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Reconstruction of long-term changes of the underwater light field in large shallow lakes Peipsi and Võrtsjärv, North-East Europe

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Abstract. The main objective of our study was to reconstruct the multi-decadal changes of the underwater light field in two large, shallow and polymictic Estonian lakes Võrtsjärv and Peipsi in order (i) to assess the potential role that light limitation may have had on phytoplankton growth in the past and (ii) to get an insight into the factors driving underwater light climate in shallow turbid lakes in the long term. We reconstructed the long-term variations of the diffuse attenuation coefficient of water ($K_{\mathrm{d,PAR}}$) in the photosynthetically active region (PAR, 400–700 nm) partly on the basis of measured beam attenuation spectra and partly using regression analysis. From $K_{\mathrm{d,PAR}}$ we calculated the depth of the euphotic zone ($z_{1\%}$) and the mean light availability in the mixed layer (E_{mix}). The reconstructed time series of these bio-optical parameters gave a plausible picture of the long-term development of light conditions in the two lakes studied, which was in accordance with their eutrophication history and changes in their water levels. Better light availability in both lakes generally coincided with years of a low water level, and the coincidence was more distinct in the shallower Võrtsjärv. Values of E_{mix} revealed a probable light limitation in Peipsi in autumn and in Võrtsjärv throughout the year.

Key words: large shallow lakes, underwater light climate, diffuse attenuation coefficient, seasonal changes, long-term changes.

INTRODUCTION

The underwater light field in lakes, one of the main prerequisites for phytoplankton primary production, results from incident solar radiation, which depends on solar altitude, meteorological conditions, time, and the optical properties of water (Kirk, 1994). The absorption of light by different optically active substances (OAS), i.e. tripton, phytoplankton, and coloured dissolved organic matter (CDOM), leads not only to the attenuation of irradiance with depth but also to a change in its spectral composition. The concentrations of OAS in water can vary by several orders of magnitude (Kirk, 1994; Paavel et al., 2008) with relative contributions of various OAS differing both seasonally and over the range of different types of natural waters (Zhang et al., 2007). In large shallow lakes the influence of resuspended sediment particles on the underwater light field is greater in comparison with that in deeper lakes (Zhang et al., 2007).

The attenuation of light caused by the sum of OAS present in the water can be described mainly by three different metrics of light attenuation: the Secchi depth (Z_{SD}), the beam attenuation coefficient of light determined from water samples (c), and the diffuse attenuation coefficient of light in the water body (K_{d}). A more detailed description of the underwater irradiance could be obtained from vertical profiles at different wavelengths (λ). The main characteristic of these profiles is the spectral diffuse attenuation coefficient, $K_{\mathrm{d}}(\lambda)$ (Dera, 1992; Kirk, 1994; Arst, 2003).

The decrease of irradiance with depth in an optically homogeneous water column is exponential, but theoretically this law is strictly correct only in the case of monochromatic radiation (Dera, 1992; Arst et al., 2000). For photosynthesis and growth of aquatic plants the quantum irradiance in the photosynthetically active

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region (PAR, 400–700 nm) is of primary interest. In many limnological studies the diffuse attenuation coefficient over the PAR band ($K_{\mathrm{d,PAR}}$) is used to describe the vertical decrease of irradiance in the water column (Paavel et al., 2006, 2008; Zhang et al., 2007; Reinart and Pedusaar, 2008). If underwater PAR irradiance at different depths is measured, the average $K_{\mathrm{d,PAR}}$ for a water column can be estimated using the least square fit of the irradiance vs. depth ($K_{\mathrm{d,PAR}}$ is the slope of this exponential regression).

When the value of incoming irradiance just below the water surface, $E_{\mathrm{d,PAR}}(z = -0)$, is known in addition to $K_{\mathrm{d,PAR}}$, the downwelling underwater irradiance at depth z, $E_{\mathrm{d,PAR}}(z)$, can also be calculated. A database containing only $K_{\mathrm{d,PAR}}$ can be used for estimating the relative values of the irradiance at different depths as well as the seasonal and long-term changes of water transparency (Wetzel, 2001; Arst, 2003).

The water layer above the compensation point in which the rate of photosynthesis and respiration become equal is called the euphotic layer. Its lower boundary is often defined as the penetration depth of 1% of the subsurface irradiance ($z_{1\%}$). In shallow lakes the value of $z_{1\%}$ allows estimation of the illuminated bottom area, which is an important parameter for the growth of macrophytes. The average light availability in the mixed water layer (E_{mix}) is the actual value to which phytoplankton is adapted. This value is biologically more relevant than individual light intensities in different water layers.

The main goal of the present study was to assess the potential role that light limitation could have had on phytoplankton growth in the past and to gain an insight into the factors driving the underwater light climate in shallow turbid lakes in the long term. The topic of our work is very important for understanding the ecology and functioning of lacustrine ecosystems. Studies focused on long-term data provide relevant information on the efficiency of management and restoration efforts in lakes impacted by human activities and also promote understanding the factors and processes stabilizing alternative ecological states. To reconstruct the characteristics of the underwater light field ($K_{\mathrm{d,PAR}}$, E_{mix}, and $z_{1\%}$) we used data on phytoplankton, hydrochemistry, and Secchi depth collected from 1964 to 2007 in eutrophic Lake Võrtsjärv and from 1982 to 2007 in mesotrophic/eutrophic Lake Peipsi.

MATERIALS AND METHODS

Study sites

Lakes Peipsi (57°51′–59°01′N, 26°57′–28°10′E) and Võrtsjärv (57º50′–58º30′N, 25º35′–26º40′E) (Fig. 1) are large, shallow eutrophic and polymictic water bodies, well mixed by the surface waves and currents. The lakes are interconnected by the Emajõgi River flowing from Võrtsjärv into Peipsi. Lake Peipsi (surface area 3555 km^2), the fourth largest lake in Europe, is located in the eastern part of Estonia, on the border between Estonia and Russia, and consists of three basins: the largest and deepest northern basin Peipsi *sensu stricto*, the middle narrow basin Lämmijärv, and the southern basin Pihkva (Pskov). The mean depth of the lake is 7.1 m and maximum depth 15.3 m. The mean water residence time is about two years. Lake Võrtsjärv (surface area 270 km^2, mean depth 2.8 m, maximum depth

