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INVESTIGATION OF ESTONIAN AND FINNISH LAKES BY OPTICAL MEASUREMENTS IN 1992–97

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Abstract. Eighteen lakes in Estonia and nine lakes in Finland were investigated during 1992–97, using mainly optical methods. A total of about 200 measurement series were undertaken, but the number was different for each lake. Vertical profiles of solar irradiance (spectral and integral) in the water were measured and the corresponding diffuse attenuation coefficients computed. Relative transparency of the water was determined by Secchi disk depth. Concentrations of chlorophyll *a* and suspended matter were measured from water samples in the laboratory. Spectrophotometrical processing of the water samples (unfiltered and filtered water) was carried out to describe the beam attenuation coefficient spectra and to determine the optical influence of yellow substance in the water. The data obtained show a rather high variability in water characteristics, the differences being sometimes high even for lakes located very near to each other. The concentrations of chlorophyll *a* and suspended matter in the surface layer of lakes varied in the limits 0.3–102 mg m^{-3} and 1.1–145 mg L^{-1}, respectively, and the effective amount of yellow substance from 1.2 to 150 mg L^{-1}. The depth 0.5 m is penetrated by 3.6–86.5% of the subsurface solar irradiance in the PAR region; the depth 2 m, by 0.01–56%. Several lakes are under human impact, which has influenced their water transparency and the degree of eutrophication. Despite rather low values for attenuation depth in lakes, water quality can be estimated using optical remote sensing data.

Key words: lake optics, optical properties of water, optically active substances, underwater light climate.

INTRODUCTION

The properties of the natural aquatic environment and their variations are important in investigating radiative, thermal, biological, and dynamic processes in water bodies. Solar radiation penetrating water diminishes with depth due to a drastic change in the energy spectrum as a result of absorption by various components of the natural water. The propagation of solar radiation in the water bodies is of interest in many areas in oceanography and limnology: light provides the energy that powers primary productivity in the water; light diffusely backscattered from the water column gives a signal for optical remote sensing of subsurface constituent concentrations; solar energy absorbed by the water heats the water body; solar energy absorbed by chemical species (particularly dissolved organics) provides energy for their dissociation (Gordon, 1994). As known, eutrophication and pollution of the water may significantly change the amount and spectral composition of solar radiation penetrating deeper layers of the water body. Thus, the optical characteristics of the water and underwater radiation field may be considered as indicators of the ecological state of that water body.

The marine optics group of the Estonian Marine Institute has carried out hydro-optical measurements in different water bodies (Baltic Sea, Lake Peipsi) since 1987. More systematic investigations started in summer 1992, with the main investigation objects being the Gulf of Riga, Pärnu Bay, and 12 small Estonian lakes. In 1994, a joint project with the Department of Geophysics, University of Helsinki, commenced. It involved five lakes in Finland and eight lakes in Estonia. In 1995 co-operation with scientists from the Võrtsjärv Limnological Station began. The aim of the project was to estimate the ecological situation of lakes using data on their bio-optical characteristics, radiation regime, and eutrophication.

During 1992–97 eighteen Estonian and nine Finnish lakes were investigated, with the number of expeditions to different lakes varying from 1 to 15. Analysis of the results obtained will help us select those lakes most suitable for more intensive investigation and refine our research programme. However, the data gathered so far are of wider interest in a comparative sense. They not only enable a comparison of Finnish and Estonian lakes, but also demonstrate a high variability of water properties in lakes located within a rather small area and in similar climatic conditions.

The programme of our project included four groups of measurements:

1. hydrooptical measurements *in situ*;
2. determination of optical properties of water and concentrations of optically active substances from water samples in the laboratory;
3. passive optical remote sensing (on board a boat);
4. determination of phytoplankton species and primary production in the water bodies.

The present paper comprises only two first sections of the programme. Below some typical examples of results and main conclusions drawn by analysing the data are presented.

MEASUREMENTS AND METHODS

The following characteristics were measured:

1. solar irradiance spectra in the range 300–1100 nm at different depths in the water;
2. downwelling vector irradiance in the PAR region (400–700 nm) at different depths in the water;
3. scalar irradiance in the PAR region at different depths in the water;
4. incident integral solar irradiance above the water surface;
5. relative transparency of the water by Secchi disk depth;
6. beam attenuation coefficient values and effective concentration of the yellow substance in the water for which spectrophotometrical processing of the water samples (filtered and unfiltered water) was carried out;
7. concentrations of chlorophyll *a* and suspended matter (from water samples in the laboratory);
8. solar zenith angle, type and amount of clouds during the measurements.

The investigations started in 1992, at the beginning without underwater light spectra measurements. These data were first obtained in August 1994, but they are absent for 1996. The integral downwelling irradiance in the water, $E_d(z)$ (at several depths z), was first measured with an underwater pyranometer designed in St. Petersburg. Later (from 1995 onward) two underwater radiation sensors have been used, which measure the integral radiation in the PAR waveband: LI-192 SA (for vector irradiance) and LI-193 SA (for scalar irradiance). In 1997 we had already two LI-192 SA sensors and started to measure the vertical change of the diffuse attenuation coefficient of light in the water. For this purpose two LI-192 SA sensors were fastened to a frame so that the vertical distance between them was 0.5 m. It allowed us to measure the downwelling irradiance simultaneously at two depths and to determine the attenuation coefficient for water layers with a thickness of 0.5 m. The incident integral solar irradiance, $E_d(z = +0)$, was also recorded by LI-192 SA, but in some cases (if the underwater spectral measurements were carried out) its values were determined by the radiation sensor LI-200 SA (1 min interval). The spectral distribution of light in the water was measured using a spectrometer LI-1800 UW.

For determining the concentrations of chlorophyll *a* and suspended matter by laboratory methods, the water samples were treated in the Estonian Marine Institute and also by scientists from the Võrtsjärv Limnological Station. For chlorophyll, Whatman glass microfibre filters were used; suspended matter was determined by its dry weight after filtration of the water through cellulose acetate filters (pore diameter 0.45 μm).

