

Dependence of spectral distribution of inherent optical properties of lake waters on the concentrations of different water constituents

Birgot Paavel¹, Helgi Arst¹ and Antti Herlevi²

¹Estonian Marine Institute, University of Tartu, Mäealuse 10a, Tallinn 12618, Estonia. E-mail helgi.arst@sea.ee; helgi.arst@ut.ee

²GEO Secretariat, Case postale 2300, CH-1211, Geneva 2, Switzerland

Received 7 February 2006; accepted is revised form 7 February 2007

Abstract The study focuses on the analysis of inherent optical properties of lake waters characterized by consisting of several optically active substances (OAS) (phytoplankton, suspended particles and dissolved organic matter). The results obtained can be useful for deriving the algorithms of optical remote sensing models which need the spectral data on inherent optical properties of the aquatic environment. The spectral absorption and attenuation coefficients were measured *in situ* using the instrument ac-9 for eight wavelengths in the range of 400–700 nm. The investigation sites were five Finnish and six Estonian lakes. The concentrations of chlorophyll *a* and total suspended particulate matter, as well as the absorption coefficient of coloured dissolved organic matter (at 380 nm) were determined in a laboratory from water samples taken concurrently with ac-9 measurements. There are three main objectives: (1) to calculate the values of absorption and specific absorption coefficients of tripton on the basis of ac-9 and laboratory data; (2) to estimate the contribution of pure water, chlorophyll *a*, dissolved organic matter and tripton to the total absorption and attenuation coefficients (results for ac-9 wavelengths and also for the PAR region, 400–700 nm); and (3) to determine the slope (and its variability) of the scattering coefficient spectrum for each measurement series and to estimate the reasons of this variability. At the wavelength of 532 nm the values of the specific absorption coefficient of tripton varied between 0.013 and 0.098 L mg⁻¹ m⁻¹, while the slope of its spectrum ranged from 0.0060 to 0.0109 nm⁻¹. The contributions of different components of the aquatic medium to the total absorption/attenuation coefficients varied noticeably from lake to lake. The slope of the scattering coefficient spectrum was in the range of 0.32–2.5, the multiple regression between the slope and three main optically active substances jointly gave the determination coefficient $R^2(\text{adjusted}) = 0.655$.

Keywords Inherent optical properties; optical properties of lakes; optically active substances

Introduction

The optical properties of water bodies show great variability, connected with their limnological/optical type, seasonal change of biological activity and human impact. The consequences of human impact are significantly expressed in coastal areas and inland waters. These water bodies can be called “multicomponental”, because, besides water itself, their properties are formed under the influence of optically active water constituents (OAS) (phytoplankton, coloured dissolved organic matter (CDOM) and suspended particles). In our opinion the term “multicomponental waters” is more suitable for lakes than the term “Case 2 waters” (Morel and Prieur 1977). “Case 2” describes marine waters where inorganic particles have a higher concentration than chlorophyll, but in lakes we can observe high values of phytoplankton and CDOM, while most suspended particles are by their origin organic, not mineral.

doi: 10.2166/nh.2007.011

There are several versions of limnological classification of lakes (e.g. Carlson 1977; Mäemets 1971, 1977; Koponen *et al.* 2002; Vollenweider and Kerekes 1982; Heinonen and Herve 1987; Zilioli and Brivio 1997; Vuoristo 1998; Ott and Kõiv 1999; Wallin and Fölster 2002). According to the Organization for Economic Cooperation and Development (OECD) protocols (Vollenweider and Kerekes 1982), the trophic state of waters can be estimated by means of the following parameters: (1) physical parameters, such as the water transparency, (2) biological parameters, such as the production of algal biomass or chlorophyll *a* concentrations, (3) chemical parameters, such as the total phosphorus content. Using these indicators, five trophic types are defined (cited in Zilioli and Brivio 1997): (1) ultra-oligotrophic, (2) oligotrophic, (3) mesotrophic, (4) eutrophic, and (5) hyper-eutrophic. Carlson (1977), analysing the situation, found that actually the trophic concept is multidimensional, involving several diverse aspects. The general conclusion is that, on the basis of only three characteristics (Secchi disk depth, chlorophyll *a* and total phosphorus), we cannot adequately describe the whole diversity of lakes and coastal waters, and consequently the five OECD classes are insufficient. A more complicated classification of lakes derived in Finland (Heinonen and Herve 1987; Vuoristo 1998; Koponen *et al.* 2002) uses about 20 variables. Mäemets (1971) and Ott and Kõiv (1999) have proposed 8 trophic types (some of which have up to seven subtypes; altogether 27 trophic types) for Estonian lakes.

In parallel, studies for elaborating the optical classification of water bodies have been conducted (Jerlov 1976; Morel and Prieur 1977; Kirk 1980, 1996; Prieur and Sathyendranath 1981; Baker and Smith 1982; Gordon and Morel 1983; Vertucci and Likens 1989; Reinart *et al.* 2003; Arst 2003). These classes are usually defined on the basis of optical properties of water, the concentrations of OAS and remote sensing reflectance spectra. A classification scheme, often used in investigations, was put forward by Morel and Prieur (1977). It describes two general reflectance types: Case 1, where phytoplankton and their derivative products play a dominant role in determining the optical properties of water, and Case 2, where an important contribution to the optical properties comes from resuspended sediments and particles, originating from different sources (river runoff, urban discharge, etc.). However, the differentiation between these two classes is a little bit vague: according to Kirk (1996) Case 1 waters can range from oligotrophic to eutrophic; in Case 2 waters, phytoplankton and their derivative products may or may not also be present in significant amounts. Note that a water body can change from one optical type to another (the reason can be the development of algal bloom, change of intensity of soil erosion due to the heavy rain or strong flow in rivers after the melting of ice, etc.) (Kirk 1996; Reinart *et al.* 2003).

In most cases the classifications made for ocean and open sea waters are not applicable to optically complex waters. Instead of looking for a general classification, valid over a wide range of ocean, sea and lake waters, classification algorithms optimized for local conditions have been found (e.g. Eloranta (1978) for Finnish lakes; Chekhin (1987) for Russian lakes; Koenings and Edmundson (1991) for Alaskan lakes; Reinart and Herlevi (1999), Reinart *et al.* (2003) and Arst (2003) for Estonian and South Finland lakes). For developing the optical classification of lakes two groups of basic characteristics were used: (1) the reflectance spectra (important for remote sensing investigations), and (2) light attenuation and/or OAS data (to describe the transparency of water as well as its dependence on OAS).

Note that optical water types can more or less correspond to trophic types of the water bodies, but the general approach is different (e.g. optical classes do not describe the chemical parameters and the productivity of the water, the limnological classes do not allow us to estimate the optical properties and remote sensing characteristics of a water body).

However, relying on any classification (neither optical nor limnological) one cannot numerically determine the contribution of each water constituent in forming the inherent optical properties of a water body. This kind of data is certainly of interest, especially when

estimating these contributions not only to the total absorption coefficient of light in the water, but also their spectral distribution.

As is known, today the optical measurements from satellite are an effective tool for investigating the aquatic environment (type and amount of OAS, their spatial distribution in a water body, undulation, ice cover, etc.). Gradually, the spatial resolution of the satellite sensors have improved (e.g. MODIS/Terra, having in some channels a resolution of 250 m) and probably will be better in the future. The best way for the interpretation of remote sensing data is to use quantitative analysis, which allows us to find out the numerical values of water constituents (see [Kutser \(1997\)](#), [Kutser et al. \(2001\)](#) and references quoted in [Arst \(2003\)](#)). The corresponding algorithms of the remote sensing models are derived on the basis of the inherent optical properties of the water environment, light absorption and backscattering coefficient. Here we need data not only on the total absorption coefficient, but also on the specific absorption coefficients of each optically active substance. This problem is rather adequately solved for phytoplankton and CDOM, but there are problems for determining the specific absorption coefficient for “nonchlorophyllous” suspended matter. Particulate attenuation of “nonchlorophyllous” matter can be separated into contributions from particulate material of different types and sizes, mainly detritus and mineral particles (altogether named “tripton”). This is the reason for the noticeable variability of the specific absorption coefficient of suspended matter. Collecting and analyzing the data on the specific absorption coefficient of tripton will help to choose the most reliable values in remote sensing models.

Another important property of the aquatic medium is the scattering coefficient of light: in lakes it varies in a large range ([Kirk 1981, 1996](#); [Herlevi et al. 1999](#); [Herlevi 2002b](#)). A special problem is the description of the spectral distribution of the scattering coefficient. Rather often the spectral invariance of b is stated ([Jerlov \(1974\)](#) for Baltic Waters; [Bukata et al. \(1979\)](#) for Lake Ontario; [Phillips and Kirk \(1984\)](#) for Australian waters), but there are a number of studies ([Morel and Prieur 1977](#); [Halturin et al. 1983](#); [Kopelevich 1983](#); [Dekker 1993](#); [Jupp et al. 1994](#); [Kirk 1996](#); [Gould and Arnone 1998](#); [Herlevi et al. 1999](#); [Herlevi 2002b](#); [Gallegos et al. 2005](#)) which suggest that scattering is relatively high at short wavelengths and lower at high wavelengths, following a power law λ^{p_b} (p_b is usually called the slope of this relationship). When examining the published data, we can see noticeable differences in the numerical values of the slope p_b , as well as the contradictory results on its dependence on the water turbidity (some results show a decrease, other results an increase of p_b with increasing turbidity). It seems that, to obtain a reliable explanation, a rather large amount of additional data is needed.

The main objectives of the present study are: (1) using the spectral values of light absorption (a) and attenuation (c) coefficients, measured *in situ*, to estimate the contribution of each water constituent to total values of a and c in the photosynthetically active region (PAR) of the spectrum (400–700 nm) as well as for some narrow spectral intervals, (2) on the basis of *in situ* and laboratory measurements, to estimate the values and variability of the specific absorption coefficient for tripton, and (3) to calculate the slopes of the scattering coefficient spectra and to analyze their variability (seasonal change, dependence on the concentrations of OAS).