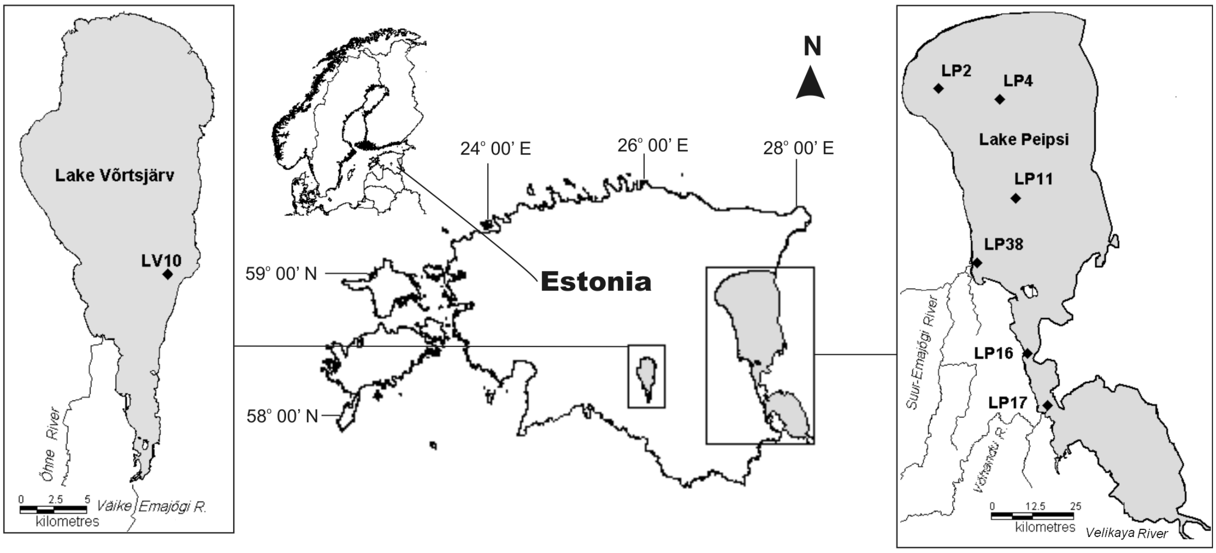

Fig. 1. Location of Lake Peipsi and Lake Võrtsjärv. Sampling points for beam attenuation coefficient measurements and long-term monitoring are indicated with symbols LV10, LP2, LP4, LP11, LP16, LP17, and LP38.

6 m) is situated in the central part of Estonia. The retention time of water in Võrtsjärv is approximately one year, but may differ greatly between dry and rainy years (Jaani, 1990).

The water levels of both lakes are unregulated and have a natural variability strongly associated with the changes in the North Atlantic Oscillation (NAO; Nõges et al., 2010a). The mean annual range of water level fluctuations is 1.4 m in Võrtsjärv and 1.15 m in Peipsi. The lakes are usually covered with ice for four months a year. The shallowness of the lakes and the wave-induced resuspension of bottom sediments contribute to the formation of high seston concentrations and high turbidity. The mean Z_{SD} in Peipsi is about 2 m and in Võrtsjärv less than 1 m. Therefore, among OAS, in addition to being absorbed by humic substances and phytoplankton pigments an important part of light in the PAR region is scattered by suspended particles.

The ratio of catchment area to lake volume (Ohle's index, C/V) is much higher in Võrtsjärv than in Peipsi. As a result, the effect of the catchment on metabolism is larger in Võrtsjärv.

All-year-round monthly hydrochemical and hydrobiological monitoring started in Võrtsjärv in 1961 (Nõges et al., 2001). Wet weight biomass of phytoplankton (PhB) and species composition data are available since 1964 and data on chlorophyll *a* concentrations (Chl *a*) since 1982. In Peipsi phytoplankton and Chl *a* measurements started in 1983. Spectral beam attenuation coefficients were recorded at monthly intervals in water samples of both lakes in 2002–2007.

Calculations of $K_{\mathrm{d,PAR}}$ from beam attenuation spectra

We did not use in situ $K_{\mathrm{d,PAR}}$ measurement data from the lakes mainly because of their scarcity and secondly because of their noisy character due to often high waves on those large lakes. In these conditions, we considered $K_{\mathrm{d,PAR}}$ calculated from the measured beam attenuation spectra more reliable. For the years 2002–2007, for which measured beam attenuation spectra were available, we calculated $K_{\mathrm{d,PAR}}$ from $K_{\mathrm{d}}(\lambda)$ using a model developed by Arst et al. (2002) and Arst (2003). This model was elaborated using 70 spectra of the diffuse attenuation coefficient, measured in situ in 18 Estonian and Finnish lakes and relevant results of the beam attenuation coefficient spectra determined from water samples in the laboratory (altogether 885 individual points). Based on measured $c(\lambda)$ spectra the model determines the ratio $A = b(\lambda_{\mathrm{r}})/c(\lambda_{\mathrm{r}})$, where $b(\lambda_{\mathrm{r}})$ is the scattering coefficient. The reference wavelength $\lambda_{\mathrm{r}} = 580\,\mathrm{nm}$ was chosen. The value of A was computed as a function of water sample measurement results:

$$A = \mathrm{f}\,[c(400), c*_{\mathrm{f}}(400), c(580)], \tag{1}$$

where $c*_{\mathrm{f}}(400)$ is the attenuation coefficient of filtered water at 400 nm. The final values of $b(580)$ and $c(580)$ were found applying the iteration method (Arst et al., 2002; Arst, 2003). Then the spectra of $b(\lambda)$ in the range of 400–700 nm were found using the power law (Herlevi et al., 1999; Arst, 2003). Knowing $b(\lambda)$ and $c(\lambda)$ we calculated the spectra of $K_{\mathrm{d}}(\lambda)$ according to the formulae by Kirk (1984, 1994). Regression between the measured and modelled values of

$$K_{\mathrm{d}}(\lambda, \mathrm{meas}) = 1.0023 K_{\mathrm{d}}(\lambda, \mathrm{calc}),$$
$$\text{with } r = 0.96, \quad p < 0.005, \quad N = 70 \tag{2}$$

showed a sufficient fit allowing the use of the model in further calculations.

To obtain $K_{\mathrm{d,PAR}}$, needed for the reconstruction of the long-term light field, we calculated from $K_{\mathrm{d}}(\lambda)$ the vertical profiles of spectral underwater irradiance, which were integrated over the PAR region. To build a regression between the vertical profile of the PAR irradiance, $E_{\mathrm{d,PAR}}(z)$, and z we found $K_{\mathrm{d,PAR}}$ for each individual case.

