Temporal Variations in Bio-Optical Properties of Four North Estonian Lakes in 1999-2000

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Abstract

To investigate the seasonal variation of bio-optical parameters in lakes of different type regular measurement campaigns were carried out in four North Estonian lakes in 1999–2000. Some parameters (relative transparency of water (z_{SD}), vertical profiles of downwelling vector irradiances in the photosynthetically active region of spectrum (PAR, 400–700nm), vertical profiles of temperature and dissolved oxygen) were measured in situ in the lakes. Concentrations of chlorophyll a (C_{chl}), suspended matter (C_S) and yellow substance ($C_{y,e}$) and spectra of light "spectrometric" attenuation coefficient ($c*_\lambda$) were determined from water samples in the laboratory. Relying on the spectra of $c*_\lambda$ the averaged over 400–700 nm values were computed ($c*(PAR)$). The lakes under investigation represent a large proportion of the variety of lakes in Estonia with respect to their trophic status and phytoplankton abundance. Lake Paukjärv, which is close to oligotrophic type, is located in a forest 70 km from Tallinn. Lakes Ülemiste and Harku are within the borders of Tallinn, and Lake Maardu is in the vicinity of the city. Although lakes Ülemiste and Harku belong both to the hypertrophic nonstratified lake type, the species composition in these lakes differs greatly. Lake Maardu is a dyseutrophic lake. In lakes Harku, Ülemiste and Maardu, the annual variation of light attenuation is strongly influenced by changes in phytoplankton. In oligotrophic Lake Paukjärv the values of optically active substances and light attenuation coefficients are small, and their annual variations are irregular. Our analysis of the database collected in the course of 87 expeditions shows that despite large optical and biological variability in the lakes investigated some general relationships exist between the measured variables throughout the whole set of lakes. The optical characteristics ($c*(PAR)$, z_{SD} and diffuse light attenuation coefficient) correlate better with phytoplankton-related variables (C_{chl}, C_S) whereas the content of mostly allochthonous humic compounds is less interrelated with other variables. The correlation coefficient $lnc*(PAR)$ vs. lnz_{SD} for all lakes together was 0.98, which confirms the suitability of $c*(PAR)$ for the characterization of water transparency.

Key words: limnology, lake optics, optically active substances, underwater light field, attenuation coefficient spectra, phytoplankton

1.   Introduction

The bio-optical properties of Estonian and Finnish lakes have been investigated by us since 1992, and the respective results have been published by *Arst et al.* (1995,

1996, 1998, 1999 a,b), *Kutser et al.* (1998 a), *Reinart et al.* (1995, 1998, 2000), *Nõges and Järvet* (1995), *Nõges and Nõges* (1998 a,b, 1999) and *Nõges et al.* (1998). The results obtained allow us to classify the lakes and to estimate the variation limits of bio-optical properties in Estonian and Finnish lakes in the ice-free period. However, these investigations were episodic (on average 2–3 measurement campaigns a year in each lake) and different lake groups were visited in different periods. As known, the bio-optical properties of lake water change during a year due to the following factors: 1) water exchange (different qualities of in- and out-flowing water), 2) seasonal and synoptic variations of hydrophysical parameters, radiation regime, stratification and mixing of the water, and 3) irregular variations of the biological activity in the water due to environmental conditions.

Abundant literature is available on seasonal variations of phytoplankton and associated chemical and biological variables in different types of lakes (e.g. *Schindler* 1978; *Schindler et al.*, 1996; *Bürgi et al.*, 1985; *Amblard*, 1988; *Brandl et al.*, 1989; *Marshall and Peters*, 1989; *Wojciechowska and Krupa*, 1992; *Cobelas and Rojo*, 1994; *Feuillade and Davies*, 1994; *Turner et al.*, 1995). However, publications containing comprehensive data sets (optical and biological parameters, temperature, concentration of yellow substance and dissolved oxygen in the water) measured repeatedly during some consecutive years are practically missing. We can refer only to the works by *Hickman et al.* (1984) and *Crisman* (1995), who estimated during a year the seasonal variation of some bio-optical characteristics (respectively in the Gippsland Lakes and in Lake Okeechobee). The data in other publications are more or less episodic, giving information (sometimes on 1–6, sometimes on 30–60 lakes) obtained from 1–4 short-time campaigns. Often only a few bio-optical characteristics were measured. At the beginning, these investigations contained mainly underwater and/or laboratory measurements (*Kirk*, 1977, 1981, 1984, 1994; *Eloranta*, 1978; *Bukata et al.*, 1979; *Phillips and Kirk*, 1984; *Schanz*, 1985; *Davis-Colley and Vant*, 1987; *Palmisano and Simmons*, 1987; *Koenings and Edmundson*, 1991; *Herlevi et al.*, 1999). Later attention was paid to the interpretation of the reflectance spectra or optical satellite data for lakes (*Davies-Colley*, 1983; *Kondratyev and Gitelson*, 1989; *Vertucci and Likens*, 1989; *Bukata et al.*, 1991; *Gallie and Murtha*, 1992; *Mittenzwey et al.*, 1992; *Kutser et al.*, 1995, 1998b; *Mayo et al.*, 1995; *Dekker et al.*, 1995, 1997; *George*, 1997; *Hoogenboom and Dekker*, 1997; *Zilioli and Brivio*, 1997; *Fraser*, 1998; *Kallio et al.*, 1998; *Pozdnyakov et al.*, 1998; *Lindell et al.*, 1999; *Pierson and Strömbeck*, 2000).

We could not describe the annual variations of the bio-optical properties of water bodies relying on our previous database collected up to 1999. Thus, a new database with a better temporal resolution was necessary. We decided to investigate the annual changes in phytoplankton biomass and the concentrations of yellow substance and suspended matter as three main optically active substances (OAS) in water together with optical and radiative characteristics. In 1999 we started a new project with the aim to analyse the dynamics of the bio-optical parameters in different types of lakes, performing *in situ* measurements repeatedly (7–13 times) during a year. Four Estonian lakes with trophic status ranging from nearly oligitrophic to hypertrophic were chosen

for this investigation. The measurements, which continued also through 2000, allowed us to find out some general relationships between the biological and optical parameters, to describe some lake-specific features and to draw some conclusions on the seasonal behaviour of the variables measured.

2.   Description of the lakes

The lakes under investigation represent a large proportion of the variety of lakes in Estonia with respect to their trophic status and phytoplankton abundance (Table 1). Lake Paukjärv at one end of this range is a stratified, oligotrophic lake, while Lake Harku is an example of the most heavily eutrophied lakes. Although lakes Ülemiste and Harku both belong to a hypertrophic nonstratified lake type, the great differences in their nutrient levels result the different species composition and size structure of plankton. Lake Maardu, a hard-water lake containing large amounts of nutrients and humic substances, was classified by *Mäemets* (1977) as dyseutrophic. As a result of macrophyte colonization suppressing phytoplankton the transparency of its water has significantly increased during the last 25 years (in 1977 the Secchi depth was 0.3–1.8 m, while in 1999-2001 it ranged from 1.8 to more than 3 m).

