Inherent optical properties and remote sensing reflectance of Pomeranian lakes (Poland)*

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Abstract

This paper describes the results of comprehensive empirical studies of the inherent optical properties (IOPs), the remote sensing reflectance $R_{rs}(\lambda)$ and the contents of the principal optically active components (OAC) i.e. coloured dissolved organic matter (CDOM), suspended particulate matter (SPM) and chlorophyll a, in the waters of 15 lakes in Polish Pomerania in 2007–2010. It presents numerous spectra of the total absorption $a(\lambda)$ and scattering $b(\lambda) \approx b_p(\lambda)$ of light in the visible band (400–700 nm) for surface waters, and separately, spectra of absorption by CDOM $a_{\text{CDOM}}(\lambda)$ and spectra of the mass-specific coefficients of absorption $a_p^{*(\text{SPM})}(\lambda)$ and scattering $b_p^{*(\text{SPM})}(\lambda)$ by SPM. The properties of these lake waters are highly diverse, but all of them can be classified as Case 2 waters (according to the optical classification by Morel & Prieur 1977) and they all have a relatively high OAC content. The lakes were conventionally divided into three types: Type I lakes have the lowest OAC concentrations (chlorophyll concentration $C_a = (8.76 \pm 7.4)$ mg m^{-3} and CDOM absorption coefficients $a_{\text{CDOM}}(440) = (0.57 \pm 0.22)$ m^{-1} (i.e. mean and standard deviation), and optical properties (including spectra of $R_{rs}(\lambda)$) resembling those of Baltic waters. Type II waters have exceptionally high contents of CDOM ($a_{\text{CDOM}}(440) = (15.37 \pm 1.54)$ m^{-1}), and hence appear brown in daylight and have very low reflectances $R_{rs}(\lambda)$ (of the order of 0.001 sr^{-1}). Type III waters are highly eutrophic and contain large amounts of suspended matter, including phytoplankton ($C_{\text{SPM}} = (47.0 \pm 39.4)$ g m^{-3}, $C_a = (86.6 \pm 61.5)$ mg m^{-3}; $a_{\text{CDOM}}(440) = (2.77 \pm 0.86)$ m^{-1}). Hence the reflectances $R_{rs}(\lambda)$ of these type of waters are on average one order of magnitude higher than those of the other natural waters, reaching maximum values of 0.03 sr^{-1} in λ bands 560–580 nm and 690–720 nm (see Ficek et al. 2011). The article provides a number of empirical formulas approximating the relationships between the properties of these lake waters.

1. Introduction

Pomerania lies in northern Poland and borders on the southern Baltic coastline. In this region there are 3381 lakes with an area of more than 1 ha; their total area is 104 197.3 ha (ca 1042 km^2), and maximum water depths range from less than 1 m (e.g. Lake Czerwica) to 68 m (Lake Wdzydze) (Jańczak 1997, Choiński 2006). The bio-optical properties of 15 lakes in central Pomerania were investigated by Ficek and co-workers in 2007–2010. These investigations are extensively described in a dissertation by Ficek (2012 in press, in Polish). The remote sensing reflectance $R_{rs}(\lambda)$ spectra of these lake waters were presented and discussed by Ficek et al. (2011). In this paper we describe the basic inherent optical properties (IOPs) of these lake waters, i.e. spectra of light absorption $a(\lambda)$ and scattering $b(\lambda)$ and some of their components. We also give a more detailed description of the remote sensing reflectance spectra $R_{rs}(\lambda)$. The waters of these lakes are highly diverse, containing variable and extreme concentrations of

coloured dissolved organic matter (CDOM), organic and mineral suspended particulate matter (SPM) and phytoplankton pigments.

The aim of this paper is to give readers an overview of the optical properties of a recently investigated group of lakes.

2. Material and methods

Comprehensive measurements of light absorption $a(\lambda)$, light attenuation $c(\lambda)$, total scattering $b(\lambda)$ and backscattering $b_b(\lambda)$, downward irradiance $E_d(\lambda)$ and upward radiance $L_u(\lambda)$ spectra were made in 15 lakes from on board a small motor boat. These optical measurements were carried out in situ in vertical profiles, at 2–3 sites representative of the open waters of each lake, 3–10 times in each lake in different seasons, mainly in 2007–2010. At the same time water samples were taken from different depths of the euphotic zone to be analysed for their content of optically active components OAC (i.e. C_{SPM}, C_a, a_{CDOM}) and some of their properties. The samples were filtered and analysed on the same day; some of the filters to be analysed for their pigment content were stored in liquid nitrogen and some, to be analysed for the dry mass of SPM, were stored in a desiccator. The number of stations and the number of measurements on each lake differ, depending on the size of the lake and its seasonal changes, including a lack of data from winter when a given lake was completely frozen over. The numbers of measurements from each lake are given in Table 1. In view of these different numbers of measurements, some comparisons of lake water properties were drawn on the basis of the mean values of the relevant magnitudes recorded in the surface waters of each lake. Obviously, the vertical profiles recorded certain differences in measured values – for the details of these, see Ficek (2012).