The experimental determination of the beam attenuation coefficient is complicated. Theoretically, the beam transmittance should contain no contribution from scattered light, but in reality small-angle forward scattering does reach the detector. The measured transmittance then exceeds the theoretical value and the attenuation coefficient determined from the measured transmittance is smaller than the true value. Zaneveld et al. (1992) and Bricaud et al. (1995) found that for Sea-Tech transmissometers the difference between the actual and measured beam attenuation coefficients is 4–10% of the total scattering coefficient b. We made our measurements with a commercial spectrophotometer Hitachi U1000. The results of measurements show the difference between the beam attenuation coefficient of water under investigation and that of distilled water. By treating the water samples the value $c^*(\lambda)$ is obtained:

$$c^*(\lambda) = c(\lambda) - \Delta b(\lambda) - c_d(\lambda)\,, \qquad (1)$$

where $c(\lambda)$ is the real beam attenuation coefficient, $\Delta b(\lambda)$ is the contribution of small-angle forward scattering to the measured radiation, and $c_d(\lambda)$ is the attenuation coefficient of distilled water (all in m^{-1}). The ratio $\Delta b(\lambda)/c^*(\lambda)$, which characterizes the underestimation of $c(\lambda)$, depends on the scattering properties of the aquatic medium (concentration, type, and size of scattering particles in water). However, our data from the Hitachi spectrophotometer showed that the $c^*(\lambda)$ spectra are rather good indicators of water transparency and quality. Thus, we decided to use these data as one characteristic to describe different water bodies. We called it the "spectrometric attenuation coefficient".

Since it is extremely difficult to determine individual organic compounds of yellow substance, their optical determination has distinct advantages over chemical analytic techniques (Dera, 1992). Using the optical method, the absorption spectra of the filtered water have to be measured. The value of the absorption coefficient (in m^{-1}) at some reference wavelength is often considered as a characteristic of the concentration of yellow substance in the water. These results can be converted to the "effective" concentration of yellow substance (mg L^{-1}), using the well-known formula (Højereslev, 1980; Baker & Smith, 1982):

$$a_y(\lambda) = a'_y(\lambda_0)C_y \exp[-S(\lambda - \lambda_0)], \qquad (2)$$

where $a_y(\lambda)$ (in m^{-1}) is the absorption coefficient of the yellow substance at the wavelength λ, $a'_y(\lambda_0)$ (in L mg^{-1} m^{-1}) is the specific absorption coefficient of the yellow substance at the 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}). Note that neither of the characteristics ($a_y(\lambda)$ or effective C_y) can express the exact real amount of the yellow substance in the water, but both are able to characterize this amount through the optical influence of the yellow substance. We chose the variant of the effective concentration of the yellow substance ($C_{y,e}$) and applied the following parameters in Eq. (2): $\lambda_0 = 380$ nm, $a'_y(380) = 0.565$ L m^{-1} mg, $S = 0.017$ nm^{-1} (Højereslev, 1980; Baker & Smith, 1982; Mäekivi & Arst, 1996). The water samples were filtered through cellulose acetate filters (diameter 0.45 µm) and the corresponding spectra were determined by Hitachi U1000.

Since the scattering of light by filtered water is rather small, it may be assumed that the results of Hitachi measurements give approximately the spectra of absorption coefficients for filtered water samples. The errors caused by the possible influence of the (weak) scattering are discussed in the papers by Bricaud et al. (1981), Davies-Colley & Vant (1987), and Mäekivi & Arst (1996).

The selection of lakes was influenced mainly by two factors: (1) taking into account available information, we tried to choose lakes different in type, and colour and composition of water; and (2) the selection of lakes and the number of expeditions depended strongly on our economic possibilities. The lakes under investigation are listed in Table 1, which also includes information on the expeditions performed in the period 1992–97.

Table 1. Estonian and Finnish lakes studied in 1992–97

Lake	Number of expeditions (and measurement stations)					
	1992	1993	1994	1995	1996	1997
			Estonian lakes			
Äntu Sinijärv	–	–	3(1)	3(1)	–	–
Piigandi	–	3(1)	–	–	–	–
Nohipalu Valgjärv	1(1)	4(1)	3(2)	3(1)	3(1)	2(1)
Kurtna Liivjärv	1(1)	4(1)	–	–	–	–
Kurtna Valgejärv	1(1)	4(1)	–	–	–	–
Kurtna Nõmmjärv	1(1)	4(1)	2(1)	3(1)	2(1)	–
Koorküla Valgjärv	–	–	–	–	2(1)	2(1)
Rõuge Suurjärv	1(1)	3(1)	–	–	–	–
Pühajärv	–	4(1)	–	–	–	–
Jõksi	1(1)	4(1)	–	–	–	–
Pangodi	1(1)	4(1)	–	–	–	–
Nõuni	1(1)	4(1)	–	–	–	–
Tamula	1(1)	4(1)	–	–	–	–
Verevi	–	–	3(3)	3(1)	(1)	2(3)
Uljaste	–	2(1)	2(2)	3(1)	(1)	–
Võrtsjärv	–	–	1(1)	3(1)	3(1)	1(3)
Nohipalu Mustjärv	1(1)	4(1)	2(2)	3(1)	3(1)	–
Paukjärv	–	–	–	–	–	1(1)
			Finnish lakes			
Puujärvi	–	–	–	–	–	2(2)
Päijänne	–	–	–	2(1)	–	–
Vesijärvi	–	–	1(4)	2(3)	2(4)	1(1)
Lammi Pääjärvi	–	–	1(4)	2(3)	1(3)	1(1)
Lohjanjärvi	–	–	–	–	–	2(4)
Valkeakotinen	–	–	–	2(1)	–	–
Tuusulanjärvi	–	–	–	2(1)	2(1)	2(1)
Keravanjärvi	–	–	–	–	–	1(1)
Enäjärvi	–	–	–	–	–	1(1)

RESULTS AND DISCUSSION

Altogether almost 200 measurement cycles were made in the surface layer and, in addition, 30 cycles in deeper layers of lakes. However, in some cases we do not have data for all characteristics. The measurements of suspended matter began in 1993, the underwater spectrometer LI-1800 UW worked from autumn 1994 to autumn 1995, and in summer 1997. As already told, the underwater measurements of vector and scalar irradiances in the PAR region of the spectrum began in 1995. There were also technical problems with LI-192 SA sensors (repeatedly broken contacts), and therefore part of these data are missing. In some (rare) cases the measurement results of some characteristic were obviously wrong (for known or unknown reasons) and were not taken into account. Our database is not uniform: only one lake (Nohipalu Valgjärv) was under investigation during the whole period 1992–97, three lakes during 1992–96, while the others were investigated in different periods (Table 1). So, the data collected do not enable to follow the periodical variations caused by seasons or by changes in the biological activity of the water. However, they give a possibility to find out the characteristic features of each lake and compare these with other lakes.

