BOREAL ENVIRONMENT RESEARCH 9: 429–445 ISSN 1239-6095
Helsinki 22 October 2004

Inherent and apparent optical properties of Lake Peipsi, Estonia

Anu Reinart[1)]*, Birgot Paavel[2)], Don Pierson[1)] and Niklas Strömbeck[1)]

[1)] *Uppsala University, Evolutionary Biology Centre, Department of Limnology, Norbyvägen 20, SE-752 36 Uppsala, Sweden (*e-mail: anu.reinart@ebc.uu.se)*
[2)] *Tartu University, Estonian Marine Institute, Mäealuse 10A, 12618 Tallinn, Estonia*

Reinart, A., Paavel, B., Pierson, D. & Strömbeck, N. 2004: Inherent and apparent optical properties of Lake Peipsi, Estonia. *Boreal Env. Res.* 9: 429–445.

Lake Peipsi on the border of Estonia and Russia is a large, shallow, biologically very productive lake. It is bordered by many wetland areas. On the basis of underwater radiation measurements and analyses of water samples we have shown that the optical properties of L. Peipsi are very variable both spatially and temporally, covering a large range of water types previously classified in Estonian and Finnish lakes. Inherent and apparent optical properties are compared with those of the two other large lakes, Vänern and Vättern in Sweden. Lake Peipsi has higher concentrations of optically active substances, which are known to influence satellite measurements and underwater light field. Therefore, the lake complements the continuum between L. Vänern and L. Vättern in terms of water optical properties and adds new data into the database about optical properties of turbid and humic lakes. Results obtained here can be used in bio-optical modeling to develop algorithms for remote sensing and calculations of underwater light field.

Introduction

The light penetrating into water is subject to absorption and scattering, forming an underwater light field and light scattered back to the space. Light conditions in water are important for primary production, species composition of phytoplankton and the depth distribution of submerged phytoplankton; but also in the application of optical measurement systems in monitoring water quality and interpretation of remote sensing images. The optically active substances (OAS: suspended particles and dissolved organic matter) determine the penetration of light to the water and consequently the light available for bio-chemical processes inside of water and detectable by optical instruments or remote sensors. Matter suspended in water consists of live organic material (phytoplankton), dead organic (*detritus*) and inorganic material.

Lakes are multicomponent waters where OAS may vary in type and amount within short distances and time intervals, often at notably higher concentrations than those occurring in the open ocean (Dekker 1993, Kirk 1994, Herlevi 2002, Arst 2003). It is not only the concentrations that are important, but also how the components absorb and scatter light at different wavelengths. Absorption and scattering coefficients are called inherent optical properties (IOP) as they depend only on the medium, while optical properties depending also on the surrounding light field (diffuse attenuation and reflectance coefficients) are called apparent optical properties (AOP) (Mobley 1994).

Although optical studies have been mostly directed to open ocean waters, in recent years coastal and inland waters have received increasing attention because of their impact on human activities (IOCCG 2000). Technological progress has made spectral optical field instruments applicable for lake studies available. New satellite sensors with improved spatial, spectral and radiometric sensitivity (MODIS/Terra&Aqua http://modis.gsfc.nasa.gov/, MERIS/ENVISAT-1 http://envisat.esa.int/, Hyperion and ALI/EO-1 http://eo1.usgs.gov/, etc.) produce images over Nordic water bodies many times per day, increasing the chances to catch a cloud-free moment.

In order to complement traditional water sampling, bio-optical models could be used to create synthetic data sets, which can later be used in the characterization of light climate in water (Morel *et al*. 2002), to elaborate remote sensing algorithms (Jupp *et al*. 1994, Pierson and Strömbeck 2000) and to be used in general ecological models (Xu *et al*. 2001). This approach is especially important for water bodies whose sampling may be hampered by large distances, unreachable areas, difficult water conditions, etc. However, at the present stage no general bio-optical model is available for optically complex waters — semi-empirical models need to be parameterized and validated using *in situ* data (Dekker 1993, Pierson and Strömbeck 2000).

Numerous optical studies were carried out on small Finnish and Estonian lakes (Arst *et al*. 1999, 2003, Kutser *et al*. 2001, Herlevi 2002, Reinart *et al*. 2003), and optical properties in many Swedish lakes were investigated in detail (Pierson and Strömbeck 2000, Strömbeck and Pierson 2001, Herlevi 2002). Much less data are available for L. Peipsi, which is the fourth largest lake in Europe after Ladoga and Onega in Russia, and Vänern in Sweden (Table 1). Attempts to relate water quality in L. Peipsi with remote sensing signals (Arst and Kutser 1994, Kutser *et al*. 1995) gave rather promising results for estimating chlorophyll *a* and water transparency. However, the need for gathering additional data during different seasons and under different conditions was also pointed out.

The purpose of our study was to collect data about optical properties of L. Peipsi and to compare these with available data from other large lakes to specify the peculiarities of L. Peipsi. The present paper concentrates on the description of optical properties and components affecting the underwater light field and reflectance in this lake. Inherent and apparent optical properties of L. Peipsi are compared with those of two other large European lakes, Vänern and Vättern in Sweden. The results obtained will be used for detailing the direction of further measurements, designing a bio-optical model specific for L. Peipsi, development of algorithms for remote sensing applications and calculations of the underwater light field. Comparison with other lakes helps to generalize results and extend the already existing bio-optical models, thereby enhancing the understanding about optical properties of turbid and humic water bodies.

Description of L. Peipsi and its water transparency

Lake Peipsi on the border of Estonia and Russia is a large shallow lake (Table 1). The nutrient load by the Estonian Suur-Emajõgi and the Russian Velikaya rivers has caused strong eutrophication of the lake. About 240 inflows enter L. Peipsi and there is only one outflow, the River

Table 1. Morphometric data and parameters relevant to the studied lakes (Nõges 2001, Kvarnäs 2001).

Parameter	L. Peipsi	L. Vänern	L. Vättern
Area (km^2)	3555	5648	1856
Mean depth (m)	7	27	40
Maximum depth (m)	15	106	128
[1]Chlorophyll *a* ($mg\ m^{-3}$)	1.8–95	0.2–10.6	< 0.1–5.2
[1]Secchi depth (m)	0.4–4.8	2.0–7.9	6.5–15.0

[1]data from long time monitoring (http://www.seiremonitor.ee/, http://info1.ma.slu.se/).

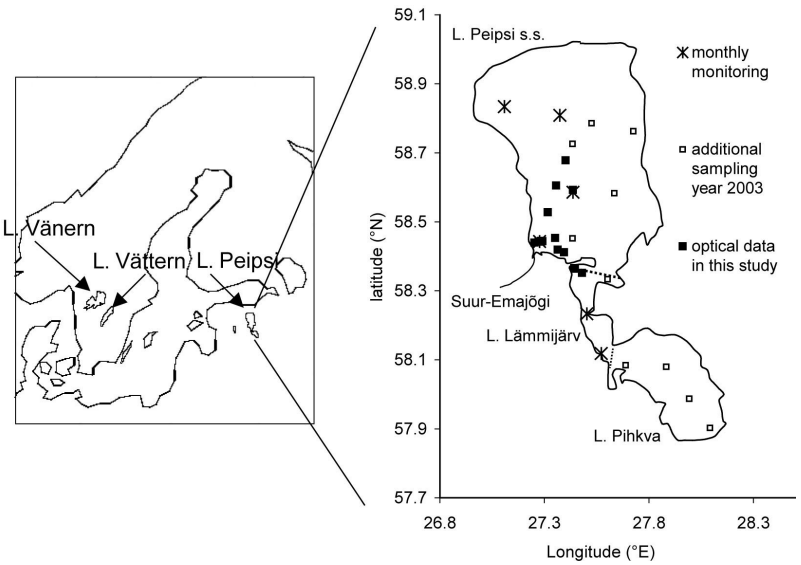

Fig. 1. Subdivision of Lake Peipsi into three parts and location in Europe. Points show locations of optical measurements and regular state monitoring (http://www.seiremonitor.ee).

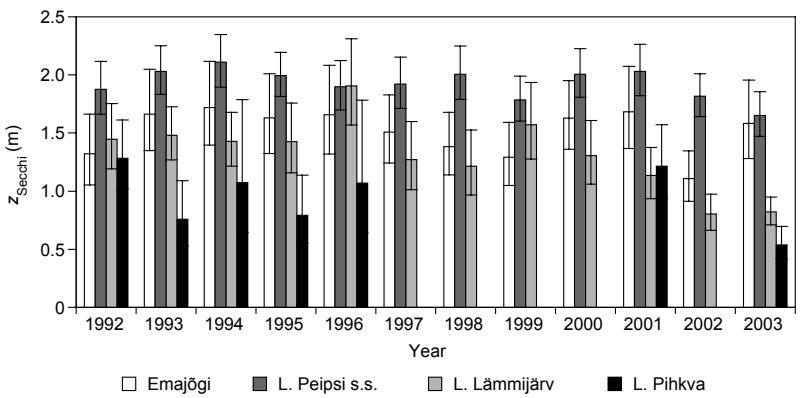

Fig. 2. Long-term changes (1992–2003) of water transparency by Secchi disc (mean ± SD) in three parts of Lake Peipsi (L. Peipsi s.s., Lämmijärv, L. Pihkva) and close to the inflow of the Suur-Emajõgi.