Depth-integrated water samples were collected monthly during the ice-free period from March to November from one sampling point in Võrtsjärv and from six sampling points in Peipsi (Fig. 1). Samples were stored in plastic bottles in the dark at 4 °C without any treatment until analyses (for maximum 12 hours). The beam attenuation coefficient of water, $c(\lambda)$, was measured with a Hitachi U-3010 dual-beam spectrophotometer over the region of 280–800 nm using distilled water as the reference:

$$c(\lambda) = c*(\lambda) + c_{\mathrm{d}}(\lambda), \tag{3}$$

where $c*(\lambda)$ is the reading of the Hitachi U-3010 spectrophotometer and $c_{\mathrm{d}}(\lambda)$ is the beam attenuation coefficient of distilled water at the wavelength λ (all in m^{-1}).

The model described by Arst et al. (2002) and Arst (2003) allows for correction of the values of $c(\lambda)$ for forward scattering, and for differentiation of $c(\lambda)$ into its two components, the absorption coefficient, $a(\lambda)$, and the scattering coefficient, $b(\lambda)$. Then, using the formulae developed by Kirk (1984, 1994), the $K_{\mathrm{d}}(\lambda)$ spectra and $K_{\mathrm{d,PAR}}$ values and the corresponding irradiance profiles were calculated for the period of 2002–2007.

Extending the $K_{\mathrm{d,PAR}}$ data series for earlier periods

To extend the $K_{\mathrm{d,PAR}}$ data series for earlier periods (1964–2001 for Võrtsjärv and 1983–2001 for Peipsi), we developed lake-specific backward stepwise multi-

Table 1. Mean phytoplankton biomass (PhB), chlorophyll *a* concentration (Chl *a*), permanganate oxygen demand (COD_{Mn}), water colour, Secchi depth (Z_{SD}), average water depth (Z_{avg}) and standard deviations (SD) in lakes Võrtsjärv and Peipsi during the observation periods indicated. *N* is the number of samples

	Peipsi, offshore (sampling points LP2, LP4, LP11)			Peipsi, inshore (sampling points LP16, LP17, LP38)			Võrtsjärv (sampling point LV10)		
	Mean ± SD	*N*	Obs. period	Mean ± SD	*N*	Obs. period	Mean ± SD	*N*	Obs. period
PhB, g m^{-3}	7.21 ± 6.13	223	1983–2007	11.0 ± 9.78	230	1964–2007	14.9 ± 14.4	639	1964–2007
Chl *a*, mg m^{-3}	18.8 ± 12.7	352	1983–2007	30.0 ± 28.6	215	1982–2007	29.8 ± 20.6	432	1982–2007
COD_{Mn}, mgO L^{-1}	29.3 ± 17.4	218	1992–2007	35.1 ± 8.46	175	1968–2007	11.5 ± 3.7	303	1968–2007
Water colour, Pt-Co°	34.8 ± 9.03	224	1992–2007	62.4 ± 23.9	177	1964–2007	55.9 ± 18.8	206	1964–2007
Z_{SD}, m	1.88 ± 0.78	337	1985–2007	1.30 ± 1.51	199	1968–2007	1.0 ± 0.5	428	1968–2007
Z_{avg}, m	9.32 ± 1.24	246	1983–2007	7.59 ± 1.20	130	1964–2007	2.55 ± 0.44	569	1964–2007

component regression models (Table 1) for calculating $K_{\text{d,PAR}}$ from the Chl *a*, PhB, Z_{SD}, permanganate oxygen demand (COD_{Mn}), and water colour data collected from both lakes at weekly to monthly intervals during the whole study period. The two last variables served as proxies for CDOM. The backward stepwise method used in this study starts with all variables in the regression model and successively removes the variable with the smallest F-to-remove statistic, provided that this is less than the threshold value for F-to-remove. Regression assumes that variables have normal distributions. The box plots and the probability plots of the residuals and the Kolmogorov–Smirnov test were used to check for normality. To avoid collinearity we omitted predictor variables if they were highly correlated with other predictor variables that remained in the model.

Phytoplankton samples were preserved with formaldehyde (until 1994) or acidified Lugol's solution (since 1995). Phytoplankton composition was identified and biovolumes determined in Goryajev's counting chamber (until 1994) or by an inverted microscope at ×400 magnification using the Utermöhl (1958) technique (since 1995). Intercalibration did not reveal any significant differences between these counting methods (Nõges et al., 2003). PhB (g m^{-3}) was calculated from cell numbers and geometry.

For Chl *a* (mg m^{-3}), 0.1–1 L of water was filtered through filters of 0.7 µm pore size, and concentrations were measured spectrophotometrically (Edler, 1979) at a wavelength of 665 nm from 90% acetone (until 1995), 96% ethanol (since 1996), or both (1996) extracts of the filters. There were no significant differences in the extraction efficiency between these two solvents (Nõges and Solovjova, 2000). In 1964–1981, Chl *a* was not monitored in Võrtsjärv and the values were calculated from PhB (g m^{-3}) using the regression obtained from the data of 1982–2007:

$$\text{Chl}\,a = 1.30\text{PhB} + 10.9, \quad \text{with } r^2 = 0.57, \quad p < 0.001, \quad N = 438. \tag{4}$$

We measured Z_{SD} (m) with a 30 cm diameter Secchi disk. COD_{Mn} (mgO L^{-1}) and water colour by Pt/Co scale (or Apha-Hazen scale) were measured as part of the State Monitoring Programme, and data were obtained from the Information Centre of the Estonian Ministry of Environment.

Determination of irradiance characteristics

Incoming irradiance (MJ m^{-2} month^{-1}) for the observation periods was measured at actinometric stations of Tõravere (58°16′N, 26°26′E, about 20 km from Võrtsjärv) and Tiirikoja (on the northern coast of Peipsi, 58°51′N, 26°57′E). These data together with corresponding values of $K_{\text{d,PAR}}$ allowed us to roughly estimate the variation of underwater light field during the observation period. We calculated $E_{\text{d,PAR}}(z)$ according to the following formula (Dera, 1992; Arst, 2003):

$$E_{\text{d,PAR}}(z) = E_{\text{d,PAR}}(z = -0)\exp(-K_{\text{d,PAR}}z), \tag{5}$$

where z is measured in m and $K_{\text{d,PAR}}$ in m^{-1}. By rough estimation the downwelling irradiance just under the water surface (immediately after refraction) $E_{\text{d,PAR}}(z = -0) = 0.934E_{\text{d,PAR}}(z = 0)$, because it is supposed that the reflection coefficient from water surface is approximately 0.066 (Jerlov, 1976).

