Proc. Estonian Acad. Sci. Biol. Ecol., 1999, **48**, 1, 63–74
https://doi.org/10.3176/biol.ecol.1999.1.05

OPTICAL MEASUREMENTS IN LAKE ÜLEMISTE

Ants ERM, Helgi ARST, Medhat HUSSAINOV, Tiit KUTSER,
and Anu REINART

Estonian Marine Institute, Paldiski mnt. 1, 10137 Tallinn, Estonia; ants@phys.sea.ee

Received 1 June 1998

Abstract. Some optical measurements were performed in Lake Ülemiste in summer 1997. Lake Ülemiste is the main drinking water reservoir of Tallinn, the capital of Estonia. Consequently, all investigations of its water quality and underwater light climate are of special importance. Five measurement series in each of four sampling stations were carried out from May to August. Vertical profiles of downwelling irradiance in the PAR region of spectra were determined, the relative transparency of the water was estimated by Secchi disk. Concentrations of chlorophyll *a* and suspended matter were determined in the laboratory from water samples. Spectrophotometrical processing of the filtered and unfiltered water was carried out to describe the beam attenuation coefficient spectra and the optical influence of yellow substance in the water. Passive optical remote sensing measurements were made from board a boat. Results obtained show that the water of Lake Ülemiste is optically turbid, comparable with such lakes as Võrtsjärv in Estonia and Lohjanjärvi in Finland. The chlorophyll content varied from 21 to 50 mg m^{-3}, that of the suspended matter from 5 to 22 mg L^{-1}, the effective concentration of yellow substance from 10 to 20 mg L^{-1}. About 25% of the subsurface irradiance (in the PAR range) reaches the depth of 0.5 m and only 5% penetrates to 1.5 m. Lake Ülemiste is often optically stratified, thicker layers occurring near the bottom.

Key words: drinking water, lake optics, water properties, underwater light climate.

INTRODUCTION

The optical properties of natural water environments, the amount of solar energy and its spectral composition in and above the water bodies are of interest not only to physical and biological oceanographers, but also to those interested in water pollution estimations and responsible for lake management. Underwater organisms need for life besides nutrients and oxygen also solar light. Deviations from the normal balance in any of these can have negative influence on the living conditions in the water. Eutrophication or water pollution may significantly change the amount and spectral composition of solar radiation penetrating deeper layers of the water body. Investigations of the optical characteristics and underwater irradiance within a water body are rather efficient tools for estimating its ecological state and water quality. Such estimations are especially important for water bodies functioning as reservoirs of drinking water.

Measurements of some optical parameters of Lake Ülemiste were carried out in summer 1997. Lake Ülemiste is the main drinking water reservoir of Tallinn. The area of the lake is 9.6 km^2 and its volume is 0.024 km^3. The average depth is 2.5 m and the maximum depth is nearly 6 m. Lake Ülemiste lies on the North-Estonian Plateau, 35.7 m above sea level. It separated from the sea about 8000 years ago. Today Lake Ülemiste is marshy, having an almost 8 m thick layer of sediments on the bottom. The main influx goes through the Pirita Channel, the only outflux through the Water Treatment Plant. The water level varies up to ±1 m. Ülemiste is a typical eutrophic lake. The reaction of water is alkaline all over the year (pH = 7.6–8.6). The water contains large amounts of calcium (70 mg L^{-1}), bicarbonates (~200 mg L^{-1}), and sulphates (~45 mg L^{-1}).

Lake Ülemiste borders on the city of Tallinn and (from the other side) on an airport. A highway is proceeding near the lake. It means considerable human impact on Ülemiste. In addition, there is a possibility that the lake is contaminated through the Kurna watercourse, which passes a populated region.

In summer 1997 the measurements were carried out in four stations: near the mouth of the Pirita Channel (station Pirita), near the pumping station of the Water Treatment Plant (station Plant), in the centre of the lake (station Centre), and near the mouth of the Kurna watercourse (station Kurna). A chart of Lake Ülemiste with the location of these four stations is presented in Fig. 1.