Narva, carrying water from L. Peipsi to the Gulf of Finland. The Estonian part of L. Peipsi constitutes 89% of the surface freshwater in Estonia and yields 95% of the freshwater fish catch of the country. Lake Peipsi has been considered a potential source of water supply for northeast Estonia and the Estonian capital Tallinn. Besides the fact that the water resources of L. Peipsi can be regarded as practically inexhaustible for Estonia, the lake is also of great importance for fishing, recreation and traffic (Nõges 2001). Due to its large surface area and high content of dissolved organic matter in water this lake may contribute significantly to the global flux of CO_2 into the atmosphere. Because of its shallowness and large surface area it may be also sensitive to possible climate changes.

Lake Peipsi consists of three parts (Fig. 1): (1) the northernmost, largest and deepest (medium depth 8.3 m) L. Peipsi *sensu stricto* (L. Peipsi s.s.) is unstratified and eutrophic; (2) the southernmost part L. Pihkva is shallower (5.3 m) and very hypertrophic and (3) narrow L. Lämmijärv (2.3 m), connecting the first two, is close to hypertrophic (Nõges 2001).

Water transparency (z_{Secchi}) in L. Peipsi has been monitored since 1950 using standard white Secchi disc. Water transparency varies in a broad range (0.3–8.8 m) (Nõges 2001; http://www.seiremonitor.ee). The clearest water is observed in the northwestern corner of L. Peipsi s.s., Secchi depth is lower in Lämmijärv, and the lowest in L. Pihkva (data for the period 1992–2003 are shown in Fig. 2). The Suur-Emajõgi

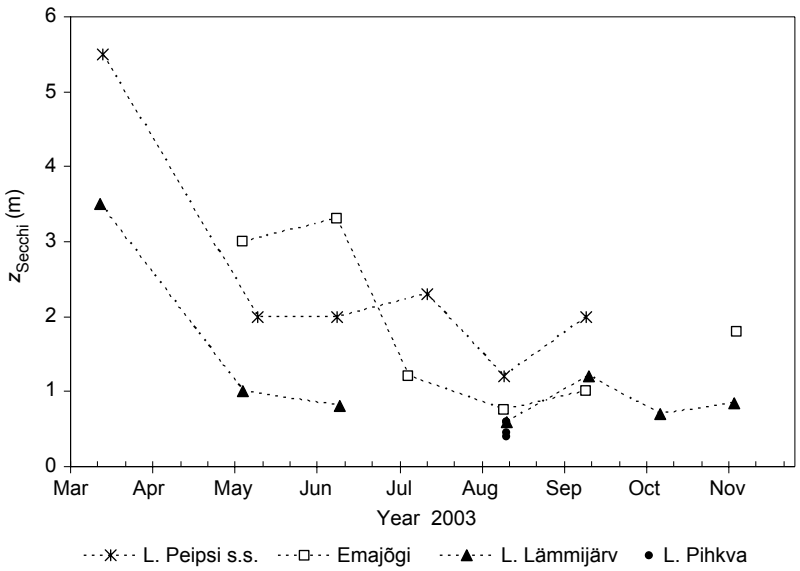

Fig. 3. Seasonal dynamics of water transparency (Secchi disc) in different parts of Lake Peipsi in 2003. (L. Pihkva was visited only once).

brings large amounts of humic matter into the lake from the surrounding bog areas, which makes the water close to the river inflow brownish and usually less transparent than the water in the deeper parts of L. Peipsi s.s. (Reinart *et al*. 2004). According to Lindpere *et al*. (1991) in L. Peipsi s.s. z_{Secchi} depends primarily on the development of phytoplankton, while in lakes Lämmijärv and Pihkva it depends also on the amount of humic substances.

Seasonal variation in z_{Secchi} is different in the three lake parts (Fig. 3) and has undergone changes over the years. According to earlier studies, z_{Secchi} had been the highest just before the ice cover began to thaw, and decreased thereafter towards autumn (Nõges 2001) having the lowest value in L. Peipsi s.s. in the first decade of September. Since 1950 the minimum shifted to early July in the 1970s and in the year 2003 it was in early August (Fig. 3). In the mouth of the Suur-Emajõgi changes in z_{Secchi} during summer are smaller than in L. Peipsi s.s. or Lämmijärv (in 2003 L. Pihkva was visited only once).

Regarding its transparency, the water of L. Peipsi is within the limits measured earlier in Estonia. The values of z_{Secchi} found earlier in Estonian and Finnish lakes and used for the elaboration of an optical classification (Reinart *et al*. 2003) vary from 6.8 m in oligotrophic Nohipalu Valgejärv down to 0.2 m in Võrtsjärv, which was unusually turbid because of extremely low water level in 1998.

It is of interest to compare L. Peipsi with other large lakes nearby. Unfortunately we were unable to receive suitable enough data about lakes Ladoga and Onega in Russia. Lakes Vänern and Vättern in Sweden often occur on the same satellite images with L. Peipsi and rather similar field research campaigns were carried out on the three lakes. The largest Swedish lake, L. Vänern, with an area of 5648 km^2 is the third largest lake in Europe; the second largest in Sweden, L. Vättern, is the fifth largest lake in Europe (Kvarnäs 2001) (Table 1). The water quality in L. Vänern is stated as oligotrophic. Ultra-oligotrophic conditions prevail in the status of L. Vättern (Willen 2001). These are clear water lakes with low concentrations of OAS. These three lakes represent a wide range of optical variability in water bodies. As compared with the two Swedish lakes, L. Peipsi has a higher concentrations of OAS. The measured water transparency by Secchi depth is the highest in L. Vättern, 6.5–15.0 m, lower in L. Vänern (2.0–7.9 m) and the lowest in L. Peipsi (Table 1). Therefore, the lake complements the continuum between Vänern and Vättern both spatially and in terms of water optical properties.

Material and methods

Water sample determinations

Measurements of optical properties of L. Peipsi water were carried out on 11–18, 26 June and 18 Aug 2003, at 10:00–16:00 local time. The water samples were collected from the same points where *in situ* optical measurements were carried out (all together 16 series). The same water analyses protocol was applied for 94 samples collected additionally during monthly state monitoring cruises in the years 2001–2003 (Fig. 1) to get larger temporal and spatial coverage.

Water samples were collected from the surface layer (0.2 m) with a standard water sampler and stored in dark and cold for less than 7 hours before filtering. During sampling, transparency was also measured with a Secchi disc. Suggestions for methods used for remote sensing of lakes are given by Lindell *et al*. (1999). For chlorophyll concentrations, 0.5–1.0 liters of water was filtered through Whatman GF/F filters, and the chlorophyll *a* + pheophytin *a* concentration (C_{Chl}) in ethanol extracts of filters was measured with a spectrophotometer, according to ISO 10260 (1992 (E)). The reproducibility variation coefficient of this method is ~11%. The concentration of suspended matter (C_{TSS}) was measured gravimetrically (precision of weights 0.01 mg) after filtration of a measured volume of water through pre-weighed and pre-combusted Whatman GF/F filters; the inorganic fraction (C_{SPIM}) was measured after combustion at 550 °C for 30 minutes. The organic fraction (C_{SPOM}) was determined by subtracting C_{SPIM} from C_{TSS}.

Absorption by colored dissolved organic matter (CDOM, called also 'yellow substance') (a_{ys}) was measured with a spectrometer (PERKIN ELMER Lambda 40 UV/VIS, in the range 300–900 nm) in water filtered through Millipore 0.2 μm filter, in a 10-cm cuvette against distilled water and corrected for residual scattering according to Davis-Colley and Vant (1987), who estimated the accuracy of the method to be better than 0.017 m^{-1}. Absorption spectra were approximated by a linear regression between the logarithm of $a_{ys}(\lambda)$ and the wavelength 400–550 nm and expressed by the formula (Bricaud *et al*. 1981):

$$a_{ys}(\lambda) = a_{ys}(400)e^{-S_{ys}(\lambda-400)} \quad (1)$$

where $a_{ys}(400)$ is absorption at 400 nm and S_{ys} is the shape factor of the spectrum.

The total particulate absorption, $a_p(\lambda)$, was measured with a spectrometer (PERKIN ELMER Lambda 40 UV/VIS in the range 400–750 nm) with the Whatman GF/F filter pad technique (summary of the method is given in Lindell *et al*. 1999) and using later depigmentation with sodium hypochloride (Tassan and Ferrary 1995), which separates phytoplankton pigment absorption, $a_{ph}(\lambda)$, and the absorption by the rest of particles, $a_t(\lambda)$ (detritus and inorganic particles, called together tripton). If it is assumed that inorganic particles do not significantly absorb light, only detritus absorption is left. Detrital absorptions, $a_d(\lambda)$, were calculated similarly to $a_{ys}(\lambda)$:

$$a_d(\lambda) = a_d(\lambda_0)e^{-S_d(\lambda-\lambda_0)} \quad (2)$$

where the reference wavelength is 400 nm and S_d is the shape factor. This method is justified for estimation of detrital absorption in lakes Vänern and Vättern where the concentration of inorganic particles is very small (Table 2). In L. Peipsi, large amounts of inorganic particles are present in the water column and they may contribute to absorption. However, there is no good way to separate them and we assume they do not absorb significantly ($a_i \approx 0$) but mainly scatter light. Tripton absorption, $a_t(\lambda)$, was calculated using Eq. 2 with the shape factor S_t. Presence of inorganic particles in L. Peipsi samples must be kept in mind, however, when comparing data presented in Table 3.