From measured data some additional characteristics can be computed. Using the spectral values of the light attenuation coefficient, $c^*(\lambda)$ (measured by Hitachi spectrophotometer), its mean value for the PAR region, $c^*(400\text{–}700)$, was calculated. An interesting characteristic is the light transmittance function, $\tau(z)$, which shows the ratio of underwater irradiance (E_d) at some depth z to its value just beneath the surface:

$$\tau(z) = \frac{E_\mathrm{d}(z)}{E_\mathrm{d}(z=-0)}\,. \tag{3}$$

Using the vertical profiles of the PAR-range radiation in the water, the mean values of diffuse vertical attenuation coefficients were determined for downwelling irradiance (K_d) and scalar irradiance (K_0). To do this, a semilog plot of radiation results *vs.* depth was applied, where the attenuation coefficient was found as the slope of the mean straight line through these points. In most cases, it was the best fit for the results obtained in the layer of 0.2–5 m. Thus, it was assumed that the attenuation of solar light is described by the exponential law not only for spectral radiation but also for the PAR region.

$$E(z) = E(z=-0)\exp(-Kz)\,, \tag{4}$$

where E is the vector (or scalar) irradiance at the depth z, $E(z=-0)$ is the same just below the water surface, and K is the mean value of the diffuse attenuation coefficient (K_d or K_0) in the layer from surface to z averaged over depth in the PAR region.

Equation (4) assumes that the diffuse attenuation coefficient is approximately constant in the layer under consideration. If K is determined as described above, its depth dependence is lost. An example of the determination of the mean value of K_d–PAR is shown in Fig. 1. The results describing the vertical change of K_d are presented later.

The spectral measurements with an LI-1800 UW were carried out at depths 0.5, 1, 1.5, 2, 2.5, 3, 4, 5, . . . m. However, quite often the results for some depth were not suitable for determining the $K_d(\lambda)$ values. First, in the conditions of clear sky and (even slightly) rough water surface the spectra of $E_d(\lambda)$ in the surface layer (up to 1.5–2 m) fluctuated strongly. Secondly, in dark, turbid lakes the values of $E_d(\lambda)$ at depths exceeding ~2 m were very small and the corresponding relative error of $K_d(\lambda)$ will be high. For these reasons we determined the spectral values of $K_d(\lambda)$ separately for different layers (from z_1 to z_2), choosing the spectra of $E_d(\lambda)$ and depths suitable for this procedure:

$$K_d(\lambda, z_1, z_2) = \frac{1}{z_2 - z_1} \ln\left[\frac{E_d(\lambda, z_1)}{E_d(\lambda, z_2)}\right]. \tag{5}$$

The $K_d(\lambda)$ data allow us to compute the attenuation depth, $z_K(\lambda)$ (called also penetration depth). It is an important parameter since 90% of the information detected by remote sensing instruments comes from above a depth where downward irradiance has fallen to a level which is 1/e from its value just below the water surface:

$$z_K(\lambda) = 1/K_d(\lambda). \tag{6}$$

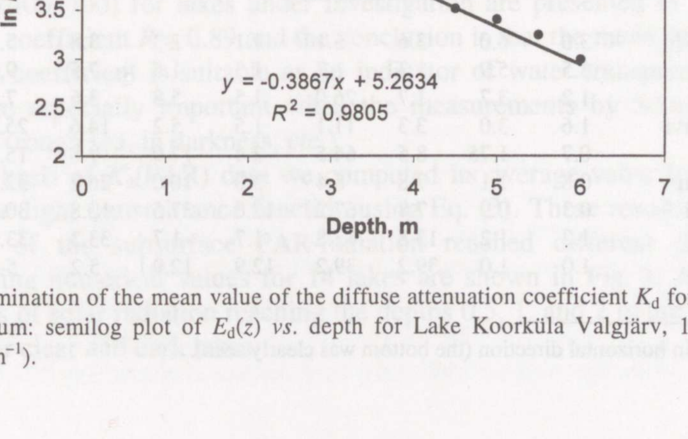

Fig. 1. Determination of the mean value of the diffuse attenuation coefficient K_d for PAR region of the spectrum: semilog plot of $E_d(z)$ *vs.* depth for Lake Koorküla Valgjärv, 17 June 1997 ($K_d = 0.387\ \mathrm{m}^{-1}$).

Considering the whole complex of results obtained, the main conclusion is that the properties of lakes under consideration vary widely. Table 2 presents the minimum and maximum values of Secchi disk depths, z_{SD}, and the concentrations of chlorophyll, yellow substance, and suspended matter. These data show that the variability limits of water properties can be considerably different in different lakes. The chlorophyll *a* content changed from 0.3 to 102 mg m^{-3}, the effective amount of yellow substance from 1.2 to 150 mg L^{-1}, and the concentration of

Table 2. Minimum and maximum values of some water characteristics for the lakes under investigation in 1992–97 (surface layer)