The coefficients of absorption $a(z, \lambda)$ and light attenuation $c(z, \lambda)$ were measured in situ at various depths in the lakes using a Wet Labs ac 9 spectrophotometer for 9 wavelengths: 412, 440, 488, 510, 532, 555, 650, 676 and 715 nm. The total scattering coefficient $b(z, \lambda)$ was determined from the difference $c(z, \lambda) - a(z, \lambda) = b(z, \lambda)$; the backscattering coefficient $b_b(z, \lambda)$ was measured in situ for one wavelength $\lambda = 532$ nm with the aid of a backscattering meter (ECO VSF – Wet Labs). Accurate spectral distributions (every 1 nm) of light absorption in the water samples were determined as the sum of absorption by SPM in the water $a_p(\lambda)$, absorption by CDOM in the water $a_{\mathrm{CDOM}}(\lambda)$ and absorption by pure water $a_w(\lambda)$. The absorptions by the SPM collected on the filter were measured with a UNICAM UV4-100 spectrophotometer, equipped with a 66 mm diameter integrating sphere. A slightly modified Transmission-Reflectance (T-R) filter-pad technique was used (Tassan & Ferrari 1995). The integrating

Table 1. The periods and number of bio-optical measurements carried out in Pomeranian lakes during the growing seasons in 2004–2010

Name of lake	Symbol	Period of investigation	Total number of expeditions	Total number of measured profiles
Łebsko	L	2007–2010	30	111
Gardno	G	2006–2010	45	88
Pyszne	P	2006–2010	28	29
Rybiec	R	2009–2010	10	10
Niezabyszewskie	N	2008	9	9
Głębokie	Gl	2008–2010	15	15
Chotkowskie	Ch	2006–2010	28	29
Dobra	D	2008–2010	11	7
Czarne	Cz	2008–2010	15	15
Obłęże	O	2007–2010	25	27
Jasień Południowy	JS	2007–2010	25	30
Jasień Północny	JN	2007–2010	22	29
Marszewskie	M	2008–2010	10	10
Boruja Mała	B	2004–2010	24	26
Jeleń	J	2004–2010	34	61

sphere was used to measure the optical density of the particles collected on the Whatman GF/F filters and on clean reference filters. It was assumed that the transmittance through each filter $+$ SPM was the same, regardless of whether the light beam impinged on the filter frontally or laterally. This substantially simplified the calculation of the optical density, equivalent to the inherent absorption of the particles accumulated on the filter $OD_f(\lambda)$. Since the optical path of the light becomes shorter, one applies the optical path length amplification factor β, which converts $OD_f(\lambda)$ into the optical density of particles in suspension $OD_{\text{sus}}(\lambda)$. Here, the formula $OD_{\text{sus}}(\lambda) = 0.592[OD_f(\lambda)]^2 + 0.4OD_f(\lambda)$, derived by Kaczmarek et al. (2003), was used (see also Stramska et al. 2003). This formula was derived on the basis of experiments with various mineral-particle-rich phytoplankton cultures, and with solutions and natural suspensions of particles from marine basins. The spectra of light absorption by SPM in the water $a_p(\lambda)$ was then determined.

In contrast, absorption spectra $a_{\text{CDOM}}(\lambda)$ were determined in samples of lake water from the difference between the spectra of light attenuation in a sample of pure water (twice distilled) and in a sample of lake water passed first through a Whatman GF/F glass-fiber filter (0.7 μm pore size), and then through a Sartorius ACN membrane filter (0.2 μm pore size). The absorption spectra of these water samples were measured with a Hitachi U 2810 UV-VIS spectrophotometer. The absorption by pure water $a_w(\lambda)$ was

based on the data of various authors gathered in the monograph by Woźniak & Dera (2007).

For determining the reflectance $R_{rs}(\lambda)$, the vertical profiles of the downward irradiance $E_d(z, \lambda)$ and the upward radiance $L_u(z, \lambda)$ were measured with a Satlantic Hyper Spectral Radiometer HyperPro in 136 channels in the 350–800 nm spectral range. The data were usually recorded at 10 cm intervals in the 0.1–2 m depth range. The reflectance was calculated as the ratio of the water-leaving upward radiance $L_u(0^+, \lambda)$ and the downward irradiance $E_d(0^+, \lambda)$ just above the water surface:

$$R_{rs}(\lambda) = L_u(0^+, \lambda)/E_d(0^+, \lambda), \tag{1}$$

where

$$L_u(0^+, \lambda) = 0.544 \, L_u(0^-, \lambda) \tag{2}$$

(see e.g. Darecki et al. 2005, Tzortziou et al. 2007); the radiance just below the water surface $L_u(0^-, \lambda)$ was extrapolated from the $L_u(z, \lambda)$ vertical profile (see the detailed description in Ficek 2012).

The SPM concentration (C_{SPM}) was determined by measuring the dry mass collected on a filter from a given volume of water. From 0.2 to 2 dm^3 water were filtered, depending on the SPM concentration of this matter. The sediment collected from the first filtering of the water sample through a Whatman GF/F glass-fiber filter (47 mm, 0.7 μm pore size) was used for measuring the dry mass of SPM, as recommended in the standard protocols for measuring SPM (Van der Linde 1998).

The concentration of chlorophyll a was determined using several methods: in situ using a Pump Probe immersion fluorometer (PrimProd-EcoMonitor, Russia, in accordance with the methodology developed by Falkowski & Kiefer 1985, Falkowski et al. 1986; see also Ostrowska 2001, Matorin et al. 2004); in samples of lake water using HPLC (Stoń-Egiert & Kosakowska 2005), and the standard spectrophotometric technique (e.g. Jeffrey & Humphrey 1975) (for details, see Ficek 2012).

235 sets of data points obtained from simultaneous measurements of the reflectance spectra $R_{rs}(\lambda)$, chlorophyll a concentrations C_a, suspended particulate matter concentrations C_{SPM}, and absorption spectra $a_{\mathrm{CDOM}}(\lambda)$ were used in the analysis and interpretation of the remote sensing reflectance spectra $R_{rs}(\lambda)$ described in Ficek et al. (2011) and in the present paper.

3. Results and discussion

The waters of the Pomeranian lakes investigated in this study differ widely in their contents of optically active components (OAC); consequently,

their spectral optical properties are also different. As in most inland and coastal sea waters, the OAC they contain consist of suspended particulate matter (SPM) and coloured dissolved organic matter (CDOM), usually in large concentrations. On the basis of numerous empirical investigations (to be presented below), these waters can be conventionally classified into three types differing in their optical properties, although this distinction is not a sharp one – waters with properties intermediate between these types have also been recorded. In waters of Type I OAC concentrations are relatively low: SPM (including phytoplankton[1]) is dominant and the concentration of CDOM[2] is relatively low (Table 2). The optical properties of these waters are similar to those of Baltic waters (see e.g. Kowalczuk et al. 1999, Ficek et al. 2011).