Lake Ülemiste serves as the main drinking water reservoir for Tallinn. In order to satisfy the growing needs of the city, the catchment area of the lake has been increased several times by connecting it with new tributaries. The shallowness and large wind-exposed area of the lake cause strong resuspension of sediments, which together with rich phytoplankton turn the water yellowish-green and turbid. The under-water light conditions are strongly affected by seasonal water level fluctuations (amplitude up to 2 m). In May 2000, the phytoplankton was clearly dominated by *Planktothrix agardhii* (80–90% of the biomass), followed by another filamentous cyanobacterium *Limnothrix redekei.*

Lake Harku is another lake located within the borders of Tallinn. It was separated from the sea by neotectonic uplift about 2000 years ago. The lake is hypertrophic. The sources of its enormous phosphorus content have remained largely unclear. In summer the water is yellowish-green and extremely turbid with a Secchi depth < 0.5 m. The phytoplankton consists mainly of small-celled green algae (chlorococcales). In May 2000, chlorococcales were represented mainly by the genera *Scenedesmus* (*S. opoliensis, S. acuminatus, S. spinosus*), *Pediastrum* (*P. kawraiskii, P. boryanum*), *Dictyosphaerium* and *Coelastrum*. Among cyanobacteria we found only the coccal forms (*Microcystis wesenbergii, M. viridis, M. aeruginosa, Snowella lacustris, Chroococcus* sp). Probably diatoms (*Diatoma elongatum, Synedra acus, S. ulna* var. *danica, Aulacoseira granulata, Fragilaria* sp.) were still rather numerous as remains from the vernal plankton.

Lake Maardu is located in the vicinity of Tallinn. After running dry in 1894, it was reconstructed as a lake in 1939 (*Mäemets*, 1977). The water is rather hard but with a noteworthy humic content that gives it a brownish colour. As a main difference from the other lakes, ¾ of the bottom in Lake Maardu is covered by macrophytes (mainly

Chara spp.), which suppress algal growth. Rapid eutrophication in the 1960s and 1970s caused heavy cyanobacterial blooms in the lake (*Aphanizomenon, Microcystis*), but now the macrophyte-dominated state has been restored. Probably, a rather rapid water exchange contributes to the stability of macrophyte stands and keeps the phytoplankton biomass low in spite of a high nutrient content in the water. In May 2000 about 80% of its small phytoplankton biomass was made up of the needle-shaped diatom *Synedra acus* and the remaining part of the delicate chrysophyte *Dinobryon divergens*.

Lake Paukjärv is located in an almost unpopulated area in North Estonia, In this sandy area a large number of lakes surrounded by forests and bogs have kept nearly their pristine status. The water in Lake Paukjärv is slightly greenish and transparent. The concentrations of both mineral and organic compounds are low. Being deeper than the other lakes studied, Lake Paukjärv is thermally stratified. This causes also an inhomogeneous distribution of the biota. In the plankton samples taken from the surface in May 2000, the chlorococcal *Crucigenia fenestrata* formed the bulk of the biomass, followed by picocyanobacteria. At a 5-metre depth, a ciliate (*Cyclidium* sp.) was most numerous. Algae were represented by a few diatoms (*Asterionella formosa, Synedra acus*), chrysophytes (*Dinobryon cylindricum*) and dinophytes (*Peridinium* sp.).

Table 1. The main limnological parameters of the studied lakes.

Parameter	L. Ülemiste	L. Harku	L. Maardu	L. Paukjärv
Area, ha	960	164	170	9
Average depth, m	2.5	1.6	1.6	5.9
Maximum depth, m	6.0	2.5	3.2	11.1
Stratification type	Nonstratified	Nonstratified	Nonstratified	Stratified, dimictic
Water exchange, y^{-1}	2.8	5	3.6	0.3
Trophic type	Hypertrophic	Hypertrophic	Dyseutrophic	Oligotrophic
Total N, mg L^{-1}	0.9–1.7	2.9	3.8	0.6–1
Total P, µg L^{-1}	70–90	600	180	10–25
HCO_3^-, mg L^{-1}	180	90–100	140	30–35
Macrophyte colonization, % area	<10	<20	75	<10
Summer phytoplankton biomass, mg L^{-1}	40–300	50–150	0.8 (1990)–123 (1967)	0.4
Dominating algal group	Filamentous cyanobacteria	Chlorococcales	Diatoms, chrysophytes	Picoplankton, chlorococcales

3. Materials and methods

The main database was collected in the course of 76 measurement campaigns performed on the studied lakes in 1999–2000 (Table 2). This database was

supplemented with the results of 11 campaigns on Lake Ülemiste in 1998. There were five sampling stations in Lake Ülemiste: Plant, Centre, Pirita, Kurna, and Loodus. In 1998, measurements were performed at all stations, in 1999–2000 the main station was Plant, and at the other stations measurements were irregular. However, according to our 1997–98 data (*Erm et al.*, 1999) the differences between the results obtained at these stations were rather small (except at the station Pirita, located in the mouth of the Pirita Channel, where somewhat clearer water in summer and higher values of dissolved organic matter in spring were observed). In 2000, the number of measurements on Lake Paukjärv was smaller than in 1999, because the lake was inaccessible by car due to bad road conditions.

Table 2. Number of measurement campaigns in 1998–2000.

Year	L. Ülemiste	L. Harku	L. Maardu	L. Paukjärv
1998	11 (May–Oct)	-	-	-
1999	13 (Mar–Nov)	8 (Mar–Nov)	10 (Mar–Nov)	8 (June–Oct)
2000	10 (Feb–Dec)	10 (Jan–Nov)	10 (Jan–Dec)	7 (Feb–Dec)

The following parameters were investigated:

1.   relative water transparency measured as the Secchi depth (z_{SD});

2.   concentrations of chlorophyll *a* (C_{chl}) and total suspended matter (C_s) in water samples measured in the laboratory;

3.   "spectrometric" attenuation coefficient of light for unfiltered and filtered water samples (respectively $c^*(\lambda)$ and $c_f^*(\lambda)$) in the spectral region of 350–700 nm;

4.   vertical profiles of the downwelling component of vector irradiance of a horizontal plane (*Dera*, 1992) in the PAR region (400–700 nm), $E_d(PAR)$;

5.   incident integral solar irradiance above the water surface, $E(z=+0)$;

6.   algal species (only in May 2000);

7.   vertical profiles of water temperature and dissolved oxygen;

8.   solar zenith angle, type and amount of clouds during the measurements.