We calculated $z_{1\%}$ from $K_{\text{d,PAR}}$ as:

$$z_{1\%} = -\ln(0.01)/K_{\text{d,PAR}}. \tag{6}$$

For calculating E_{mix} (Phlips et al., 1995), we first derived an integral (ζ) from irradiance values over depth in the range from $z = 0$ to $z = z_{\text{mix}}$:

$$\zeta = \int_0^{z_{\text{mix}}} E_{\text{d,PAR}}(z = -0)\exp(-K_{\text{d,PAR}}z)\,\mathrm{d}z. \tag{7}$$

According to its definition, $E_{\text{mix}} = \zeta/z_{\text{mix}}$. This leads to the following equation:

$$E_{\mathrm{mix}} = \frac{E_{\mathrm{d,PAR}}(z=-0)}{K_{\mathrm{d,PAR}} z_{\mathrm{mix}}}[1-\exp(-K_{\mathrm{d,PAR}} z_{\mathrm{mix}})], \quad (8)$$

where E_{mix} is in the same units as $E_{\mathrm{d,PAR}}(z=-0)$. In lakes Võrtsjärv and Peipsi, water is typically mixed down to the bottom, therefore z_{mix} was taken equal to the average water depth, Z_{avg}, of the lake (Table 1).

For calculating E_{mix} we converted energy units (MJ $\mathrm{m^{-2}\,day^{-1}}$) into quantum units (mol $\mathrm{m^{-2}\,day^{-1}}$) according to the relationship 1 J $\mathrm{m^{-2}\,s^{-1}}$ = 4.61 µmol $\mathrm{m^{-2}\,s^{-1}}$ in air (Reinart et al., 1998; Reinart and Pedusaar, 2008).

Data analysis

The software Statistica 8.0 (StatSoft Inc., 2007) was applied for analysing the data. Spearman's Rank Order correlation was used to find relationship between indices. The significance level to indicate relationships was set at $p < 0.05$.

RESULTS

Estimates of $K_{\mathrm{d,PAR}}$ from OAS, their proxies, and Z_{SD}

The best stepwise multiple regression model for $K_{\mathrm{d,PAR}}$ included Z_{SD} as the only independent variable for Peipsi and Chl *a* as the only independent variable for Võrtsjärv (Table 2). The best fit for $K_{\mathrm{d,PAR}}$ was achieved with Chl *a* by linear relationship and with Z_{SD} by a power function (Table 2).

Long-term changes of $K_{\mathrm{d,PAR}}$, $z_{1\%}$, and E_{mix}

In Peipsi (1983–2007) the $K_{\mathrm{d,PAR}}$ values were usually about 20% higher and more variable in the inshore sampling points (LP16, LP17, LP38) than in the offshore sampling points (LP2, LP4, LP11) (Figs 2a and 3a, Table 3). Low $K_{\mathrm{d,PAR}}$ values were characteristic of the whole lake at the beginning of the 1990s (e.g., on average 1.1 $\mathrm{m^{-1}}$ offshore and 1.4 $\mathrm{m^{-1}}$ inshore in 1993). Since then, $K_{\mathrm{d,PAR}}$ developed several peaks in the inshore areas, reaching the highest mean values of about 1.9 $\mathrm{m^{-1}}$ in 2002, 2003, and 2007. In offshore areas, the peaks remained much lower (the annual mean value reaching a maximum of 1.4 $\mathrm{m^{-1}}$ in 2004) and lagged behind the inshore peaks by one or two years. The relationship between $K_{\mathrm{d,PAR}}$ and Z_{avg} was statistically significant ($p < 0.05$) in the inshore and non-significant in the offshore areas of Peipsi (Table 4). In inshore areas $K_{\mathrm{d,PAR}}$ will increase when Z_{avg} are high in spring or low in summer and autumn (Table 4).

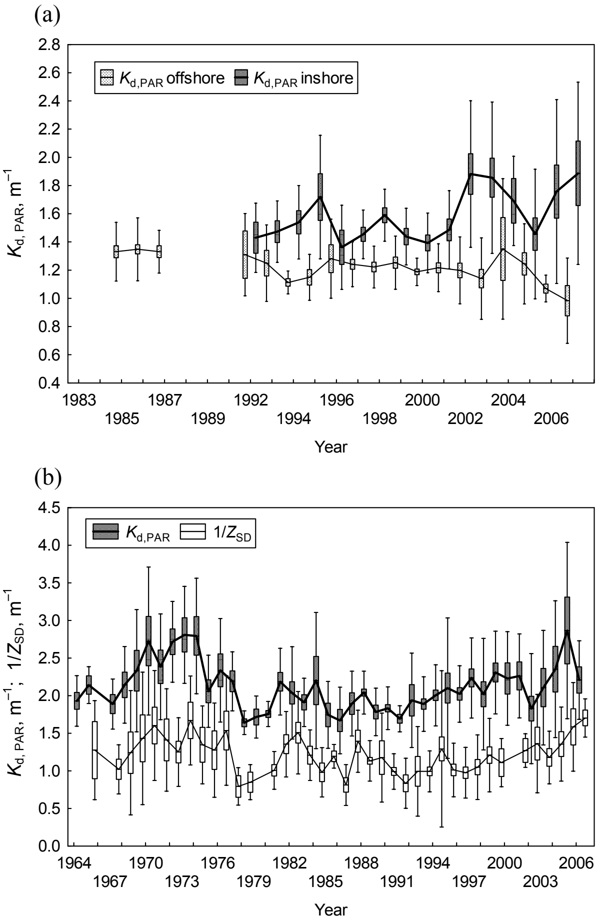

Fig. 2. Long-term changes of the yearly average values of the diffuse attenuation coefficient ($K_{\mathrm{d,PAR}}$, $\mathrm{m^{-1}}$) for the ice-free period (a) in offshore (LP2, LP4, LP11) and inshore (LP16, LP17, LP38) sampling points of Peipsi in 1983–2007 and (b) in Võrtsjärv in 1964–2007. The reciprocal of Secchi depth ($1/Z_{\mathrm{SD}}$) is also shown in Võrtsjärv. Standard error is shown as vertical boxes and standard deviation as vertical lines.