Table 2. Mean concentrations of the optically active components (OAC) and some optical properties of the three types of surface waters in Pomeranian lakes[*]

Quantity and units	Type I waters (mean values ± standard deviation)	Type II waters (mean values ± standard deviation)	Type III waters (mean values ± standard deviation)
C_{SPM} [g m^{-3}]	2.78 ± 1.93	3.83 ± 1.75	47.0 ± 39.4
$a_{\mathrm{CDOM}}(440)$ [m^{-1}]	0.57 ± 0.22	15.37 ± 1.54	2.77 ± 0.86
$\overline{S}_{\mathrm{CDOM}}(\lambda)$ [nm^{-1}][**]	0.018 ± 0.003	0.015 ± 0.001	0.017 ± 0.001
C_a [mg m^{-3}]	8.76 ± 7.4	19.8 ± 16.0	86.6 ± 61.5
waveband of max $R_{rs}(\lambda)$ [nm]	560–580 high 650 weak 690 weak	690–710 weak	560–580 high 650 weak 690–720 high

[*]Lakes Chotkowskie and Czarne are not included in this table as they do not lend themselves to such classification (see curves Ch and Cz on Figure 1b),
[**]$\overline{S}$ – mean slope of the absorption spectra.

The waters we designated as Type II (humic lakes[3]) have a very high CDOM concentration, so high that the light attenuation coefficient and other properties of such waters are completely dominated by the light absorption a_{CDOM} in practically the whole spectral range of visible light.

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[1]In this paper the phytoplankton concentration is taken to be the measured chlorophyll a concentration C_a.

[2]The concentration of Coloured Dissolved Organic Matter (CDOM) is taken to be the measured coefficient of light absorption in the 440 nm band, $a_{\mathrm{CDOM}}(440)$.

[3]These are usually small lakes with brown water – they are common in the study area. In this work they are represented only by Lake Pyszne, as access to other such lakes with boats and measuring gear was too difficult.

Our Type III lake waters are supereutrophic, in which the OAC is dominated by phytoplankton; for practical purposes the absorption/scattering properties of this phytoplankton determine the optical properties of such waters (see Table 2).

3.1. Light absorption

Figures 1 to 4 illustrate light absorption spectra in the surface waters of the lakes investigated. Figures 1a and b emphasize above all the very great differentiation in the absorption properties of these waters due to the large differences in OAC concentrations in them. The various types of waters are also distinguishable in these figures, especially Type I with low absorption (low CDOM concentration) and Type II with very high absorption (high levels of CDOM), although it is hard to precisely define the criterion for such a division, because not all the waters of the lakes we studied lend themselves to such classification. The absorption spectra $a_{CDOM}(\lambda)$ of these three types of water are better illustrated in Figure 2, which shows spectra from some of the lakes that have distinctive absorption properties. There are clear differences between Types I and II, as regards both the value and the course of the absorption spectra. These differences are due mainly to CDOM, especially to its concentration (indicated among other things by the extremely different absorption coefficients $a(440 \text{ nm})$) and the qualitative composition of the individual substances in CDOM (indicated
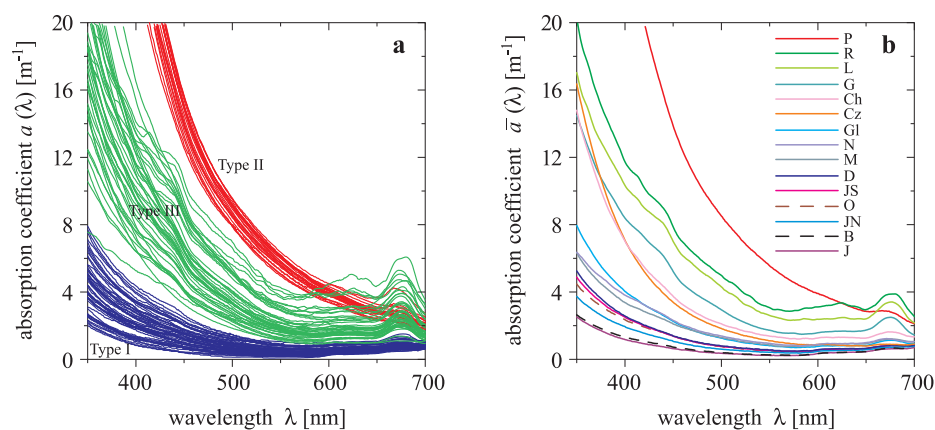

Figure 1. Light absorption spectra $a(\lambda)$ recorded in surface waters of Pomeranian lakes: a) for all types of lake, b) averaged for particular lakes on the basis of all the recorded spectra. The abbreviations for the names of the lakes are explained in Table 1
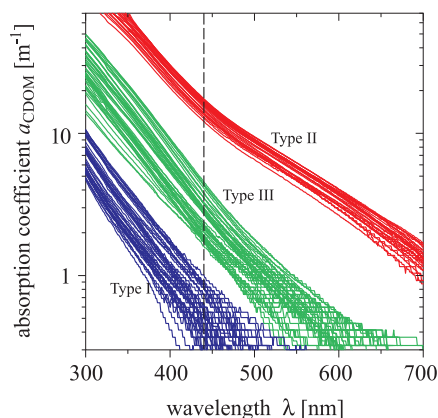
Figure 2. Spectra of coefficients of light absorption by CDOM $a_{\mathrm{CDOM}}(\lambda)$, recorded in three types of water in Pomeranian lakes: Type I (Lakes Jeleń, Boruja Mała, Jasień), $\overline{a}(440 \text{ nm}) = 0.57 \text{ m}^{-1}$, $\overline{S} = 0.018 \text{ nm}^{-1}$; Type II (Lake Pyszne), $\overline{a}(440 \text{ nm}) = 15.0 \text{ m}^{-1}$, $\overline{S} = 0.015$; Type III (Lakes Łebsko, Gardno, Rybiec), $\overline{a}(440 \text{ nm}) = 2.77 \text{ m}^{-1}$, $\overline{S} = 0.017 \text{ nm}^{-1}$. The vertical dashed line shows the wavelength of 440 nm, the absorption coefficient of which $a_{\mathrm{CDOM}}(440)$ is used here as the indicator of CDOM concentration

by the different slopes of the absorption spectra $\overline{S}$ – see e.g. Haltrin 2006, Woźniak & Dera 2007). In intermediate, strongly eutrophic waters, which we have classified as Type III, besides absorption by CDOM of wavelengths from the short-wave end of the light spectrum, there are distinct pigment absorption bands, including that of chlorophyll a in the red region.