Materials and methods

We had at our disposal a dataset containing the spectral values of light absorption and attenuation coefficients in lake waters measured in connection with the co-operation project SUVI between the University of Helsinki and Estonian Marine Institute. The *in situ* measurements were carried out using the instrument ac-9 ([Herlevi et al. 1999](#); [Herlevi 2002a,b](#)). The ac-9 ([WET Labs. Inc. 1995](#)) is a spectral absorption/attenuation meter that

uses nine bandpass filters in different spectral channels for measurements of the vertical profiles of the spectral values of light attenuation and absorption coefficients (correspondingly c and a) in the water. There is a possibility to measure using two different path lengths, but for lakes the shorter one (10 cm) was chosen. In 1997–1999, the central wavelengths of these channels were 412, 440, 488, 510, 532, 555, 650, 676 and 715 nm (beginning in 2000 the channel 532 was replaced by 630 nm). We studied the optical properties in the photosynthetically active region (PAR, 400–700 nm), so we left out the data for 715 nm. Note that the dataset of ac-9 contains the vertical profiles of parameters determined with very small depth-step (1–2 cm) down to 2–6 m in a lake. However, the depth variation of variables in our lakes was only 2–3% (Herlevi *et al.* 1999; Herlevi 2002b) and we used the averaged values for the layer of 0.5–1 m. Note that similar results were obtained in Belzile *et al.* (2004) for clear oligotrophic L. Taupo, where down to 40 m the values of a practically did not change. From the whole dataset of ac-9 (1997–2000) we chose the spectra for different types of lakes, where concurrently the characteristics of optically active substances (OAS) were determined. The second group of our initial data (obtained by the Estonian Marine Institute) consisted of the laboratory measurement results: the concentrations of chlorophyll a (C_{chl}) and total suspended matter (C_s), obtained from water samples, and the beam attenuation coefficient of filtered water at the wavelength 380 nm ($c_f^*(\lambda)$). It was assumed that the absorption coefficient of the coloured dissolved organic matter, $a_{\text{CDOM}}(\lambda)$ is practically equal to $c_f^*(\lambda)$. The small difference between these two parameters is caused by fine inorganic particles and colloids passing through the filter (Bricaud *et al.* 1995; Sipelgas *et al.* 2003; Arst 2003).

Study sites and optically active substances

A short characterization of our study sites, 11 Finnish and Estonian lakes, is shown in Table 1. As we can see, rather different limnological and optical types of lakes were studied (altogether 73 series of measurements). The measurements were carried out in May/June and in August, describing, respectively, the early and late summer situations. Sometimes (e.g. in L. Lohjanjärvi, L. Vesijärvi, L. Päijänne, L. Ülemiste and L. Lammi Pääjärvi) the measurements were carried out during the same day in different sampling stations.

The water samples were collected in the same stations where *in situ* optical measurements were carried out. For determining the concentration of chlorophyll a , water was filtered through Whatman GF/C glass microfibre filters (pore size $\sim 1.2 \mu\text{m}$; Whatman International Ltd., Mainstone, UK). Then the pigments were extracted with hot ethanol, its absorption coefficients at the wavelengths of 665 and 750 nm were measured and the value of C_{chl} was calculated according to the Lorenzen (1967) method. The concentration of total suspended matter (C_s) was determined by its dry weight after filtration of the water through polycarbonate membrane filters (pore size $0.45 \mu\text{m}$, Millipore Corporation, Bedford, MA). The same filters were also used to find the values of $c_f^*(\lambda)$, measured from filtered water samples using a spectrophotometer Hitachi U1000. Note that in both cases more correct results could be obtained when the filters with pore size $0.2 \mu\text{m}$ were used (Lindell *et al.* 1999). However, we could not use these filters because the water of many lakes was so rich in particles that it would have clogged up the fine filters.

The term “suspended matter” is interpreted by different authors as follows: sometimes as the hydrosols (mineral particles), sometimes as a mixture of organic (dead algae, humic particles, detritus) and mineral particles. Actually, when determining C_s by its dry weight, the result will describe the amount of all kinds of particles, including living phytoplankton. Note that different authors use different terms/definitions for “nonchlorophyllous” particles (Kishino *et al.* 1985; Iturriaga and Siegel 1988; Nelson and Robertson 1993; Tassan and Ferrari 1995; Hoogenboom and Dekker 1997; Darecki *et al.* 2003). Rather often the

Table 1 Measurement series in Estonian and Finnish lakes carried out in 1997–2000. The variation range of the Secchi disk depth measured by us from May to September in 1994–2002 is also shown

Lake	Limnological type	Area (km ²)	Mean depth (m)	Secchi disk depth (m)	Station No.	No. of series
Estonian lakes						
Koorküla Valgjärv(E)	oligotr./mesotr.	0.441	8.5	2.8–5	–	5
Nohipalu Valgjärv (E)	oligotr./mesotr.	0.063	6.2	3–7	–	5
Paukjärv (E)	oligotrophic	0.086	5	4.5–6.5	–	4
Verevi (E)	hypertrophic	0.126	3.6	0.7–4	–	6
Võrtsjärv (E)	eutrophic	270	2.8	0.15–1.6	–	6
Ülemiste (E)	hypertrophic	9.6	2.5	0.3–1.8	1, 2	5
Finnish lakes						
Lammi Pääjärvi(F)	mesotr./mesoh.	13.4	14.4	1.3–3	1, 3, 6	7
Lohjanjärvi (F)	eutrophic	94	15	0.8–1.8	2, 5, 6, 8	12
Päijänne (F)	oligotrophic	70.3	15.9	3.5–6	1, 2	5
Tuusulanjärvi (F)	hypertrophic	6.1	3.1	0.3–1.5	–	7
Vesijärvi (F)	eutrophic	112	6.6	1.2–3.7	1, 5	11

“nonchlorophyllous” material is equated with detritus, obviously supposing that the contribution of mineral particles in tripton is very small. Because our study sites included shallow lakes where also mineral particles can exist, we used the term “tripton”, i.e. the sum of detritus and mineral particles.

Hoogenboom and Dekker (1997), using the measurements in Dutch lakes, proposed for the separation of the dry weight of nonchlorophyllous particles (tripton, C_t) from the dry weight of total particles (C_s) the following relation:

$$C_t = C_s - K_1 C_{\text{chl}} \quad (1)$$

where K_1 is 0.07, when C_s and C_t are in mg L^{-1} and C_{chl} is in mg m^{-3} . According to Kutser et al. (2001) for the Finnish lakes K_1 is in the range of 0.03–0.06. We used the value $K_1 = 0.045$, because our estimates showed that the variation of K_1 from 0.06 to 0.03 brings about errors below $\pm 8\%$ (except some cases where C_s is less than 2 mg L^{-1}).

Inherent optical properties

The data obtained using the instrument ac-9 gave us the spectral values of light attenuation (c) and absorption (a) coefficients. As is known (Kirk 1996; Prieur and Sathyendranath 1981; Herlevi 2002b; Arst 2003), the total absorption coefficient a can be expressed in the following way:

$$a = a_w + a_{ph} + a_{\text{CDOM}} + a_t = a_w + a'_{ph} C_{\text{chl}} + a_{\text{CDOM}} + a'_t C_t \quad (2)$$

where a_w is the absorption coefficient of absolutely pure water; a_{ph} , a_{CDOM} and a_t are, respectively, the absorption coefficients of phytoplankton, coloured dissolved organic matter (CDOM) and tripton; a'_{ph} and a'_t are the specific absorption coefficients of these substances, C_{chl} and C_t are their concentrations in water. Note that in equation (2) and later the wavelength dependence notation is suppressed for brevity.

In equation (2) the values of a_w , a_{ph} and a_{CDOM} can be estimated rather easily. Practically always the spectral values of a_w are considered as known data (e.g. Baker and Smith 1982; Pope and Fry 1997). The empirical relationship between a'_{ph} and C_{chl} was derived by Bricaud et al. (1995):

$$a'_{ph}(\lambda) = A(\lambda) C_{\text{chl}}^{-B(\lambda)} \quad (3)$$

where A and B are positive, wavelength-dependent parameters (they are tabulated in steps of 2 nm in the paper of Bricaud et al. (1995)). Usually the absorption spectra of CDOM are described by an exponential function depending on the wavelength (results by different authors are described in Aas (2000)):

$$a_{\text{CDOM}}(\lambda) = a_{\text{CDOM}}(\lambda_0) \exp[-S(\lambda - \lambda_0)] \quad (4)$$

where λ_0 is the reference wavelength (usually it is between 360 and 420 nm: we chose the value of 380 nm) and S is the slope parameter. As mentioned before, we assumed that $a_{\text{CDOM}}(380 \text{ nm}) \approx c_f^*(380 \text{ nm})$, and used this value in equation (4). The estimation of S has been performed by numerous authors: for coastal and lake waters, the reasonable mean of S was found to be in the limits $0.016\text{--}0.019 \text{ nm}^{-1}$, while often the value $S = 0.017 \text{ nm}^{-1}$ is recommended for use (Mäekivi and Arst 1996; Kallio 1999; Sipelgas et al. 2003). Usually S is determined for the spectral range 380–550 nm.

Consequently, we can determine the values of a , a_w , a_{ph} and a_{CDOM} using *in situ* and laboratory data and methods described above. The values of a_w were taken from Pope and Fry (1997). The value of a_t can be estimated as a residual on the basis of equation (2):

$$a_t = a - (a_w + a_{ph} + a_{CDOM}) \quad (5)$$

Naturally, the reliability of a_t determined in such a way can be low, because its value is influenced by measurement errors of a , a_w , a_{ph} and a_{CDOM} .