The term "spectrometric attenuation coefficient" needs explanation. Actually, the water samples in a 5-cm long cuvette were investigated by means of a spectrophotometer *Hitachi* U1000, which gives the results

$$c^*(\lambda) = c(\lambda) - Fb(\lambda) - c_d(\lambda) \qquad (1)$$

where $c^*(\lambda)$ is the direct spectrophotometric reading at a given wavelength (λ), $c(\lambda)$ is the beam attenuation coefficient of light in the water, $b(\lambda)$ is the light scattering coefficient, $c_d(\lambda)$ is the beam attenuation coefficient of distilled water and F is a coefficient which shows the contribution of small-angle forward scattering to the

radiation measured by spectrophotometer. According to *Zaneveld et al.* (1992) and
Bricaud et al. (1995) F is between 0.04 and 0.10. For filtered water, i.e. for $c^*_f(\lambda)$,
equation (1) is also valid, but the term $Fb(\lambda)$ is considerably smaller due to a decrease in
b and, hence, forward scattering after filtration. We measured the spectra of $c^*(\lambda)$ and
$c^*_f(\lambda)$ in the range 350–700 nm, taking records with a wavelength increment of 10 nm.
Relying on these data, the average values of c^* over PAR were calculated (c^*(PAR)).
We found earlier (*Arst et al.* 1996, 1999a,b) that although $c^*(\lambda)$ differs from the real
beam attenuation coefficient, the values of c^*(PAR) can be used for characterizing the
optical quality and transparency of water at different depths (it has a good correlation
with Secchi disk depth data; its values are in correspondence with the summary
influence of water constituents (besides pure water itself) on the light attenuation).

For filtered water the value of $b(\lambda)$ is small and $c^*_f(\lambda)$ can be approximately
considered as the absorption coefficient of dissolved organic matter (yellow substance)
in the water. As known (*Højerslev*, 1980; *Baker and Smith*, 1982; *Mäekivi and Arst*,
1996) the spectra of the absorption coefficient of the yellow substance ($a_y(\lambda)$, in m^{-1})
can be described by the following equation:

$$a_y(\lambda) = a`_y(\lambda_0)C_y \exp\ (-S(\lambda - \lambda_0)) \tag{2}$$

where $a`_y(\lambda_0)$ (in L mg^{-1} m^{-1}) is the specific absorption coefficient of the yellow
substance at the reference wavelength λ_0, S (in nm^{-1}) is the slope parameter, and C_y is
the concentration of the yellow substance (in mg L^{-1}). The following values are rather
widely used: $\lambda_0 = 380$ nm, $a`_y(380) = 0.565$ L m^{-1} mg^{-1} and $S = 0.017$ nm^{-1} (*Højerslev*,
1980; *Baker and Smith*, 1982; *Mäekivi and Arst*, 1996; *Lindell et al.*, 1999; *Kallio*,
1999; *Erm et al.*, 2001), and we accepted these values in our study. As known, the light
attenuation coefficient of yellow substance measured from filtered water samples can be
considered as the sum of the absorption coefficient of coloured dissolved organic matter
(CDOM) and the scattering/absorption coefficient of colloids (extremely small particles
penetrated through the filter), whose values are small in comparison with those for
CDOM (*Bricaud et al.*, 1981; *Davis-Colley and Vant*, 1987). Additionally the dissolved
matter contains also some optically non-active fraction (*Kallio*, 1999). There are two
main ways for characterizing the optical influence of the yellow substance on light
absorption: (1) to present the measurement results of $a_y(\lambda)$ for the reference wavelength
(it is not always 380 nm, also other wavelengths between 350 and 440 nm are used), (2)
to compute the yellow substance concentration (we call it "effective concentration",
$C_{y,e}$) by Eq. (2), using some constant values of λ_0, $a`_y(\lambda_0)$ and S (*Mäekivi and Arst*,
1996; *Arst et al.*, 1996, 1999a,b). Of course, neither $a_y(\lambda)$ nor $C_{y,e}$ can account for the
exact real concentration of the yellow substance as a mixture of different fractions with
variable molecular weight and optical properties, but both are able to give some
approximate estimations on the amount of yellow substance through its optical
influence. We preferred $C_{y,e}$, because (1) in this case analogous concentration units are
used for all optically important water constituents, and (2) the data on $a_y(\lambda_0)$ by
different authors are often presented for different values of λ_0, and thus direct

comparison of these results with one another is impossible. As mentioned before we used $a`_y(380) = 0.565$, obtained by *Højerslev* (1980) (relying on the data of *Nyquist* (1979)) for the Baltic Sea (which is geographically the closest region to our lakes). In a review made by *Baker and Smith* (1982), including results from five different studies of the ocean and coastal waters, $a`_y(380)$ is in one case 2.16 L mg^{-1} m^{-1}, but ranges in the rest of the studies between 0.25 and 0.565 L mg^{-1} m^{-1}. We could find practically no data on $a`(\lambda_0)$ for lakes, except in the investigation by *Kallio* (1999). He determined the values of the special absorption coefficient separately for dissolved organic matter (DOM or yellow substance) and for CDOM. By his results $a`_y(380) = 0.44$ L mg^{-1} m^{-1} and $a`_{CDOM}(380) = 1.01$ L mg^{-1} m^{-1}, the difference is caused by the large amount of optically non-active fraction in lakes under investigation (*Kallio*, 1999).

The concentration of total suspended matter was determined by its dry weight after filtration of the water through cellulose acetate filters (pore size 0.45 μm, diameter 47 mm; Millipore Corporation, Bedford, MA, USA). The same filters were used also to determine the values of $c*_f(\lambda)$. The concentration of chlorophyll *a* was determined by filtering the water samples through Whatman GF/C glass microfibre filters (pore size 1.2 μm, diameter 47 mm; Whatman International Ltd., Mainstone, England), extracting the pigments with hot ethanol (90%, 75°C) and measuring the absorption at the wavelengths 665 and 750 nm. The concentration was calculated by the *Lorenzen* (1967) formula.

We estimated the tripton concentration, C_t (difference between the dry weight of total suspended matter and the dry weight of phytoplankton), using the data of C_{chl} and C_S. Relying on the data by *Reynolds* (1984) the ratio of C_{chl} and the dry weight of phytoplankton is 1:100.

As known, phytoplankton, total suspended matter and yellow substance are the main optically active substances (OAS) in the natural waters. They were determined from water samples, taken from layers, whose number depended on the bottom depth of the lake (in shallow lakes, such as Ülemiste, Maardu and Harku, the typical measurement depths were 0.1 and 1.5–2 m, in deeper Lake Paukjärv the depths between 4 and 8 m were additionally included).

