

Euphotic Holding Capacity for Optically Active Substances

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Abstract

*Euphotic holding capacity is defined as the amount of pure water or a substance that could be contained in the euphotic layer if it would be the single optically active component in the system. Comparing the actual amount of optically active substances in the euphotic layer of a lake to the holding capacities allows to estimate the contribution of different optically active components to the overall attenuation of PAR. Investigations made on 8 optically contrasting lakes in Estonia revealed a high role of yellow substances in most of the lakes studied. Chlorophyll *a* and particulate matter affected light penetration in almost equal proportions whereas the role of pure water was remarkable only in some exceptional cases.*

Key words: Euphotic layer, optically active substances, light attenuation

1. Introduction

The concentrations as well as the proportions of optically active substances in surface waters, i.e. yellow substances, suspended solids and phytoplankton pigments, vary over a wide range. Only in exceptional cases it is possible to evaluate visually which of them is the most responsible for light attenuation in a particular water body. Such exceptions might be, for example, bog pools in which light is mainly absorbed by yellow substances, or some siltated waters where the role of eroded soil particles in light attenuation is overwhelming. The occurrence of phytoplankton affects already two of the components – pigments and suspended solids, in proportions depending on the size structure and pigment content of phytoplankton. The optical effect of different substances can not be compared based only on their concentrations because the attenuation of light caused by one weight unit of e.g. chlorophyll *a* is incomparable with that caused by the same weight unit of suspended solids or yellow substances. In order to normalize the effect of different optically active components, the new term “euphotic holding capacity” (EHC_c) was introduced, which means the amount of pure water or a substance that could be contained in the euphotic layer if it would be the single opti-

cally active component in the system. In this paper the euphotic zone has been defined in the most traditional way as the layer in which the surface value of photosynthetically active radiation (PAR) is attenuated to the level of 1% of the incoming light (*Tilzer, 1987*):

$$E_o(0-)/E_o(z_{1\%})=100 = \exp[K_o \cdot z_{1\%}] \quad (1)$$

where $E_o(0-)$ is the scalar irradiance immediately under the water surface, $E_o(z_{1\%})$ is equal to 0.01 $E_o(0-)$ and K_o is the vertical diffuse attenuation coefficient of scalar irradiance. It follows that

$$z_{1\%} = \ln 100/K_o = 4.605/K_o \quad (2)$$

The ratio of the actual amount of a substance within the euphotic layer to its holding capacity gives us the role of this substance in the overall light attenuation.

The contribution of the different components to absorption of total PAR can be accurately assessed only by carrying out the appropriate calculations at a series of narrow wavebands and summing the results (*Kirk, 1994*). In this respect the proposed *EHC*-concept is a simplification which still allows an insight into the optical processes of different lakes from only a few measurements.

2. *Material and methods*

2.1 *Field and laboratory measurements*

Data illustrating the euphotic capacity concept were collected in 1995-96 during six expeditions to eight optically different small lakes in Estonia. A general description of the lakes is given in *Nõges and Nõges (1998)*.

Vertical diffuse attenuation coefficient for scalar irradiance in the PAR region was measured using a $4\text{-}\pi$ light collector constructed by Aivo Reinart at Tartu University according to drawings by *Williams and Jenkinson (1980)*. In order to diminish the effect of small-scale temporal variability in light levels caused e.g. by clouds and waves, measurements were performed simultaneously with two light collectors fixed to a vertical rod at a distance of 1 m from each other. The logarithm of the ratio between signals was registered.

For chlorophyll *a* (C_{Chl}) measurements, 50-200 ml of lake water was filtered through glass fibre filters Whatman GF/C. Filters were placed into 5 ml of ethanol and transported to the lab in thermos boxes on ice. After extraction at 4 °C, C_{Chl} was measured spectrophotometrically and calculated according to *Lorenzen (1967)*.

The concentration of suspended solids (C_{SS}) was measured as the weight increment of dry acetate cellulose filters (pore size 0.45 μm) after filtrating water through it

during one minute using vacuum -0.2 atm. The amount of filtered water was registered. Before weighing, filters were dried at 60 °C for 24 h.