Thus, the first task of our study was to estimate the spectral values of a_t using our dataset for other parameters. Additionally, since we had measured the concentration of total suspended matter C_s and then determined the concentration of tripton (C_t) by equation (1) we could estimate a corresponding specific absorption coefficient (a'_t) for each channel of ac-9:

$$a'_t = \frac{a_t}{C_t}. \quad (6)$$

The data on light attenuation and absorption coefficients, measured by instrument ac-9, allow calculating the corresponding scattering coefficient (b) by a well-known formula:

$$b = c - a. \quad (7)$$

Similarly to the total absorption coefficient, the total scattering coefficient (b) can be expressed as a sum of contributions from different substances (Sathyendranath *et al.* 1989):

$$b = b_w + b_{ph} + b_t = b_w + b'_{ph}C_{chl} + b'_tC_t. \quad (8)$$

In equation (8) the scattering of light by CDOM, caused by colloids, is not taken into account. Its numerical value is rather complicated to determine in each separate case, and, by our estimations, in most of the lakes b_{CDOM} is about 0.5–1.5% from total b_{PAR} and only in “yellow” and/or clear-water lakes can it increase up to 3–4%. In lakes the contribution of scattering coefficient of pure water to the total scattering is also negligible.

It is rather difficult to distinguish b_{ph} and b_t from measured b spectra. Most publications contain different versions of the dependence of b_{ph} on C_{chl} , but often the data are given only for one or two wavelengths. The models for describing the spectral variation of b_{ph} that could be found in the literature seem to give even contradictory results. For instance, Gordon and Morel (1983) and Fransisco and McCormick (1994) obtained the following relationship:

$$b_{ph}(z, \lambda) = 0.3[C_{chl}(z)]^{0.62} \left(\frac{550}{\lambda} \right)^n. \quad (9)$$

Here $0.3(C_{chl})^{0.62}$ is the scattering coefficient at the wavelength of 550 nm and $n = 1$ or close to 1. However, the numerical value of $b(550)$ is different from that obtained by Morel (1980) and used in Sathyendranath *et al.* (1989), in whose studies it was $0.12(C_{chl})^{0.63}$. According to equation (9) $b_{ph}(z, \lambda)$ decreases with increasing wavelength. However, by the data of Ahn *et al.* (1992) and Paavel (2004) in the range 420–580 nm $b_{ph}(z, \lambda)$ increases with wavelength and only in the red part of the spectrum is its slight decrease observed.

Contribution of different components of the aquatic medium to the total absorption and attenuation coefficients

There are numerous publications where the absolute values of total and/or substance-specific absorption, scattering and attenuation coefficients are presented, both for the PAR region and for different wavelengths. However, we could find only a few investigations where the contributions of different components of aquatic medium to total a (or c) are estimated (Kirk 1980, 1996; McKee *et al.* 2002; Paavel 2004; Reinart *et al.* 2004). This kind of information allows us to compare the water bodies from the point of view of relative importance of water constituents in the formation of inherent optical properties in different lakes and times.

On the basis of the ac-9 and laboratory measurements data we calculated these contributions, i.e. the ratios a_w/a , a_{ph}/a , a_{CDOM}/a and a_t/a at eight ac-9 wavelengths.

The spectral data for a_w , and formulas for a_{ph} and a_{CDOM} (equations (3) and (4)), allow us to determine their averaged values for the whole PAR band (400–700 nm). The corresponding values of total absorption coefficient, averaged over the PAR region, were estimated on the basis of the ac-9 measurements. It appeared that the spectra of $a(\lambda)$ can be described as a function of wavelength using polynomial and/or power function trendlines through the ac-9 “points” (separately for the wavelengths 412–532 nm and 532–676 nm). Then we could calculate the contribution of each optically active substance to the total absorption coefficient in the PAR region: $a_{w,PAR}/a_{PAR}$, $a_{ph,PAR}/a_{PAR}$ and $a_{CDOM,PAR}/a_{PAR}$. The value of $a_{t,PAR}/a_{PAR}$ was estimated in the following way:

$$\frac{a_{t,PAR}}{a_{PAR}} = a_{PAR} - \left(\frac{a_{w,PAR}}{a_{PAR}} + \frac{a_{ph,PAR}}{a_{PAR}} + \frac{a_{CDOM,PAR}}{a_{PAR}} \right). \quad (10)$$

Note that these estimates, made on the basis of four measured parameters (each having some measurement error) at eight wavelengths, cannot be with high accuracy, but qualitatively we can get reliable results.

We determined also the contributions of different OAS to the total attenuation coefficient, consequently the ratios a_w/c , a_{ph}/c , a_{CDOM}/c and a_t/c at different wavelengths and also $a_{w,PAR}/c_{PAR}$, $a_{ph,PAR}/c_{PAR}$, $a_{CDOM,PAR}/c_{PAR}$ and $a_{t,PAR}/c_{PAR}$ were calculated. For the reasons mentioned before we had difficulties in separating the contribution of different OAS to the total scattering coefficient, and decided to show only the total contribution of scattering coefficient to the attenuation coefficient (the ratio b/c). This was done for eight ac-9 channels and also for the PAR region.

Slope of the scattering coefficient spectra

Data provided by the ac-9 allow us to describe the dependence of the total scattering coefficient, b , on wavelength. Usually this dependence is expressed by the power law

$$b(\lambda) = b(\lambda_0) \left(\frac{\lambda_0}{\lambda} \right)^{p_b}. \quad (11)$$

Here λ_0 is some reference wavelength and p_b is called the slope of the scattering coefficient spectrum. However, looking at the published data, we can see different estimations of p_b values, from 0–1.3 (Jerlov 1974; Halturin et al. 1983; Kopelevich 1983; Phillips and Kirk 1984). According to these data it seems that p_b decreases with increasing turbidity of the water. However, on the basis of the whole ac-9 database A. Herlevi obtained noticeably variable values of p_b , which in some cases were high (exceeding 1.5) even for turbid lakes (Herlevi et al. 1999; Herlevi 2002b). In the present study we tried to estimate the seasonal variation of p_b (comparing May/June and August data) and the connections between its values and corresponding OAS. For these purposes the values of p_b were determined for all 73 spectra under consideration. The value of λ_0 was chosen to be 555 nm. A multiple regression formula between p_b and three OAS jointly was determined, using the Multiple Linear Regression module of STATISTICA 6.0 (StatSoft Inc. 2001).

Results and discussion

Variation of optically active substances

A characterization of our OAS measurement results for lakes under investigation is shown in Table 2. Looking at this table we can see marked variability of OAS not only when comparing different lakes, but also for different measurement series in the same lake. Note that the values of C_s and C_t below 3 mg L^{-1} are often determined with large relative errors and in this case the determination of a_t and corresponding contribution to the total absorption

Table 2 Variation ranges of C_{chl} , a_t^* (380), C_s and C_t in 11 lakes (altogether 73 measurement series)

Lake	C_{chl} (mg m ⁻³)	a_t^* (380) (m ⁻¹)	C_s (mg L ⁻¹)	C_t (mg L ⁻¹)
Koorküla Valgjärv	2.0–9.2	1.7–2.2	1.2–3.0	1.0–2.8
Lammi Pääjärvi	2.8–8.8	9.5–14	1.1–8.4	0.7–8.0
Lohjanjärvi	9.2–45	4.7–15	3.5–18	3.3–16
Nohipalu Valgjärv	2.6–13	2.4–3.7	1.2–7.0	1.0–6.4
Paukjärv	1.6–6.9	0.9–1.4	1.0–2.8	0.9–2.5
Päijänne	1.5–4.9	3.7–4.0	0.5–1.5	0.4–1.4
Tuusulanjärvi	17–47	6.3–17	13–35	12–32
Verevi	3.8–60	3.9–10	3.7–13	3.1–10
Vesijärvi	4.8–12	2.1–8.1	1.8–10	1.6–9.5
Vörtsjärv	16–47	5.9–9.9	8.8–20	8.1–19
Ülemiste	26–61	5.5–7.6	12–21	11–18

coefficient is problematic (remember that a_t was found as a residual according to equation (5)). For this reason we left out L. Päijänne, L. Koorküla Valgjärv and L. Paukjärv when we estimated the specific absorption coefficients of tripton. However, these lakes were included in our “contribution analysis” and in studies on the slope of the scattering coefficient spectra.

Estimation of absorption by tripton

We calculated the spectral values of a_t and a_t' according to equations (5) and (6). Note that the generally accepted result is that the absorption coefficient of detritus/tripton decreases with increasing wavelength and can be approximately expressed as an exponential function

$$a_t(\lambda) = a_t(\lambda_0) \exp[-t(\lambda - \lambda_0)] \quad (12)$$

where λ_0 is a reference wavelength and the exponent t varies over a wide range, from 0.006–0.016 nm⁻¹ (Roesler *et al.* 1989; Bricaud and Stramski 1990; Strömbeck and Pierson 2001; Darecki *et al.* 2003). Because of the great variability of suspended matter constituents, the assessment of the numerical values of their absorption as well as of the specific absorption coefficients is complicated and is still one of the most difficult problems in the building of remote sensing models.

As shown in Table 2, the values of C_{chl} are in the range 2–61 mg m⁻³ and C_s in the range 0.5–35 mg L⁻¹. The respective values of a_t at the wavelength 412 nm were mostly between 0.02 and 0.8 m⁻¹ (from 55 cases only 7 were between 1 and 1.45 m⁻¹). Note that the values of $a_t(412 \text{ nm})$ measured by Darecki *et al.* (2003) for the Baltic Sea in summer 1998 were usually up to 0.65 m⁻¹ (the maximum was 1 m⁻¹). Here we have to take into consideration that in lakes the amount of tripton is probably higher than that in the sea.

Some examples of the spectral variation of a_t' , obtained by us, are shown in Figure 1(a) and (b). Four spectra in Figure 1(a) are characterized by a high determination coefficient and rather stable value of the exponent t , which was between 0.0068–0.0082 nm⁻¹. However, there is a group of measurements where the maximum value of a_t' is at the wavelength 440 nm, the value of R^2 is lower (sometimes even less than 0.5) and the values of a_t' at 532 and 555 nm are very small (Figure 1(b)). As one can expect, the numerical values of a_t' are very variable (see also Table 3). Naturally, the slope of the exponent is the same for a_t and a_t' .