Table 2. Mean and standard deviation values for parameters showing concentrations of optically active substances in water during optical measurements.

	L. Peipsi $N = 94$	L. Vänern[1] $N = 48$	L. Vättern[1] $N = 22$
C_{Chl} (mg m^{-3})	27.9 ± 17.1	3.9 ± 1.2	2.0 ± 0.5
C_{TSS} (g m^{-3})	8.5 ± 5.9	1.2 ± 0.4	0.6 ± 0.6
C_{SPIM} (g m^{-3})	3.9 ± 6.1	0.6 ± 0.2	0.2 ± 0.1
C_{SPOM} (g m^{-3})	5.3 ± 4.0	0.6 ± 0.4	0.3 ± 0.2
$a_{ys}(400)$ (m^{-1})	2.6 ± 1.22	2.51 ± 1.05	0.52 ± 0.19
z_{Secchi} (m)	1.7 ± 0.7	4.0 ± 0.6	9.0 ± 0.4

[1]Strömbeck (2001).

The specific absorption coefficient of phytoplankton, $a_{ph}^*(\lambda)$, was calculated by dividing the measured $a_{ph}(\lambda)$ by C_{Chl}. The following power function (Bricaud *et al*. 1995)

$$a_{ph}^*(\lambda) = A(\lambda) C_{Chl}^{-B(\lambda)} \quad (3)$$

with positive wavelength-dependent parameters A and B is most appropriate for describing the relationship of $a_{ph}^*(\lambda)$ with C_{Chl}.

Total absorption was calculated as:

$$a(\lambda) = a_{ys}(\lambda) + a_p(\lambda) + a_w(\lambda) \quad (4)$$

All these components were measured as described above ($a_p = a_{ph} + a_d + a_i$ and $a_i \approx 0$), except for pure water (a_w), where the results from Pope and Fry (1997) were used.

The same methods were used to analyze data on lakes Vänern and Vättern collected during previous years (1999 and 2002) and published by Strömbeck (2001), Pierson and Strömbeck (2000) and Reinart *et al*. (2002). These data are shown in the present paper for comparison.

Radiometric measurements

HydroScat-6 (HOBILabs, Inc.) and two GER 1500 portable spectrometers (GER Corporation) (range ~350–1050 nm) in a waterproof box with a fiber optic cable and a cosine sensor were mounted on a frame together with depth, temperature and fluorescence sensors (C-Star transmissiometer and WetStar chlorophyll fluorometer (WETLabs, Inc.) (Strömbeck 2001, Pierson and Strömbeck 2000). All instruments were regularly calibrated. HydroScat-6 has spectral bands 442, 470, 510, 589, 620 and 671 nm (10 nm bandwidth). The error of HydroScat-6 measurements is smaller than 5×10^{-4} m^{-1}, and depth precision is 0.2 cm. C-Star transmissiometer measures beam attenuation coefficient at 660 nm (bandwidth 20 nm). WetStar chlorophyll fluorometer's dynamic range is 0.03–75 mg m^{-3}. GER spectrometer's wavelength repeatability is ±0.1 nm, and accuracy of radiometric calibration is ±4%–5% in the range 400–1000 nm. The sensitivity of GER 1500 is lowest in the blue region of the spectra (at 400 nm: 6.0 × 10–10 W cm^{-2} nm^{-1} sr^{-1}), therefore radiation measurements below 400 nm at depths > 1.5 m were not used.

The frame was lowered slowly through the water column and all instruments were logged continuously. For radiation measurements a second profiling was made at a fixed depth with 0.5–1.0 m step. This configuration was worked out for measurements in deep lakes such as Vänern and Vättern in Sweden (Strömbeck 2001). However, L. Peipsi is much shallower and it was not possible to go everywhere with a big ship necessary to lower this rather heavy frame. Therefore, additional measurements (13 series) with HydrosScat-6 and the same GER instruments in a hand-held mode were carried out from a boat.

At first incident irradiance (E_0) was estimated from the nadir measurement of a Spectralon diffuse reflectance plate (L_s) assuming Lambertian reflection ($E_0 = \pi L$). The water-leaving radiance, L_{wu}, was measured just below the water surface using a black tube to avoid surface reflection. Remote sensing reflectance (ratio of water-leaving radiance in the air, L_w, and incident irradiance) is calculated as (Mobley 1994):

Table 3. Absorption parameters of L. Peipsi as compared with lakes Vänern and Vättern in Sweden.

	L. Peipsi N = 16	L. Vänern[1] N = 48	L. Vättern[1] N = 22
$a_t(400)$ (m^{-1})	0.72 ± 0.50	0.14 ± 0.17	0.05 ± 0.02
$S_t(400–550)$ (nm^{-1})	0.012 ± 0.001	0.012 ± 0.001	0.014 ± 0.004
$a_{ys}(400)$ (m^{-1})	4.62 ± 2.75	2.51 ± 1.17	0.52 ± 0.13
$S_{ys}(400–550)$ (nm^{-1})	0.017 ± 0.001	0.014 ± 0.001	0.017 ± 0.007

[1]Strömbeck (2001), there symbols a_d and S_d are used instead of a_t and S_t, as absorption by inorganic particles was omitted in lakes Vänern and Vättern.

$$R_{rs}(\lambda) = \frac{L_w}{E_0} = \frac{L_{wu}}{\left[\frac{n^2}{(1-r)}\right]\pi L_s} = \frac{0.551 L_{wu}}{\pi L_s} \quad (5)$$

where n is the refraction index of water (1.333) and r stands for the Fresnel reflectance the for 0 degree angle of incidence (0.021).

Diffuse attenuation coefficient ($K_d(\lambda)$) is defined as (Mobley 1994):

$$K_d(\lambda) = -\frac{1}{E_d(z,\lambda)} \frac{\partial E_d(z,\lambda)}{\partial z} \quad (6)$$

where $E_d(z)$ is downwelling irradiance at depth z. We used the measured irradiances to estimate the depth (z) averaged spectral diffuse attenuation coefficient, $K_d(\lambda)$. For these calculations irradiance values at any depth (from the 0.5–2 m layer) are fitted by least squares to a straight line on a semilog plot, whose slope gives K_d. The values of R^2 for fit were always higher than 0.97.

Estimation of scattering and backscattering coefficients

The backscattering coefficient (b_b) was measured *in situ* with HydroScat-6. These measurements are sensitive to the attenuation of water, and this effect is strongest in humic waters. A correction procedure specially adapted for humic lake waters with variable amounts of inorganic and organic particles was proposed and tested for Swedish lakes and coastal waters by Strömbeck (2001) in addition to the correction suggested by HOBI Labs (2000). The method uses additional data, including all main absorbers (Eq. 4) and scatters (Eq. 7) as independent components as well as measurements of beam attenuation coefficient at 660 nm, $c(660)$.

To get estimates of spectral scattering and backscattering coefficients of different components in water, measurements and models were combined (Pierson and Strömbeck 2000, 2001), as there is no good way to separate the effects of organic and inorganic particles.

Total scattering can be portioned into three components:

$$b(\lambda) = b_t(\lambda) + b_{ph}(\lambda) + b_w(\lambda) \quad (7)$$

where the subscript t denotes nonchlorophyllous particles (tripton), ph phytoplankton cells and w pure water; dissolved organic matter is assumed not to scatter light.

Backscattering b_b, measured with HydroScat-6, is composed of the same three components:

$$b_b(\lambda) = b_{bt}(\lambda) + b_{bph}(\lambda) + 0.5 b_w(\lambda). \quad (8)$$

The ratio of b_b to b depends on the refraction index, size and shape of particles. For pure water b_b/b is 0.5 (Mobley 1994). There is very little information about scattering caused by detrital particles. As their size distribution may be comparable with inorganic particles but the refraction index is larger and they also absorb light, their scattering coefficient is about two times lower, and backscattering coefficient about ten times lower than those of inorganic particles (Stramski *et al.* 2001). Dekker (1993) estimated that the effect of detrital particles could be much smaller than the effect of mineral particles in turbid waters. However, peculiarities of detrital particles may be more important after a heavy bloom when phytoplankton cells degrade rapidly. We assume that in L. Peipsi in June and August phytoplankton and inorganic particles have a much greater scattering effect than detrital particles.

For correction of backscattering measurements, first the scattering caused by particles at 660 nm was calculated by subtracting the total absorption $a(660)$ and $b_w(660)$ (Pope and Fry 1997) from the measured $c(660)$.

$$b_t(660) + b_{ph}(660) = c(660) - b_w(660) - a(660). \quad (9)$$

As we had no direct measurements of scattering, several relationships from the literature were assumed to reflect the spectral behavior of the scattering coefficients of phytoplankton and inorganic particles. Those are given below.