For measuring the downward vector irradiance in a PAR waveband, $E_d(PAR)$, a sensor designed by LI-COR company (LI-192 SA) was used. For determining the vertical profiles of the diffuse attenuation coefficient ($K_d(PAR)$), two LI-192 SA sensors were fastened to a frame with a vertical distance of 0.5 m between them. This arrangement allowed us to measure the downwelling vector irradiance simultaneously at two depths and to determine the values of $K_d(PAR)$ for water layers with a thickness of 0.5 m, the results not being influenced by possible quick variations of incident irradiance. The incident solar irradiance ($E_{d,+0}$) was also recorded by a LI-192 SA or by an integral radiation sensor LI-200 SA. Relying on the measurements of $E_d(PAR)$ the depth-averaged values of diffuse attenuation coefficient ($K_{d,av}(PAR)$) were determined by semi-logarithmic plotting of ln$E_d(PAR)$ vs. depth. As the underwater radiation measurements were not carried out in all campaigns, we could calculate $K_{d,av}(PAR)$ only for 55 cases.

Algal samples taken in May 2000 were fixed with Lugol iodine and analysed qualitatively after settling 10 mL of the sample in the Utermöhl chamber. Species were identified at [x]600 magnification.

The whole set of parameters was measured in 55 campaigns (from 87). The values of OAS concentrations, temperature and oxygen, the spectra of $c*(\lambda)$ and $c*_f(\lambda)$ (thus also $c*(PAR)$) were obtained in all 87 cases. The underwater radiation was measured in 55 campaigns, and the Secchi depth in 68 campaigns (determination of the Secchi depth in Lake Maardu was practically impossible as in most cases the bottom was visible even in the deepest 3.5-m region of the lake). However, the data collected are sufficient to find out some regularities of annual variations and correlations between the bio-optical properties for lakes under investigation.

4.   Results and discussion

4.1   Seasonal variations

Each of the four lakes showed different values of C_{chl} and $c*(PAR)$ in the surface layer (0.1–0.3m) as well as different signatures of annual variations (Fig. 1). However, in most lakes (except Lake Paukjärv) the temporal variation of C_{chl} was rather similar to that of $c*(PAR)$, which confirms a significant role of phytoplankton in forming the under-water radiation field. Comparing the results obtained in the years 1999 and 2000, we see some differences in the location of maximums, but the general character of annual variations, typical of each lake, remained unchanged.

In lakes Ülemiste and Harku the maximum of chlorophyll a developed in the second half of the growing period with C_{chl} values reaching approximately 100 and 1000 mg m^{-3}, respectively (Fig. 1a,b). The vernal chlorophyll peak, reported by *Marshall and Peters* (1989) as typical for temperate eutrophic lakes, was less pronounced. The increase of C_{chl} towards autumn in productive polymictic lakes can be attributed to sediment resuspension as fresh sediments accumulated during summer may contain large amounts of chlorophyll a (*Sinke et al.*, 1991).

In Lake Maardu the typical annual variation of C_{chl} had one or two peaks in the period April – June, but rather small values (less than 10 mg m^{-3}) were observed from July to October (Fig. 1c). This indicated increasing competition between the phytoplankton and macrophytes with the seasonally increasing macrophyte biomass. As shown by *Portielje and Van der Molen* (1999), the macrophyte coverage as low as 5% decreases already significantly the ratio of chlorophyll a to total nutrients. In Lake Maardu, were 75% of the bottom is colonized by macrophytes, phytoplankton can grow only during a short period in spring before the mass development of higher aquatic vegetation. Not only the competition for nutrients but also the increasing shading effect (*Kirk*, 1994), increasing grazing by zooplankton residing in macrophyte communities (*Jeppesen et al.*, 1997), and probably also the allelopathic effects (*Wium-Andersen et al.*, 1982), are included in the competition mechanisms between microalgae and macrophytes.
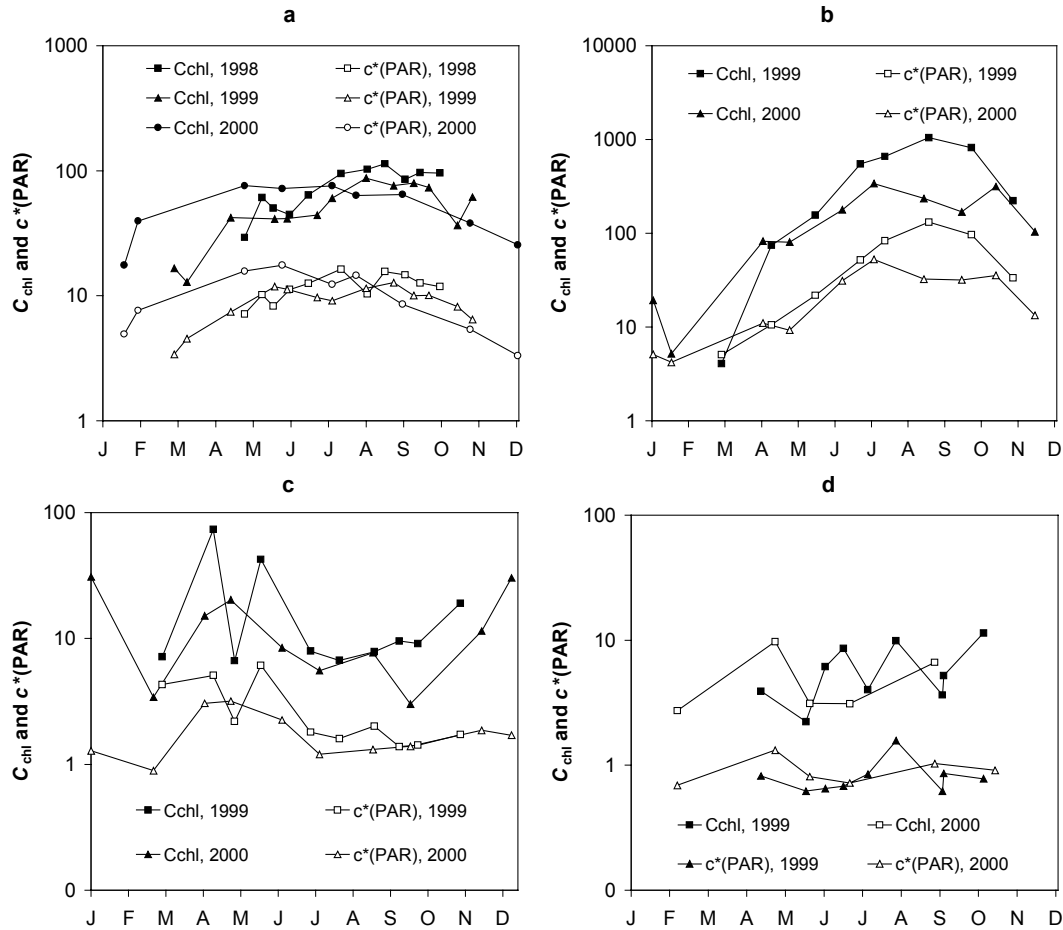
Fig. 1. Annual variations of C_{chl} and $c*$(PAR) (respectively in mg m^{-3} and m^{-1}) in four North Estonian lakes: (a) Ülemiste, (b) Harku, (c) Maardu, (d) Paukjärv.