As we can see, the slope of the exponent varies between 0.0060–0.0109 nm⁻¹ (with two exceptions, the lower boundaries being 0.0044 and 0.0052). It is a little lower in comparison with the data mentioned before (Roesler *et al.* 1989; Bricaud and Stramski 1990; Strömbeck and Pierson 2001), but the magnitude of the results is acceptable. The values of $a_t'(532)$ varied from 0.013–0.098 L mg⁻¹ m⁻¹, but this can be explained not only by variability of

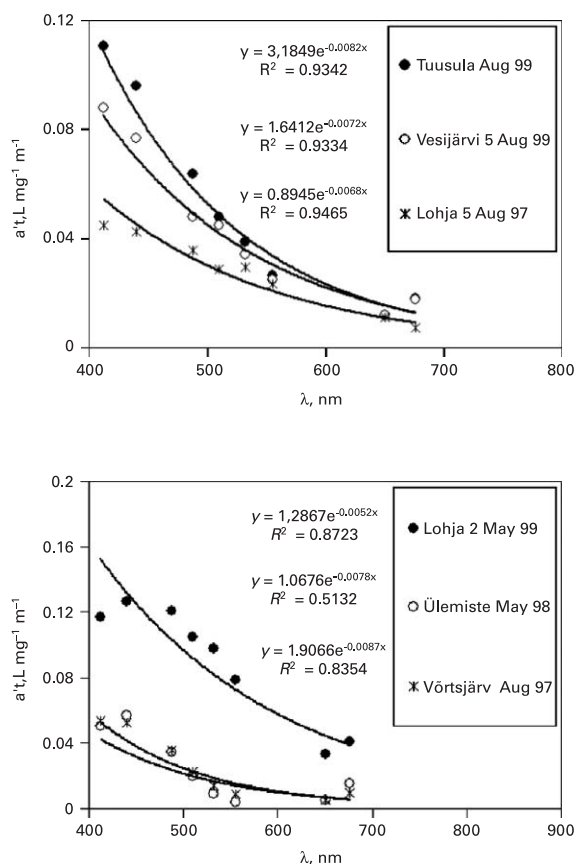


Figure 1 Some examples of the spectral distribution of $a_t(\lambda)$, calculated by equations (5) and (6) on the basis of our *in situ* and laboratory measurements: (a) shows the trendlines fitting well with the measurement results, while in case of (b) the points showing the spectral distribution of $a_t(\lambda)$ are rather irregular

tripton constituents, but also by errors of the results obtained. We could not find a good correlation between the values of $a_t(532)$ and C_t , but, using the Microsoft Excel Data Analysis program we found a good relationship between $a_t(532)$ and exponent t (for linear regression $R^2 = 0.584$, st. error = $0.00092 \text{ L mg}^{-1} \text{ m}^{-1}$, $p = 1.42 \times 10^{-6}$). These results are shown in Figure 2, where we can see that a higher R^2 can be obtained using, not linear, but a power function trend line.

In Paavel (2004) the values of $a_t(400)$ were estimated for two Swedish lakes (L. Vänern and L. Vättern), for Lake Peipsi (Estonia) and for some small Estonian and Finnish lakes. The results obtained were between $0.11\text{--}0.20 \text{ L mg}^{-1} \text{ m}^{-1}$. On the basis of ac-9 measurements we could estimate $a_t(400)$ only very approximately (by extrapolation), using trend lines of the $a_t(\lambda)$ spectra. According to our data, $a_t(400)$ varies between $0.050\text{--}0.176 \text{ L mg}^{-1} \text{ m}^{-1}$. This large variability is not easy to explain, but there can be the influence of different compositions of tripton and also some seasonal changes.

Contributions of different water constituents to absorption and attenuation of light

The absolute values of a , b and c for all our lakes (Table 1) measured using the instrument ac-9 are already presented in Herlevi *et al.* (1999) and Herlevi (2002b). We made a step forward, trying to estimate the contributions (ctr) of different water constituents to total absorption and attenuation coefficients. As said before, for this we have to find the ratios

Table 3 The slope of the exponent (t) of the absorption coefficient spectra of tripton, the corresponding determination coefficient R^2 and specific absorption coefficient a'_t at 532 nm. Only the cases when $C_t > 3 \text{ mg L}^{-1}$ and $R^2 > 0.6$ were included in this table ($N = 29$). The values of t and a'_t are correspondingly in nm^{-1} and in $\text{L mg}^{-1} \text{ m}^{-1}$

Lake	Time	Station	Slope (t)	R^2	$a'_t(532)$
Lammi Pääjärvi	August 1999	1	0.0064	0.852	0.035
Lohjanjärvi	May 1997	2	0.0067	0.923	0.067
		5	0.0074	0.951	0.051
	August 1997	2	0.0090	0.932	0.030
		5	0.0068	0.946	0.029
		6	0.0062	0.860	0.045
		8	0.0080	0.841	0.027
	May 1998	2	0.0070	0.932	0.050
		5	0.0077	0.903	0.047
	August 1998	5	0.0060	0.898	0.072
	May 1999	2	0.0052	0.872	0.098
		5	0.0044	0.858	0.087
N. Valgjärv	August 1999	–	0.0081	0.716	0.019
Tuusulanjärvi	August 1997	–	0.0083	0.866	0.022
	May 1999	–	0.0085	0.975	0.039
	August 1999	–	0.0082	0.934	0.029
Verevi	August 1998	–	0.0096	0.674	0.016
	August 1999	–	0.0066	0.862	0.028
	June 2000	–	0.0080	0.710	(0.017)*
Vesijärvi	August 1997	5	0.0108	0.956	0.018
	May 1998	5	0.0068	0.976	0.039
	August 1998	5	0.0076	0.981	0.046
	August 1999	5	0.0072	0.933	0.034
	May 2000	2	0.0077	0.883	(0.050)*
Vörtsjärv	August 1997	–	0.0109	0.722	0.013
	August 1998	–	0.0074	0.659	0.032
	June 1999	–	0.0066	0.745	0.040
	August 1999	–	0.0070	0.695	0.042
Ülemiste	May 1998	–	0.0084	0.623	0.013

*Obtained by interpolation

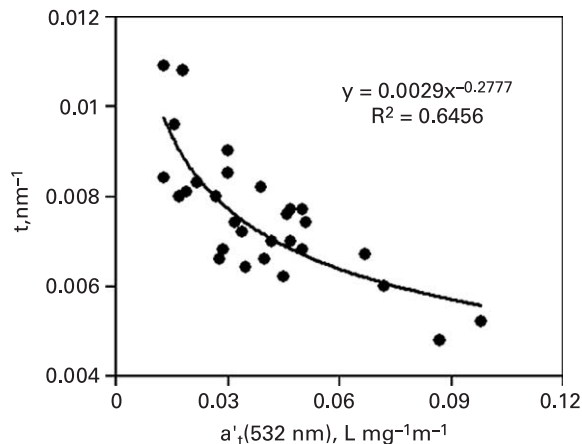


Figure 2 Relationship between the exponent t (equation (12)) and the values of $a'_t(532 \text{ nm})$ (only the cases when $C_t > 3 \text{ mg L}^{-1}$ and the determination coefficient of trendline $R^2 > 0.6$ were included, $N = 29$)

a_w/a , a_{ph}/a , a_{CDOM}/a and a_t/a as well as a_w/c , a_{ph}/c , a_{CDOM}/c and a_t/c . These ratios were calculated for eight wavelengths of ac-9 and, in some cases, also for the whole PAR region. The results for four individual cases (we tried to choose different types of lakes) are shown in Figures 3 and 4. The averaged values (for each lake) of contributions of phytoplankton, CDOM, water and tripton (respectively $ctr(a_{ph})$, $ctr(a_{CDOM})$, $ctr(a_w)$ and $ctr(a_t)$) in the total spectral absorption coefficient for two ac-9 channels, 440 and 676 nm (central wavelengths of two main absorption bands of chlorophyll *a*) are shown in Table 4. We can see that the contributions change from lake to lake and can be very different for 440 and 676 nm (especially $ctr(a_{CDOM})$ and $ctr(a_w)$). With two exceptions (L. K. Valgjärv and L. Paukjärv) $ctr(a_{ph})$ for 676 nm markedly exceeds that for 440 nm. At the wavelength 440 nm the value of $ctr(a_{ph})$ changes from 3.2% to 13% and $ctr(a_{CDOM})$ from 56% to 90%. The values of $ctr(a_w)$ (and their absolute changes) are small. At the wavelength 676 nm $ctr(a_{ph})$ changes from 8.1% to 35%, $ctr(a_{CDOM})$ from 1.6% to 11% and $ctr(a_w)$ from 39% to 82%. The numerical values of $ctr(a_t)$ have to be accepted with caution, but surely their highest contributions in the three most turbid lakes (L. Tuusulanjärvi, L. Vörtsjärv and L. Ülemiste) are logical. It is interesting that the maximum values of $ctr(a_{CDOM})$ at 440 nm (90% and 88%) are observed in two different types of lakes: in mesotrophic/mesohumic L. Lammi Pääjärvi and in oligotrophic L. Pääjärve.

The values of contributions of OAS to *a* and *c* at different wavelengths, as well as those for the entire PAR region (Figures 3 and 4 and Table 4) are, to some extent, in correspondence with the optical types of the lakes (Reinart *et al.* 2003; Arst 2003). According to Figure 3, the value of $a_{w, PAR}/a_{PAR}$ is almost 20% in L. Vesijärvi, but only about 6% in L. Vörtsjärv and L. Lammi Pääjärvi. The contribution of CDOM ($a_{CDOM, PAR}/a_{PAR}$) is about 50% in L. Vesijärvi and L. Vörtsjärv, to some extent higher in L. Lohjanjärvi (65%), but in L. Lammi Pääjärvi it reaches 77%. The values of $a_{ph, PAR}/a_{PAR}$ and $a_{CDOM, PAR}/a_{PAR}$ are the highest in L. Vesijärvi and L. Vörtsjärv (14%), but only 7% in L. Lohjanjärvi and 3.4% in L. Lammi Pääjärvi. As can be expected, the ratio $a_{t, PAR}/a_{PAR}$ is highest in shallow and turbid L. Vörtsjärv (30%), but almost similar in the other three lakes (13–18%).