Table 2. Regression formulas describing the relationships between the diffuse attenuation coefficient (K_{dPAR}, $\mathrm{m^{-1}}$) and phytoplankton biomass (PhB, g $\mathrm{m^{-3}}$), chlorophyll *a* concentration (Chl *a*, mg $\mathrm{m^{-3}}$), and Secchi depth (Z_{SD}, m) in lakes Võrtsjärv and Peipsi for the period of 2002–2007. *N* is the number of samples. In all cases $p < 0.001$

y	*x*	Peipsi				Võrtsjärv			
		Relationship	SE	r^2	*N*	Relationship	SE	r^2	*N*
$K_{\mathrm{d,PAR}}$	Chl *a*	$y = 0.02x + 0.998$	0.32	0.59	137	$y = 0.03x + 1.07$	0.59	0.71	43
$K_{\mathrm{d,PAR}}$	PhB	$y = 0.05x + 1.04$	0.36	0.48	143	$y = 0.05x + 1.47$	0.80	0.27	43
$K_{\mathrm{d,PAR}}$	Z_{SD}	$y = 1.72x^{-0.546}$	0.30	0.76	163	$y = 1.73x^{-0.803}$	0.63	0.59	43

Table 3. Mean, minimum, and maximum values of the diffuse attenuation coefficient ($K_{\mathrm{d,PAR}}$, m^{-1}), average light availability in the mixed layer (E_{mix}, mol m^{-2} day^{-1}), and the depth of the euphotic zone ($z_{1\%}$, m) in offshore (LP2, LP4, LP11) and inshore (LP16, LP17, LP38) sampling points of Peipsi in 1983–2007 and in Võrtsjärv in 1964–2007. *N* is the number of samples. Spring is defined as March, April, and May; summer as June, July, and August; autumn as September, October, and November

Sampling area	Season	$K_{\mathrm{d,PAR}}$			E_{mix}			$z_{1\%}$		
		Mean	Min/Max	*N*	Mean	Min/Max	*N*	Mean	Min/Max	*N*
Peipsi offshore	Spring	1.11	0.65/1.72	27	11.6	6.77/18.1	25	4.33	2.67/7.03	27
	Summer	1.22	0.96/2.23	41	14.1	7.02/22.4	39	3.84	2.06/4.81	41
	Autumn	1.38	1.00/1.72	36	3.92	0.73/11.7	36	3.39	2.67/4.60	36
	ALL	1.24	0.65/2.23	104	9.72	0.73/22.4	100	3.81	2.06/7.03	104
Peipsi inshore	Spring	1.35	1.03/1.70	19	11.2	6.33/15.7	18	3.50	2.71/4.46	19
	Summer	1.66	1.25/2.52	33	11.7	5.56/16.2	29	2.87	1.82/3.67	33
	Autumn	1.64	1.18/2.60	30	3.73	0.55/11.3	30	2.92	1.77/3.90	30
	ALL	1.58	1.03/2.60	82	8.48	0.55/16.2	77	3.03	1.77/4.46	82
Võrtsjärv	Spring	1.67	0.88/3.10	119	5.66	2.31/11.6	119	2.91	1.48/5.22	119
	Summer	2.27	1.12/4.19	123	6.50	2.78/11.7	123	2.15	1.10/4.10	123
	Autumn	2.46	1.53/3.96	119	1.83	0.29/4.97	119	1.97	1.16/3.01	119
	ALL	2.14	0.88/4.19	361	4.68	0.29/11.7	361	2.34	1.10/5.22	361

Table 4. Spearman correlation coefficients for the relationship between average light availability in the mixed layer (E_{mix}, mol m^{-2} day^{-1}) and chlorophyll *a* concentration (Chl *a*, mg m^{-3}) and average water depth (Z_{avg}, m) and between average water depth (Z_{avg}, m) and diffuse attenuation coefficient ($K_{\mathrm{d,PAR}}$, m^{-1}) in the offshore (LP2, LP4, LP11) and inshore (LP16, LP17, LP38) sampling points of Peipsi in 1983–2007 and in Võrtsjärv in 1964–2007. Correlation analyses were performed on a seasonal basis. Spring is defined as March, April, and May; summer as June, July, and August; autumn as September, October, and November. *N* is the number of samples and correlation coefficients in bold type indicate $p < 0.05$

Sampling area	Season	E_{mix} vs Chl *a*			E_{mix} vs Z_{avg}			$K_{\mathrm{d,PAR}}$ vs Z_{avg}		
		r	*p*	*N*	*r*	*p*	*N*	*r*	*p*	*N*
Peipsi offshore	Spring	0.16	0.45	24	−0.32	0.12	25	0.14	0.49	27
	Summer	−0.26	0.13	36	**−0.47**	0.00	36	0.05	0.78	41
	Autumn	−0.31	0.07	35	−0.12	0.47	36	0.06	0.71	36
Peipsi inshore	Spring	0.15	0.56	18	−0.40	0.09	18	**0.46**	0.05	19
	Summer	−0.22	0.23	31	−0.12	0.52	31	**−0.45**	0.01	33
	Autumn	−0.26	0.17	29	−0.02	0.93	30	**−0.36**	0.05	30
Võrtsjärv	Spring	−0.16	0.08	119	**−0.36**	0.00	119	**0.19**	0.04	119
	Summer	**−0.64**	0.00	123	0.06	0.48	123	**−0.41**	0.00	123
	Autumn	−0.14	0.12	119	−0.15	0.08	119	**−0.28**	0.00	119

Being a function of $K_{\mathrm{d,PAR}}$, the euphotic depth varied from 1.8 to 4.6 in the inshore areas and from 2.1 to 7.0 m in the offshore areas of Peipsi with corresponding average values of 3.0 and 3.8 m (Fig. 4a, Table 3). In the offshore areas E_{mix} decreased with increasing Z_{avg} in summer whereas no significant correlations with E_{mix} were found in the inshore areas (Fig. 5a, Table 4). The relationship between E_{mix} and Chl *a* was non-significant, although the trend was clearly different for the spring and summer/autumn data (Table 4).