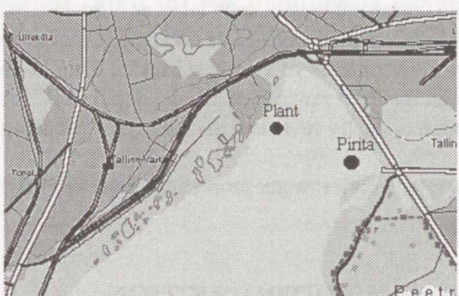

Fig. 1. Lake Ülemiste near the capital of Estonia, Tallinn, with sampling stations.

MEASUREMENTS AND METHODS

Three groups of measurements were made:

1. *In situ* underwater measurements: (a) relative transparency of the water, z_{SD} (Secchi disk depth); (b) vector and scalar irradiances in the PAR region (400–700 nm) of the solar spectrum at different depths in the lake (E_d(PAR) and E_0(PAR)).

2. Processing of the water samples in the laboratory: (a) determination of the light attenuation coefficient spectra of filtered and unfiltered water ($c_f*(\lambda)$ and $c*(\lambda)$); (b) measurement of the concentrations of chlorophyll *a* and suspended matter (C_{chl} and C_s) in the water.

3. Passive optical remote sensing of the lake on board a boat: spectra of the water-leaving radiance, $L_u(\lambda)$, and incident solar irradiance, $E_d(0,\lambda)$.

The measurements were carried out with underwater quantum sensors LI-192 SA (for E_d(PAR)) and LI-193 SA (for E_0(PAR)). From the measured underwater irradiances the values of diffuse attenuation coefficients, K_d(PAR) and K_0(PAR), were determined for separate layers (with a thickness of 0.5 m) and averaged over the depth value. The beam attenuation coefficient measurements were carried out using a commercial spectrophotometer Hitachi U1000. The results of the measurements give us the difference between the beam attenuation coefficient of water under investigation and that of distilled water. By spectrophotometrical processing of 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 the water). To elaborate a method for estimating the correction $\Delta b(\lambda)$ for Hitachi U1000 special, complicated investigations are needed. However, an analysis of our earlier data (Arst et al., 1995, 1996, 1998) shows that $c*(\lambda)$ spectra and their values averaged over the PAR region, $c*(400\text{–}700)$, are rather good indicators of water transparency and quality.

Hitachi U1000 was also used to measure the spectra of filtered water and the values of $c_f*(\lambda)$ were obtained:

$$c_f*(\lambda) = c_f(\lambda) - c_d(\lambda). \qquad (2)$$

As the scattering coefficient $b_f(\lambda)$ for $c_f*(\lambda)$ is practically zero, also $\Delta b_f(\lambda) = 0$ and the values of $c_f*(\lambda)$ are approximately equal to the absorption coefficient of yellow substance, $a_y(\lambda)$ (there is actually a small discrepancy, caused by the influence of colloids penetrating the filter (Mäekivi & Arst, 1996)). However, we assumed that in the ultraviolet part of the spectrum:

$$a_y(350\text{ nm}) = c_f^*(350\text{ nm}). \quad (3)$$

The amount of yellow substance in the water was described by means of its effective value, $C_{y,e}$, which is calculated using the data on a_y at the wavelength 350 nm (Arst et al., 1996):

$$C_{y,e} = 1.06\, a_y(350\text{ nm}), \quad (4)$$

where $C_{y,e}$ will be in mg L^{-1}.

Note that neither $a_y(\lambda)$ nor $C_{y,e}$ can express the real amount (by weight) of yellow substance in the water, but both are able to characterize this amount through its optical influence. However, since it is extremely difficult to determine individual organic compounds of yellow substance, the optical determination has distinct advantages over chemical analytic techniques (Dera, 1992).

The concentration of suspended matter was determined by its dry weight after filtration of the water through cellulose acetate filters (firm Sartorius, pore diameter 0.45 µm). The same filters were used also to determine the values of $c_f^*(\lambda)$. For chlorophyll *a* a standard method based on measuring the absorption of dissolved in ethanol phytoplankton at 665 nm was used.