The values of b_{PAR}/c_{PAR} also vary from lake to lake: in L. Vörtsjärv it is 84%, in L. Vesijärvi 72%, in L. Lohjanjärvi 65% and in L. Lammi Pääjärvi only 38% (Figure 4). In our very turbid lakes (L. Vörtsjärv, L. Tuusulanjärvi and L. Ülemiste) the scattering coefficient can be rather high (typical values of $b(412\text{ nm})$ in these lakes were 10–26 m^{-1}). Kirk (1981, 1996) presented the values of b_{PAR} for five Australian freshwater lakes, with a minimum of 1.5 m^{-1} and maximum of 59.8 m^{-1} . So, there are lakes with very high values of scattering coefficient and, correspondingly, the ratio b/c is relatively high. For the cases shown in Figure 4, the values of b_{PAR} were between 1.9–12.3 m^{-1} .

As already mentioned, there is not much data from other authors for comparing with our results. Kirk (1980, 1996) presents some estimations of the contribution of (1) water itself, (2) soluble fraction, and (3) particulate fraction to absorbed PAR quantum irradiance for coastal–oceanic, estuarine and inland waters (all together 12 cases). In the oceanic waters the contribution of the water itself was 68%, the contributions of soluble and particulate fractions correspondingly 23.9% and 8%. However, in inland waters these values varied between 6% and 39% (water itself), 7.5% and 60.4% (soluble fraction) and 5.2% and 86.6% (particulate fraction). The general agreement with our data is good, but our turbid lakes show to some extent lower values of $a_{w, PAR}/a_{PAR}$ and higher values of $a_{CDOM, PAR}/a_{PAR}$. Reinart *et al.* (2004) studying L. Peipsi in Estonia (94 water samples were analyzed) calculated the values of the contributions of water, CDOM and particles (all kind of particles together) to the total absorption coefficient measured in three wavebands (400–450 nm, 550–650 nm and 660–680 nm). For these wavebands the ratio of a_w/a was correspondingly 0.1–0.3%,

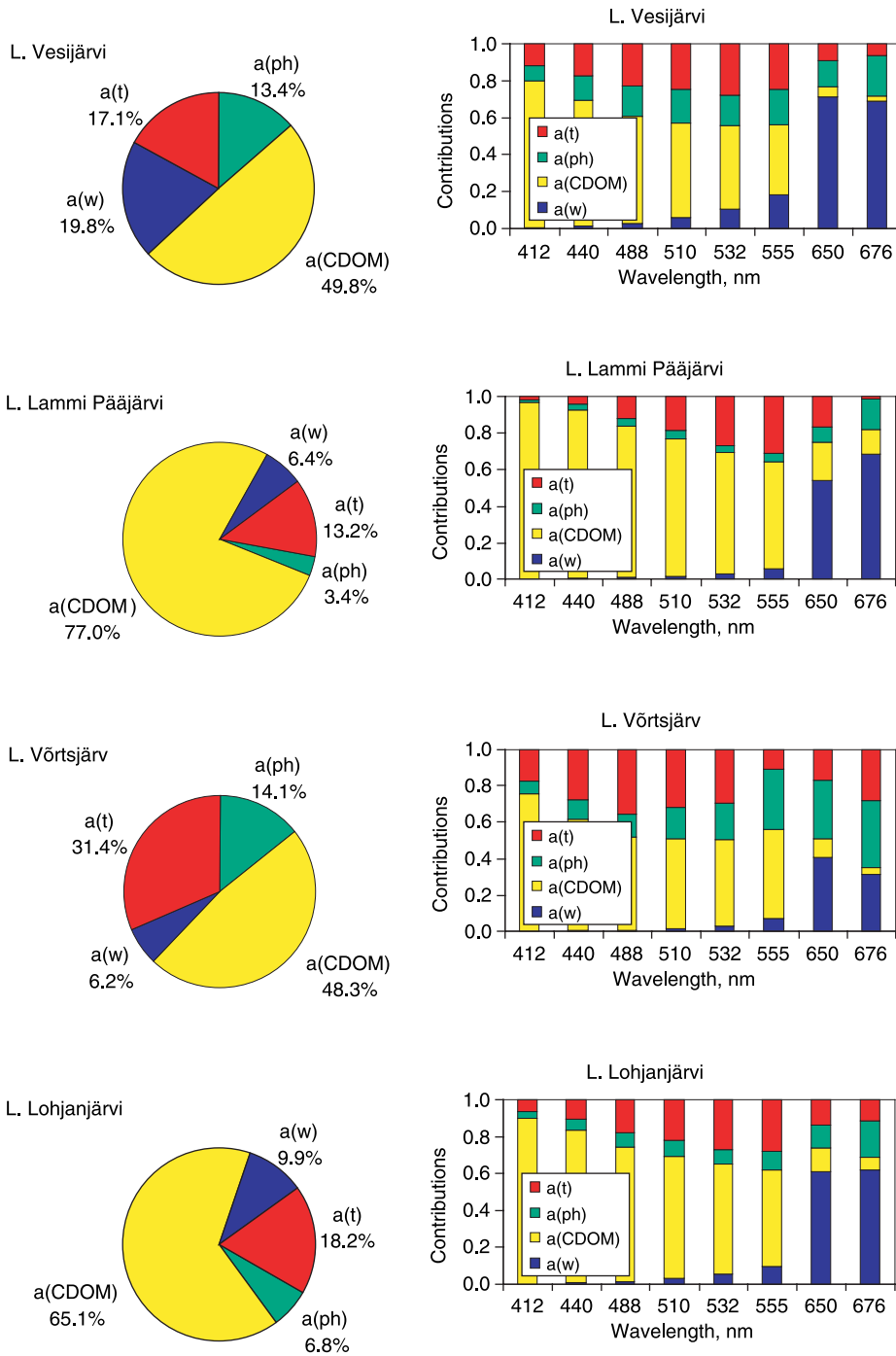


Figure 3 Contributions of phytoplankton, CDOM, water and tripton to the total absorption coefficient a (calculated correspondingly as a_w/a , a_{ph}/a , a_{CDOM}/a and a_t/a) for eight wavelengths and also for the PAR region). In the figure the abbreviations a_{ph} , a_{CDOM} , a_w and a_t were used

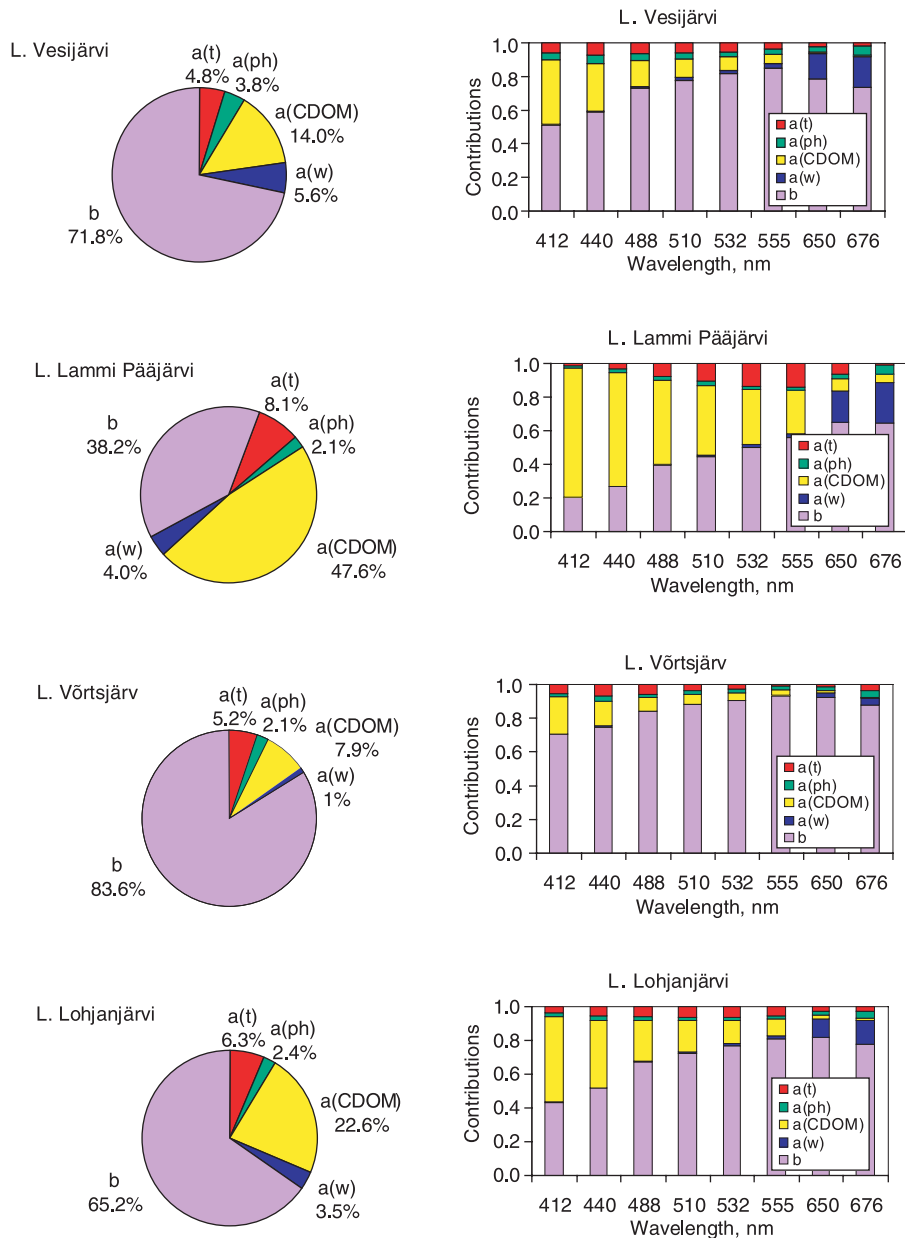


Figure 4 Contributions of a_{ph} , a_{CDOM} , a_w , a_t and scattering coefficient b to the total attenuation coefficient c (calculated correspondingly as a_w/c , a_{ph}/c , a_{CDOM}/c , a_t/c and b/c) for eight wavelengths and PAR region). In the figure the abbreviations a_{ph} , a_{CDOM} , a_w , a_t and b were used