The value of C_{chl} in the surface layer of oligotrophic Lake Paukjärv was mostly below 10 mg m^{-3}, showing several peaks located differently in 1999 and 2000 (Fig. 1d). In this lake both C_{chl} and $c*$(PAR) have rather inconsistent variations in 1999.

The annual dynamics of C_s and C_{chl} were closely related in Lake Harku, somewhat related in lakes Ülemiste and Maardu, but rather independent in Lake Paukjärv. The maximums and minimums of C_{chl}, $c*$(PAR) and C_s were connected with variations of biological activity, sometimes expressed by large changes (e.g. an intensive algal bloom as in Lake Harku in late summer 1999), but sometimes caused only by small variations in C_{chl} (Lake Paukjärv).

As known, a large fraction of the yellow substance, especially in lakes and coastal waters, may be derived from soil leaching and surface runoff, transported mainly by rivers (*Kalle*, 1966; *Kirk*, 1983; *Kopelevich*, 1983; *Davies-Colley and Vant*, 1987). Therefore, the maximum amount of yellow substance occurs in spring, during some time after ice-break. Yellow substance may be derived also from degradation and breakdown of plankton and other aquatic organisms; thus, after phytoplankton blooms some increase in $C_{y,e}$ is expected. Consequently, the seasonal variation of the yellow

substance concentration depends on the natural conditions in each concrete water body. Our lakes were characterized by different effective concentrations of yellow substance: in Lake Harku the values of $C_{y,e}$ were from 12 to 35 mg L^{-1}, in Lake Ülemiste 9–15 mg L^{-1}, in Lake Maardu 2–17 mg L^{-1}, and in Lake Paukjärv 1–2 mg L^{-1}. Until early autumn the values of $C_{y,e}$ in all the lakes were higher in 1999 than in 2000 (in midsummer in Lake Paukjärv by about 10% and in other lakes by 30%), which probably can be explained by abundant precipitation in summer 1999. A general decreasing tendency of $C_{y,e}$ from April to October was observed, except in Lake Paukjärv, where $C_{y,e}$ even increased slightly in autumn (Fig. 2).
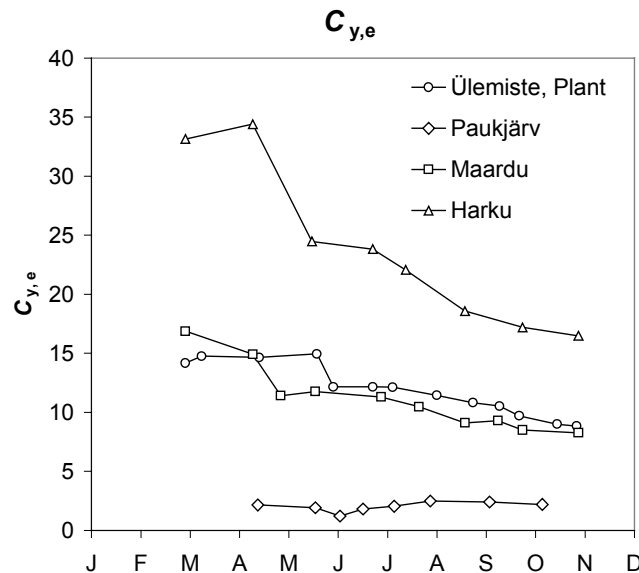

Fig. 2. Annual variation of $C_{y,e}$ (mg L^{-1}) in four lakes in 1999.

The variation range of the Secchi depth (z_{SD}) was 0.1–0.9 m in Lake Harku, 0.3–1.8 m (mostly 0.5–1 m) in Lake Ülemiste, 0.9–>3.5 (bottom) in Lake Maardu, and 4–6.5 m in Lake Paukjärv.

The values of $K_{d,av}(PAR)$ showed a generally similar seasonal dynamics with $c^*(PAR)$ (Fig. 3). The greatest discrepancy between these parameters occurred in Lake Ülemiste in October 1999, when the increase in C_{chl} values was clearly reflected in $K_d(PAR)$ but not in $c^*(PAR)$.

We calculated also the ratio $E_d(1)/E_d(-0)$, which shows the portion of PAR just below the surface that penetrates to the depth of 1 m. In Lake Paukjärv its value is about 45–65% in Lake Maardu 30–40%, in Lake Ülemiste 1–20%, while in Lake Harku it is less than 1% (except in winter and early spring).
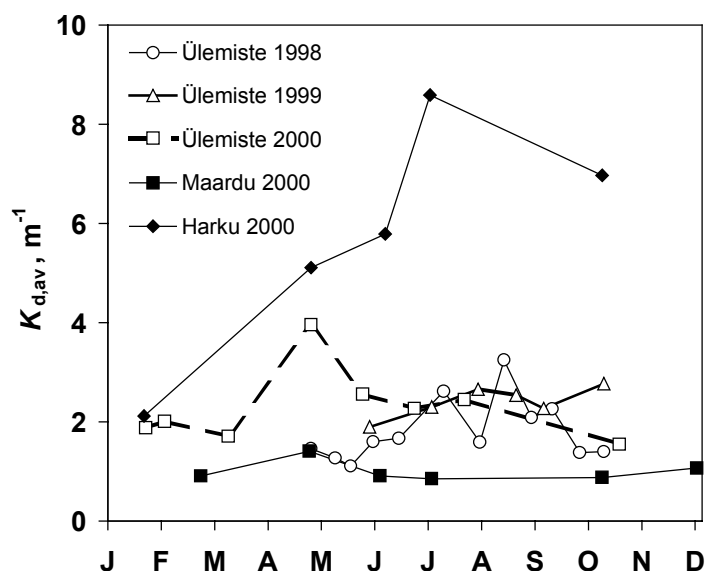
Fig. 3. Annual variation of $K_{d,av}$(PAR) in three lakes.

The values of K_d(PAR) can be used to estimate also the euphotic depth in the PAR region $z_e = 4.6/K_{d,av}$(PAR) if we define it traditionally as a depth where the downwelling irradiance is 1% of that measured just below the water surface (*Dera*, 1992; *Kirk*, 1994; *Tilzer et al.*, 1995). Relying on our data on K_d(PAR), it is possible to estimate the values of the euphotic depth in our lakes. In Lake Harku the values of z_e decreased slowly from spring (2 m) to autumn (about 0.5 m). Lake Ülemiste was characterized by different maximums in different years, the variation range being from 4 to 1.5 m. In Lake Maardu z_e had a minimum in May (3.5 m), but mostly the values of z_e were about 5 m. For Lake Paukjärv we got $z_e = 6–10$ m, but the amount of data for this lake is small.