Chemical determination of humic or so-called yellow substances is complicated, time consuming and expensive (Dera, 1992). Therefore, several authors (Højerslev, 1980; Baker and Smith, 1982; Mäekivi and Arst, 1996) transform the absorption coefficient of yellow substance at a certain wavelength in the violet or UV region into concentration of yellow substance using the following equation:

$$C_y = a_y(\lambda) / \{a_y^*(\lambda_0) \cdot \exp[-S_y \cdot (\lambda - \lambda_0)]\} \quad (3)$$

where $a_y(\lambda)$ is the absorption coefficient, $a_y^*(\lambda_0)$ the specific absorption coefficient and S_y the slope factor of yellow substance which characterizes the exponential increase of the absorption towards shorter wavelengths. We used the values $a_y^*(380) = 0.565 \text{ L m}^{-1} \text{ mg}^{-1}$ and $S_y = 0.017 \text{ nm}^{-1}$ calculated by Højerslev (1980) from data measured in the Baltic Sea. Water was filtered through membrane filters (Sartorius, pore diameter 0.45 μm) and the beam attenuation coefficients $c_f(\lambda)$ were measured at $\lambda = 350 \text{ nm}$ using a spectrophotometer Hitachi. As the light scattering in filtered water is presumably small, the $c_f(\lambda)$ values could be taken for $a_y(\lambda)$. Equation 3 was applied in the following form:

$$C_y = c_f(350) / \{0.565 \cdot \exp[-0.017 \cdot (350 - 380)]\} \quad (4)$$

2.2 Euphotic holding capacity (EHC) calculations

The smallest mean $K_d(\text{PAR})$ among natural waters 0.03 m^{-1} has been given in a list by Kirk (1994) for Sargasso Sea. This value was used as an approximation to evaluate the light attenuating effect of pure water. Putting this value into eq. 2, we get the euphotic holding capacity (euphotic depth) for pure water equal to:

$$EHC_w = z_{1\%w} = 4.605 / 0.03 = 153.5 \text{ m} \quad (5)$$

The contribution of water to light attenuation in a particular lake was calculated as the percentage ratio of the actual euphotic depth and EHC_w :

$$W(\%) = z_{1\%} \text{ for a particular lake} \cdot 100\% / 153.5 \quad (6)$$

As a concessions in the physical exactness of the methodology, K_o was used instead of beam attenuation coefficient while applying Beer's law:

$$K_o = K_c^* \cdot C \quad (7)$$

where C is the concentration and K_c^* the specific attenuation coefficient of a particular optically active substance. However, the use of K_o as an inherent optical property (IOP) of water could be partly justified by the design of the instrument, by similar timing of

all measurements around noon, and also due to the fact that absorption was clearly the dominating IOP in the lakes.

The specific attenuation coefficient for chlorophyll $K_{\text{Chl}}^* = 0.02 \text{ m}^2 \text{ mg}^{-1}$ for PAR was taken from *Sakamoto and Hogetsu (1969)*. EHC for chlorophyll was calculated as:

$$EHC_{\text{Chl}} = [C_{\text{Chl}} \cdot z_{1\%}]_{\text{max}} = \ln 100 / K_{\text{Chl}}^* = 4.605 / 0.02 = 230 \text{ mg m}^{-2} \quad (8)$$

The contribution of chlorophyll to light attenuation was calculated as:

$$Chl (\%) = C_{\text{Chl}} \cdot z_{1\%} \cdot 100\% / 230 \quad (9)$$

The specific attenuation coefficient for yellow substance in the PAR region was calculated on the basis of one data set from Lake Nohipalu Mustjärv (*mustjärv = black lake*) from May 1995. In this case the calculated concentration of yellow substance was extremely high ($C_Y = 94.6 \text{ g m}^{-3}$) while concentrations of other substances were relatively low ($C_{\text{SS}} < 8 \text{ g m}^{-3}$; $C_{\text{Chl}} < 1 \text{ mg m}^{-3}$). The light attenuation was strong in this dark brown water ($K_o = 5.5 \text{ m}^{-1}$). K_Y^* , EHC_Y and the proportion of light attenuation caused by yellow substance were calculated as follows:

$$K_Y^* = 5.5 / 94.6 = 0.058 \text{ m}^2 \text{ g}^{-1} \quad (10)$$

$$EHC_Y = \ln 100 / K_Y^* = 4.605 / 0.058 = 79 \text{ g m}^{-2} \quad (11)$$

$$Y (\%) = C_Y \cdot z_{1\%} \cdot 100 / 79 \quad (12)$$

The rest of light attenuation left after subtracting the contributions by water, chlorophyll and yellow substance, was attributed to scattering by suspended solids including phytoplankton:

$$SS (\%) = 100 - W (\%) - Chl (\%) - Y (\%) \quad (13)$$

A couple of cases in which the sum of three components (W , Chl and Y) exceeded 100% were omitted. Other results obtained during six expeditions were averaged by lakes.