For remote sensing measurements a spectrophotometer ST 1000, designed by Ocean Optics Inc. (USA), was used. From the measured spectra of $L_u(\lambda)$ and $E_d(\lambda)$ the values of remote sensing reflectance, $r(\lambda)$, were calculated:

$$r(\lambda) = \frac{L_u(\lambda)}{E_d(\lambda)/\pi}. \quad (5)$$

Our measurements were only episodic as we had no possibilities to carry out continuous or regular measurements. The measurements were performed on 21 May, 6 June, 25 June, 15 July, and 27 August 1997. Note that remote sensing measurements were carried out only on 27 August.

RESULTS AND DISCUSSION

The variability limits of bio-optical parameters for Lake Ülemiste are shown in Table 1. Here three stations are quite similar to one other, while the station Pirita is distinguished by a higher transparency of water and also by a bigger amount of yellow substance. However, the light attenuation coefficient in deeper layers (1.5–2 m) had often bigger values for Pirita than for the other stations. For this reason the averaged by depth light attenuation coefficient for Pirita is similar to those of the other stations.

Table 1. Variation of bio-optical parameters of Lake Ülemiste from 21 May to 27 August 1997

Parameter	Variability limits			
	Pirita	Centre	Kurna	Plant
SD, m	1–1.75	0.7–0.9	0.7–1.0	0.75–1.2
C_{chl}, mg m^{-3}	13–44	31–49	31–50	29–50
$C_{y,e}$, mg L^{-1}	12–20	10–13	11–14	11–13
C_s, mg L^{-1}	8–21	16–26	20–25	10–27
$c^*(400–700)$, m^{-1}	4–12	6–14	7–14	6–12
K_d(PAR)[a], m^{-1}	1.1–1.7	1.1–2.2	1.1–2.1	1.6–2.0

[a] Measured for the layer 0.5–1.0 m.

Two spectra of $c^*(\lambda)$ obtained for Lake Ülemiste are compared with those for other lakes in Fig. 2. We can see that the waters of Ülemiste are similar to the turbid lakes Võrtsjärv and Tuusulanjärvi (Secchi disk depth 0.75 and 0.5 m, chlorophyll *a* concentration 40 and 68 mg m^{-3}, respectively). The spectra of comparatively clear lakes (Nohipalu Valgjärv, Paukjärv, $Z_{SD} = 4.5–5$ m) are far away, the spectrum of Lammi Pääjärvi shows high values of $c^*(\lambda)$ only in the blue region, which is due to the high amount of yellow substance in this lake.

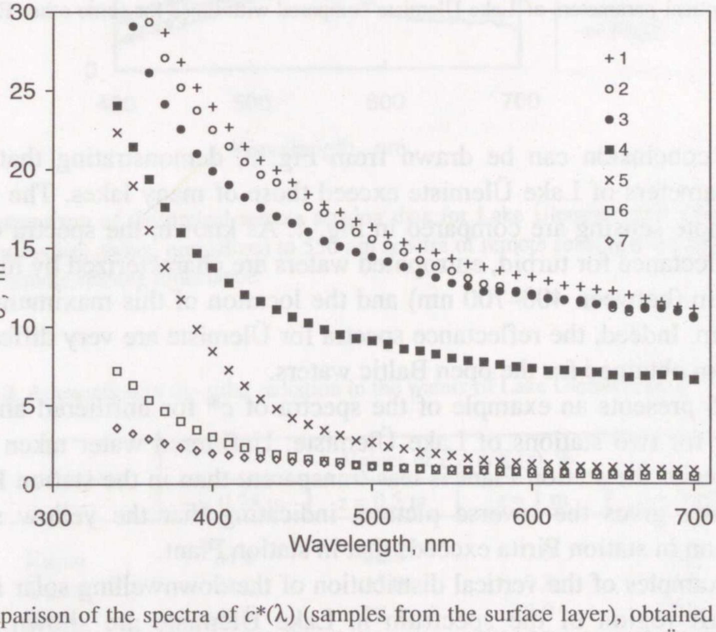

Fig. 2. Comparison of the spectra of $c^*(\lambda)$ (samples from the surface layer), obtained for different types of lakes: 1, Tuusulanjärvi (14.08.97); 2, Võrtsjärv (16.06.97); 3 and 4, Ülemiste (Centre, 25.06.97 and 10.06.97); 5, Lammi Pääjärvi (station 5, 13.08.97); 6, Nohipalu Valgjärv (10.08.97); 7, Paukjärv (15.06.97).