Scattering at 550 nm can be estimated using the relationship by Dekker (1993) derived from measurements in mesotrophic and eutrophic lakes:

$$b_{ph}(550) = 0.173(\pm 0.122) C_{Chl} \quad (10)$$

In order to predict the spectral variation in

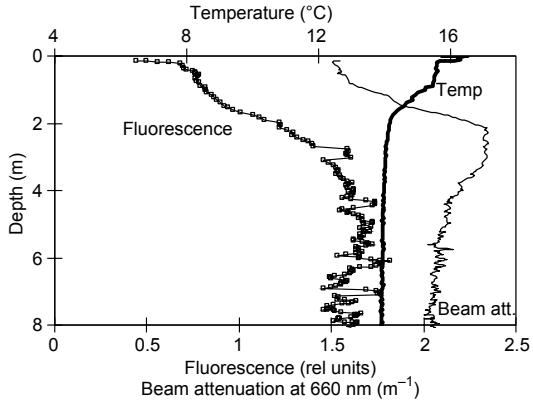

Fig. 4. Example of vertical variation of Lake Peipsi water properties, as measured on 11 June 2003, 10:25–11:00 UTM.

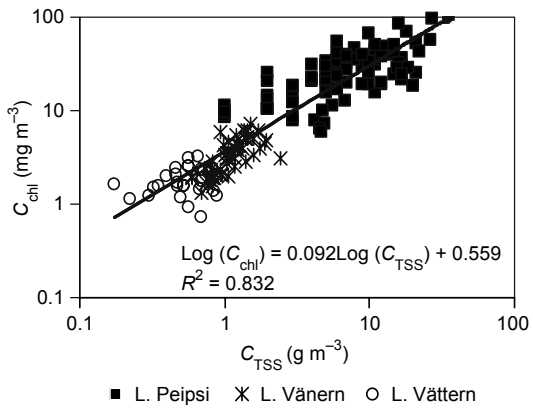

Fig. 5. Relationship between total suspended matter and chlorophyll *a* concentration in lakes Peipsi, Vänern and Vättern.

derived phytoplankton scattering, $b_{ph}(\lambda)$, it is assumed that the beam attenuation coefficient ($c = a + b$) for phytoplankton is spectrally flat (Sathyendranath and Platt 1988) and $b_{ph}(\lambda)$ can be calculated as:

$$b_{ph}(\lambda) = [a_{ph}(550) + b_{ph}(550)] - a_{ph}(\lambda) \quad (11)$$

where $a_{ph}(550)$ and $a_{ph}(\lambda)$ are as measured from water samples, and $b_{ph}(550)$ is from Eq. 10. Spectra are reconstructed according to HydroScat-6 bands.

Different authors have reported very variable values of the b_b/b ratio of phytoplankton, but these do not exceed 0.01 in waters where C_{Chl} is greater than 1 mg m^{-3} (Morel *et al*. 2002 and references therein). For our dataset we used a fixed value of 0.0039, which was estimated in intensive sampling with HydroScat-6 and ac-9 in Finnish and Swedish lakes (A. Lindfors pers. comm. 2003). Although for L. Peipsi the ratio was not directly estimated, we can assume that the effect of phytoplankton is small anyway.

When scattering and backscattering of phytoplankton and pure water are known, then only the tripton component in Eqs. 7, 8 and 9 is unknown. The value of $b_t(660)$ can be calculated from Eq. 9 and $b_{bt}(\lambda)$ at HydroScat-6 bands from Eq. 8, using measurements with HydroScat-6.

The scattering coefficient of nonchlorophyllous particles may have a very variable spectral shape, depending on particle size and composition. For inorganic particles the scattering coefficient is conventionally considered to be inversely proportional to the wavelength. As we have used the measurements at 660 nm as reference, the shape can be expressed as:

$$b_i(\lambda) = b_i(\lambda_0)(\lambda_0/\lambda)^n \quad (12)$$

where λ_0 = 660 nm and n varies between 0 and 2 (Jupp *et al*. 1994). The value of n for the present dataset was estimated iteratively (Strömbeck 2001) to get coincidence between the spectral shape of the backscattering (b_{bt} derived from Eq. 8) and scattering coefficients b_t (the same relationship as for b_i in Eq. 12) assuming that tripton contains mainly inorganic particles.

This combined method enables us to get better estimates of scattering and backscattering coefficients by HydroScat-6 measurements, which are affected by attenuation within the optical path of the instrument.

Results and discussion

Optically active substances

Despite the fact that L. Peipsi has been considered to be a nonstrafied lake, during warm and calm summer days a temporary thermocline still forms, as in many other shallow lakes at this latitude (Horne and Goldman 1994). Vertical profiles of the beam attenuation coefficient and of fluorescence are similar (Fig. 4) showing

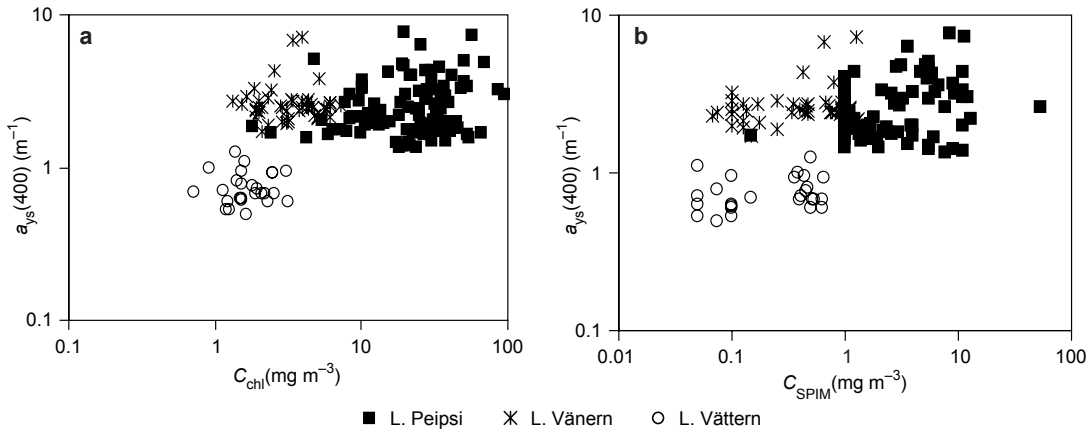

Fig. 6. Absorption by dissolved organic matter $a_{ys}(400)$ as (**a**) a function of chlorophyll *a* concentration, C_{Chl}; and (**b**) a function of inorganic suspended matter concentration C_{SPIM}.

that water turbidity is highly correlated with the phytoplankton biomass in the water column. According to the measured profiles, the maximum of beam attenuation coefficient $c(660)$ was at a depth of 0.2–3.2 m and it was less notable in early morning samplings. This large vertical variation indicates that water samples that we used to collect from 0.2 m depth cannot always be representative for the whole water column and may also cause misinterpretation of the remote sensing data.

Concentrations of optically active substances in water and the Secchi disc depth for L. Peipsi during campaigns are presented in Table 2. In spite of the large variation of the variables in L. Peipsi, Secchi depth and C_{Chl} corresponds well to average values of long term monitoring (Table 1). According to these parameters L. Peipsi falls in the same range with lakes investigated earlier in Estonia (data in Arst 2003), but has significantly higher concentrations of all OAS than the two large lakes in Sweden (Strömbeck 2001, Pierson and Strömbeck 2000) (Table 1). Only the lowest values of $a_{ys}(400)$ in L. Peipsi are comparable to the highest values of the same parameter in L. Vänern. Therefore L. Peipsi data enlarge the range of optical properties dataset of large lakes collected previously in Vänern and Vättern.

There was a strong relationship between the concentrations of total suspended matter (C_{TSS}) and C_{Chl} in all three large lakes (Fig. 5), indicating that generally suspended matter contains a large amount of phytoplankton cells ($R^2 = 0.83$). However, at low values, the variables C_{Chl} and C_{TSS} did not correlate anymore, partly because of uncertainty of the weighing method. High values of C_{TSS} can be caused by high amounts of biomass or suspended solids, which both are typical for shallow eutrophic lakes. Separately in lakes Vänern and Vättern the corresponding determination coefficients were 0.35 and 0.03 and in L. Peipsi 0.40. According to Laugaste *et al*. (1996) there is a strong seasonal and spatial variation in the composition of suspended particles, for example because of cyanobacteria blooms in the southern area of L. Peipsi (L. Pihkva) in late summer, but in L. Peipsi s.s. diatoms may cause high water turbidity even in November.