Lakes Harku, Ülemiste and Maardu are shallow, well mixed and practically unstratified (Table 1). Thus, the vertical changes of OAS were usually only slight (and irregular) in these lakes. In the case of strong winds, resuspension of sediments from the bottom may occur, which makes the bottom layer less transparent (*Erm et al.*, 1999). Lake Paukjärv is considerably deeper and stratified with rather transparent water. In several cases a simultaneous increase in C_{chl} and c^*(PAR) with depth was observed with comparatively high values appearing near the bottom (Fig. 4). In stratified lakes where nutrients are removed from the epilimnion by settling algae, and the metalimnetic density gradient almost isolates the illuminated mixed upper layers from the underlying dark and cold hypolimnion, phytoplankton has to compromise its nutrient and light requirements. In these lakes algal maximums are often found in the metalimnion (*Ichimura et al.*, 1968; *Fee*, 1976; *Nõges and Nõges*, 1998b) where nutrients become available and the light intensity still enables a positive net production. Hypolimnetic chlorophyll *a* peaks have been described by *Fee* (1978) in the Experimental Lake Area. They occurred typically at low light levels (~0.1% of surface light) and at oxygen

concentrations close to zero and were dominated by *Cryptomonas* spp., *Mallomonas elongata*, *Trachelomonas* sp., *Chlamydomonas* sp., and *Euglena* sp.
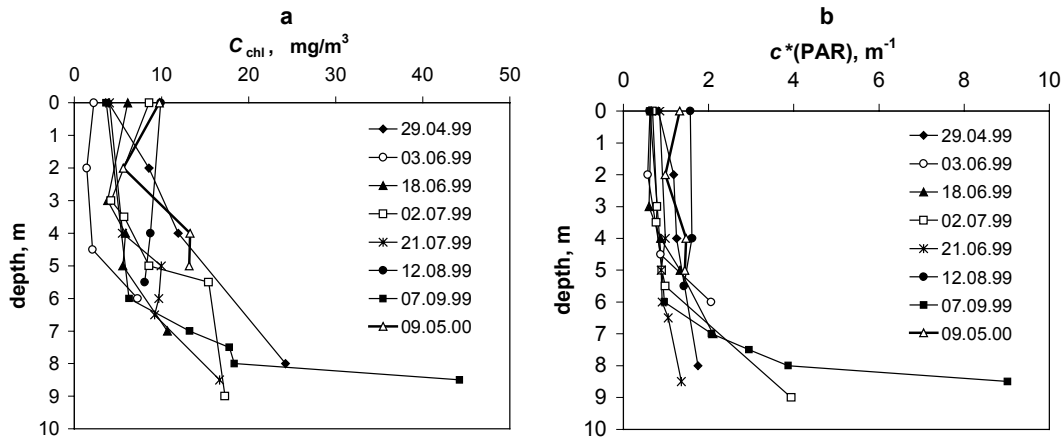

Fig. 4. Vertical profiles of C_{chl} (a) and c^*(PAR) (b) in Lake Paukjärv.

The saturation level of dissolved oxygen in the water was the highest in Lake Ülemiste, varying in the range 80–130 % during the ice-free period and from 45% (at a depth of 4 m) to 145% (under the ice) in winter. In Lake Maardu O_2 varied between 40% and 125% and in Lake Harku from 70% to 140%. In these three shallow lakes the O_2 concentration practically did not change with depth during the ice-free period. In deeper and stratified Lake Paukjärv O_2 concentration was 75–115% at the surface, but could drop to 20% in the bottom layers (8–9 m). In this lake we also observed a metalimnetic oxygen maximum (Fig. 5), which can be caused both by intensive primary production and reduced gas exchange between the water and the atmosphere during the summer thermal stratification.
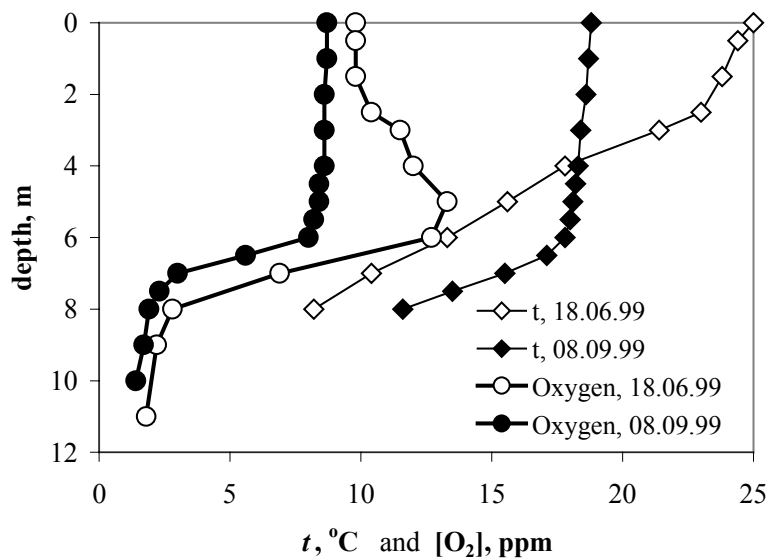

Fig. 5. Two examples of vertical profiles of temperature and dissolved oxygen in Lake Paukjärv.

4.2   Correlations

We investigated the correlation between OAS and optical characteristics for each lake separately and all four lakes together. As known, the nature of these relationships is logarithmic ($\ln c^*$(PAR) vs. $\ln$(OAS)), but we studied also semilogarithmic correlations. The results showed that in most cases the highest values of correlation coefficients were obtained in the case of logarithmic relationships (Table 3). A noteworthy exception is Lake Maardu where the version $\ln c^*$(PAR) vs. (OAS) gives about 10–20% higher values of R than the "logarithmic" version. To explain this result additional measurement data are needed. Note that semilogarithmic correlations $\ln c^*$(PAR) vs. OAS gave considerably higher correlation coefficients than c^*(PAR) vs. $\ln$(OAS). Some examples of logarithmic correlations are presented in Fig. 6.

Table 3. Correlation coefficients (R) between the variables.

y	x	L. Harku	L. Ülemiste	L. Maardu	L. Paukjärv	All lakes together
$\ln C_s$	$\ln C_{chl}$	0.95	0.74	0.36	0.44	0.88
$\ln c^*$(PAR)	$\ln C_{chl}$	0.95	0.87	0.61	0.83	0.92
$\ln c^*$(PAR)	$\ln C_s$	0.94	0.89	0.70	0.65	0.93
$\ln c^*$(PAR)	$\ln C_{y,e}$	-0.60	-0.15	0.63	0.72	0.75
$\ln c^*$(PAR)	$\ln z_{SD}$	-0.94	-0.86	-	-0.71	-0.98
$\ln C_s$	C_{chl}	0.74	0.62	0.44	0.42	0.65
$\ln c^*$(PAR)	C_{chl}	0.86	0.77	0.66	0.83	0.66
$\ln c^*$(PAR)	C_s	0.91	0.84	0.81	0.69	0.71
$\ln c^*$(PAR)	$C_{y,e}$	-0.64	-0.19	0.74	0.61	0.65
$\ln c^*$(PAR)	z_{SD}	-0.85	-0.86	-	-0.68	-0.92