The evident minimum absorption in the 550 nm region for Type I lake waters coincides with the distinct broad maximum reflectance $R_{rs}(\lambda)$, as shown in Figure 6.

Figures 2 and 3 respectively illustrate absorption by CDOM and by SPM. Figure 2 shows spectra of the coefficients of light absorption by CDOM $a_{\mathrm{CDOM}}(\lambda)$ recorded in all three types of lake water. This shows the evident differences in absorption, i.e. the differences in the positions of the spectra on the plot, for the three types of water, dependent on the CDOM concentration as given by $a_{\mathrm{CDOM}}(440 \text{ nm})$. It also shows certain differences in the mean slopes of the spectra $\overline{S}$ in the 350–450 nm wave band, the values of which are given beneath Figure 2. These differences in the mean spectral slopes testify to the different compositions of CDOM in these waters (Haltrin 2006, Woźniak & Dera 2007).

Figure 3a illustrates plots of spectra of light absorption by only SPM $a_p(\lambda)$, recorded in all the lakes. The position of these spectra on the plot depends to a large degree on the SPM content of a given water (see Figure 3b), but the spectra of the mass-specific coefficients of light
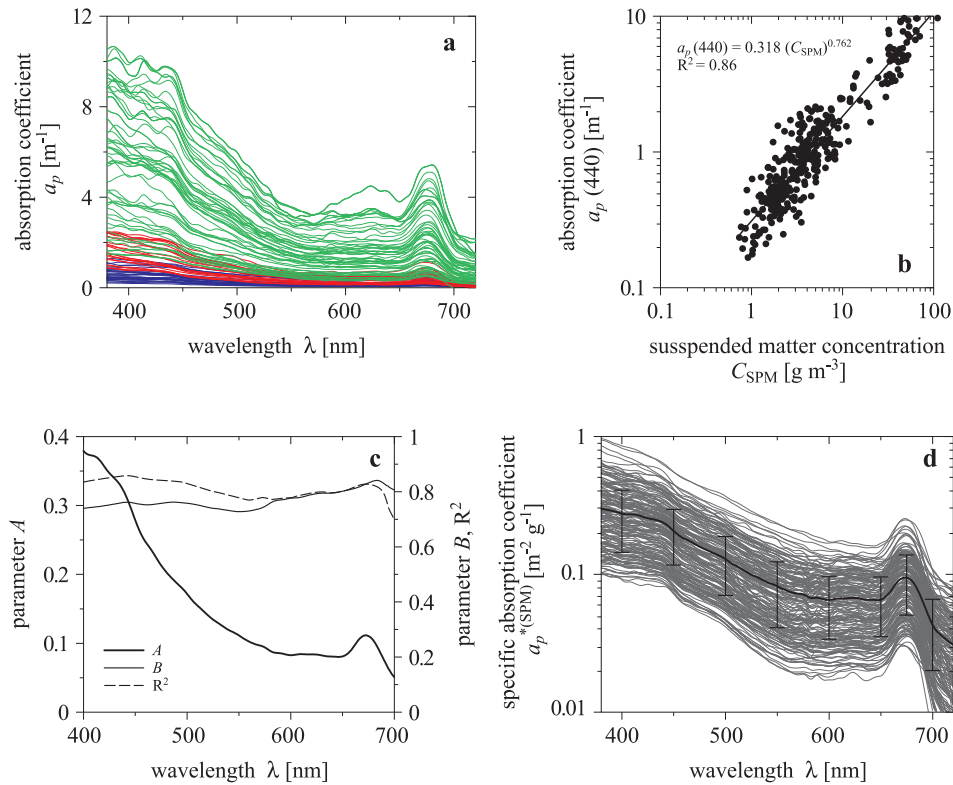
Figure 3. Light absorption by particles of suspended matter in Pomeranian lakes: a) spectra of light absorption $a_p(\lambda)$, recorded in the surface waters of all the lakes (blue lines – Type I waters, red – Type II, green – Type III); b) empirical dependence of the absorption coefficient $a_p(440\ \text{nm})$ on the concentration of dry mass of suspended matter C_{SPM}; c) dependence of constants A and B and the coefficient of determination R^2 on wavelength λ, obtained from the approximate empirical relationship of $a_p(\lambda)$ versus C_{SPM} in formula (3); d) spectra of the mass-specific coefficients of light absorption by particles of SPM $a_p^{*(\text{SPM})}(\lambda)$, recorded in the surface waters of all the lakes. The thick black line represents their average value $< a_p^{*(\text{SPM})}(\lambda) >$ determined for the set of all spectra, and the whiskers indicate the standard deviations from the mean values for selected light wavelengths