Yellow substance may be produced in a lake itself or transported from the drainage area. Based on the relationship between yellow substance and C_{Chl} (Fig. 6a) in L. Peipsi, similarly to L. Vänern and L. Vättern (Strömbeck 2001), the yellow substance was clearly of allochthonous origin, according to the relationship from Davies-Colley and Vant (1987). The correlative relationship between inorganic matter and yellow substance in lakes Vänern and Vättern (Fig. 6b) shows that C_{SPIM} values are somewhat higher when the values of $a_{ys}(400)$ are higher, which usually indicates samples from river mouths or shallower areas close to the shore of lakes. In L. Peipsi the highest values of a_{ys} (up to 11.0 m^{-1}) were also measured in the mouth of the Suur-

Emajõgi and in narrow L. Lämmijärv; however, C_{SPIM} values may be rather high everywhere over L. Peipsi, as in shallow lakes they depend more on the depth and wind conditions than on inflows (Nõges *et al*. 1996).

It was earlier shown by Herlevi (2002) and Reinart *et al*. (2003) that lake water in Estonia and Finland can be optically classified into five types (*Clear*, *Moderate*, *Turbid*, *Very Turbid* and *Brown*) relying on the concentrations of three main optically active components in water (phytoplankton, yellow substance and total suspended matter). Applying this classification scheme to lakes, we found water of L. Vättern to be entirely of the *Clear* type (26 measurements) while that of L. Vänern was mainly of the *Clear* type (95% from 48 measurements) and a very small part of it was of *Moderate* type. Lake Peipsi, on the contrary, showed large variation in water type: of all water samples 42% belonged to the *Moderate* type, 26% to both *Clear* and *Turbid* types, 3% to the *Very Turbid* type, and 2% to the *Brown* type. In addition, noteworthy seasonal and spatial patterns were revealed in the water types of L. Peipsi. The *Clear* type occurred after the end of the spring bloom at the end of May and in early June in the open area of L. Peipsi, while the water belonging to the *Very Turbid* class in L. Lämmijärv in August, September or even in November, when there may occur large autumn phytoplankton blooms (Nõges 2001). The distribution of optical properties may depend on the sampling strategy and possibilities. However, this north–south trend of water quality and some optical properties of L. Peipsi were found to be typical also in previous investigations (Kutser *et al*. 1995, Nõges 2001).

Inherent optical properties

The values of the specific absorption coefficients, $a_{ph}^*(\lambda)$, are not constant and theoretically they vary for individual species due to the combined influence of the pigment composition and the so-called package effect. The package effect describes variations of $a_{ph}^*(\lambda)$ as a function of a cell size and cellular matter (Kirk 1994). The coefficient $a_{ph}^*(\lambda)$ expresses the absorption per 1 mg m^{-3} of C_{Chl} and it has a trend to decrease with increasing C_{Chl} as found in a large range of water bodies (Bricaud *et al*. 1995). The same tendency was also observed in the samples from Lake Peipsi and lakes Vänern and Vättern (Fig. 7a) in the spectral regions 400–480 nm and to a smaller extent in the region around 670 nm. The variation among samples from each lake (up to 55%) is much larger than the variation between lakes in all spectral regions, except 666–686 nm, where L. Peipsi has notably lower values of a_{ph}^*. The average $a_{ph}^*(\lambda)$ calculated for 16 samples from L. Peipsi was slightly lower than the average values in lakes Vänern and Vättern, but in those lakes the average C_{Chl} values are much lower (Table 2), which indicates somewhat higher package effect in eutrophic L. Peipsi than in oligotrophic lakes.

For parameterization of phytoplankton absorption spectra in the bio-optical model, spectral parameters *A* and *B* in Eq. 3 were calculated from chlorophyll-specific absorption spectra. Our results were compared with the same parameters *A* and *B* estimated by Bricaud *et al*. (1995) for variable sea waters with C_{Chl} = 0.02–24.5 mg m^{-3} (Fig. 7b), as these have been used in many bio-optical models. The parameter *A* shows a_{ph}^* at unit C_{Chl} and the parameter *B* deformations of a_{ph}^* spectrum with increase of C_{Chl}. Despite the higher values *A* and *B* of L. Peipsi, the spectral behavior is in general rather similar: the parameter *A* had a maximum around 440 nm and *B*'s maximum was shifted towards 480 nm. This means that a_{ph}^* changes most of all in the region 440–480 nm with changes in C_{Chl} due to varying amount of phytoplankton pigments. The lowest values for *B* were in the region 600–630 nm, where a_{ph}^* is less correlated with C_{Chl} (R^2 = 0.30). Higher *A* values in the region 400–470 nm compared with the estimate by Bricaud *et al*. (1995) show a weaker overall package effect; this was also observed in lake samples from six Swedish lakes (Strömbeck 2001). Higher values of the parameter *B* over the whole investigated spectrum point to a different pigment composition in oceanic and lake phytoplankton, but also to differences between L. Peipsi samples as the samples contain varying amounts of different particles. Bricaud's parameters are suggested for lower C_{Chl} values than those in L. Peipsi, and the data set should not include low-light conditions,

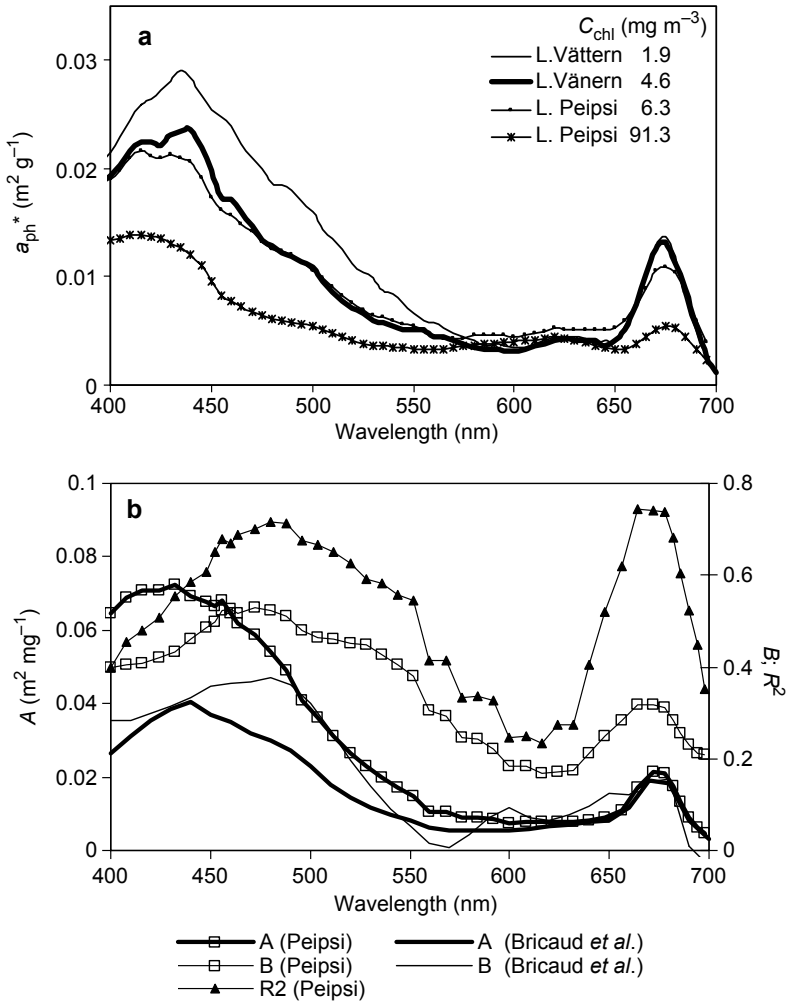

Fig. 7. — **a**: Examples of specific absorption coefficients of phytoplankton, a_{ph}* at varying concentrations of chlorophyll *a* as estimated in lakes Peipsi, Vänern and Vättern. — **b**: Parameters *A* and *B* in Eq. 3 (together with R^2 values of power regression) for Lake Peipsi and from Bricaud *et al.* (1995).

which could be typical for lakes where absorptions by dissolved organic matter decrease light especially in the blue region of the spectrum.

Differences in phytoplankton absorption depend on species composition, availability of nutrients and light as well as on age of the phytoplankton community. In August cyanophycocyanin and phycoerythrin are common in cyanobacteria, which occurred in L. Peipsi samples (http://www.seiremonitor.ee), while in June silicates (containing chlorophyll *c*) dominate. More detailed analyses using additional data from different seasons together with estimation of species composition of phytoplankton need to be done before we can suggest lake specific values of parameters *A* and *B*. It should also be mentioned that there may have remained some improperly eliminated particulate absorption as we were not able to discriminate phytoplankton and other particles that may be differently colored.

Tripton absorption was notably higher in eutrophic L. Peipsi than in L. Vättern (Table 3). However, their spectral shapes, characterized by S_t, were very similar without any possible effect of the origin of particles (compare Tables 2 and 3). The shape factor of tripton absorption varied from 0.011 to 0.013 nm^{-1} and was therefore in the range reported for particles in a large range of waters (0.0006–0.016 nm^{-1} by Roesler *et al.* 1989). The variation of tripton absorption inside each lake exceeded the variation between the lakes.