Lake	z_{SD}, m		C_{chl}, mg m^{-3}		C_s, mg L^{-1}		$C_{y,e}$, mg L^{-1}		Number of measurements
	min	max	min	max	min	max	min	max	
Estonian lakes									
Äntu Sinijärv	(15)[a]	(15)[a]	0.3	0.8	2.0	7.2	1.2	4.7	5
Piigandi	4.7	6.0	1.5	2.0	2.0	5.0	4.2	5.8	3
Nohipalu Valgjärv	3.5	6.7	1.2	30.0	1.5	7.0	2.6	8.0	15
Kurtna Liivjärv	3.5	5.6	1.3	7.1	2.0	5.0	4.5	11.0	5
Kurtna Valgejärv	3.3	5.1	0.7	2.6	2.0	7.0	8.4	14.4	5
Kurtna Nõmmjärv	2.5	4.5	0.7	3.3	1.5	10.0	4.0	14.1	13
Koorküla Valgjärv	2.9	4.8	2.3	11.5	2.8	3.4	2.7	10.7	5
Rõuge Suurjärv	2.5	4.2	2.6	3.2	2.0	5.0	6.1	9.1	5
Pühajärv	2.2	3.1	2.2	10.1	1.5	7.0	6.6	7.3	4
Jõksi	2.4	3.2	4.3	11.2	3.8	6.0	10.0	13.0	5
Pangodi	2.0	2.4	2.8	15.3	3.5	8.0	4.6	7.0	5
Nõuni	1.4	2.7	2.4	8.3	5.0	7.5	5.7	8.0	5
Tamula	1.7	2.0	5.7	10.7	5.5	8.0	7.1	13.0	4
Verevi	1.5	3.8	4.4	28.4	1.8	10.3	8.1	13.8	15
Uljaste	1.0	3.4	3.1	45.8	3.0	16.5	8.8	18.4	9
Võrtsjärv	0.15	1.0	25.0	102	5.0	145	9.7	16.4	8
Nohipalu Mustjärv	0.40	0.75	1.7	46.5	2.0	16.0	68	150	13
Paukjärv	5	5	4.2	4.2	3.3	3.3	1.2	1.2	2
Finnish lakes									
Puujärvi	3.0	6.0	3.6	6.1	1.1	2.3	3.8	5.5	3
Päijänne	3.5	5.9	1.3	1.7	1.5	1.5	7.5	9.6	3
Vesijärvi	1.2	3.7	1.7	26.0	1.5	5.8	3.6	7.1	12
Lammi Pääjärvi	1.6	3.0	3.3	11.1	1.5	5.2	14.6	25.2	11
Lohjanjärvi	0.7	1.75	8.5	64.5	3.4	17.9	9.8	15.8	7
Valkeakotinen	0.8	1.1	7.8	8.4	3.0	10.0	26.2	32.7	2
Tuusulanjärvi	0.3	0.9	7.8	67.2	12.0	37.5	10.8	30.6	5
Keravanjärvi	1.2	1.2	13.8	13.8	1.7	1.7	33.3	33.3	1
Enäjärvi	1.0	1.0	39.2	39.2	12.9	12.9	5.2	5.2	1

[a] Determined in horizontal direction (the bottom was clearly seen).

suspended matter from 1.1 to 145 mg L^{-1}. Considering the Secchi disk values we can see that the lakes under consideration were mostly with low transparency, drastically different from ocean water (z_{SD} up to 7 m except Lake Äntu Sinijärv, where the bottom was clearly seen and z_{SD} was estimated horizontally to be about 15 m). It is hard to draw conclusions for one concrete lake comparing it with other lakes, because the duration of observation periods was different. However, C_{chl} for Lake Kurtna Nõmmjärv changed only from 0.7 to 3.3 mg m^{-3} (13 measurements), but for Lake Uljaste from 3.1 to 45.8 mg m^{-3} (9 measurements). Two strongly turbid lakes – Võrtsjärv and Tuusulanjärvi – showed different variability limits for suspended matter: for Võrtsjärv it was from 5 to 145 mg L^{-1}, for Tuusulanjärvi from 12 to 37.5 mg L^{-1}.

Lake Nohipalu Valgjärv showed comparatively high variability of z_{SD} (from 3.5 to 6.7 m), C_{chl} (from 1.2 to 30 mg m^{-3}), and yellow substance (from 2.6 to 8 mg L^{-1}). Lakes Jõksi and Nõuni seemed rather stable (except the C_{chl} values), but there were only five measurement series. Still, some lakes probably have more stable bio-optical properties than others.

The same conclusion can be drawn considering the minimum and maximum values of $c^*(400–700)$ for each lake (Table 3). In this table analogical data for $K_d(\mathrm{PAR})$ and $K_0(\mathrm{PAR})$ are presented. Comparison of these data with the variability limits of z_{SD} (Table 2) shows that the characteristic most sensible to the variation of water transparency is $c^*(400–700)$. This sensibility was estimated by means of the relative variation $\delta(x)$:

$$\delta(x) = \frac{2(x_{\max} - x_{\min})}{x_{\max} + x_{\min}}, \qquad (7)$$

where x stands for the value of z_{SD} or $c^*(400–700)$. The following results were obtained: $\delta(z_{SD}) < 60\%$ for 13 lakes and 60–130% for 9 lakes, but $\delta[c^*(400–700)] < 60\%$ only for 7 lakes and 60–160% for 15 lakes. We reached a similar conclusion earlier, analysing the results of optical measurements for Pärnu Bay (Arst et al., 1992, 1994). There the values of $c^*(400–700)$ varied from 1.5 to 7.3 m^{-1}, but z_{SD} only from 0.7 to 1.9 m. Correlative relationships between z_{SD} and $c^*(400–700)$ for lakes under investigation are presented in Fig. 2. The correlation coefficient $R = 0.89$ and the conclusion is that the mean spectrometric attenuation coefficient is suitable as an indicator of water transparency. These data can be especially important when the measurements by Secchi disk are impossible (rough sea, in darkness, etc.).

On the basis of $K_d(\mathrm{PAR})$ data we computed its average value for each lake and also the light transmittance function using Eq. (3). These results show what proportion of the subsurface PAR-radiation reached different depths. The corresponding numerical values for 14 lakes are shown in Fig. 3. As seen, the percentages of solar radiation reaching the depths 0.5, 1, and 2 m are remarkably different for clear and dark lakes.

Table 3. Minimum and maximum values of $c^*(400–700)$, $K_d(\mathrm{PAR})$, and $K_0(\mathrm{PAR})$ for lakes under investigation (surface layer)