absorption $a_p^{*(\text{SPM})}(\lambda)$ by that SPM (i.e. converted to per unit dry mass of SPM, Figure 3d) take values over a wide range (for 440 nm from ca 0.08 to 0.7 m^2 g^{-1}). This is an indicator of the highly differentiated qualitative composition of the various types of lake, and in particular of the various ratios of organic SPM (including phytoplankton) to inorganic SPM. In Figure 3a the absorption spectra $a_p(\lambda)$ for Type I waters lie lowest on the plot, which is indicative of the low level of SPM in such waters. The spectra
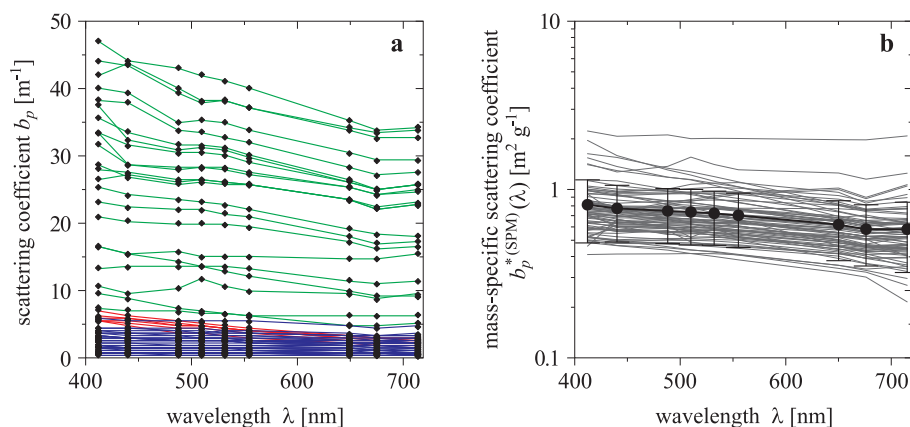
Figure 4. Spectra of light scattering by suspended particulate matter, recorded in the surface water of Pomeranian lakes: a) all recorded spectra of $b_p(\lambda)$: points – measurement data, lines – simple interpolation; blue lines – Type I waters, red lines – Type II waters, green lines – Type III waters; b) spectra of the mass-specific coefficients of light scattering by SPM $b_p^{*(\text{SPM})}(\lambda)$: points – mean values from measurements, lines interpolated as in (a); the thick black line represents the average value $< b_p^{*(\text{SPM})}(\lambda) >$ determined for the set of all spectra, and the whiskers show the standard deviations

of $a_p(\lambda)$, lying higher up on this plot, refer to waters with a greater SPM concentration and visualize the evident selectivity of absorption in respect of light wavelengths – absorption by numerous coloured suspended organic matter and phytoplankton pigments, including chlorophyll a in the 670–680 nm band.

With the results of our many measurements we were able, among other things, to establish an approximate empirical relationship between the spectra of visible light absorption by particles of suspended matter $a_p(\lambda)$ and the concentration of these particles C_{SPM} in the waters under study. This relationship can be written as follows:

$$a_p(\lambda) = A(\lambda)(C_{\text{SPM}})^{-B(\lambda)}, \tag{3}$$

where $a_p(\lambda)$ is expressed in $[\text{m}^{-1}]$ and C_{SPM} in $[\text{g m}^{-3}]$ (i.e. grams of dry mass of material suspended in 1 m^3 of water); the values of the constants A and B, and the coefficient of determination R^2 are given in Table 3 for selected light wavelengths and plotted for the entire visible light spectrum in Figure 3c. This formula gives the best approximation, with a coefficient of determination of $R^2 = 0.86$, for light wavelengths in the ca 440 nm band; this is also illustrated by the plots in Figures 3b and 3c.

Table 3. Values of the constants A, B and the coefficient of determination R^2 for formula (3)

λ [nm]	A	B	R^2	λ [nm]	A	B	R^2
400	0.379	0.740	0.83	550	0.112	0.728	0.78
425	0.347	0.752	0.85	575	0.094	0.746	0.78
440	0.318	0.762	0.86	600	0.083	0.776	0.78
450	0.279	0.758	0.85	625	0.084	0.793	0.80
475	0.213	0.758	0.84	650	0.081	0.802	0.80
500	0.172	0.758	0.83	675	0.111	0.832	0.83
525	0.135	0.740	0.80	700	0.051	0.806	0.70

3.2. Light scattering

Let us now turn to light scattering in these lake waters. Here, the molecular scattering of light, i.e. scattering by molecules of water and the substances dissolved in it, can be practically ignored in view of the many times stronger scattering from the large amounts of various kinds of SPM present. Plots of light scattering in the waters of the lakes are illustrated in Figure 4. Figure 4a shows all the recorded spectra of $b_p(\lambda)$, with the three types of water highlighted in different colours. Here again, as in the case of absorption, the scattering spectra for Type I waters lie the lowest on the plot, but the scattering spectra of Type II waters lie at a very similarly low level, which is indicative of relatively low concentrations of SPM in these waters (see above in Table 2). The figure also shows the very limited selectivity of scattering relative to wavelength, which very generally testifies to the dominance of scattering from suspended particles much larger than the wavelengths of visible light (e.g. Dera 1992).

The spectral distributions of light scattering from SPM, free of the effect of the concentration of this matter in the water, that is, calculated per unit dry mass of suspended particles, are called the mass-specific scattering coefficients of particles $b_p^{*(\text{SPM})}(\lambda)$. Spectra of these coefficients for the lake waters are illustrated in Figure 4b: they show that in the visible region these coefficients range from ca 0.2 to 2 $m^2\ g^{-1}$, that is, in an interval higher and slightly wider than the one for coastal and open sea waters described by Babin et al. (2003) and the papers cited therein.