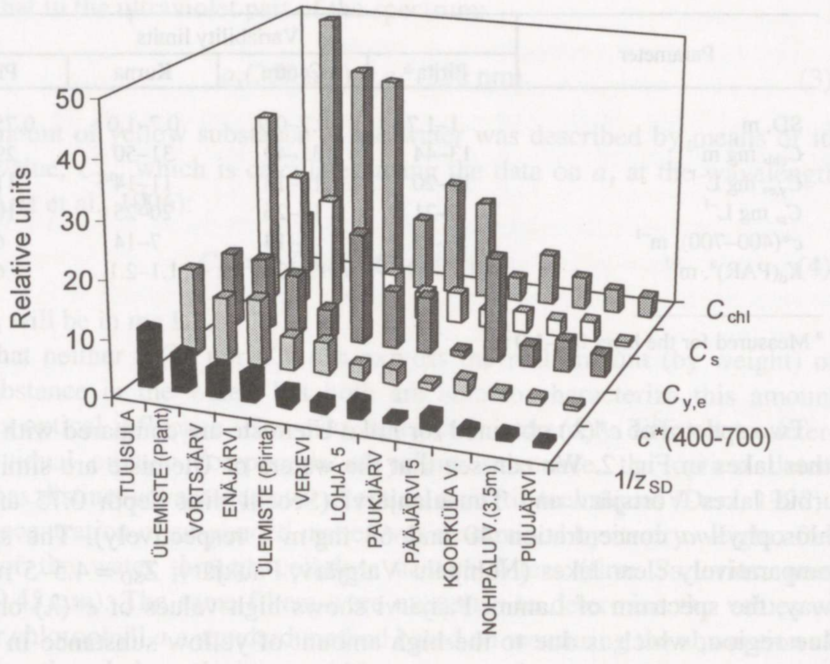

Fig. 3. Bio-optical parameters of Lake Ülemiste compared with those for some other Estonian and Finnish lakes.

The same conclusion can be drawn from Fig. 3, demonstrating that the bio-optical parameters of Lake Ülemiste exceed those of many lakes. The results of optical remote sensing are compared in Fig. 4. As known, the spectra of remote sensing reflectance for turbid, eutrophied waters are characterized by high values of maximum (between 400–700 nm) and the location of this maximum between 550–650 nm. Indeed, the reflectance spectra for Ülemiste are very different from the spectrum obtained for the open Baltic waters.

Figure 5 presents an example of the spectra of c^* for unfiltered and filtered (c_f^*) water for two stations of Lake Ülemiste. Unfiltered water taken from the surface layer of the station Plant is less transparent than in the station Pirita, but filtered water gives the reverse picture, indicating that the yellow substance concentration in station Pirita exceeds that in station Plant.

Some examples of the vertical distribution of the downwelling solar irradiance for the PAR region of the spectrum in Lake Ülemiste are shown in Fig. 6 (27 Aug. 1997, four stations). Table 2 gives information on how much irradiance from incident irradiance reaches different levels.