Lake	$c^*(400–700)$, m^{-1}		$K_d(\mathrm{PAR})$, m^{-1}		$K_0(\mathrm{PAR})$, m^{-1}	
	min	max	min	max	min	max
			Estonian lakes			
Äntu Sinijärv	0.2	1.0	0.28	0.32	0.21	0.26
Piigandi	1.6	1.7	–	–	–	–
Nohipalu Valgjärv	0.6	4.7	0.6	1.1	0.46	0.99
Kurtna Liivjärv	1.2	2.7	–	–	–	–
Kurtna Valgejärv	1.4	3.2	–	–	–	–
Kurtna Nõmmjärv	0.9	4.3	0.7	1.2	0.59	0.82
Koorküla Valgjärv	0.9	4.7	0.35	0.85	0.37	0.83
Rõuge Suurjärv	1.5	3.2	–	–	–	–
Pühajärv	1.9	3.4	–	–	–	–
Jõksi	2.7	3.3	–	–	–	–
Pangodi	2.3	3.2	–	–	–	–
Nõuni	2.1	4.7	–	–	–	–
Tamula	2.8	3.7	–	–	–	–
Verevi	1.5	7.5	0.61	1.9	0.69	1.4
Uljaste	1.1	6.7	0.92	3.8	0.84	3.9
Võrtsjärv	3.3	28.2	1.1	19.6	1.2	10.1
Nohipalu Mustjärv	13.7	20.1	3.0	8.3	2.6	6.3
Paukjärv		(1.0)[a]		(0.27)[a]		(0.30)[a]
			Finnish lakes			
Puujärvi	0.7	1.8	0.29	0.48	0.29	0.58
Päijänne	1.3	1.9	0.65	0.85	0.70	0.89
Vesijärvi	1.2	5.3	0.69	1.3	0.65	1.4
Lammi Pääjärvi	1.9	5.4	0.90	2.0	0.90	1.85
Lohjanjärvi	2.1	8.4	0.50	1.9	0.48	1.8
Valkeakotinen	5.1	7.5	2.8	3.4	2.5	3.2
Tuusulanjärvi	8.6	17.8	2.3	4.6	2.4	4.6
Keravanjärvi		(5.3)[a]		(1.3)[a]		(1.4)[a]
Enäjärvi		(5.8)[a]		(0.72)[a]		(0.78)[a]

[a] Only one measurement;
– not determined.

As said above, the measuring system “two sensors LI-192 SA at a constant distance from each other” allows the determination of the values of $K_d(\mathrm{PAR})$ separately for 0.5 m thick layers and then the examination of the vertical change in $K_d(\mathrm{PAR})$ in the water. Let us first consider what kind of vertical change of $K_d(\mathrm{PAR})$ is normal in an optically homogeneous water column. As known, the spectral values $K_d(\lambda)$ (practically its values for very narrow spectral intervals) do not change with depth in an optically homogeneous water body. If there are

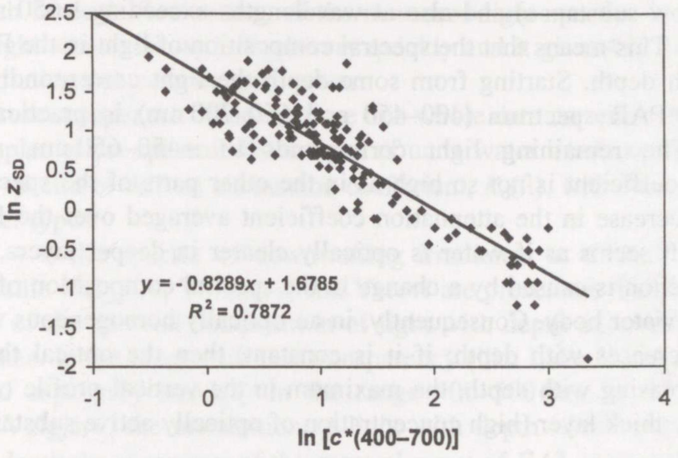

Fig. 2. Correlation lnz_{SD} *vs.* ln[c*(400–700)] obtained for Estonian and Finnish lakes in 1992–97.

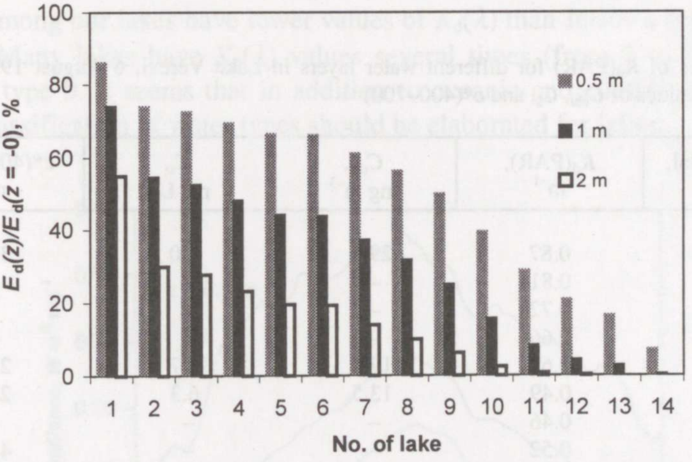

Fig. 3. The values of $E_d(z)/E_d(z = -0)$ computed from K_d(PAR) averaged for each lake: 1, Äntu Sinijärv; 2, Koorküla Valgjärv; 3, Nohipalu Valgjärv; 4, Päijänne; 5, Kurtna Nõmmjärv; 6, Vesijärvi; 7, Verevi; 8, Lohjanjärvi; 9, Lammi Pääjärvi; 10, Uljaste; 11, Võrtsjärv; 12, Valkeakotinen; 13, Tuusulanjärvi; 14, Nohipalu Mustjärv.

variations in the vertical profile of $K_d(\lambda)$ these indicate a decrease or an increase in the water transparency with depth. The situation is different in case of integral radiation (in our case the light integrated over the PAR interval). As known, the absorption of light is very strong in the violet and blue parts of the solar spectrum (due to yellow substance) and also at wavelengths exceeding ~650 nm (due to water itself). This means that the spectral composition of light in the PAR region changes with depth. Starting from some depth the light corresponding to both ends of the PAR spectrum (400–450 and 650–700 nm) is practically totally absorbed. The remaining light corresponds to ~450–650 nm, where the absorption coefficient is not so high as in the other parts of the spectrum. This leads to a decrease in the attenuation coefficient averaged over the PAR range with depth. It seems as if water is optically clearer in deeper layers, but really this phenomenon is caused by a change in the spectral composition of light with depth in the water body. Consequently, in an optically homogeneous water body K_d(PAR) decreases with depth; if it is constant, then the optical thickness of water is increasing with depth, the maximum in the vertical profile of K_d(PAR) shows a very thick layer (high concentration of optically active substances in the water).

As an example, the vertical profile of K_d(PAR) (values for separate layers) measured for Lake Verevi is presented in Table 4. In the same table also the values C_{chl}, C_s, and $c^*(400–700)$ determined for depths 0.5, 2, 2.5, 4, 4.5, and 6 m are shown. These data indicate very low transparency and high concentration of phytoplankton below ~4 m in this lake.