In Võrtsjärv (1964–2007) $K_{\mathrm{d,PAR}}$ was continuously much higher than in Peipsi with annual mean values exceeding 2.0 for most of the time (Table 3). The period of highest $K_{\mathrm{d,PAR}}$ values in Võrtsjärv at the beginning of the 1970s (on average 2.8 m^{-1} in 1973, Fig. 2b) was followed by a decline in the 1980s. As a result of a new growth since 1987, especially in summer and autumn, $K_{\mathrm{d,PAR}}$ reached a peak in 2006 equal to those of the 1970s. In Võrtsjärv both long-term and seasonal changes of $K_{\mathrm{d,PAR}}$ and $1/Z_{\mathrm{SD}}$ followed a similar trend (Figs 2b and 3b). The correlation between $K_{\mathrm{d,PAR}}$ and Z_{avg} was significant and identical to the inshore area of Peipsi (Table 4).

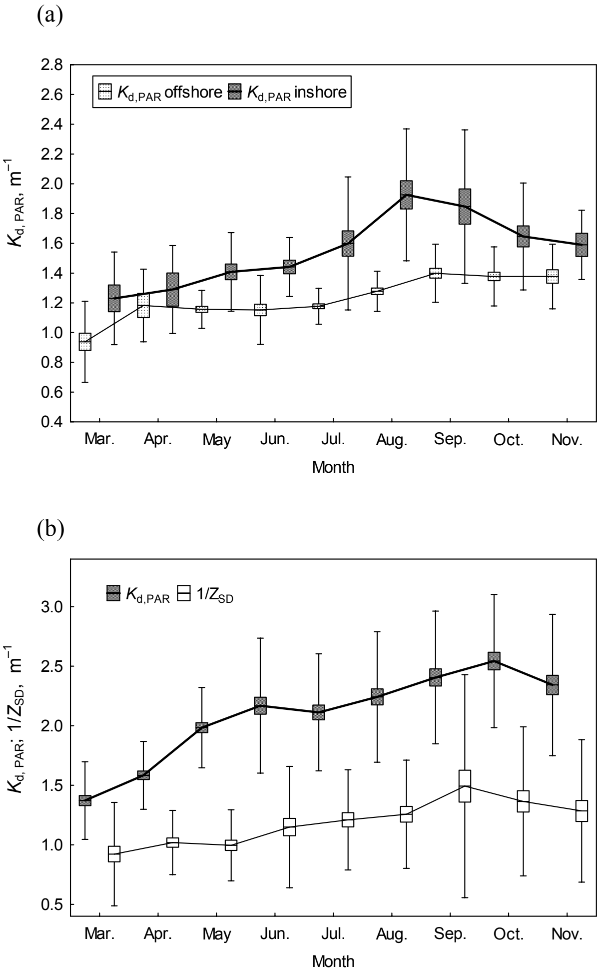

Fig. 3. Seasonal distribution of the monthly averages of the diffuse attenuation coefficient ($K_{d,PAR}$, m^{-1}) for the ice-free period (a) in offshore (LP2, LP4, LP11) and inshore (LP16, LP17, LP38) sampling points of Peipsi in 1983–2007 and (b) in Võrtsjärv in 1964–2007. The reciprocal of Secchi depth ($1/Z_{SD}$) is also shown in Võrtsjärv. Standard error is shown as vertical boxes and standard deviation as vertical lines.

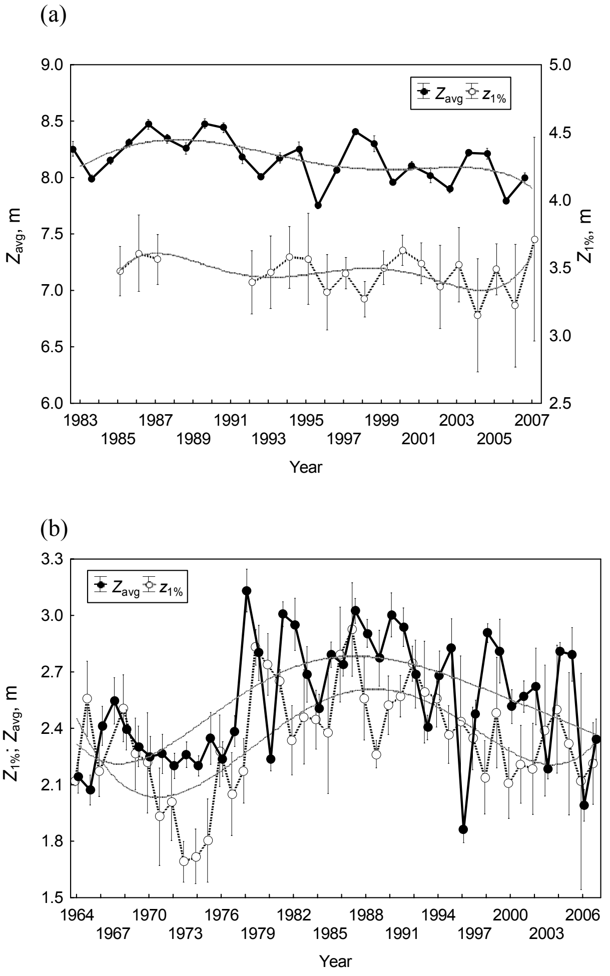

Fig. 4. Long-term changes of the yearly average values of the water depth (Z_{avg}, m) and depth of the euphotic zone ($z_{1\%}$, m) for the ice-free period (a) in Peipsi in 1983–2007 and (b) in Võrtsjärv in 1964–2007. Standard errors are shown as vertical lines and polynomial trends as grid lines.

The euphotic depth varied in Võrtsjärv from 1.1 to 5.2 m (Fig. 4b) having an average value of 2.3 m, which was slightly smaller than the long-term mean depth of the lake (2.8 m). E_{mix} had its annual maximum value (8.25 mol m^{-2} d^{-1}) at the beginning of the study period (1964), the minimum level in the late 1970s, and a slight increase since that time (Fig. 5b). E_{mix} decreased with increasing Chl *a* over summers, and with increasing Z_{avg} over springs (Table 4).