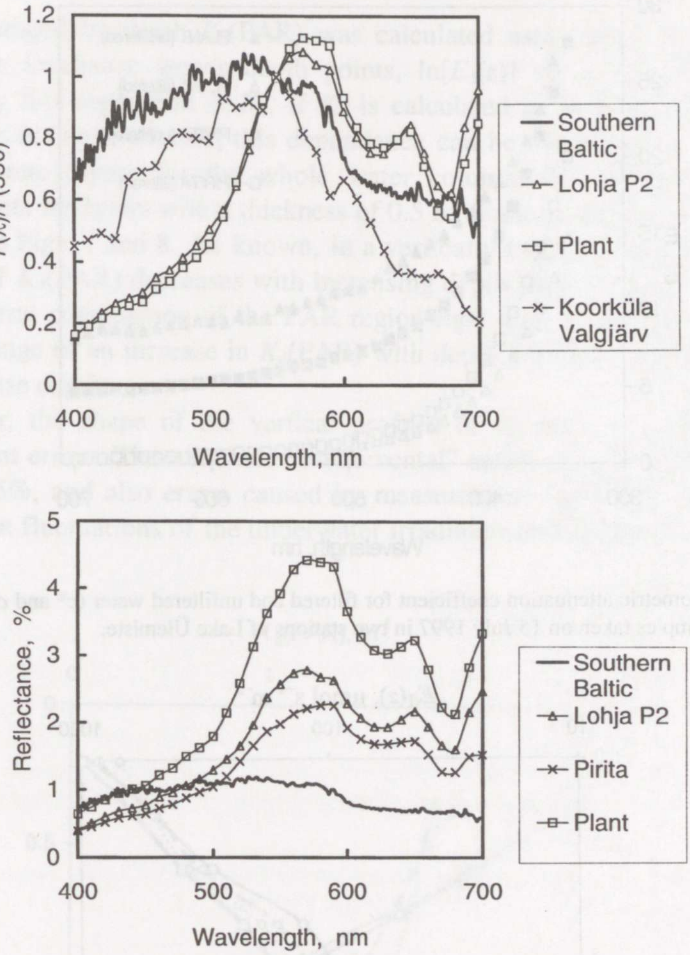

Fig. 4. Comparison of the optical remote sensing data for Lake Ülemiste with those obtained for other water bodies: above, normalized to 550 nm spectra of remote sensing reflectance $r(\lambda)$; below, spectra of remote sensing reflectance.

Table 2. Attenuation of the solar radiation in the waters of Lake Ülemiste on 27 August 1997

Station	Values of $E_d(0)/E_d(z)$, %			
	$z = 0.25$ m	$z = 0.5$ m	$z = 1$ m	$z = 1.5$ m
Kurna	34.8	22.8	7.6	4.0
Centre	44.2	25.0	7.8	4.6
Pirita	42.9	27.8	10.9	5.9
Plant	31.0	22.1	7.8	4.3

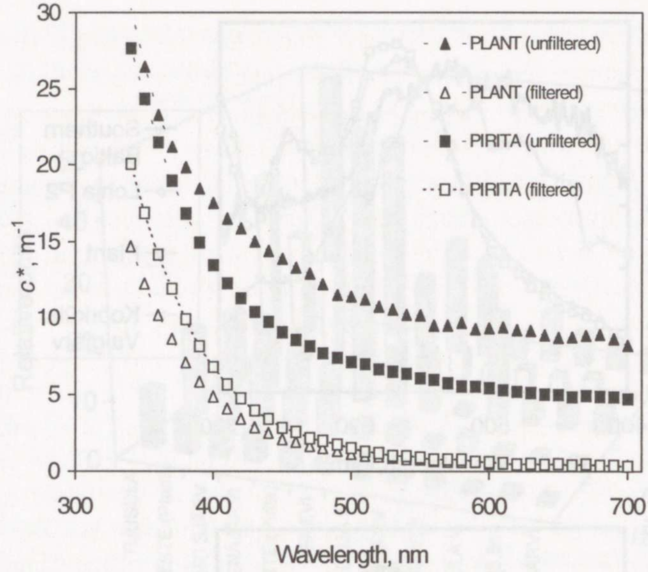

Fig. 5. Spectrometric attenuation coefficient for filtered and unfiltered water (c^* and c_f^*), measured from water samples taken on 15 July 1997 in two stations of Lake Ülemiste.