Table 4. Values of K_d(PAR) for different water layers in Lake Verevi, 6 August 1997, and the corresponding values of C_{chl}, C_s, and $c^*(400–700)$

Depth interval, m	K_d(PAR), m^{-1}	C_{chl}, mg m^{-3}	C_s, mg L^{-1}	$c^*(400–700)$, m^{-1}
0.3–0.8	0.87	29.1	6.0	3.06
0.5–1.0	0.81	–	–	–
0.9–1.4	0.72	–	–	–
1.2–1.7	0.66	–	–	–
1.7–2.2	0.62	17.5	5.7	2.69
2.2–2.7	0.49	13.5	6.3	2.75
2.7–3.2	0.46	–	–	–
3.2–3.7	0.52	–	–	4.19
3.7–4.2	1.03	112.7	22.8	9.51
4.2–4.7	1.02	112.4	25.5	17.4
5.9–6.1	–	103.5	18.0	15.5

– not determined.

The data complex describing the spectral distribution of the downwelling and upwelling irradiance at different depths for lakes under investigation is rather large, but varies greatly in its quality. Part of the spectra were measured in stable light conditions, while the others were influenced by a quickly changing cloud cover. Even a slight undulation generates solar flashes in the surface layer of the lakes, which leads to fluctuations of the measured light spectra. In dark, turbid lakes the light attenuates with depth very quickly and it gives big relative errors in small radiation values in deeper layers.

In the present paper we do not analyse this whole data complex. We give only some examples of the spectral distribution of underwater irradiance and compare the typical spectra of diffuse attenuation coefficient, $K_d(\lambda)$, with those for Jerlov's (1976) water types.

In Figs. 4–6 the spectra of downwelling irradiance at different depths for lakes Koorküla Valgjärv, Võrtsjärv, and Verevi are presented. They demonstrate the change of the spectral composition of light with depth and with differences between lakes. In the lakes with low transparency (like Lake Võrtsjärv) the light is absorbed especially strongly in the range 400–500 nm, in the clear lakes (Koorküla Valgjärv) the attenuation of light with depth is more uniform. With increasing depth the maximum of the spectral curve of $E_d(\lambda, z)$ transfers to longer wavelengths. Figure 6 shows the results influenced by subsurface solar flashes; in this case spectra without fluctuations can be obtained only below ~2.5 m.

Figure 7 presents the spectra of $K_d(\lambda)$ typical of lakes under investigation. Comparison with the corresponding spectra of Jerlov's water types shows that one lake – Äntu Sinijärv – is comparable with oceanic type III, and only the clearest among our lakes have lower values of $K_d(\lambda)$ than Jerlov's type of coastal water 9. Many lakes have $K_d(\lambda)$ values several times (from 2 to 8) exceeding those for type 9. It seems that in addition to oceanic and coastal water types a special classification of water types should be elaborated for lakes.

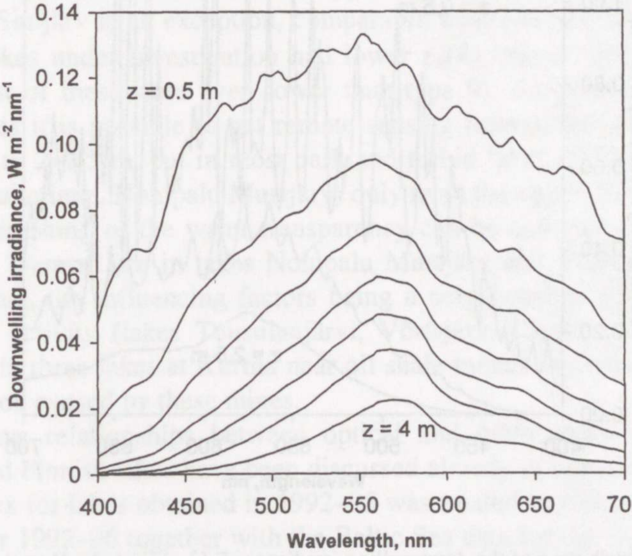

Fig. 4. Spectral distribution of the downwelling irradiance, $E_d(\lambda, z)$, in Lake Koorküla Valgjärv in June 1997 (depths 0.5, 1, 1.5, 2, 2.5, 3, and 4 m).

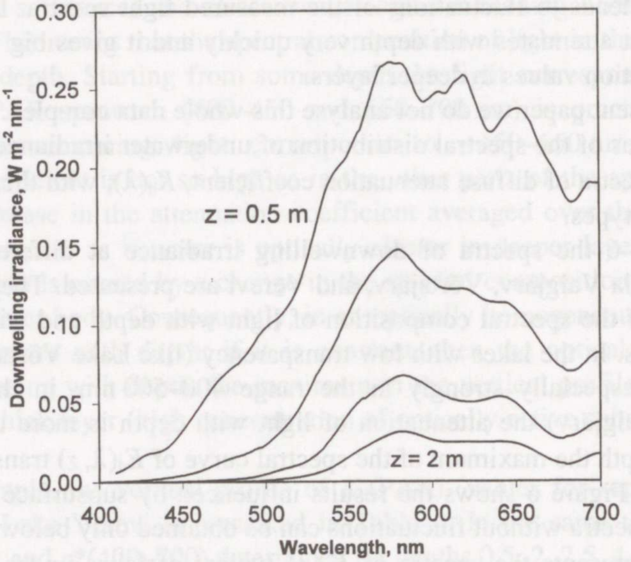

Fig. 5. Spectral distribution of the downwelling irradiance, $E_d(\lambda, z)$, in Lake Võrtsjärv in August 1997 (depths 0.5, 1, 1.5, and 2 m).

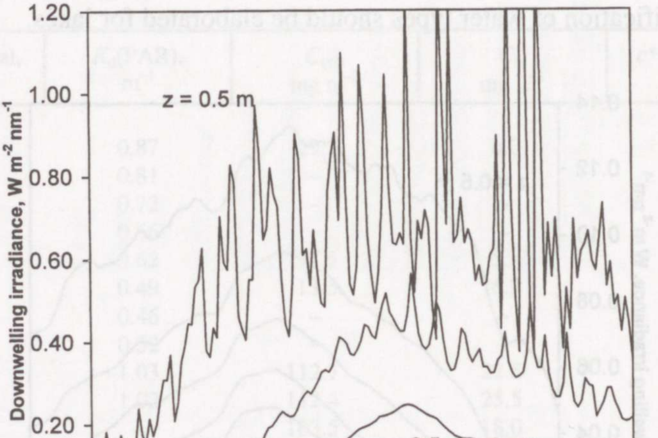

Fig. 6. Spectral distribution of the downwelling irradiance, $E_d(\lambda, z)$, in Lake Verevi in August 1997 (depths 0.5, 1.5, and 2.5 m).