Absorption by yellow substance was higher in L. Peipsi than in lakes Vänern and Vättern

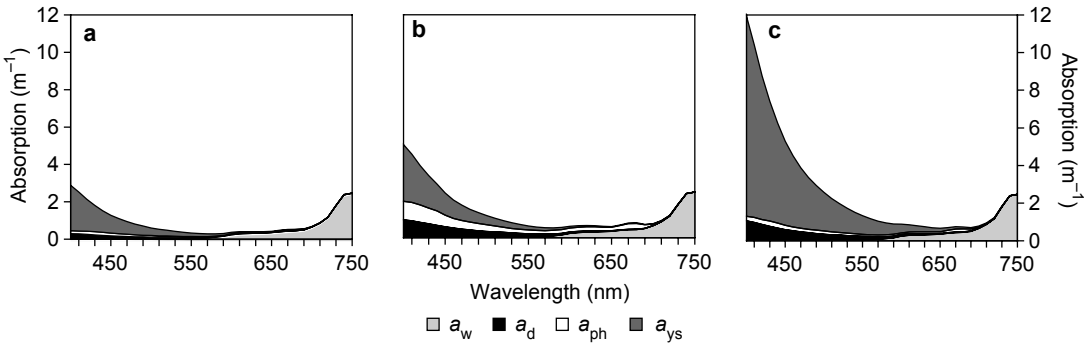

Fig. 8. Spectral absorption coefficients *a* (ph = phytoplankton, t = tripton, ys = CDOM, w = water) in Lake Peipsi as examples of (**a**) *Clear*, (**b**) *Turbid* and (**c**) *Brown* water type.

(Table 3), but within the limits estimated in many small lakes in Estonia (Reinart *et al*. 2004). The respective range of S_y for lakes is 0.0013–0.020. Some authors note a general trend in the shape factor which increases with a decrease in yellow substance absorption in a large range of lakes and sea area (Davies-Colley and Vant 1987, Aas 2000). Still, in some lakes with a high concentration of yellow substance the shape factor may be high (Herlevi *et al*. 1999, Arst 2003) like also in L. Peipsi (0.017 nm^{-1} compared with 0.014 nm^{-1} in L. Vänern). Mäekivi and Arst (1996) suggested the value 0.017 nm^{-1} for Estonian lakes. This variation may be caused by different organic compounds forming yellow substance (Kallio 1999).

Yellow substance is certainly the most absorbing component in the majority of the lakes in Estonia (Arst *et al*. 1999) including L. Peipsi (Fig. 8a, b, c). In the 16 samples from L. Peipsi 55%–80% of the total absorption (Table 4) in the blue region of spectra was caused by yellow substance and its effect was higher than absorption by pure water even in the middle of the visible region in the sampling points close to the Suur-Emajõgi mouth (*Brown* water type in Table 4). *Clear* water in the central part of the lake had the smallest absorption coefficient among the samples from the lake (Fig. 8a). The effect of yellow substance was high in the blue region, but in other spectral regions the water itself was responsible for absorption (Table 4). In *Turbid* type, particles absorb 36%–50% of the radiance over the region 400–700 nm. As shown in Fig. 8b, in this type of water phytoplankton cells have a significant effect on absorption. The effect of different components in the *Moderate* type varied between values of *Clear* and *Turbid* in Table 4, according to concentrations of OAS.

Table 4. Percentage of absorption by different components in water of the total absorption in three spectral ranges by examples representing different water types in L. Peipsi.

Water type	400–450 nm	550–650 nm	660–680 nm
Absorption by water			
Clear	0.2%–0.3%	47%–57%	75%–83%
Turbid	0.1%–0.2%	35%–37%	56%–59%
Brown	0.2%–0.3%	22%–26%	59%–60%
Absorption by CDOM			
Clear	74%–80%	17%–29%	2%–6%
Turbid	55%–63%	18%–23%	3%–5%
Brown	85%–87%	52%–57%	12%–17%
Absorption by particles			
Clear	15%–33%	13%–29%	12%–20%
Turbid	36%–45%	40%–50%	36%–41%
Brown	13%–15%	20%–23%	24%–29%

In L. Vättern the effect of pure water was comparable with the effect of yellow substance over the entire PAR region (absorption 49% and 40%, respectively) and particles had little effect. In L. Vänern the average absorption by yellow substance over PAR (73%) was even higher than in L. Peipsi (average 64%), but the effect of particles was more than two times smaller (8% in L.Vänern and 19% in L. Peipsi).

The scattering coefficient for phytoplankton at 550 nm estimated with Eq. 10 ranged in L. Peipsi from 0.33 to 1.19 m^{-1} (C_{Chl} varied 1.9–6.9 mg m^{-3}) and the resulting spectrum shows increased scattering towards longer wavelengths (Fig. 9a). Because only a few bands (according

to HydroScat-6 bands) were used here no details are visible in the range where absorption is highest (660–680 nm), as can be actually seen in the measured and simulated spectra by Ahn *et al.* (1992) and Stramski *et al.* (2001); however, the general trend is the same.

Both inorganic and organic particles are important in scattering. These spectra have weak and variable spectral dependence. The average value for exponent n in Eq. 12 was 1.01 ± 0.16 (Table 5), which is actually slightly lower than the value estimated for large Swedish lakes (1.25–1.45) by Strömbeck (2001), indicating that particles of larger size are more typical in L. Peipsi than in deep Swedish lakes. These may be particles that can be resuspended from the lake bottom by wind. Decreased spectral variation may also be caused by the presence of weakly absorbing detrital particles, as these absorb more at short wavelengths, decreasing scattering in this region. The exponent for the total scattering coefficient in turbid Estonian and Finnish lakes varies in a large range: from 0.61 to 1.24 m^{-1} (Herlevi *et al.* 1999).

Out of the total backscattering the phytoplankton backscattering has only a minor effect (Fig. 9b). With an increase in the concentration of particles the total b_b tends to increase (Morel and Ahn 1991). This was also true for L. Peipsi samples. The b_{bt} values in the centre of L. Peipsi were comparable with those in L. Vänern (Table 5) but about six times higher than those in L. Vättern. The backscattering ratio of inorganic particles (average values over the spectra in Table 5) was more or less spectrally flat, but the values were higher than 0.006–0.012 reported by Lide (2001). However, these results strongly depend on the particle composition. Values of backscattering ratio for L. Peipsi were slightly higher than for deep Swedish lakes, but on average close to the average estimated in Dutch lakes (0.030 in Dekker 1993), which are also shallow and eutrophic or mesotrophic.

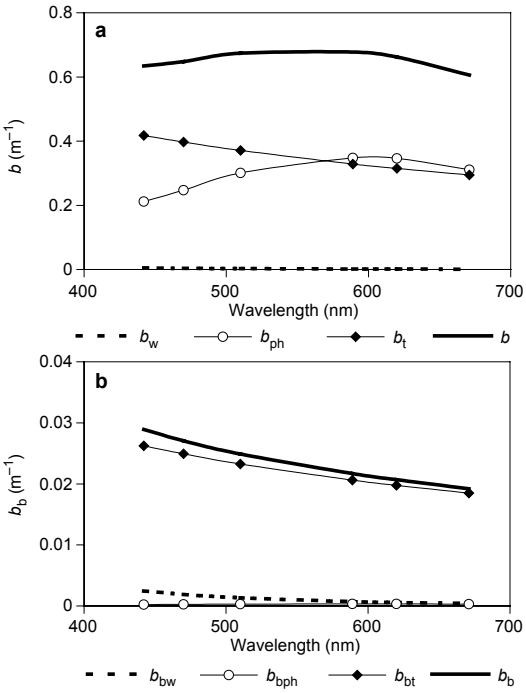

Fig. 9. Example of (**a**) scattering coefficient, b, and (**b**) backscattering coefficient, b_b, as estimated for Lake Peipsi by calculations (Eqs. 7–12) from corrected HydroScat-6 measurements (11 June 2002).

It must be noted that scattering properties of L. Peipsi may vary even in a larger range, as measurements of vertical profiles of c, needed for HydroScat-6 corrections, were carried out

Table 5. Preliminary scattering parameters (mean ± SD) of L. Peipsi, compared with those of Lakes Vänern and Vättern.

	L. Peipsi N = 3	L. Vänern[1] N = 21	L. Vättern[1] N = 13
b_b (442) (m^{-1})	0.041 ± 0.018	0.029 ± 0.006	0.005 ± 0.001
b_{bt}(442) (m^{-1})	0.038 ± 0.017	0.028 ± 0.006	0.005 ± 0.001
n	1.01 ± 0.16	1.46 ± 0.13	1.25 ± 0.18
b_b/b	0.029 ± 0.015	0.025 ± 0.005	0.020 ± 0.006
b_{bt}/b_t	0.046 ± 0.020	0.037 ± 0.009	0.032 ± 0.015

[1]Strömbeck (2001), there inorganic scattering (denoted with the subscript i) was shown instead of tripton (t) scattering, as detrital scattering was omitted in lakes Vänern and Vättern.