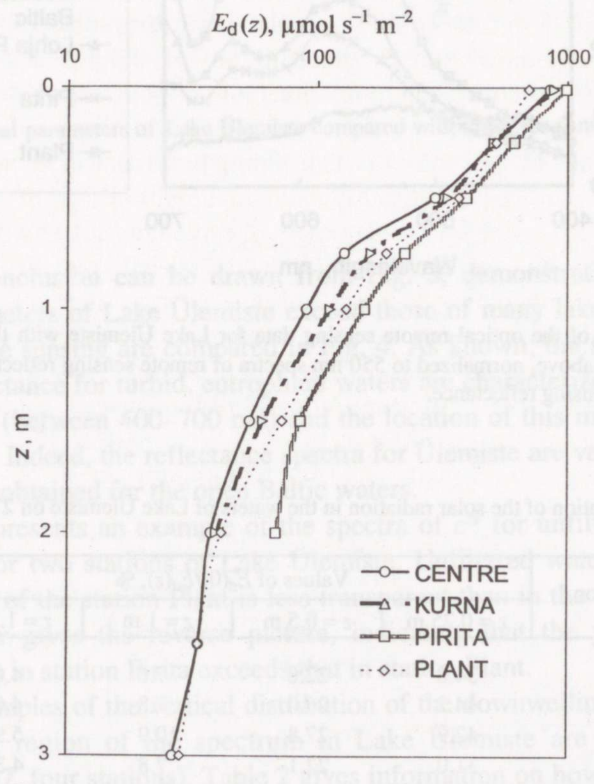

Fig. 6. Vertical profiles of downwelling solar irradiance in the range 400–700 nm for four stations of Lake Ülemiste on 27 August 1997.

The averaged by depth K_d(PAR) was calculated using the least square fit through the irradiance versus depth points, $\ln[E_d(z)]$ vs. z. The mean slope obtained by this regression is K_d. If K_d is calculated in such a way its depth dependence is lost. However, this dependence can be described by measuring K_d of separate layers for the whole water column. We carried out these measurements for layers with a thickness of 0.5 m. Some examples of results are presented in Figs. 7 and 8. As known, in a vertically homogeneous water body the value of K_d(PAR) decreases with increasing depth (the reason is the change in the spectral composition of the PAR region light with depth). So, a lack of vertical change or an increase in K_d(PAR) with depth indicates optically thicker layers at these depths.

However, the shape of the vertical profiles of K_d may be influenced by measurement errors. These include "instrumental" errors, by our estimation not exceeding 5%, and also errors caused by measurement conditions. Undulation brings about fluctuations of the underwater irradiance and despite of averaging

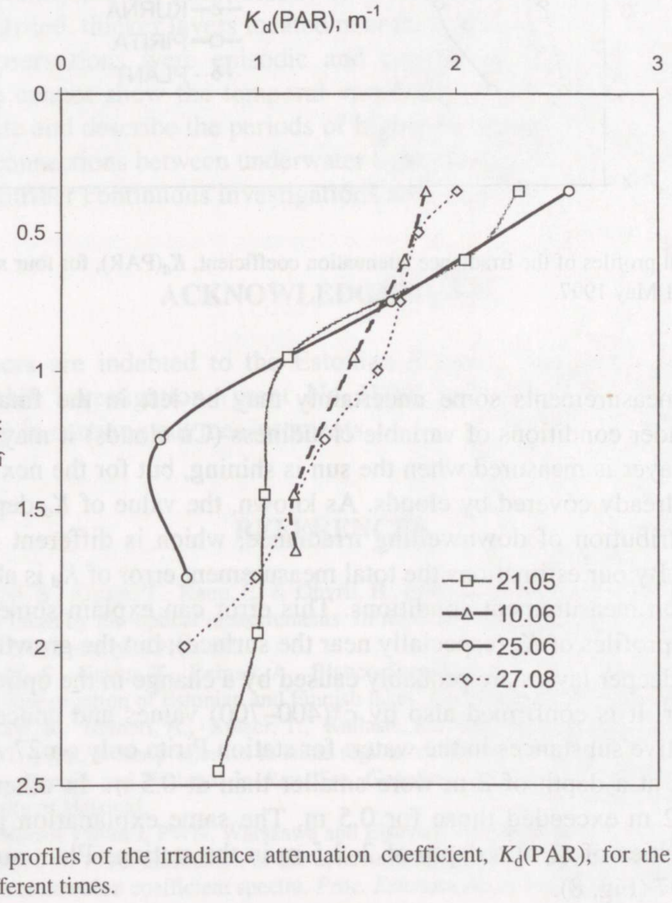

Fig. 7. Vertical profiles of the irradiance attenuation coefficient, K_d(PAR), for the station Pirita measured at different times.