All correlations shown in Table 3 were statistically significant ($p < 0.05$). In most cases data on all depths and all stations were used, except for $\ln c^*$(PAR) vs. $\ln z_{SD}$, where only the sub-surface data were included. As seen from Table 3, the "spectrometric" attenuation coefficient, Secchi depth, and concentrations of chlorophyll a and total suspended matter were very strongly interrelated in Lake Harku. In the other lakes these relationships were weaker (in Lake Ülemiste still rather strong), but $|R|$ mostly exceeds 0.6. Such (comparatively low) values of $|R|$ can be expected when only the "one-lake" data are used. As known, the lakes are multicomponent systems and all three OAS influence simultaneously the water transparency. Hence, relying on the data of one lake we cannot expect a good correlation between water transparency characteristics and some (only one from three) OAS. The highly turbid lakes, where the phytoplankton growth dominates in determining the seasonal variation of optical characteristics, are an exception. Note that for any type of water body data analysis by means of multiple regressions yields higher correlation coefficients (some results are presented below).
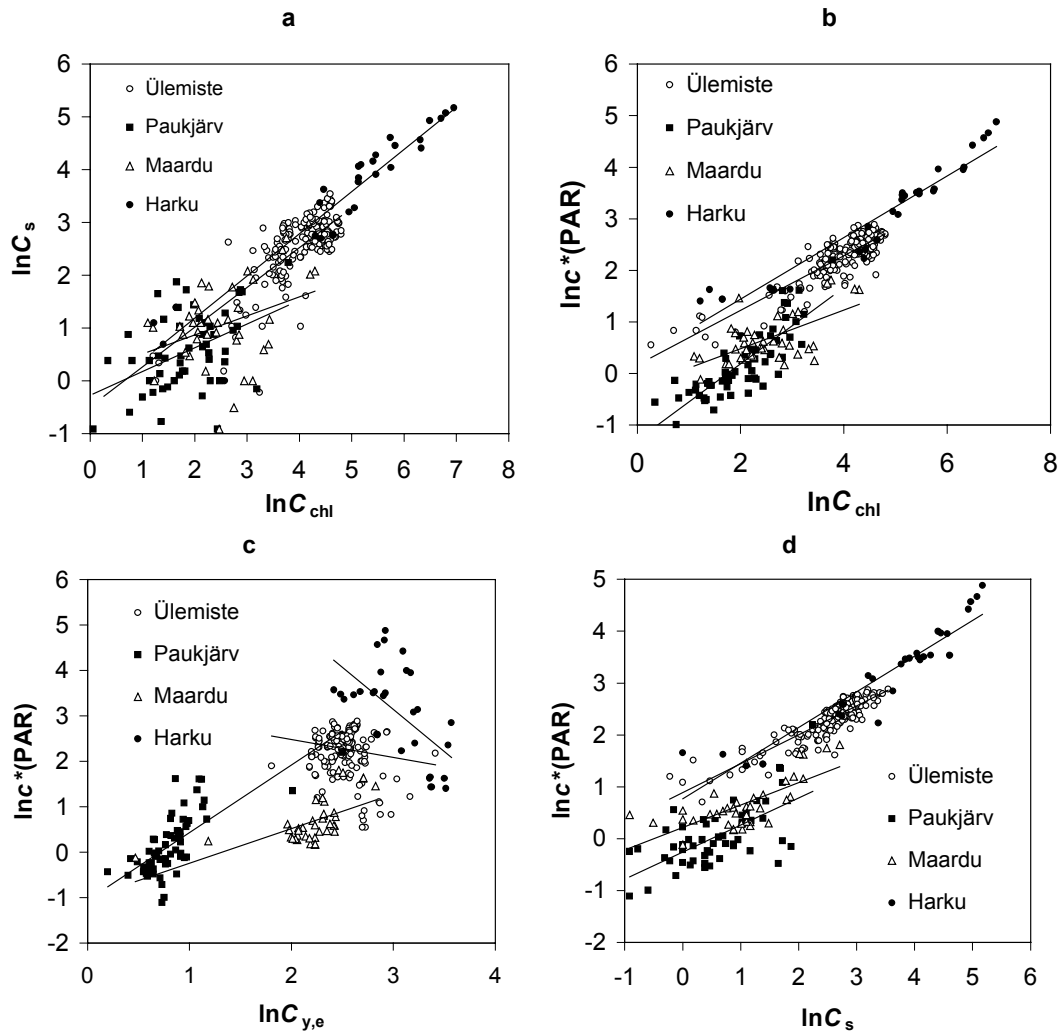
Fig. 6. Correlation between different bio-optical characteristics in four lakes: (a) $\ln C_s$ vs. $\ln C_{chl}$, (b) $\ln c^*(PAR)$ vs. $\ln C_{chl}$, (c) $\ln c^*(PAR)$ vs. $\ln C_{y,e}$, (d) $\ln c^*(PAR)$ vs. $\ln C_s$. The regression lines for each lake are shown separately.

In stratified Lake Paukjärv the values of R in the surface layer were much lower than for the whole water column. In the other lakes the differences were small. The weak (and negative) correlation $\ln c^*(PAR)$ vs. $\ln C_{y,e}$ in turbid lakes Harku and Ülemiste (Table 3 and Fig. 6c) is very interesting. The reason is that in comparison with great temporal variation of phytoplankton and total suspended matter (high concentrations) the temporal change of yellow substance is monotonous and relatively small, not dominating in the formation of maximums and minimums in the seasonal variation of water transparency in these lakes. Of course, we cannot draw the conclusion that yellow substance has no influence on the transparency of the lakes; actually this influence is essential (for "all lakes together" R=0.75). The correlation coefficients $\ln c^*(PAR)$ vs. $\ln z_{SD}$ were rather high (0.86–0.94) for turbid lakes Harku and Ülemiste, and comparatively high (0.71) for Lake Paukjärv. This coefficient for "all lakes

together" was very high (0.98), which confirms the suitability of $c*$(PAR) for the characterization of water transparency.

The regression lines determined separately for each lake differ from each other, but almost always the correlation coefficient for all lakes together exceeded that for individual lakes (Table 3). Indeed, the variation ranges of OAS and optical characteristics, caused by their seasonal variation, as well as by the changing trophic status of the lakes, exceed the respective range caused only by seasonal variation in some separately taken lake. Relying on the data with a large variation range truthful algorithms describing relationships between water properties can be derived. Our results for "all lakes together" show that despite large differences between individual lakes there exists a common general relationship between the variables.