The spectra of the coefficients of scattering by SPM in the visible region decline only slightly and monotonically in the direction of long waves and do not exhibit any significant maxima. These spectra can be approximated by the relationship:

$$b_p(\lambda) = b_p(\lambda_0) \left(\frac{\lambda_0}{\lambda} \right)^{\gamma}, \tag{4}$$

where γ is called the Ångstrom exponent describing the spectral shape (Haltrin 2006). The value of γ determined for the lakes under investigation is $0.551\,(\mathrm{SD} = 0.397)$. The scattering coefficients $b_p(\lambda)$ in the visible light region depend largely on SPM concentration (see Figure 5). This minimal selectivity of scattering with respect to light wavelength has a significant influence on the spectra of the remote sensing reflectance $R_{rs}(\lambda)$ of these lakes.
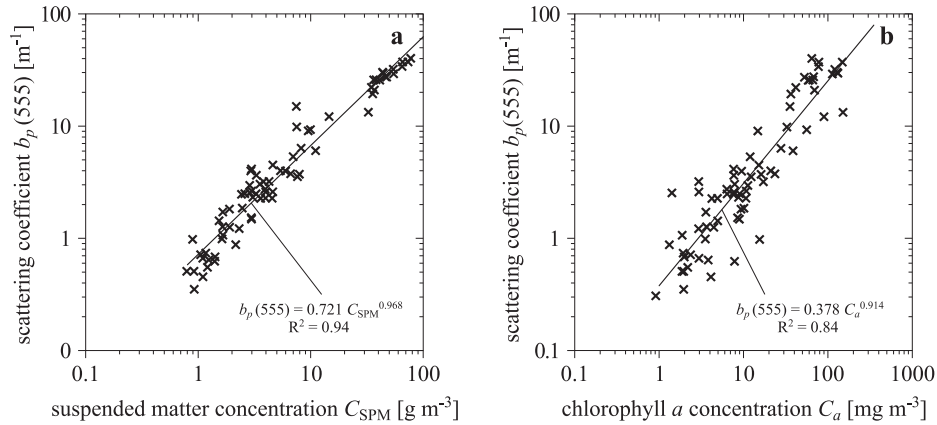

Figure 5. Empirical relationships between the coefficients of light scattering $b_p(555)$ and the concentration of dry mass of SPM C_{SPM} (a) and the chlorophyll a concentration C_a (b) in the surface layer of Pomeranian lakes. The lines and equations on the graph show the regression curves corresponding to the points shown

The correlations of the scattering coefficient $b_p(555)$ with concentrations of dry mass of SPM C_{SPM} and with concentrations of chlorophyll a C_a in these waters are best in the ca 555 nm band. These correlations and the relevant regression equations are shown in Figure 5.

3.3. Remote sensing reflectance

Given the only slight dependence of scattering at SPM on the wavelength of the scattered light, spectral maxima of the reflectance $R_{rs}(\lambda)$ are observed only in those wavelength bands with minima of the overall light absorption and/or fluorescence of the constituents of the lake waters. In Type I waters the overall light absorption usually drops to a distinct minimum in the 560–580 nm band: in this band absorption by CDOM is weak (Figure 1 – Lakes J, B, JN, Ob, and Type I in Figure 2) and, moreover, only phycobilins among the many phytoplankton pigments absorb light to a measureable extent (Woźniak & Dera 2007). It is for these reasons that the remote sensing reflectance $R_{rs}(\lambda)$ in these waters reaches a distinct maximum in

this 560–580 nm band (Figure 6, Type I, Ficek et al. 2011). The height and width of this maximum depends not only on the concentration of scattering SPM in this type of water but also on its other light-absorbing constituents. In the waters of humic lakes, i.e. Type II, with their very high CDOM concentration (average $a_{\mathrm{CDOM}}(440 \mathrm{~nm}) \approx 15 \mathrm{~m}^{-1}$), the light absorption spectrum, dominated as it is by CDOM absorption, has its minimum shifted towards the long wavelengths (690–710 nm) and takes conspicuously high values over the entire spectral region (Figure 1 – Lake P and Type II in Figure 2). This absorption strongly reduces the intensity of backscattered light. Hence the reflectance $R_{rs}(\lambda)$ displays a weak maximum only in the red region of the 690–710 nm band, that is, between absorption by CDOM increasing towards the short wavelengths and absorption by water increasing towards wavelengths longer than those in this band. This weak reflectance maximum is probably reinforced by the natural fluorescence of chlorophyll a (see Type II in Figure 6).
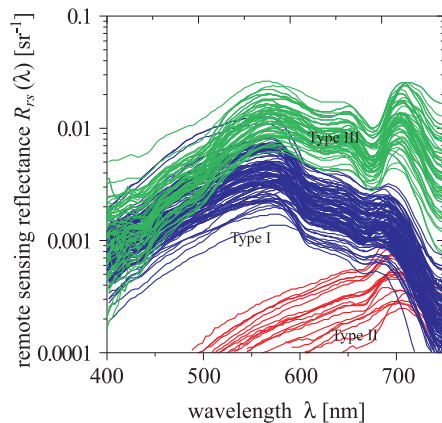

Figure 6. Recorded remote sensing reflectance spectra of selected Pomeranian lakes, clearly fitting the three types of water (Type I, blue lines – Lakes Jeleń, Boruja Mała, Jasień Północny, Jasień Południowy; Type II, red lines – Lake Pyszne; Type III, green lines – Lakes Łebsko, Rybiec, Gardno)

The third group of lake waters studied, Type III, are supereutrophic, with CDOM concentrations slightly higher than in Type I waters but distinctly lower than the waters in humic lakes, as indicated by the values of the absorption coefficients a_{CDOM} (average $a_{\mathrm{CDOM}}(440 \mathrm{~nm} \approx 2.77 \mathrm{~m}^{-1}$; see Table 1, Type III in Figure 1a and Lakes Ga, L, R in Figure 1b). The chlorophyll a levels in these waters are exceptionally high (average $C_a \approx 87 \mathrm{~mg~m}^{-3}$, up to 336 mg m^{-3} recorded once in Lake Gardno). Total SPM concentrations are equally high in in Type III waters (see Table 2),

whereas the ratio of the concentration of chlorophyll a to that of the dry mass of SPM is here on average only 0.21 (± 0.09)%; in comparison, this ratio is 0.40 (± 0.27)% in Type I waters and 0.60 (± 0.38)% in Type II. Consequently, in Type III lakes we observe two broad maxima of the reflectance spectrum $R_{rs}(\lambda)$ in the 560–580 nm and 690–720 nm bands, due to the dominance of backscattering over absorption in these bands for the reasons given earlier. A third local reflectance maximum in the ca 650 nm band is also well in evidence in this third group of waters, though only scarcely perceptible in the other two groups. This must also be a result of the relevant relations between the total absorption and the scattering of light in this band.