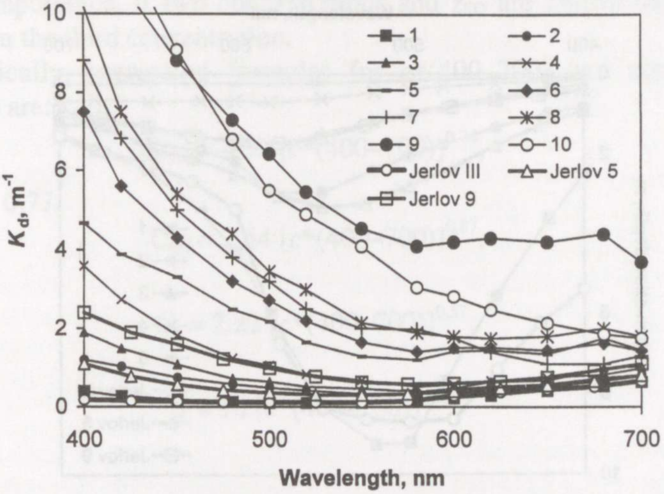

Fig. 7. Spectral distribution of the diffuse attenuation coefficient for downwelling irradiance, $K_d(\lambda)$, measured in Estonian and Finnish lakes: 1, Äntu Sinijärv, Aug. 1995; 2, Paukjärv, June 1997; 3, Nohipalu Valgjärv, Aug. 1997; 4, Päijänne, June 1995; 5, Enäjärvi, Aug. 1997; 6, Uljaste, Aug. 1995; 7, Lammi Pääjärvi, May 1995; 8, Võrtsjärv, June 1995; 9, Tuusulanjärvi, Aug. 1995; 10, Valkeakotinen, May 1995. For comparison also the $K_d(\lambda)$ spectra for Jerlov's (1976) water types III, 5, and 9 are shown.

In Fig. 8 a comparison of the spectral distributions of the attenuation depth for five lakes with those for Jerlov's water types is presented. As already mentioned, Lake Äntu Sinijärv is an exception, comparable with Jerlov's water type III; all the other lakes under investigation had lower $z_K(\lambda)$ values than Jerlov's water type 5 (most of these were even lower than type 9). As seen in Fig. 8, in our clearest lakes it is possible to get remote sensing information from the surface layer down to 2–2.5 m, but in most dark and turbid lakes (Võrtsjärv, Tuusulanjärvi, Valkeakotinen, Nohipalu Mustjärv) only from the upper 20–50 cm.

The diminishing of the water transparency can be caused by natural factors (brown bog waters, like in lakes Nohipalu Mustjärv and Valkeakotinen) or by human impact, the influencing factors being a neighbouring town or long-term agricultural activity (lakes Tuusulanjärvi, Võrtsjärv, Uljaste, Verevi, Tamula, and Jõksi). In three lakes at Kurtna near oil shale mines we found practically no contamination caused by these mines.

Correlative relationships between optical and other characteristics of the Estonian and Finnish lakes have been discussed already in our earlier works. The data complex for lakes obtained in 1992–95 was treated in Arst et al. (1996); the lake data for 1992–96 together with the Baltic Sea data for the same period were considered in Arst et al. (1998). In the present contribution the regression formulas were derived on the basis of data on Estonian and Finnish lakes from

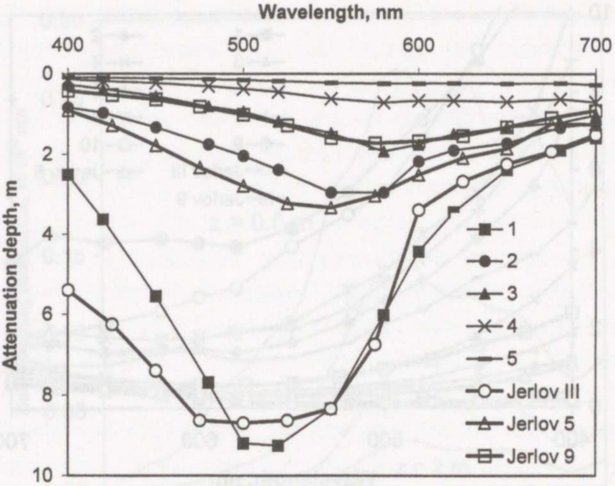

Fig. 8. Spectral distribution of the attenuation depth, $z_K(\lambda)$, computed from the values of $K_d(\lambda)$ by Eq. (6). Lakes: 1, Äntu Sinijärv, Aug. 1995; 2, Paukjärv, June 1997; 3, Päijänne, June 1995; 4, Uljaste, Aug. 1995; 5, Tuusulanjärvi, Aug. 1995. For comparison also the $z_K(\lambda)$ spectra for Jerlov's water types III, 5, and 9 are shown.

1992–97. Considering the relationship between the Secchi disk depth and three main optically active substances we got:

$$C_{y,e} = 18.6\ z_{SD}^{-0.76}\ , \tag{8}$$

where the correlation coefficient $R = 0.68$;

$$C_{chl} = 12.4\ z_{SD}^{-0.96}\ , \tag{9}$$

$R = 0.69$; and

$$C_s = 6.6\ z_{SD}^{-0.67}\ , \tag{10}$$

$R = 0.64$.

As seen, all the correlation coefficients are below 0.7. However, a considerably higher value of R can be obtained for the formal sum of substances

$$S = C_{y,e}\ (\mathrm{mg\ L^{-1}}) + C_{chl}\ (\mathrm{mg\ m^{-3}}) + C_s\ (\mathrm{mg\ L^{-1}}). \tag{11}$$

Then

$$S = 46.8\ z_{SD}^{-0.9}\ , \tag{12}$$

$R = 0.87$.

Of course, Eq. (12) does not allow computing the concentrations of $C_{y,e}$, C_{chl}, and C_s separately, but it demonstrates that the water transparency is determined by joint influence of these substances. This regression formula can be of practical importance, if two concentrations and z_{SD} are known but no data are available on the third concentration.