Comparison of the regression algorithms (all lakes together) with corresponding expressions obtained relying on summer measurements in 27 Estonian and Finnish lakes (*Arst et al.*, 1999a) shows a good correspondence only for "ln$c*$(PAR) vs. lnC_{chl}" and "ln$c*$(PAR) vs. lnz_{SD}". The following equations were obtained:

$$\ln c*(PAR) = 0.82 \ln C_{chl} - 1.12$$

$$\ln c*(PAR) = -1.22 \ln z_{SD} + 1.89 \text{ (present work);}$$ (3)

and

$$\ln c*(PAR) = 1.15 \ln C_{chl} - 1.07$$

$$\ln c*(PAR) = -1.21 \ln z_{SD} + 2.02 \text{ (by } Arst \text{ } et \text{ } al., 1999a)$$ (4)

The correlation coefficient between $K_{d,av}$(PAR) and $c*$(PAR) in the surface layer was 0.88 (Fig. 7). An approximately linear relationship was found between the reciprocal of the Secchi depth and $c*+K_{d,av}$(PAR) with a slope factor of 9.8 (N=44, R=0.94). By the results of *Vant and Davies-Colley* (1984) and *Kirk* (1994) this slope varies from 4 to 12.

The diffuse attenuation coefficient for downward irradiance in a natural water can be partitioned into a set of partial diffuse attenuation coefficients, each corresponding to a different component of the medium (water itself K_w, chlorophyll related components K_{chl}, yellow substance K_y and tripton K_t) (*Kirk*, 1994). The nature of their contribution to the light attenuation can vary markedly from one component to another (mainly due to different absorption, scattering or backscattering coefficients). In general, diffuse attenuation will certainly increase when the amount of OAS increases, but it is not linearly related to their concentrations. Therefore the relationships between K_d(PAR) (or $c*$(PAR)) and OAS concentrations were investigated by means of the multiple regression method (instead of total suspended matter the concentration of tripton, C_t, was included). The following expressions were obtained:

$$K_d(PAR) = 0.44(\pm 0.21) + 0.012(\pm 0.002) \, C_{chl} + 0.037(\pm 0.020) \, C_{y,e} + 0.066(\pm 0.017) \, C_t$$

$$N = 44 \quad p < 0.0001 \quad R = 0.93 \quad SE = 0.62$$ (5)

$$c^*(\text{PAR}) = 0.084(\pm0.006)C_{\text{chl}} + 0.14(\pm0.03)C_{\text{y,e}} + 0.39(\pm0.04)C_{\text{t}} - 0.02 \tag{6}$$

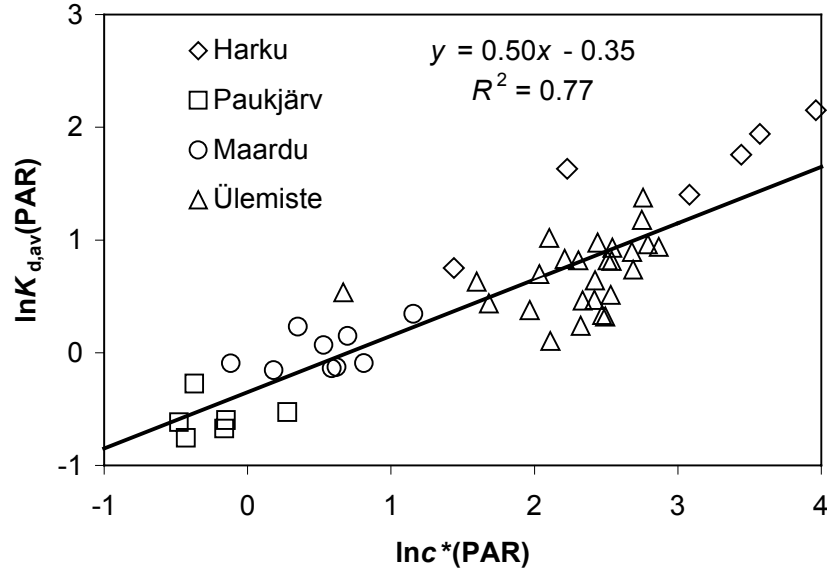$$N = 44 \quad p < 0.0001 \quad R = 0.99 \quad SE = 1.6$$

Fig. 7. Correlation between $K_{\text{d,av}}(\text{PAR})$ and subsurface $c^*(\text{PAR})$.

As $K_{\text{d}}(\text{PAR})$ depends not only on the concentrations of substances, but also on the spectral composition of irradiance, and the conditions of the sky and water surface (which were not taken into account, but probably influence the intercept of Eq. 5), the corresponding correlation coefficient is lower than that for $c^*(\text{PAR})$.

The multiple regression shown in Eq. 6 can be compared with our earlier results. Using the database collected in 1992–95 for 16 Estonian and 5 Finnish lakes multiple regression analysis for $c^*(\text{PAR})$ was performed in *Arst et al.* (1996) and the following expression was obtained:

$$c^*(\text{PAR}) = 0.066C_{\text{chl}} + 0.131C_{\text{y,e}} + 0.280C_{\text{s}} - 0.168, \tag{7}$$

where R(adjusted) = 0.92

We can see that the constants in Eqs. 6 and 7 are rather similar (except the value of intercept). Multiple regression equations can be of practical value: if three parameters from the four are known, it is possible to calculate the fourth.

5.   Conclusions

1.   The annual variations of optically active substances in lakes under investigation were rather different regardless of almost the same synoptic conditions. To some

extent they depended on the trophic status of the lake and water exchange conditions.

2.   In lakes Harku, Ülemiste and Maardu the dominating factor in the annual variations of the optical properties is phytoplankton, despite the rather high values of yellow substance in these lakes. As the annual variation of the content of yellow substance is rather monotonous and relatively small, it is not the cause of the maximums and minimums of the light attenuation coefficient during the year. In clear-water Lake Paukjärv the values of optically active substances and light attenuation coefficients are small, influenced more or less equally by all three OAS, and their annual variations are irregular.

3.   The concentrations of yellow substance are typical for each lake, decreasing from extremely turbid Lake Harku to clear-water Lake Paukjärv. In most lakes (except Lake Paukjärv) the amount of yellow substance decreases from spring towards autumn with a different slope depending on its values in spring.

4.   The correlation coefficient $\ln c^*(\text{PAR})$ vs. $\ln z_{SD}$ for all lakes together was -0.98, which confirms the suitability of $c^*(\text{PAR})$ for the estimation of the optical quality of water. By means of $c^*(\text{PAR})$ we can characterize the water layers at any depth, by z_{SD} only the surface layer. The water samples necessary for the determination of $c^*(\text{PAR})$ can be taken in conditions of low illumination, there is no dependence on the sun's elevation or the properties of human eye.

5.   Despite large optical and biological variability in the lakes investigated, general relationships exist between the measured variables throughout the whole set of lakes. The optical characteristics correlated better with phytoplankton-related variables (chlorophyll *a*, total suspended matter) whereas the content of mostly allochthonous humic compounds was less interrelated with other variables.

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