The three types of reflectance spectra R_{rs} are illustrated in Figure 6; omitted are a few other recorded spectra – indirect, atypical ones, of the kind that inevitably emerge from any conventional classification of nature (see also Ficek et al. 2011).

The Type I reflectance spectra are very similar to the reflectance spectra typical of the open waters of the Baltic (see Darecki et al. 1995, Kowalczuk et al. 1999, Darecki et al. 2003, Ficek et al. 2011). Table 2 lists the positions of the reflectance maxima $R_{rs}(\lambda)$ along with other selected properties of the three groups of lakes.

The empirical dependence of absorption $a_{\mathrm{CDOM}}(440 \text{ nm})$ on the spectral reflectance band ratio $x = R_{rs}(570 \text{ nm})/R_{rs}(655 \text{ nm})$ was approximated for the waters of these lakes by the expression (Ficek et al. 2011):

$$a_{\mathrm{CDOM}}(440 \text{ nm}) = 3.65 x^{-1.93} \qquad (5)$$

with a coefficient of determination of $R^2 = 0.85$. Here we found an appropriate empirical relationship between the coefficient of light absorption by SPM $a_p(440 \text{ nm})$ and the reflectance $R_{rs}(800 \text{ nm})$, but only for lake waters of Types I and III in our classification. We present this relationship on Figure 7, described by regression equation 6, with a coefficient of determination of $R^2 = 0.86$.

$$a_p(440 \text{ nm}) = 235 x^{0.745} \, , \qquad (6)$$

where $a_p(440 \text{ nm})$ – coefficient of light absorption by SPM, measured in [m^{-1}], $x \equiv R_{rs}(800 \text{ nm})$ – the remote sensing reflectance measured in [sr^{-1}].

For the same lake waters of Types I and III we also established, on the basis of the form of the dependence in Woźniak et al. (2011), the empirical dependence of the total volume absorption coefficient $a(440)$ in these waters for a light wavelength of $\lambda = 440$ nm on the spectral reflectance band ratio at
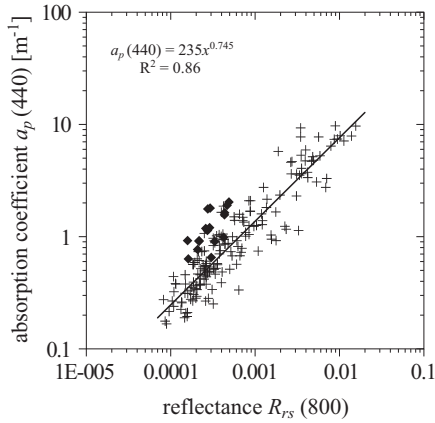
Figure 7. The empirical dependence of the coefficient of light absorption by SPM $a_p(440$ nm) on the remote sensing reflectance (where $x \equiv R_{rs}(800$ nm)), established for Type I and II lakes. The black rectangles indicate the points obtained from measurements in the Type II lake, which were not used in calculating this dependence

selected wavelengths $R_{rs}(490)/R_{rs}(655)$ (equation (7) and Figure 8), with a coefficient of determination of $R^2 = 0.90$:

$$a(440 \text{ nm}) = 10^{0.554(\log x)^2 - 1.380\log x + 0.161} , \qquad (7)$$

where $x = R_{rs}(490 \text{ nm})/R_{rs}(665 \text{ nm})$.

Likewise on Figure 8 the dashed line represents the dependence for Baltic waters taken from Woźniak et al. (2011): this shows that these dependences are similar for low values of absorption $a(440)$, typical of Type I lake waters.

The empirical dependence of the scattering coefficient on scattering b and the reflectance R_{rs} was also determined for selected wavelengths in Type I and III lake waters. The scattering coefficient has without doubt a significant influence on values of R_{rs}, but the relationship is an involved one. Determining this coefficient required the well-known dependence $R_{rs}(\lambda) \sim \dfrac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)}$ (Gordon & Morel 1983) and formula (7) (derived in this work) describing the relationship between the light absorption coefficient a and the reflectance R_{rs} to be taken into consideration. It was additionally assumed that the scattering coefficient b is associated with the backscattering coefficient b_b and the SPM concentration, the latter being highly correlated with ca $R_{rs}(800$ nm) (see Ficek et al. 2011).
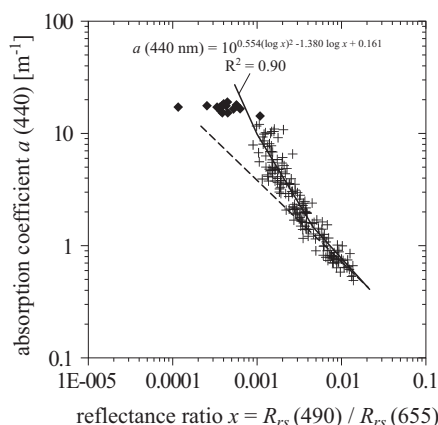
Figure 8. The empirical dependence of the total coefficient of absorption $a(440\ \text{nm})$ in lake waters of Types I and III on the spectral reflectance band ratio at selected wavelengths $R_{rs}(490\ \text{nm})/R_{rs}(655\ \text{nm})$. Points – measurement data, continuous line – regression curve, dashed line – regression curve for Baltic waters, described by the formula $a(440\ \text{nm}) = 10^{0.096 - 0.965\log x}$. This formula was taken from Woźniak et al. (2011) for a slightly different wavelength of the reflectance band ratio $x = R_{rs}(490\ \text{nm})/R_{rs}(665\ \text{nm})$, i.e. 665 nm for the Baltic; for Types I and III the correlation turned out to be better for 655 nm. The black rectangles indicate the measurement points from the Type II lake, which were not taken into consideration in the derivation of this dependence

The relationship obtained is shown in Figure 9 and expressed by formula (8):

$$b(440\ \text{nm}) = 15.59 \times R_{rs}(800\ \text{nm})^{0.282} \times 10^{0.554(\log x)^2 - 1.380\log x + 0.161}, \quad (8)$$

where $x = R_{rs}(490\ \text{nm})/R_{rs}(665\ \text{nm})$.