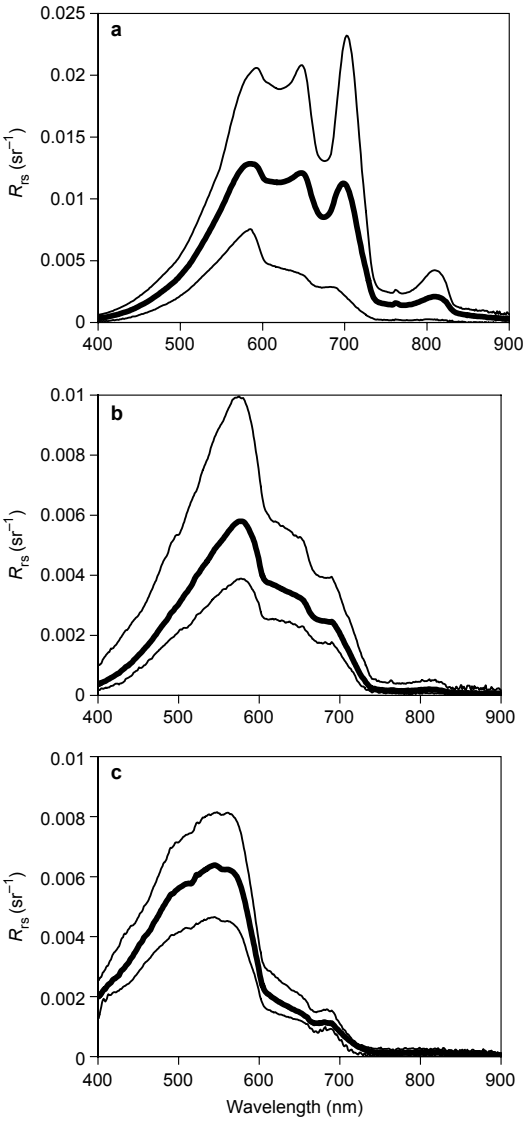

Fig. 10. Measured remote sensing reflectance $R_{rs}(\lambda)$ from lakes (**a**) Peipsi, (**b**) Vänern and (**c**) Vättern. Thick solid lines represent average values; thin lines maximum and minimum values.

only in deeper areas of the lake. These results are very preliminary now, as we did not have direct estimates for b_{bph}/b for Eq. 8. Phytoplankton scattering parameterization in Eq. 10 has a significant effect on the scattering coefficient, but a very small effect on the backscattering coefficient. Still, these preliminary estimates can be used as a starting point for a bio-optical model. They show the need to concentrate in further investigations on the estimation of the size and origin of suspended particles.

Apparent optical properties

Remote sensing reflectance spectra, $R_{rs}(\lambda)$, are necessary for elaborating bio-optical remote sensing models to relate the signal measured by the satellite sensor to water quality. The R_{rs} spectra calculated by Eq. 5 (Fig. 10) indicate also a strong influence of yellow substance at shorter wavebands mentioned in the section 'Optically active substance'. These spectra confirm that lakes may be highly reflective in the green and red regions of the spectrum, but the absolute values of reflectance and its spectral shape may differ greatly. The reflectance values 0.02%–0.2% in the region 750–770 nm in L. Peipsi and L. Vänern are far from being zero. This means that the standard methods in estimation of aerosol properties from SeaWiFS and MODIS images may cause a failure of the atmospheric correction procedure (Reinart *et al*. 2002).

The R_{rs} spectra (Fig. 10) were compared with those in the classifications of lake water proposed by Vertucci and Likens (1989) and Reinart *et al*. (2003), the latter was especially elaborated for Estonian and Finnish lakes. Lake Peipsi had the highest variability of the measured reflectance spectra. In the central regions of L. Peipsi s.s., where water is deeper and usually more transparent, the *Clear* type can be observed, high spectra with a maximum at 580–600 nm correspond to the *Turbid* type. An addditional reflectance maximum around 690–710 nm is a result of a combined effect of a phytoplankton absorption peak around 676 nm, a fluorescence peak at 685 nm and a rapid increase of water absorption above 700 nm. R_{rs} spectra belonging to the *Very Turbid* type were observed during a phytoplankton bloom (all seen in Fig. 10a). In some parts of L. Peipsi the water may be so shallow that the bottom is visible, and this may also cause spectra looking like the highest one in Fig. 10a. The L. Vättern spectra (Fig. 10c) had maximum reflectance at the wavelengths 550–580 nm and the reflectance at 500 nm was higher than at 650 nm, which corresponds to the *Clear* type by Reinart *et al*. (2003) and type 3 by Vertucci and

Likens (1989). The L. Vänern reflectance spectra (Fig. 10b) had, similarly to waters of *Clear* type, a maximum at 550–580 nm, but the reflectance at 500 nm was smaller than at 650 nm and therefore they do not correspond to any type by Vertucci and Likens (1989) but belong to the *Moderate* type by Reinart *et al.* (2003).

All optically active components affect irradiance attenuation in water in a different manner, therefore the absolute values and shape of K_d spectra may differ notably (Fig. 11). The attenuation coefficient of L. Peipsi was higher than those of L. Vänern and L. Vättern over the whole visible spectrum. Lake Vättern as the clearest of the compared lakes had the lowest attenuation coefficient. The irradiance that penetrates to the deepest layers was in the range 530–570, and diminished down to 1% of the subsurface value at an average depth ($z_{1\%}$) of 21 m. In L. Vänern irradiance 570–600 nm penetrated to the deepest layers and $z_{1\%}$ was down to 10.3 m. The depth to which 1% of the irradiance penetrated into water reaches, is considered to be the lower limit where photosynthesis can take place (Kirk 1994). Its numeric value can be calculated from known K_d values ($z_{1\%} = \ln 100/K_d = 4.6/K_d$). In L. Peipsi vertical profile spectral measurements were made only in the deepest part of the lake, and therefore in Fig. 11 only the lowest measured $K_d(\lambda)$ values are shown. However, radiation attenuation may be even 6 times higher in the case of a phytoplankton bloom or very high turbidity, as estimated by model calculations (Reinart *et al.* 1999). This spectrum was added to Fig. 11 to illustrate the large variation in L. Peipsi optical properties. So, when in the clearer regions of L. Peipsi irradiance at 580 nm penetrates down to 7 m, then in some areas the maximum 1% depth is only 1.5 m and the spectral maximum is shifted to the red part of the spectrum (700 nm).

Such a varying underwater light availability causes very different conditions for phytoplankton growth and therefore has an effect on primary production in the lake. As the lake is shallow, the bottom is well lighted in many areas, which affects the living conditions of bottom flora and fauna (Pihu and Haberman 2001). All this must be taken into account when modeling the conditions of L. Peipsi. Optical properties cannot be considered similarly over the whole basin and for better parameterization of bio-optical models spatial and seasonal variation of water types needs to be clarified.

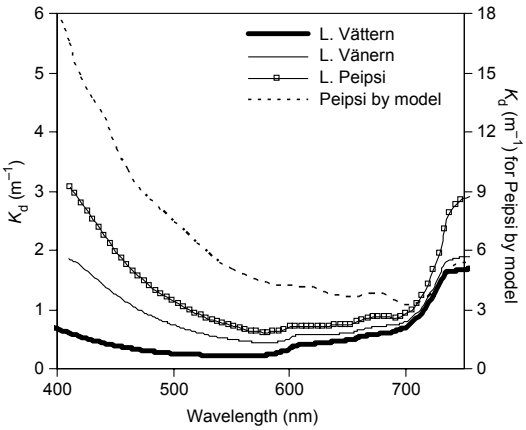

Fig. 11. Mean spectra of diffuse attenuation coefficients, $K_d(\lambda)$ measured in three large lakes. For Lake Peipsi the spectrum according to very high attenuation ($K_d(490)$ = 8.0 m^{-1}) estimated by model calculations (Reinart *et al.* 2003) is shown in addition.

Conclusions

We have studied inherent and apparent optical properties and variation of optically active substances of one of the largest lakes in Europe, Lake Peipsi. Relationships between optical characteristics are of interest in constructing semi-analytical algorithms of remote sensing of this lake and for bio-optical modeling of radiation penetration into water.

In L. Peipsi, as well as in other Estonian lakes and large Swedish lakes Vänern and Vättern, the major absorber is yellow substance, which also affects the spectra of remote sensing reflectance and diffuse attenuation coefficient. In L. Peipsi, however, absorption by phytoplankton may be more than 10% over the whole visible spectrum and therefore gives better chances than in lakes Vänern and Vättern to estimate chlorophyll *a* by the satellite sensors.

The scattering by nonchlorophyllous particles in L. Peipsi is much stronger than in lakes Vänern and Vättern. Backscattering measurements confirm that the backscattering coefficient has a weaker spectral dependence in L. Peipsi than in large Swedish lakes. The scattering coef-

ficient is significantly affected both by organic and inorganic particles. For further application better parameterization of scattering properties is needed, together with analyses of particle size and type composition.

Lake Peipsi's optical properties are very variable both spatially and temporally, covering a large range of water types previously classified in small Estonian and Finnish lakes. Swedish large Lake Vättern has only optically *Clear* lake water, characteristic for waters with relatively low amounts of optically active substances. Lake Vänern may have also some *Moderate* type areas. In central regions of L. Peipsi, the *Clear* water type comparable to that in L.Vänern was observed but mainly the *Moderate* type can be found. *Turbid,* even *Very Turbid* (in the case of phytoplankton bloom) and *Brown* (typical of humic lakes) are present in certain areas. For further applications more data about each type need to be collected.