In both lakes the highest $K_{d,PAR}$ values occurred in summer and autumn (Fig. 3a, b; Table 3). Also the interannual ranges were largest in summer and autumn values whereas the spring values were much more stable. In the shallower sites (Võrtsjärv and the inshore area of Peipsi), $K_{d,PAR}$ increased with decreasing water levels (expressed as Z_{avg}) in the summer and autumn series, and was positively correlated in the spring series (Table 4) whilst no significant correlation was found between $K_{d,PAR}$ and water level in the offshore areas of Peipsi. In Võrtsjärv the general long-term dynamics of the euphotic depth followed the water level changes ($r = 0.33$, $p < 0.005$, $n = 361$), but not in Peipsi (Fig. 4). The values of E_{mix} were always much lower in Võrtsjärv than in Peipsi. In both lakes E_{mix} was much higher in spring and summer than in autumn (Table 3).

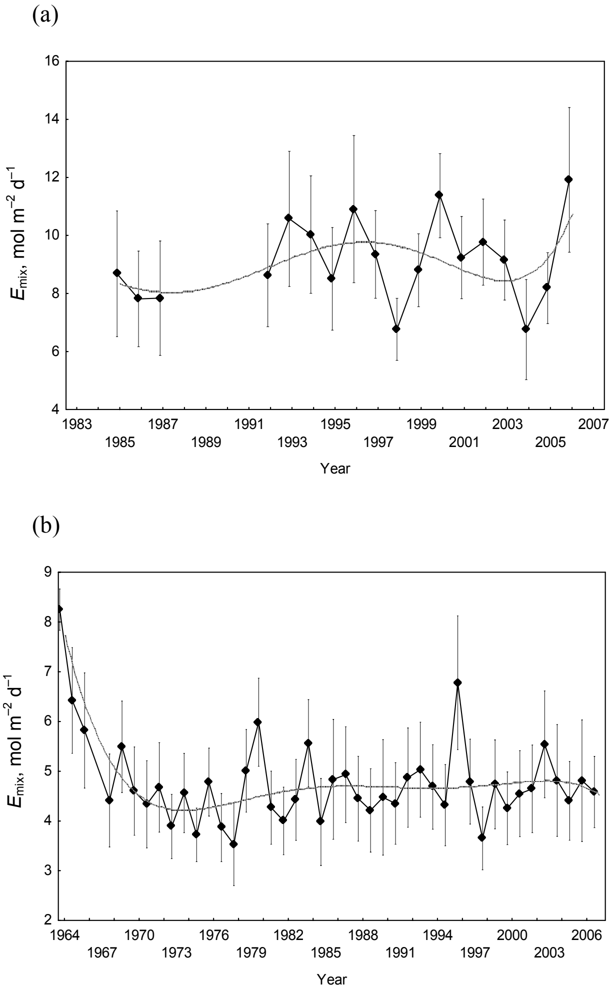

Fig. 5. Long-term changes of the average light availability in the mixed layer (E_{mix}, mol m^{-2} d^{-1}) for the ice-free period (a) in Peipsi in 1983–2007 and (b) in Võrtsjärv in 1964–2007. Standard errors are shown as vertical lines and polynomial trends as grid lines.

DISCUSSION

Correct measurement of light attenuation in situ requires sophisticated and relatively expensive equipment and is easily disturbed by high surface waves, which occur frequently on large lakes; therefore these data are rare in historical data sets. Empirical regressions potentially enable estimation of light attenuation if the concentrations of detritus, inorganic suspended matter, and chlorophyll are measured, but often only chlorophyll is available in data sets (Scheffer, 1998). The long-term data sets that were available for lakes Võrtsjärv and Peipsi included Chl *a*, PhB, Z_{SD}, COD_{Mn}, and water colour.

In Võrtsjärv Chl *a* described 71% of the variation of $K_{d,PAR}$ and was used for long-term calculations (Table 2). The mean Chl *a* was relatively high and varied over a wide range (Table 1). Among OAS, chlorophyll *a* is one of the main components that together with total suspended matter and dissolved organic matter determines the optical properties of water.

In Peipsi Z_{SD} accounted for 76% of the variation in $K_{d,PAR}$ (Table 2) and was used for long-term calculations. Equally strong relationships with similar coefficients of the power function formulae were found by Arst et al. (2008) for 21 Estonian and Finnish lakes. The relationship between $K_{d,PAR}$ and Z_{SD} is strongly dependent on lake type because scattering has a stronger effect on Z_{SD} than on the vertical light attenuation (Wetzel, 2001). For instance, a lake in which turbidity is mainly caused by suspended clay particles, which scatter rather than absorb, will have a lower light attenuation than a lake with the same Z_{SD} in which the turbidity is mainly due to phytoplankton (Scheffer, 1998). The high correlation between $K_{d,PAR}$ and Z_{SD} in Peipsi could be attributed to a presumably stronger effect of algal blooms on optical properties of water compared to suspended mineral particles. In much shallower Võrtsjärv the more intensive resuspension of sediments brings more mineral particles into the water column, affecting strongly the optical properties of water.

Water colour and COD_{Mn} as proxies for CDOM appeared to be less important than Chl *a* or Z_{SD} in describing the variation of $K_{d,PAR}$ in both lakes. It certainly does not mean that CDOM has a marginal effect on light attenuation, but due to the narrow seasonal range of COD_{Mn} and water colour, their impact on the variation in light climate turned out to be weaker than that of PhB and Chl *a*, which both vary over a wide range. Still the positive relationship between $K_{d,PAR}$ and Z_{avg} and the negative relationship between E_{mix} and Z_{avg}, appearing in spring in Võrtsjärv and in the inshore areas of Peipsi (Table 4) was most likely caused by poorer light conditions due to higher concentrations of dissolved organic matter because the concentration of dissolved organic matter is usually high at high water levels in April and May (Toming et al., 2009). Furthermore, according to Reinart and Nõges (2004) and Reinart et al. (2004), up to 53% of light attenuation in the PAR region can be attributed to CDOM in lakes Peipsi and Võrtsjärv. In Võrtsjärv, where $K_{d,PAR}$ was calculated from Chl *a* for most of the period, it could not account directly for CDOM; however, an adaptive response to deeper mixing in darker water resulting in an increase in Chl *a* could be inferred. The negative correlation between $K_{d,PAR}$ and Z_{avg} in summer and autumn months (Table 4) was obvious evidence of the increasing impact of sediment resuspension during the seasonally lowest water levels that carried freshly sedimented algae and chlorophyll *a* back into the water column. According to Nõges et al. (2003), PhB in Võrtsjärv is significantly higher in years of low water level. The decreasing E_{mix}

with increasing Chl *a* in summer reveals the greater relative role of phytoplankton in light attenuation during this time of the year compared to spring and autumn.