22–57% and 59–83%. The ratio a_{CDOM}/a was correspondingly 55–87%, 17–57% and 2–17%, and the ratio $a_{PARTICLES}/a$ was 13–45%, 13–50% and 12–49%. We cannot carry out the appropriate comparison with our data here (due to different wavebands), but the results for L. Peipsi seem to be close to those for L. Vesijärvi (in both lakes the mean value of Secchi depth is about 2 m). In [McKee et al. \(2002\)](#) the measurements and radiative transfer modelling were performed in a Scottish fjord, Loch Elive (down to 40 m). This water body is different from most of our shallow lakes, but three lakes (L. Paukjärv, L. Koorküla Valgjärv and L. N. Valgjärv) showed rather similar values of chlorophyll and yellow substance

Table 4 Averaged values of contributions of phytoplankton, CDOM, water and tripton ($\text{ctr}(a_{ph})$, $\text{ctr}(a_{CDOM})$, $\text{ctr}(a_w)$ and $\text{ctr}(a_t)$, respectively) to the total spectral absorption coefficient at 440 nm and 676 nm. The corresponding standard deviations are shown in parentheses

Lake	$\text{ctr}(a_{ph})$ (%)	$\text{ctr}(a_{CDOM})$ (%)	$\text{ctr}(a_w)$ (%)	$\text{ctr}(a_t)$ (%)
440 nm				
Koorküla Valgjärv	12 (± 4)	73 (± 7)	1.6 (± 0.2)	13 (± 7)
Lammi Pääjärvi	3.2 (± 0.7)	90 (± 4)	0.3 (± 0.03)	6.0 (± 4.0)
Lohjanjärvi	12 (± 3)	69 (± 6)	1.1 (± 0.1)	13 (± 5)*
Nohipalu Valgjärv	7.5 (± 2.2)	75 (± 9)	1.0 (± 0.3)	16 (± 8)
Paukjärv	13 (± 4)	65 (± 8)	2.1 (± 0.2)	20 (± 7)
Päijänne	5.8 (± 1.5)	88 (± 2)	1.0 (± 0.003)	5.6 (± 1.7)
Tuusulanjärvi	7.5 (± 2.1)	56 (± 12)	0.3 (± 0.03)	36 (± 10)
Verevi	11 (± 1)	76 (± 7)	0.4 (± 0.14)	17 (± 4)
Vesijärvi	6.5 (± 2)	80 (± 9)	0.4 (± 0.1)	17 (± 8)
Vörtsjärvi	8.7 (± 1.8)	67 (± 7)	0.3 (± 0.05)	24 (± 6)
Ülemiste	12 (± 1)	62 (± 6)	0.4 (± 0.05)	27 (± 5)
676 nm				
Koorküla Valgjärv	11 (± 3)	2.2 (± 0.2)	79 (± 2)	7.6 (± 3.9)
Lammi Pääjärvi	14 (± 4)	11 (± 2)	65 (± 6)	9.0 (± 7)
Lohjanjärvi	22 (± 8)	2.8 (± 1.6)	70 (± 10)	16 (± 10)
Nohipalu Valgjärv	12 (± 6)	3.3 (± 0.5)	68 (± 9)	17 (± 7)
Paukjärv	10 (± 5)	1.6 (± 0.2)	82 (± 2)	6.0 (± 3)
Päijänne	8.1 (± 1.8)	4.3 (± 0.2)	80 (± 1)	7.1 (± 2.4)
Tuusulanjärvi	29 (± 5)	5.2 (± 2.4)	39 (± 6)	27 (± 4)
Verevi	35 (± 10)	5.0 (± 0.4)	40 (± 13)	25 (± 7)
Vesijärvi	18 (± 3)	7.2 (± 0.4)	55 (± 5)	9 (± 3)
Vörtsjärvi	30 (± 6)	5.0 (± 1.2)	40 (± 8)	25 (± 3)
Ülemiste	34 (± 3)	3.5 (± 0.6)	39 (± 7)	23 (± 5)

* $\text{ctr}(a_t)$ was estimated as residual

content. In Loch Elive the contributions of water, CDOM and phytoplankton (obviously together with tripton) to the total absorption in PAR were correspondingly 36%, 44% and 20%. For our clear-water lakes we obtained similar results, except that the contribution of CDOM in lakes was higher than that in the fjord.

Slope of the scattering coefficient spectra

A data complex of scattering coefficients obtained by ac-9 measurements and the corresponding discussion of the results are published in Herlevi *et al.* (1999) and Herlevi (2002a,b). In the present study we focused our attention on the spectral distribution of scattering coefficient (b) and on the corresponding slope of its trendline. Some examples of the measured values of b are shown in Figure 5. As usually the spectral distribution of b is expressed by equation (11), we show the same spectra also in the form of normalized values, the reference wavelength being 555 nm (Figure 6). The slope p_b (equation (11)) was determined using the power function trendline. In most cases the determination coefficient was high ($R^2 > 0.94$). However, there were also some individual spectra where the measurement result for one ac-9 channel was obviously incorrect (e.g. some data for channel 630 nm in 2000).

The values of p_b varied in a large range, being between 0.32–2.53, and the average value was 0.847 ($N = 73$, st. dev. = 0.439). Note that for lake waters the value $p_b = 0.8$ is often used in practice (Herlevi *et al.* 1999; Arst *et al.* 2002; Herlevi 2002b; Arst 2003). We tried to find out whether the value p_b has some seasonal dependence and/or if there is some influence

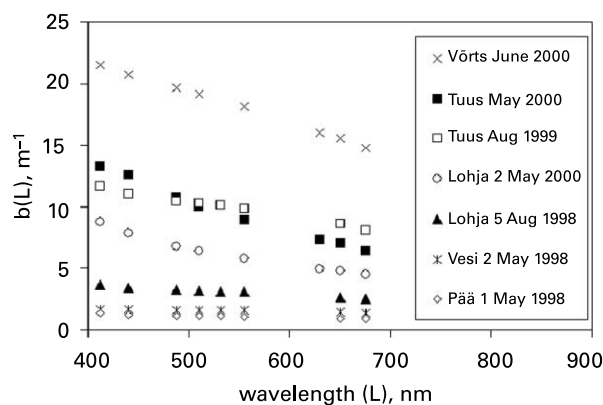


Figure 5 Some examples of the spectral distribution of the total scattering coefficient measured with ac-9 in different lakes

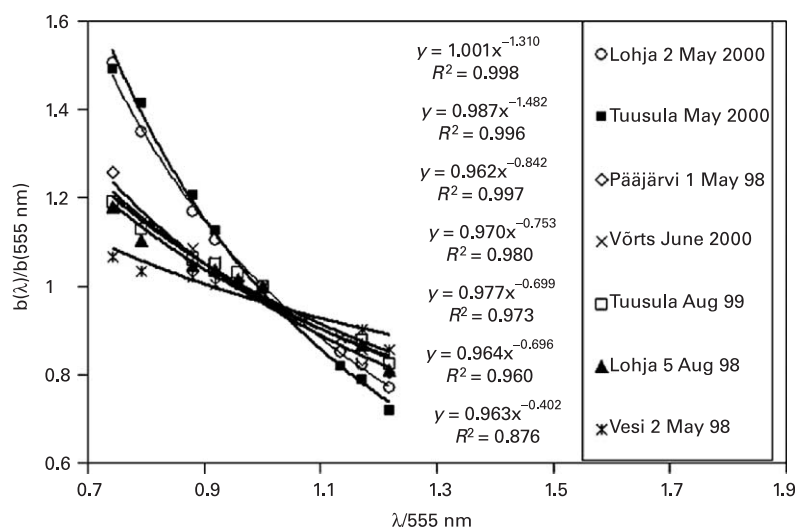


Figure 6 The spectra, shown in Figure 5, are normalized to $\lambda = 555$ nm. The power function trendlines and corresponding regression formulas are also presented

of the concentrations of OAS on p_b . The first was not an easy task, because for some lakes we had only 4–5 measurement series. Despite this, in five lakes we found distinguishable differences between p_b averaged for May/June and for August (Figure 7). The early summer values are rather variable, from 0.44–2.1, but in August p_b varies only from 0.33–0.66. Averaged for each of the remaining lakes p_b is presented in Figure 8 (seasonal change was not found). Most of these results are rather close to the value 0.8. Gallegos *et al.* (2005) showed that p_b can vary widely within and between years: there appeared to be a trend characterized by relatively high values in early spring soon after the break-up of ice, declines during the bloom of *Prorocentrum minimum*, followed by a steady rise to a late summer peak. The reason why the wavelength dependence of the scattering coefficient is larger in spring than in late summer could be the different size and type of particles in water, which can have different scattering properties (including the spectral distribution of b). For the conclusive analysis a large dataset is necessary.