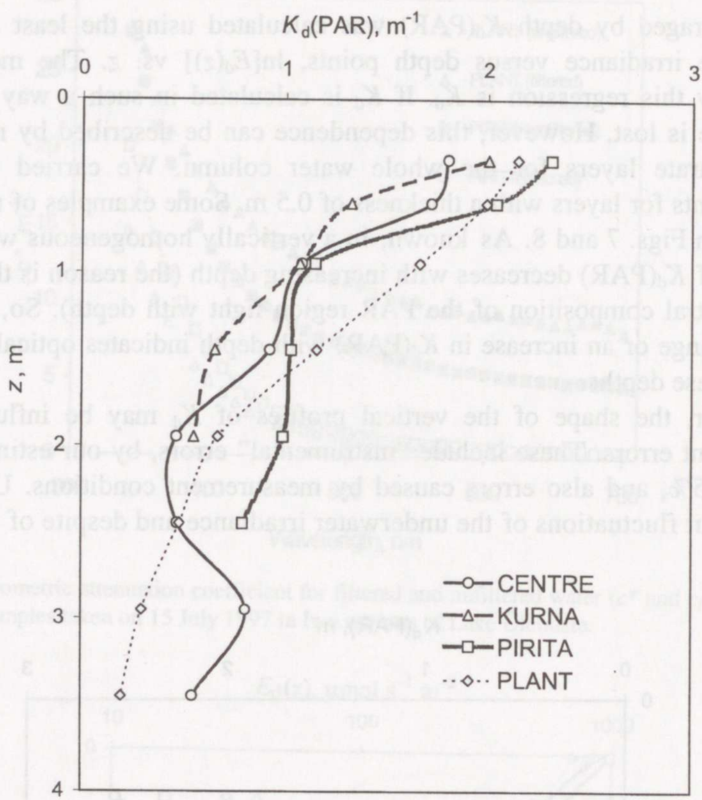

Fig. 8. Vertical profiles of the irradiance attenuation coefficient, K_d(PAR), for four stations in Lake Ülemiste on 21 May 1997.

numerous measurements some uncertainty may be left in the final results. In addition, under conditions of variable cloudiness (Cu clouds) it may happen that K_d for one layer is measured when the sun is shining, but for the next layer when the sun is already covered by clouds. As known, the value of K_d depends on the angular distribution of downwelling irradiance, which is different in clear and cloudy sky. By our estimations the total measurement error of K_d is about 3–10%, depending on measurement conditions. This error can explain some "waves" in the vertical profiles of K_d (especially near the surface), but the growth of K_d or its stability in deeper layers are probably caused by a change in the optical thickness of the water. It is confirmed also by c^*(400–700) values and concentrations of optically active substances in the water: for station Pirita only on 27 August 1997 their values at a depth of 2 m were smaller than at 0.5 m. In other cases their values for 2 m exceeded those for 0.5 m. The same explanation is valid also for irregularities of K_d at a depth of 2–3.5 m in the stations Plant and Centre on 21 May 1997 (Fig. 8).

Our observations were episodic and the observation period was short. The drinking water reservoir, Lake Ülemiste, needs undoubtedly additional investigations in the future for finding out the temporal variability of its bio-optical parameters and estimating the trend of its ecological state.

CONCLUSIONS

1. The water of the drinking reservoir of Tallinn, Lake Ülemiste, is optically turbid, comparable with such lakes as Võrtsjärv in Estonia and Lohjanjärvi in Finland.

2. The chlorophyll content in Lake Ülemiste is high: the concentration of chlorophyll *a* changed in summer 1997 from 21 to 50 mg m^{-3}. The effective concentration of yellow substance was in the limits 10–20 mg L^{-1}, the concentration of suspended matter was 5–22 mg L^{-1}.