Having established the empirical relationships between the absorption and scattering of light of particular wavelengths, we can determine approximate values of these selected inherent optical properties of Type I and III lake waters for any wavelength from the PAR range from measurements of remote reflectance spectra $R_{rs}(\lambda)$. We obtain the spectrum of the coefficient of light absorption by SPM by first determining the value of this coefficient for $\lambda = 440\ \text{nm}$ from equation (6) and then using equation (3) and Table 3 to determine its value for other wavelengths. The spectrum of light absorption by CDOM is also determined in two stages. In the first stage we determine $a_{\text{CDOM}}(440\ \text{nm})$ from equation (5); then, using the relationship $a_{\text{CDOM}}(\lambda) = a_{\text{CDOM}}(440\ \text{nm})\exp[-\overline{S}(\lambda - 440\ \text{nm})]$ we obtain the value of this coefficient for waves of different lengths. The parameter $\overline{S}$ appearing in this equation varies from 0.015 to 0.018 nm^{-1} and depends on the type of lake (see the
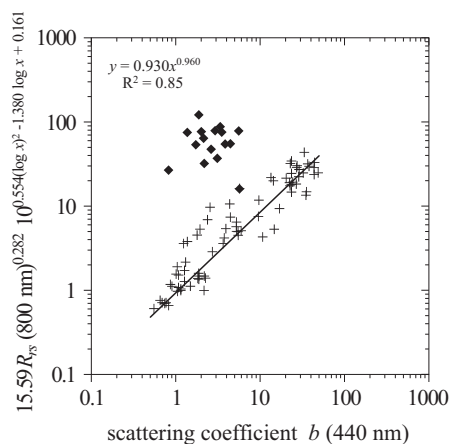
Figure 9. Dependence between the scattering coefficient b (440 nm) measured in lake waters of Types I and III and determined from remote reflectances spectra at wavelengths $R_{rs}(490 \text{ nm})$, $R_{rs}(665 \text{ nm})$ and $R_{rs}(800 \text{ nm})$ on the basis of formula (8). The black rectangles indicate the measurement points from the Type II lake, which were not taken into consideration in the derivation of this dependence

caption to Figure 2). We obtain the total absorption spectrum by summing the coefficients of absorption by SPM $a_p(\lambda)$, dissolved substances $a_{\text{CDOM}}(\lambda)$ and the water itself $a_w(\lambda)$. Values of the last-mentioned component can be found in e.g. Woźniak & Dera (2007).

We obtain the spectrum of the light scattering coefficient by first determining this factor for light of wavelength 440 nm, and then its values for other wavelengths using equation (4). In these calculations we could also take the values for water molecules into account. But since scattering by water is negligible compared to that by SPM (see e.g. Haltrin 2006), it makes no significant difference to the final result of the calculations.

The great complexity of the results presented in this work precludes the precise definition of the errors of measurements and analyses, even though we took the greatest care with the measurement procedures stated in the Introduction. These procedures and the measuring apparatus they require govern the accuracy of these studies, in which we estimated the measurement errors of different magnitudes to be from 3 to 10% and more, e.g. with respect to the remote sensing reflectance R_{rs} and the scattering coefficients.

On the other hand it is relatively easy to calculate the variously defined errors of the formulas approximating the absorption and scattering coefficients, which we give below in Table 4 along with the definitions below Table 4. These errors can hardly be treated as insignificant, but such is the nature of the object of these studies and at this stage in the research we have to accept them as they are.

Table 4. 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 [%]	$< \varepsilon >_g$ [%]	x	σ_- [%]	σ_+ [%]
$a_p(440)$ (eq. (5), Figure 7)	7.59	44.3	-0.19	1.47	-32.0	47.0
$a(440)$ (eq. (6), Figure 8)	3.74	27.1	0.08	1.31	-24.1	31.8
$b(400)$ (eq. (7), Figure 9)	9.08	49.1	-0.29	1.52	-34.6	52.9

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 : $\sigma_\varepsilon = \sqrt{\dfrac{1}{N}\left(\sum(\varepsilon_i - < \varepsilon >)^2\right)}$

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

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

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

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 properties of the waters of the Pomeranian lakes investigated in this study are highly diverse: all the waters can be classified as Case 2 according to the optical classification of Morel & Prieur (1977). They can be conventionally subdivided into 3 types. Type I lakes have the lowest concentrations of OAC and optical properties (including the reflectance spectra $R_{rs}(\lambda)$) similar to those of Baltic Sea waters (see e.g. Darecki et al. 2003, Woźniak S. B. 2011). The waters of Type II lakes (humic lakes) have extremely high levels of CDOM, hence their brown colour in daylight and very low reflectances $R_{rs}(\lambda)$ (of the order of 0.001 sr^{-1}). Type III waters are highly eutrophic, containing large amounts of SPM, including phytoplankton (see Table 2). Hence the reflectances $R_{rs}(\lambda)$ of these Type III waters are on average one order of magnitude higher than those of the other waters, reaching maximum values of 0.03 sr^{-1} in λ bands 560–580 nm and 690–720 nm; see Figure 6 and Ficek et al. (2011). The empirical relations obtained between selected inherent optical properties (IOPs) of Type I and III lake waters and the characteristics of the reflectance $R_{rs}(\lambda)$ make it possible to utilize the latter for an approximate determination of these IOPs.

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