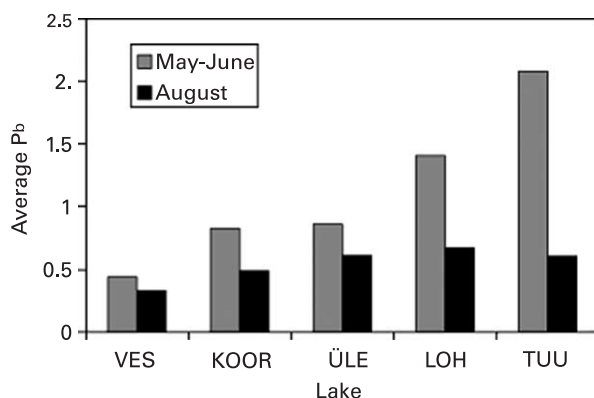


Figure 7 Averaged values of the slope p_b separately for May/June and August in five lakes: L. Vesijärvi, L. Koorküla Valgjärv, L. Ülemiste, L. Lohjanjärvi and L. Tuusulanjärvi. The standard deviations of p_b were correspondingly 0.054, 0.119, 0.102, 0.093 and 0.29 (May/June) and 0.054, 0.028, 0.084, 0.173 and 0.097 (August)

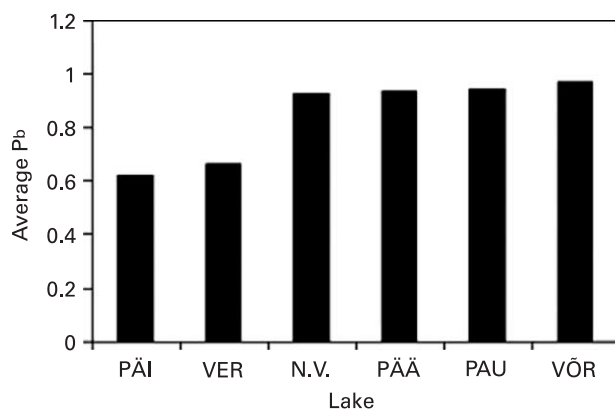


Figure 8 Averaged values of the slope p_b for L. Päijänne, L. Verevi, L. Nohipalu Valgjärv, L. Lammi Pääjärvi, L. Paukjärv and L. Vörtsjärv (all data). The standard deviations of p_b were correspondingly 0.13, 0.25, 0.30, 0.12, 0.15 and 0.22

It was rather problematic to assume that we can find the connections between the values of p_b and the concentrations of the OAS. We had no success in finding a good correlation between p_b and the concentration of some single OAS. However, it occurred that the multiple regression between p_b and three OAS jointly can give a rather high determination coefficient. To predict this slope we used the Multiple Linear Regression module of STATISTICA 6.0 (StatSoft Inc. 2001) including the measured OAS values as well as their pairwise products ($C_{chl}C_s$, $C_{chl}c_f^*(380\text{ nm})$ and $C_s c_f^*(380\text{ nm})$) in the analysis. Forward stepwise method was applied to select the best fitting model. The regression formula obtained is the following:

$$p_b = 0.7964 + 0.00964 C_s c_f^*(380) - 0.0453 C_s - 0.0124 C_{chl} \quad (13)$$

The statistical parameters of this regression were: $N = 73$, $R^2 = 0.668$, $R^2(\text{adjusted}) = 0.655$, st. error of estimate = 0.259, $p < 0.000001$, with all variables and the intercept being highly significant ($p < 0.001$). The product $C_s c_f^*(380)$ had the strongest impact on the slope (beta = 1.49) followed by single OAS C_s and C_{chl} (corresponding betas -0.729 and -0.395). The comparison of $p_b(\text{meas})$ and $p_b(\text{regr})$ is presented in Figure 9.

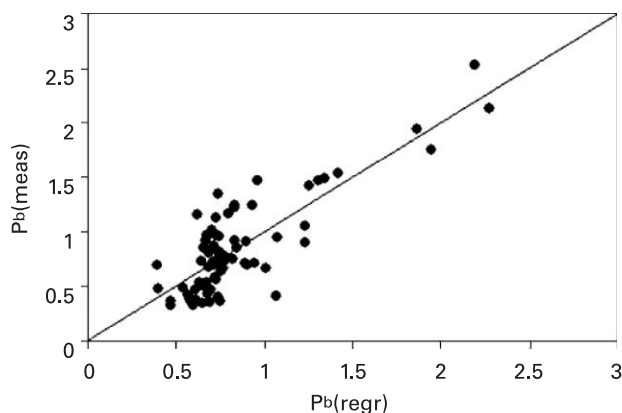


Figure 9 Comparison of p_b values, derived from ac-9 measurements and calculated by regression formula (equation (13)) ($N = 73$, $R^2(\text{adjusted}) = 0.655$, st. error = 0.259, $\rho < 0.000001$)

These results show that, to some extent, the slope of the scattering coefficient spectrum depends all at once on the concentrations of three OAS.

Conclusions

The spectra of specific absorption coefficient of tripton, $a'_t(\lambda)$, had the slope (t) varying between $0.0060\text{--}0.0109\text{ nm}^{-1}$, which is a little lower in comparison with the data by other authors ($0.006\text{--}0.016\text{ nm}^{-1}$). We could not find any correlation between the values of specific absorption coefficient $a'_t(532)$ and the concentration of tripton (C_t), but we found a rather good relationship between $a'_t(532)$ and the slope t . There were earlier data for $a'_t(400)$, obtained by Paavel (2004) in three Swedish and Estonian lakes, showing the variability between $0.11\text{--}0.20\text{ L mg}^{-1}\text{ m}^{-1}$. We could estimate $a'_t(400)$ only by extrapolation (using trendlines) and we got the values between $0.050\text{--}0.176\text{ L mg}^{-1}\text{ m}^{-1}$. The reasons of this variability can be the influence of different composition of tripton and also some seasonal changes. Our results of determining the inherent optical properties of lakes (including specific absorption coefficient of tripton) could be useful for elaborating the algorithms of optical remote sensing models.

The contributions (ctr) of different water constituents to total absorption coefficient changed from lake to lake, depending strongly on wavelength. In the narrow waveband centered at 440 nm, the averaged values of these contributions varied in the following way: ctr(a_{ph}) from 3.2% to 13%, ctr(a_{CDOM}) from 56% to 90%, ctr(a_w) from 0.3% to 2.1% and ctr(a_t) (calculated as residual on the basis of the other data) from 5.6% to 36%. At the wavelength 676 nm the corresponding values were 8.1% to 35%, 1.6% to 11%, 39% to 82% and 6.0% to 27%. The proportion of the total scattering coefficient in the total attenuation coefficient also depended on wavelength and varied from lake to lake (e.g. in eutrophic L. Vörtsjärvi the ratio b_{PAR}/c_{PAR} is 84%, but in L. Lammi Pääjärvi (rich in yellow substance) it was only 38%).

The values of the slope of scattering coefficient spectra (p_b) varied in a large range, being between 0.32–2.53, and the average value was 0.847. Note that in the publications of many authors the value $p_b = 0.8$ is often used in practice for lake waters. Comparing the results obtained in May/June and in August we found that in five lakes there is a rather marked seasonal dependence of p_b , but for the other six lakes this kind of change was not found. We had no success in finding a good correlation between p_b and the concentration of some single OAS. However the multiple regression between p_b and three OAS jointly gave a rather high

determination coefficient ($R^2(\text{adjusted}) = 0.655$, st. error = 0.259, $p < 0.000001$ (the Multiple Linear Regression module of STATISTICA 6.0 was used).

Further investigations on the basis of a larger dataset, describing the seasonal variation of parameters and the corresponding contributions of OAS to total absorption and attenuation coefficients, are obviously necessary. One of their purposes should be to separate the contributions of living phytoplankton, tripton and CDOM in the formation of total scattering coefficient, which is not done in the present study. Additional data on the specific absorption coefficient of tripton as well as on the scattering/backscattering coefficient spectra are needed for testing and improving the remote sensing reflectance models.

Acknowledgements

The authors are indebted to Peeter Nõges for help in the statistical analysis of our data. We are grateful also to the Estonian Science Foundation (grant 5594), to the Academy of Finland, to the University of Helsinki, and to the UT Estonian Marine Institute for financial support of this investigation.

References

- Aas, E. (2000). Spectral slope of yellow substance: problems caused by small particles. In: *Proc. XV Conference of Ocean Optics, Monaco, 14–16 October 2000*. Office Naval Res., USA (CD-ROM).
- Ahn, Y.H., Bricaud, A. and Morel, A. (1992). Light backscattering efficiency and related properties of some phytoplankters. *Deep-Sea Res.*, **39**, 1835–1855.
- Arst, H. (2003). *Optical Properties and Remote Sensing of Multicomponental Water Bodies*, Springer, Praxis-Publishing, Chichester.
- Arst, H., Erm, A., Reinart, A., Sipelgas, L. and Herlevi, A. (2002). Calculating irradiance penetration into water bodies from the measured beam attenuation coefficient II: application of improved model to different types of lakes. *Nordic Hydrol.*, **33**(2), 207–226.
- Baker, K.S. and Smith, R.C. (1982). Bio-optical classification and model of natural waters. *Limnol. Oceanogr.*, **27**, 500–509.
- Belzile, C., Vincent, W.F., Howard-Williams, C., Hawes, I., James, M.R., Kumagai, M. and Roesler, C.S. (2004). Relationship between spectral properties and optically active substances in a clear oligotrophic lake. *Water Res. Res.* **40**, W12512, DOI:10.1029/2004WR003090.
- Bricaud, A. and Stramski, D. (1990). Spectral absorption coefficients of living phytoplankton and nonalgal biogenic matter: a comparison between the Peru upwelling area and the Sargasso Sea. *Limnol. Oceanogr.*, **35**, 562–583.
- Bricaud, A., Babin, M., Morel, A. and Claustre, H. (1995). Variability in the chlorophyll-specific absorption coefficients of natural phytoplankton: analysis and parametrization. *J. Geophys. Res.*, **100**, 13 321–13 332.
- Bukata, R.P., Jerome, J.H., Bruton, J.E. and Jain, S.C. (1979). Determination of inherent optical properties of Lake Ontario coastal waters. *Appl. Opt.*, **18**, 3926–3932.
- Carlson, R.E. (1977). Trophic state index. *Limnol. Oceanogr.*, **22**(2), 361–369.
- Chekhin, L.P. (1987). *Light Regime in the Water Bodies*. Karelia Section of the Academy of Sciences USSR, Petrozavodsk (in Russian).
- Darecki, M., Weeks, A., Sagan, S., Kowalczyk, P. and Kaczmarek, S. (2003). Optical characteristics of two contrasting Case 2 waters and their influence on remote sensing algorithms. *Cont. Shelf Res.*, **23**, 237–250.
- Dekker, A.G. (1993). *Detection of Optical Water Quality Parameters for Eutrophic Waters by High Resolution Remote Sensing*. PhD thesis, Proefschrift Vrije Universiteit, Amsterdam.
- Eloranta, P. (1978). Light penetration in different types of lakes in Central Finland. *Holarctic Ecol.*, **1**, 362–366.
- Francisco, P.W. and McCormick, N.J. (1994). Chlorophyll concentration effects on asymptotic optical attenuation. *Limnol. Oceanogr.*, **39**, 1195–1205.
- Gallegos, C.L., Jordan, T.E., Hines, A.H. and Weller, D.E. (2005). Temporal variability of optical properties in shallow eutrophic estuary: seasonal and interannual variability. *Estuarine Coastal Shelf Sci.*, **64**, 156–170.
- Gordon, H. and Morel, A. (1983). *Remote Assessment of Ocean Colour for Interpretation of Satellite Visible Imagery. A Review. Lecture Notes on Coastal and Estuarine Models*, Springer-Verlag, Berlin.