3. About 25% of the subsurface irradiance (in the PAR range) penetrates to a depth of 0.5 m while only 5% reaches 1.5 m.

4. Lake Ülemiste is not deep, mostly only to 2–2.5 m. Nevertheless it is often optically stratified, thicker layers located near the bottom.

5. Our observations were episodic and carried out during a short period; therefore we cannot show the temporal variability of bio-optical parameters in Lake Ülemiste and describe the periods of higher biological activity of the water. To find out connections between underwater light climate and biological processes in Ülemiste further continuous investigations are necessary.

ACKNOWLEDGEMENTS

The authors are indebted to the Estonian Science Foundation for financial support to this investigation (grant No. 1804) and to AS *Tallinna Vesi* for practical help in carrying out measurements.

REFERENCES

Arst, H., Mäekivi, S., Kutser, T., Kaup, E. & Ohvril, H. 1995. Investigation of some Estonian and Finnish lakes by bio-optical measurements. In *Rep. Ser. Geophys.*, **32** (Pulkkinen, K., ed.), pp. 7–17. University of Helsinki.

Arst, H., Mäekivi, S., Kutser, T., Reinart, A., Blanco-Sequeiros, A., Virta, J. & Nõges, P. 1996. Optical investigation of Estonian and Finnish lakes. *Lakes Reserv. Manage.*, **2**, 187–198.

Arst, H., Mäekivi, S., Reinart, A., Kutser, T., Kallaste, K., Blanco-Sequeiros, A., Nõges, P. & Nõges, T. 1998. Water properties in some regions of the Baltic Sea and in different type of lakes in Estonia and Finland. In *Rep. Ser. Geophys.*, **38** (Pulkkinen, K., ed.), pp. 7–21. University of Helsinki.

Dera, J. 1992. *Marine Physics.* PWN, Warszawa and Elsevier, Amsterdam.

Mäekivi, S. & Arst, H. 1996. Estimation of the concentration of yellow substance in natural waters by beam attenuation coefficient spectra. *Proc. Estonian Acad. Sci. Ecol.*, **6**, 3/4, 108–123.

OPTILISED MÕÕTMISED ÜLEMISTE JÄRVEL

Ants ERM, Helgi ARST, Medhat HUSSAINOV, Tiit KUTSER
ja Anu REINART

Suvel 1997 tehti optilisi mõõtmisi Ülemiste järvel. See järv on Tallinna, Eesti pealinna põhiline joogiveereservuaar, seega on kõik uuringud, mis aitavad hinnata ja prognoosida tema vee kvaliteeti ja veealust valguskliimat, erilise tähtsusega. Mõõtmised toimusid maist augustini järve neljas punktis, igaühes viis mõõteseeriat. Määrati allasuunduva kiiritustiheduse vertikaalsed profiilid PAR-spektripiirkonna jaoks, vee relatiivset läbipaistvust hinnati Secchi ketta abil. Veeproovidest määrati klorofüll *a* ja heljumi kontsentratsioonid vees. Filtreeritud ja filtreerimata vee spektrofotomeetrilise töötluse tulemuste põhjal kirjeldati suunatud kiirguse nõrgenemiskoefitsiendi spektreid ja hinnati kollase aine optilist mõju vees. Passiivne optiline kaugsondeerimine toimus mõõtmiste teel paadist. Saadud tulemused näitavad, et Ülemiste järve veed on optiliselt hägused, võrreldavad Võrtsjärve (Eesti) ja Lohjanjärvi (Soome) vetega. Klorofülli hulk varieerus 21–50 mg m^{-3}, heljumi oma 5–22 mg L^{-1} ja kollase aine efektiivne kontsentratsioon oli 10–20 mg L^{-1}. Sügavusele 0,5 m jõuab ligi 25%, sügavusele 1,5 m ainult 5% veepinda läbinud PAR-piirkonna päikesekiirgusest. Ülemiste järv on tihti optiliselt kihistunud, kusjuures tihedamad kihid asuvad enamasti järvepõhja kohal. Tehtud uurimusi tuleb pidada esialgseiks, töö jätkamine Ülemistel on kindlasti vajalik.