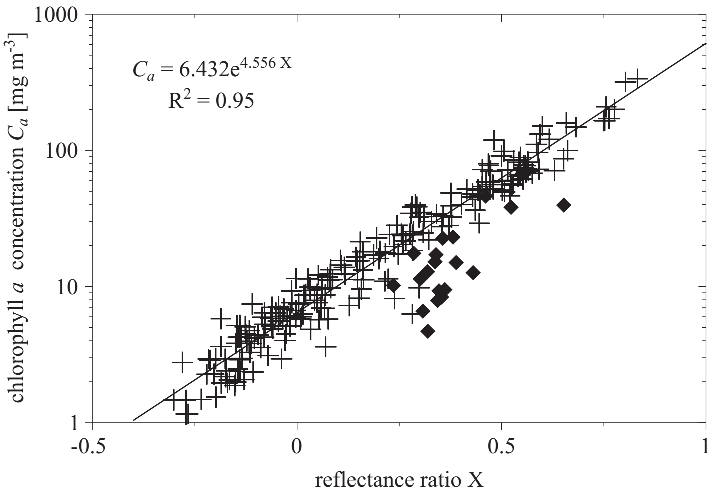

Figure 7. Correlations of the chlorophyll *a* concentration C_a with the spectral reflectance band ratio $X = [\max R_{rs}(695 \leq \lambda \leq 720) - R_{rs}(\lambda = 670)] / \max R_{rs}(695 \leq \lambda \leq 720)$ for Pomeranian lakes in accordance with equation (1) for all the lakes investigated except the dystrophic lake (the black squares on the plot)

chlorophyll a concentration and are the signals available for the remote sensing detection of chlorophyll a (Gitelson et al. 2007). This is shown for one of the lakes (L. Gardno) in Figure 6 a, b. The change in position of this maximum was used to construct a correlation formula linking R_{rs} and C_a.

The correlations of the spectral reflectance band ratio with the concentrations of particular OACs enable the approximate levels of these components in the euphotic zones of the lakes investigated to be determined from reflectance spectra measurements. For example, the correlation shown in Figure 7 was obtained for chlorophyll a; it is described by the exponential equation:

$$C_a = 6.432\, e^{4.556X}, \qquad (1)$$

where $X = [\max R_{\mathrm{rs}}(695 \le \lambda \le 720) - R_{\mathrm{rs}}(\lambda = 670)] / \max R_{\mathrm{rs}}(695 \le \lambda \le 720)$, and the coefficient of determination $\mathrm{R}^2 = 0.95$. This approximation does not include the discrepant data from the dystrophic lake (humic lake – with brown water). The usefulness of this correlation is confirmed by its high coefficient of determination.

We obtained another good correlation for the concentration C_{SPM} (Figure 8) and a slightly weaker one for $a_{\mathrm{CDOM}}(440 \text{ nm})$ (Figure 9). The use of these correlations may facilitate the monitoring of the state of these lakes with the aid of reflectance measurements.

The errors of approximation were also estimated. For this purpose we compared the concentration values of $C_{a,\mathrm{C}}$, $C_{\mathrm{SPM,C}}$ and $a_{\mathrm{CDOM,C}}(440 \text{ nm})$, computed (index C) from the spectral reflectance by the equations given in

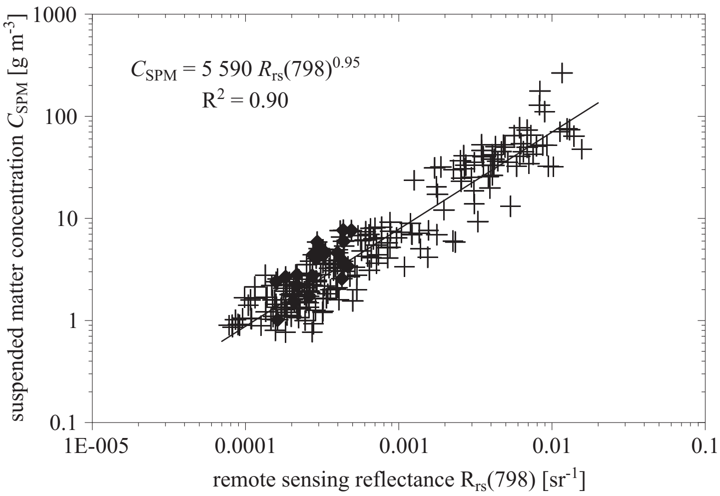

Figure 8. Correlation of the suspended particulate matter concentration C_{SPM} with the spectral reflectance $R_{\mathrm{rs}}(798 \text{ nm})$