- Gould, R.W., Jr. and Arnone, R.A. (1998). Three-dimensional modeling of inherent optical properties in a coastal environment coupling ocean color imagery and in situ measurements. *J. Remote Sens.*, **19**, 2141–2159.
- Halturin, V.J., Suietin, V.S. and Shutikov, S.P. (1983). *Tables of the Hydrooptical Characteristics for Open Ocean Waters 1* (in Russian), Acad. Sci. Ukrainian SSR, Marine Hydrophysics Institute, Sevastopol.
- Heinonen, P. and Herve, S. (1987). Water quality classification of inland waters in Finland. *Aqua Fennica*, **17**(2), 147–156.
- Herlevi, A. (2002a). A study of scattering, backscattering and a hyperspectral reflectance model for boreal waters. *Geophysica*, **38**, 113–132.
- Herlevi, A. (2002b). *Inherent and Apparent Optical Properties in Relation to Water Quality in Nordic Waters*. Academic dissertation in Geophysics. Report Series in Geophysics, No. 45. University of Helsinki, Finland.
- Herlevi, A., Virta, A., Arst, H. and Erm, A. (1999). Results of light absorption/attenuation measurements in Finnish and Estonian lakes in summer 1997. *Proc. Estonian Acad. Sci. Biol. Ecol.*, **48**(1), 46–62.
- Hoogenboom, J. and Dekker, A.G. (1997). Simulation of the medium-resolution imaging spectrometer (MERIS) performance for detecting chlorophyll-a over turbid inland waters. *Proc. SPIE*, **2963**, 440–447.
- Iturriaga, R. and Siegel, D.A. (1988). Discrimination of the absorption properties of marine particulates using the microphotometric technique. *SPIE Ocean Optics IX 925*.
- Jerlov, N.G. (1974). *Optical Aspects of Oceanography*, Academic, New York.
- Jerlov, N.G. (1976). *Marine Optics. Elsevier Oceanography Series 5*, Elsevier, Amsterdam.
- Jupp, D.L.B., Kirk, J.T.O. and Harris, G.P. (1994). Detection, identification and mapping of cyanobacteria - using remote sensing to measure the optical quality of turbid inland waters. *Aust. J. Mar. Freshwater Res.*, **45**, 801–828.
- Kallio, K. (1999). Absorption properties of dissolved organic matter in Finnish lakes. *Proc. Estonian Acad. Sci. Biol. Ecol.*, **48**, 75–83.
- Kirk, J.T.O. (1980). Spectral absorption properties of natural waters: contribution of the soluble and particulate fraction to light absorption in some inland waters of south-eastern Australia. *Aust. Mar. Freshwater Res.*, **31**, 287–296.
- Kirk, J.T.O. (1981). Estimation of the scattering coefficient of natural waters using underwater irradiance measurements. *Aust. Mar. Freshwater Res.*, **32**, 533–539.
- Kirk, J.T.O. (1996). *Light and Photosynthesis in Aquatic Ecosystems*, Cambridge University Press, Cambridge.
- Kishino, M., Takahashi, M., Okami, N. and Ichimura, S. (1985). Estimation of the spectral absorption coefficients of phytoplankton in the sea. *Bull. Mar. Sci.*, **37**(2), 634–642.
- Koenings, J.P. and Edmundson, J.A. (1991). Secchi disk and photometer estimates of light regimes in Alaskan lakes: effects of yellow colour and turbidity. *Limnol. Oceanogr.*, **36**(1), 91–105.
- Kopelevich, O.V. (1983). A few-parameter model of the optical properties of seawater (in Russian). In A. Monin (Ed.), *Optics of the Ocean*, Nauka, Moscow, 208–234.
- Koponen, S., Pulliainen, J., Kallio, K. and Hallikainen, M. (2002). Lake water quality classification with airborne hyperspectral spectrometer and simulated MERIS data. *J. Remote Sens. Environ.*, **79**, 51–59.
- Kutser, T. (1997). *Estimation of Water Quality in Turbid Inland and Coastal Waters by Passive Optical Remote Sensing*. PhD thesis, Tartu University, Tartu.
- Kutser, T., Herlevi, A., Kallio, K. and Arst, H. (2001). A hyperspectral model for interpretation of passive optical remote sensing data from turbid lakes. *Sci. Total Environ.*, **268**, 47–58.
- Lindell, T., Pierson, D., Premazzi, G. and Zilioli, E. (1999). *Manual for Monitoring European Lakes Using Remote Sensing Techniques*, European Communities, Luxembourg.
- Lorenzen, C.J. (1967). Determination of chlorophyll and phaeopigments: spectrophotometric equations. *Limnol. Oceanogr.*, **12**, 343–346.
- Mäekivi, S. and Arst, H. (1996). Estimation of the concentration of yellow substance in natural waters by beam attenuation coefficient spectra. *Proc. Estonian Acad. Sci. Ecol.*, **6**, 108–123.
- Mäemets, A. (1971). *Estonian Limnology*, Valgus, Tallinn.
- Mäemets, A. (1977). *Lakes of Estonian SSR and Their Protection*. Valgus, Tallinn (in Estonian).
- McKee, D., Cunningham, A. and Jones, K.J. (2002). Optical and hydrographic consequences of freshwater runoff during spring phytoplankton growth in a Scottish fjord. *J. Plankton Res.*, **24**, 1163–1171.
- Morel, A. (1980). In-water and remote measurements of color. *Boundary Layer Meteorol.*, **18**, 177–201.
- Morel, A. and Prieur, L. (1977). Analysis of variations in ocean color. *Limnol. Oceanogr.*, **22**, 709–722.

- Nelson, J.R. and Robertson, C.Y. (1993). Detrital spectral absorption: laboratory studies of visible light effects on phytodetritus absorption, bacterial spectral signal, and comparison to field measurements. *J. Mar. Res.*, **51**, 181–207.
- Ott, I. and Kõiv, T. (1999). *Estonian Small Lakes: Special Features and Changes*, EV Keskkonnaministeeriumi Info-ja Tehnokeskus, Tallinn.
- Paavel, B. (2004). *Optical Properties of Lake Peipsi Waters*. MSc thesis, Tartu University, Tartu (in Estonian).
- Phillips, D.M. and Kirk, J.T.O. (1984). Study of the spectral variation of absorption and scattering in some Australian coastal waters. *Aust. Mar. Freshwater Res.*, **35**, 635–644.
- Pope, R.M. and Fry, E.S. (1997). Absorption spectrum (380–700 nm) of pure water, II. Integrating cavity measurements. *Appl. Opt.*, **36**, 8710–8723.
- Prieur, L. and Sathyendranath, S. (1981). An optical classification of coastal and oceanic water based on the specific absorption curves of phytoplankton pigments, dissolved organic matter, and other particulate materials. *Limnol. Oceanogr.*, **26**, 671–689.
- Reinart, A. and Herlevi, A. (1999). Diffuse attenuation coefficient in some Estonian and Finnish lakes. *Proc. Estonian Acad. Sci., Biology, Ecology*, **48**(4), 267–283.
- Reinart, A., Herlevi, A., Arst, H. and Sipelgas, L. (2003). Preliminary optical classification of lakes and coastal waters in Estonia and South Finland. *J. Sea Res.*, **49**, 357–366.
- Reinart, A., Paavel, B., Pierson, D. and Strömbeck, N. (2004). Inherent and apparent properties of Lake Peipsi, Estonia. *Boreal Environ. Res.*, **9**, 429–445.
- Roesler, C.S., Perry, M.J. and Carder, K.L. (1989). Modeling in situ phytoplankton absorption from total absorption spectra in productive inland marine waters. *Limnol. Oceanogr.*, **34**, 1510–1524.
- Sathyendranath, S., Prieur, L. and Morel, A. (1989). A three-component model of ocean colour and its application to remote sensing of phytoplankton pigments in coastal waters. *J. Remote Sensing*, **10**(8), 1373–1394.
- Sipelgas, L., Arst, H., Kallio, K., Erm, A., Oja, P. and Soomere, T. (2003). Optical properties of dissolved organic matter in Finnish and Estonian lakes. *Nordic Hydrol.*, **34**(4), 361–386.
- Strömbeck, N. and Pierson, D.C. (2001). The effects of variability in the inherent optical properties on estimations of chlorophyll a by remote sensing in Swedish freshwaters. *Sci. Total Environ.*, **268**, 123–137.
- Tassan, S. and Ferrari, G.M. (1995). An alternative approach to absorption measurements of aquatic particles retained on filters. *Limnol. Oceanogr.*, **40**, 1358–1368.
- Vertucci, F.A. and Likens, G.E. (1989). Spectral reflectance and water quality of Adirondack mountain region lakes. *Limnol. Oceanogr.*, **34**, 1656–1672.
- Vollenweider, R.A. and Kerekes, J.J. (1982). *Eutrophication of Waters: Monitoring, Assessment and Control*, OECD, Paris.
- Vuoristo, H. (1998). Water quality classification of Finnish inland waters. *Europ. Water Manage.*, **1**(6), 35–41.
- Wallin, M. and Fölster, J. (2002). WFD typologies in the Nordic countries. In M. Ruoppa and K. Karttunen (Eds.), *Typology and Ecological Classification of Lakes and Rivers*, Nordic Council of Ministers, Copenhagen. pp. 14–17.
- WET Labs. Inc. (1995). *AC-9 User's Manual, Version 1.0*, WET Labs. Inc., Philomath, OR.
- Zilioli, E. and Brivio, P.A. (1997). The satellite derived optical information for the comparative assessment of lacustrine water quality. *Sci. Total Environ.*, **196**, 229–245.