Long-term variations of underwater irradiance are controlled by human impact, climate change, and water level fluctuations. The eutrophication of Estonian lakes from agricultural and point sources accelerated since the 1950s (Heinsalu et al., 2007; Heinsalu and Alliksaar, 2009) and culminated in the 1970s and 1980s (Ott and Kõiv, 1999). As a large portion of these nutrients was accumulated in lake sediments and is still supporting high primary productivity of lakes, the decreased pollution loads and use of fertilizers have not caused a corresponding improvement in the bio-optical properties of water. On the contrary: we can see an increase in the reconstructed $K_{\mathrm{d,PAR}}$ series for Võrtsjärv and the inshore areas of Peipsi. The situation is somewhat better in the offshore areas of Peipsi, where the influences of the river discharges and sediment resuspension are smaller (Toming et al., 2009).

Lake depth has a very pronounced impact on the light climate experienced by algae, and thus for their growth rates and realized biomass (Scheffer, 1998). Since algal cells are dispersed throughout the mixed layer, the light they experience depends not only on the $K_{\mathrm{d,PAR}}$ but also on z_{mix}, which in most shallow lakes is the entire water column (Scheffer, 1998). Oliver (1981) showed that the threshold level of E_{mix} for light limitation of phytoplankton standing crop is 3.5 mol m^{-2} day^{-1}. Some other authors have estimated that the range at which light availability is the major factor in controlling the phytoplankton growth is 0.9–4.0 mol m^{-2} day^{-1} (Geddes, 1984), 2.0–3.5 mol m^{-2} day^{-1} (Phlips et al., 1995), and 0.24–3.9 mol m^{-2} day^{-1} (Reinart and Pedusaar, 2008). Minimum E_{mix} values (Table 4) were below the critical threshold in Peipsi in autumn (0.6–0.7 mol m^{-2} day^{-1}) and in Võrtsjärv throughout the year (0.3–2.8 mol m^{-2} day^{-1}), showing that phytoplankton in these lakes could be light limited and that this issue is more critical in Võrtsjärv.

Comparison of Figs 2b, 4b, and 5b gives a good example of the predominant role of the water level in determining the light climate in Võrtsjärv. E_{mix} reached its highest values in low water years in the 1960s and in 1996 and the minimum in 1978, the year of the highest water level. It is noteworthy that the water was most transparent in 1978 and the low E_{mix} can be fully attributed to the high water level in that year. A large change in phytoplankton composition took place at that time with two highly shade tolerant species appearing among dominants (Nõges et al., 2010b). The leading role of water level in the formation of light conditions for phytoplankton can be seen also in the general increase of E_{mix} since the 1970s, which has occurred despite increasing $K_{\mathrm{d,PAR}}$ and which can be explained by the decrease in water levels.

CONCLUSIONS

Reconstruction of the diffuse attenuation coefficient ($K_{\mathrm{d,PAR}}$) based on regressions with optically active substances or their proxies offers a good approach for calculating the euphotic depth ($z_{1\%}$) and the mean light intensity in the mixed layer (E_{mix}). These are crucial parameters for understanding the light conditions for phytoplankton and aquatic macrophytes and indispensable for modelling primary production.

The reconstructed time series of $K_{\mathrm{d,PAR}}$, $z_{1\%}$, and E_{mix} gave a plausible picture of the long-term development of light conditions in the two lakes studied, which was in accordance with their eutrophication history and changes in water levels.

The dependence of bio-optical parameters on water quality and lake levels differed by seasons and sites. In the shallower sites, $K_{\mathrm{d,PAR}}$ increased with decreasing water levels in summer and autumn, which could be attributed to intensified resuspension in low water, and was positively correlated with water level in the spring series, most likely due to larger amounts of dissolved organic matter contained in high flood waters. In offshore areas of Peipsi $K_{\mathrm{d,PAR}}$ remained independent of water level.

The analysis showed the more important role of water level changes compared to changes of $K_{\mathrm{d,PAR}}$ in determining E_{mix} in the shallower Võrtsjärv. In this lake a general increase of E_{mix} occurring since the 1970s, despite increasing $K_{\mathrm{d,PAR}}$, could be explained by the decrease in water levels. E_{mix} is a crucial parameter for phytoplankton photosynthesis and for identifying light limitation. Minimum E_{mix} values remaining below the critical threshold showed that in Peipsi phytoplankton was probably light limited in autumn and in Võrtsjärv throughout the year.

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Veealuse valgusvälja pikaajaliste muutuste taastamine suurtes ja madalates Kirde-Euroopa järvedes (Peipsi ning Võrtsjärv)

Kaire Toming, Peeter Nõges, Helgi Arst, Toomas Kõiv ja Tiina Nõges

Meie töö peamine eesmärk oli taastada veealuse valgusvälja mitme aastakümne pikkused muutused kahes suures madalas ja polümiktilises Eesti järves – Võrtsjärves ning Peipsi järves: a) et hinnata valguse limitatsiooni mõju fütoplanktoni kasvule minevikus, b) vaadelda, mis mõjutavad veealust valgusvälja madalates segunenud järvedes pikal ajaskaalal. Me rekonstrueerisime vee difuusse nõrgenemise koefitsiendi ($K_{\mathrm{d,PAR}}$) pikaajalise varieeruvuse fotosünteetiliselt aktiivses spektri piirkonnas (PAR, 400–700 nm), kasutades nii mõõdetud kiirguse nõrgenemise spektreid kui ka regressioonanalüüsi. $K_{\mathrm{d,PAR}}$-ist arvutasime omakorda eufootilise tsooni sügavuse ($z_{1\%}$) ja järvevee segunenud kihi keskmise valguse kättesaadavuse (E_{mix}). Eelnimetatud biooptiliste parameetrite rekonstrueeritud aegread andsid Peipsi ja Võrtsjärve pikaajalistest valgustingimuste muutustest tõepärase pildi, mis oli kooskõlas eutrofeerumise ajaloo ning veetaseme varieerumisega nimetatud järvedes. Veealused valgustingimused olid üldiselt paremad madalaveelistel aastatel. E_{mix}-i väärtused näitasid, et Peipsi järves on valgus limiteerivaks teguriks suurema tõenäosusega sügisel ja Võrtsjärves kogu aasta jooksul.