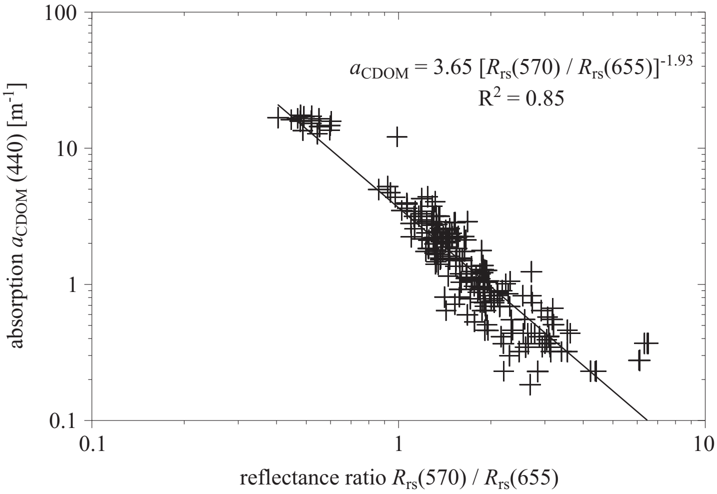

Figure 9. Correlation of the absorption coefficient $a_{\mathrm{CDOM}}(440\ \mathrm{nm})$ with the spectral reflectance band ratio $R_{\mathrm{rs}}(570)/R_{\mathrm{rs}}(655)$

Figures 7, 8 and 9, with the respective measured values (index M) of $C_{a,\mathrm{M}}$, $C_{\mathrm{SPM,M}}$ and $a_{\mathrm{CDOM,M}}(440\ \mathrm{nm})$. The estimated errors of approximation are given in Table 1.

Table 1. The relative errors in the approximations

Models	Arithmetic statistics		Logarithmic statistics			
	Systematic error	Statistical error	Systematic error	Standard error factor	Statistical error	
	$< \varepsilon >$ [%]	σ_ε [%]	$< \varepsilon >_{\mathrm{g}}$ [%]	x	σ_- [%]	σ_+ [%]
C_a (eq. (1), Figure 7)	5.1	37.5	−0.02	1.36	−26.4	35.8
C_{SPM} (Figure 8)	10.5	54.1	−0.29	1.56	−36.1	56.5
$a_{\mathrm{CDOM}}(400)$ (Figure 9)	8.7	47.8	−0.49	1.46	−31.4	45.8

Relative mean error (systematic): $< \varepsilon >= N^{-1} \sum_i \varepsilon_i$ (where $\varepsilon_i = (X_{i,C} - X_{i,M})/X_{i,M}$)

Standard deviation (statistical error) of ε : $\sigma_\varepsilon = \sqrt{\frac{1}{N}\left(\sum(\varepsilon_i - < \varepsilon >)^2\right)}$

Mean logarithmic error: $< \varepsilon >_g = 10^{[<\log(X_{i,C}/X_{i,M})>]} - 1$

Standard error factor: $x = 10^{\sigma_{\log}}$

Statistical logarithmic errors: $\sigma_+ = x - 1,\ \sigma_- = \frac{1}{x} - 1$,

where $X_{i,M}$ – measured values, $X_{i,C}$ – estimated values (subscript M stands for ‘measured’, C for ‘calculated’);

$< \log(X_{i,C}/X_{i,M}) >$ – mean of $\log(X_{i,C}/X_{i,M})$;

$\sigma_{\log}$ – standard deviation of the set $\log(X_{i,C}/X_{i,M})$.

4. Conclusions

The broad range of concentrations of the optically active components (OACs) contained in the waters of the investigated lakes (e.g. chlorophyll a concentration C_a from ca 1 mg m^{-3} to 336 mg m^{-3}) enables the influence of each group of these OACs on the reflectance spectra $R_{rs}(\lambda)$ of these waters to be established. Three types of reflectance spectra with quite different shapes and values were distinguished. The first one, for waters with intermediate (or low) concentrations of all three OACs, has a conspicuous, broad peak in the 560–580 nm band (with maximum values of R_{rs} very much less than 0.01 sr^{-1}), and two very weak, scarcely discernible peaks in the long-wave bands. These type I spectra $R_{rs}(\lambda)$ of the lake waters resemble those commonly observed for the Baltic Proper. The second type, for lake waters with very high CDOM concentrations (a_{CDOM}(440 nm)$>$ 10 m^{-1}), has very low reflectance values ($R_{rs} < 0.001$ sr^{-1}) over the entire spectral range, with two visible reflectance spectra peaks: a very weak one at ca 650 and a somewhat stronger one at 690–710 nm. The third type of spectrum $R_{rs}(\lambda)$, for lake waters with low CDOM concentrations (a_{CDOM}(440 nm)$<$ 5 m^{-1}) and high chlorophyll a levels ($C_a > 4$ mg m^{-3}, up to 336 mg m^{-3}) exhibits three peaks ($R_{rs} > 0.005$ sr^{-1}): a broad one at 560–580 nm, a smaller one at ca 650 nm and a well-pronounced one at 690–720 nm. The correlations of the relevant spectral reflectance bands with the chlorophyll a concentration and with the total SPM concentration for the lake waters have high coefficients of determination: $R^2 = 0.95$ and 0.90 respectively. The correlation of the coloured dissolved organic matter absorption coefficient a_{CDOM}(440 nm) with the spectral reflectance band ratio $R_{rs}(570)/R_{rs}(655)$ is somewhat weaker, with a coefficient of determination $R^2 = 0.85$. As expected, the errors in determining optically active components (OAC) with the new equations are also quite satisfactory. The standard error factors are as follows: for the estimated chlorophyll a concentration $x = 1.36$, for the estimated total SPM concentration $x = 1.56$ and for the estimated coloured dissolved organic matter absorption coefficient $x = 1.46$.

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