Analogically, regression formulas for $c^*(400–700)$ and optically active substances are:

$$C_{y,e} = 4.37\,[c^*(400–700)]^{0.74}, \qquad (13)$$

where $R = 0.77$;

$$C_{chl} = 2.54\,[c^*(400–700)]^{0.87}, \qquad (14)$$

$R = 0.66$;

$$C_s = 2.22\,[c^*(400–700)]^{0.57}, \qquad (15)$$

$R = 0.64$;

$$S = 10\,[c^*(400–700)]^{0.82}, \qquad (16)$$

$R = 0.90$.

Comparison of the coefficients in the regression formulas (13)–(16) with those in Arst et al. (1998) (obtained for lakes and the Baltic Sea together in 1992–96) shows that for $C_{y,e}$ both the first coefficient and the exponent differ by 14%, for C_{chl} the corresponding differences are 26 and 8%, for C_s 48 and 52%, and for S 18 and 5%. Note that in our earlier work the correlation coefficient for C_s was only 0.42, so the corresponding regression formula was probably very approximate. The differences in coefficients imply the necessity to collect more data for improving the regression algorithms.

Hence, the regression formulas presented above are not final and universal. They are derived on the basis of measurements in 27 lakes, but only in the summer period. Moreover, the number of measurement cycles for each lake varied between 1 and 15. Most correlation coefficients are not very high (yet exceeding 0.64), but it was often caused by the influence of 5–6 "bad" points. If these doubtful points are left out, the values of correlation coefficients will increase remarkably. Here we can draw the conclusion that our results confirm the possibility that the type and amount of optically active substances in water bodies can be assessed by correlations with their optical characteristics. However, due to the "shadowing effect" (the influence of one substance shadows that of the other) in turbid, multicomponental water bodies, the correlative relationships cannot describe in detail all possible variants of the composition of water.

CONCLUSIONS

1. The investigation objects were Estonian and Finnish lakes, very different in their optical properties. Measurements of hydro-optical, radiative, and other characteristics revealed a great variability of these characteristics, the differences being sometimes high even for lakes situated very near to each other (e.g. Nohi-

palu Mustjärv and Nohipalu Valgjärv). According to our measurements the chlorophyll *a* content changed from 0.3 to 102 mg m^{-3}, effective amount of yellow substance from 1.2 to 150 mg L^{-1}, concentration of suspended matter from 1.1 to 145 mg L^{-1}, beam attenuation coefficient averaged over the PAR region from 0.2 to 28.2 m^{-1}, and downwelling irradiance attenuation coefficient in the water from 0.28 to 19.6 m^{-1}. Probably the range of variation of these properties (from Äntu Sinijärv to Tuusulanjärvi and Nohipalu Mustjärv) describes the variability limits for all other Estonian and Finnish lakes.

2. The spectrometric light attenuation coefficient, determined from water samples in the laboratory, and its value averaged over the PAR range are good characteristics of water transparency. They have especially high practical importance, if measurements by Secchi disk are impossible (strong undulation, in darkness, etc.).

3. The relative amount of light energy at different depths varies remarkably from lake to lake: if in Lake Äntu Sinijärv 75% of subsurface light (PAR region) penetrates to a depth of 1 m, then in Lake Verevi about 40%, in Lake Võrtsjärv ~7%, and in Lake Nohipalu Mustjärv practically no light reaches this depth.

4. Comparison of the spectra of irradiance attenuation coefficient for Estonian and Finnish lakes with those for Jerlov's oceanic and coastal water types shows that only one lake is comparable with oceanic type III and only the clearest from these lakes have lower $K_d(\lambda)$ values than Jerlov's "darkest" coastal water type 9. Rather a big number of lakes show $K_d(\lambda)$ values exceeding 2–8 times those for Jerlov's type 9. It implies a necessity to elaborate a classification for lakes, additionally to ocean and coastal water classifications.

5. Correlative connections between the concentrations of optically active substances in the water and optical (including remote sensing) characteristics are mostly nonlinear and can be described by the power law. As can be expected, the correlation coefficient is higher for the sum of concentrations than for each optically active substance separately.

6. Although the observation period was almost six years (from summer 1992 to autumn 1997), the measurements were rather episodic (1–4 measurement series a year, mostly in different lakes). Therefore, it was impossible to follow the periodical variations caused by seasons or changes in the biological activity of the water. However, some lakes (Jõksi, Tamula, Piigandi, Nohipalu Mustjärv, Vesijärvi, Lammi Pääjärvi) seem to be more stable by their properties than others. Lakes Uljaste, Verevi, Nohipalu Valgjärv, Tuusulanjärvi, and Kurtna Nõmmjärv gave rather variable results.

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OPTILISED UURINGUD EESTI JA SOOME JÄRVEDEL 1992–97

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Aastatel 1992–97 uuriti kaheksatteist Eesti ja üheksat Soome järve, kasutades peamiselt optilisi meetodeid. Selle aja jooksul tehti 200 mõõteseeriat, kuid nende arv ei olnud iga järve puhul sama. Mõõdeti päikese kiiritustiheduse (nii spektraalse kui ka integraalse) vertikaalset jaotust vees ning arvutati vastavad difuusse kiirguse nõrgenemiskoefitsiendid. Vee relatiivne läbipaistvus määrati Secchi ketta abil. Laboris mõõdeti klorofüll *a* ja heljumi kontsentratsioon veeproovidest. Filtreeritud ja filtreerimata vett töödeldi spektromeetriliselt eesmärgiga kirjeldada suunatud kiirguse nõrgenemiskoefitsiendi spektreid ja hinnata kollase aine optilist mõju vees.

Saadud andmed näitavad vee omaduste suurt varieeruvust uuritavates järvedes. Klorofüll *a* ja heljumi kontsentratsioon järvede pinnakihis oli vastavalt 0,3–102 mg m^{-3} ja 1,1–145 mg L^{-1} ning kollase aine efektiivne hulk 1,2–150 mg L^{-1}. Sügavusele 0,5 m jõuab 3,6–86,5% PAR-regiooni (400–700 nm) kiirgusest, mis on mõõdetud vahetult veepinna all, sügavusele 2 m 0,01–56% sellest kiirgusest. Mõned järved on olulise antropogeense koormuse all, mis rohkem või vähem mõjutab nende vee läbipaistvust ja eutrofikatsiooni määra. Vaatamata kiirguse nõrgenemissügavuse väikestele väärtustele on võimalik hinnata järvede vee kvaliteeti optilise kaugsondeerimise meetodil.