Acknowledgments: This study was supported by EU Marie Curie Fellowship, contract No HPMF-CT-2001-01284, Swedish National Space Board grant 169/02 and Kristjan Jaak Foundation (Estonia). We acknowledge the Estonian Maritime Administration for providing a boat for the field survey and Dr. T. Nõges (Võrtsjärv Limnological Station, Estonia) for the Lake Peipsi data, collected under contract EVK1-CT-2002-00121 (CLIME) (financed by European Commissions's Environment and Sustainable Development Programme).

References

Aas E. 2000. *Spectral slope of yellow substance: Problems caused by small particles*. Proceedings of the XV Conference of Ocean Optics, Monaco (CD-ROM).

Ahn Y.H., Bricaud A. & 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*. Praxis Publishing, Springer, Chichester, UK.

Arst H. & Kutser T. 1994. Data processing and interpretation of sea radiance factor measurements. *Polar Res*. 13: 3–12.

Arst H., Erm A., Reinart A., Sipelgas L. & 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. *Nord. Hydrol*. 33(2): 207–226.

Arst H., Erm A., Kallaste K., Mäekivi S., Reinart A., Nõges P. & Nõges T. 1999. Investigation of Estonian and Finnish lakes by optical measurements in 1992–1997. *Estonian Acad. Sci. Biol. Ecol*. 48: 5–24.

Bricaud A., Morel A. & Prieur L. 1981. Absorption by dissolved organic matter in the sea (yellow substance) in the UV and visible domain. *Limnol. Oceanogr*. 26: 43–53.

Bricaud A., Babin M., Morel A. & Claustre H. 1995. Variability in the chlorophyll-specific absorption coefficients of natural phytoplankton: Analysis and parameterisation. *J. Geophys. Res*. 100(C7): 1321–1332.

Davies-Colley R.J. & Vant W.N. 1987. Absorption of light by yellow substance in freshwater lakes. *Limnol. Oceanogr.* 32: 416–425.

Dekker A.G. 1993. *Detection of optical water quality parameters for eutrophic waters by high resolution remote sensing*. Proefschrift (Ph.D. thesis) Vrije Universiteit, Amsterdam.

Herlevi A. 2002. A study of scattering, backscattering and a hyperspectral reflectance model for boreal waters. *Geophysica* 38(1–2): 113–132.

Herlevi A., Virta H., Arst H. & Erm A. 1999. Results of light absorption/attenuation measurements in Finnish and Estonian lakes in summer 1997. *Estonian Acad. Sci. Biol. Ecol*. 48: 46–62.

Horne A.J. & Goldman C.R. 1994. *Limnology*. McGraw-Hill, New York.

IOCCG 2000. Remote sensing of ocean color in coastal and other optically-complex waters. In: Sathyendranath S. (ed.), *Report of the International Ocean Color Coordinating Group*, No. 3, IOCCG, Dartmouth, Canada, pp. 145.

ISO 10260 1992(E). *Water quality — Measurements of biochemical parameters — Spectrophotometric determination of chlorophyll-a concentration*. (Geneva, Switzerland: ISO), pp. 1–6.

Jupp D.L.B., Kirk J.T.O. & 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. Freshw. Res*. 45: 801–828.

Kallio K. 1999. Absorption properties of dissolved organic matter in Finnish lakes. *Estonian Acad. Sci. Biol. Ecol*. 48: 75–83.

Kirk J.T.O. 1994. *Light and photosynthesis in aquatic ecosystems*. University Press, Cambridge.

Kutser T., Herlevi A., Kallio K. & Arst H. 2001. A hyperspectral model for interpretation of passive optical remote sensing data from turbid lakes. *Sci. Total Environ*. 268: 47–58.

Kutser T., Arst H., Miller T., Käärmann L. & Milius A. 1995. Telespectrometrical estimation of water transparency, chlorophyll-a and total phosphorus concentration of Lake Peipsi. *Int. J. Rem. Sens*. 16(16): 3069–3085.

Kvarnäs H. 2001. Morphometry and hydrology of the four large lakes of Sweden. *Ambio* 30: 467–474.

Laugaste R., Jastremskij V.V. & Ott I. 1996. Phytoplankton of lake Peipsi-Pihkva: species composition, biomass and seasonal dynamics. *Hydrobiologia* 338: 49–62.

Lide D.R. 2001. *CRC Handbook of physics and chemistry*, 82 ed. CRC Press.

Lindell T., Pierson D., Premazzi G. & Ziliolli E. (eds.) 1999. *Manual for monitoring European Lakes using remote*

sensing techniques. Office for Official Publications of the European Communities, Luxembourg.

Lindpere A., Starast H., Milius A. & Saan T. 1991. Quantitative changes of water composition in Lake Peipsi-Pihkva in 1985–1989. *Proc. Estonian Acad. Sci, Ecol.* 1: 86–92.

Mobley C.D. 1994. *Light in water — radiative transfer in natural waters*. Academic Press, San Diego.

Morel A. & Ahn Y.H. 1991. Optics of heterotrophic nanoflagellates and ciliates: a tentative assessment of their scattering role in oceanic waters compared to those of bacterial and algal cells. *J. Mar. Res*. 49: 177–202.

Morel A., Antoine D. & Gentili B. 2002. Bidirectional reflectance of oceanic waters: Accounting for Raman emission and varying particle phase function. *Appl. Opt.* 41: 6289–6306.

Mäekivi S. & 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.

Nõges T. (ed.) 2001. *Lake Peipsi. Meteorology, hydrology, hydrochemistry*. Sulemees Publishers, Tartu, Estonia.

Nõges T., Habermann J., Jaani A., Laugaste R., Lokk S., Mäemets A., Nõges P., Pihu E., Starast H., Timm T. & Virro T. 1996. General description of Lake Peipsi-Pihkva. *Hydrobiology* 338: 1–9.

Pierson D.C. & Strömbeck N. 2000. A modelling approach to evaluate preliminary remote sensing algorithms: Use of water quality data from Swedish Great Lakes. *Geophysica* 36(1–2): 177–202.

Pihu E. & Habermann J. (eds.) 2001. *Lake Peipsi. Flora and fauna*. Sulemees Publishers, Tartu, Estonia.

Pope M. & Fry E.S. 1997. Absorption spectrum (380–700 nm) of pure water. II integrating cavity measurements. *Appl. Opt*. 36: 8710–8723.

Reinart A. & Herlevi A. 1999. Diffuse attenuation coefficient in some Estonian and Finnish lakes. *Proc. Estonian Acad. Sci. Biol. Ecol*. 48(4): 267–283.

Reinart A., Herlevi A., Arst H. & Sipelgas L. 2003. Preliminary optical classification of lakes and coastal waters in Estonia and South-Finland. *J. Sea Res*. 49: 357–366.

Reinart A., Pierson D. & Land P. 2002. Large European Lakes in SeaWIFS and MODIS images. *Proceedings of Ocean Optics XVI*, 2002, CD-ROM.

Reinart A., Paavel B. & Pierson D. 2004. Effect of colored dissolved organic matter on attenuation of photosynthetically active radiation in Lake Peipsi. *Proc. Estonian Acad. Sci. Ecol.* 53: 88–105.

Roesler C.S., Perry M.J. & Carder K.L. 1989. Modeling *in situ* phytoplankton absorption spectra from total absorption spectra in productive inland marine waters. *Limnol. Oceanogr*. 34: 1510–1523.

Sathyendranath S.L. & Platt T. 1988. The spectral irradiance field at the surface and in the interior of the ocean: A model for application in oceanography and remote sensing. *J. Geophys. Res*. 93: 9270–9280.

Stramski D., Bricaud A. & Morel A. 2001. Modeling the inherent optical properties of the ocean based on the detailed composition of the planktonic community. *Applied Optics* 40(18): 2929–2945.

Strömbeck N. 2001. *Water quality and optical properties of Swedish lakes and coastal waters in relation to remote sensing*. Comprehensive Summaries of Uppsala Dissertations from faculty of Science and Technology 633. Uppsala.

Strömbeck N. & Pierson D. 2001. The effects of variability in the inherent optical properties on the estimations of the chlorophyll a by remote sensing in Swedish freshwaters. *Sci. Total Environ*. 268: 123–137.

Tassan S. & Ferrari G.M. 1995. An alternative approach to absorption measurements of aquatic particles retained on filters. *Limnol. Oceanogr*. 40: 1358–1368.

Vertucci F.A. & Likens G.E. 1989. Spectral reflectance and water quality of Adirondack mountain region lakes. *Limnol. Oceanogr*. 34: 1656–1672.

Willén E. 2001. Phytoplankton and water quality characterization: Experiences from the Swedish large lakes Mälaren, Hjälmaren, Vättern and Vänern. *Ambio* 30: 529–537.

Xu F., Dawson R.W., Tao S., Cao J. & Li B. 2001. A method for lake ecosystem health assessment: an Ecological Modeling Method (EMM) and its application. *Hydrobiologia* 443: 159–175.

Received 23 November 2003, accepted 10 August 2004