3. Results and discussion

The contribution of pure water to light attenuation varied from 0.5% in brown water lake Nohipalu Mustjärv to 19% in Äntu Sinijärv (Fig. 1), the most transparent lake in Estonia, where the euphotic zone would reach 27-36 m if the lake would be so deep (the maximum depth is only 6 m). The mean contribution of water to absorption of total PAR was 4% in studied Estonian lakes being 5 times smaller than stated by *Kirk (1994)* for a set of Australian inland water bodies where on an average 23% of photosynthetic quanta were absorbed by water. In pure water the 1% of surface PAR reaches

in fact a depth more than 150 m, because the average attenuation coefficient 0.03 m^{-1} is calculated for the whole PAR range, including longer wave lengths which are rapidly absorbed by water. At greater depths the spectrum narrows and its average attenuation becomes smaller. The absolute error caused by ignoring these spectral changes is small in most cases, as the euphotic depth in lakes is small and determined mainly by other components. The mean $z_{1\%}$ calculated from K_o varied from 0.6 m in Nohipalu Mustjärv to 30 m in Äntu Sinijärv.

Table 1. General hydro-optical characteristics of the lakes studied and concentrations of optically active substances in the euphotic layer (average \pm standard deviation).

Lake	$z_{1\%}$ m	K_o m^{-1}	Secchi depth, m	C_{chl} mg m^{-3}	$C_{\text{chl}} \cdot z_{1\%}$ mg m^{-2}	C_y mg L^{-1}	C_s mg L^{-1}
Kurtna	6.1	0.79	3.6	1.7	10.4	8.5	7.2
Nömmejärv	± 1.1	± 0.18	± 0.8	± 0.4	± 3.0	± 3.5	± 6.3
Äntu	29.8	0.16	6.5	1.1	30.6	1.1	5.0
Sinijärv	± 3.8	± 0.02	(bottom)	± 0.8	± 20.8	± 0.6	± 3.1
Koorküla	6.0	0.76	3.0	10.0	65.5	5.4	3.8
Valgjärv	± 0.1	± 0.02	± 0.1	± 3.8	± 5.6	± 1.6	± 0.5
Nohipalu	0.6	5.76	0.5	9.5	7.6	91.0	3.5
Mustjärv	± 0.1	± 0.95	± 0.1	± 10.2	± 8.2	± 12.5	± 2.0
Nohipalu	6.5	0.73	4.8	7.8	64.1	5.2	4.9
Valgjärv	± 1.0	± 0.14	± 0.3	± 4.2	± 36.1	± 1.2	± 4.8
Uljaste	4.0	1.27	2.6	13.1	40.5	12.2	5.0
	± 1.3	± 0.42	± 1.1	± 11.9	± 30.7	± 2.5	± 1.8
Verevi	4.3	1.08	2.8	6.6	28.4	11.1	4.5
	± 0.3	± 0.09	± 0.8	± 1.3	± 7.4	± 0.4	± 0.2
Vörtsjärv	2.0	2.45	0.6	26.2	84.4	14.4	57.2
	± 0.6	± 0.68	± 0.3	± 6.0	± 43.3	± 2.0	± 76.1

The calculated EHC_{Chl} value of 230 mg m^{-2} fitted well into the range of the euphotic chlorophyll contents $179\text{--}325 \text{ mg m}^{-2}$ found by *Talling et al.* (1973) in Ethiopian soda lakes, the most productive waterbodies in the World. Nearly the same range ($\sim 200\text{--}300 \text{ mg m}^{-2}$) has been expected for euphotic chlorophyll on theoretical grounds by *Steemann-Nielsen* (1962). The euphotic chlorophyll content varied from 8 to 84 mg m^{-2} (Table 1). The role of chlorophyll in light attenuation (Figure 1) was large in L. Vörtsjärv (37%), L. Koorküla Valgjärv and Nohipalu Valgjärv (in both 28% of the total attenuation). By other qualities these lakes are very different: L. Vörtsjärv is a large (270 km^2), shallow (maximum depth 6 m), eutrophic lake with water transparency usually less than 1 m, while lakes Koorküla Valgjärv and Nohipalu Valgjärv are small (44 and 6 ha correspondingly) and deep (27 and 12 m) with rather transparent water. They were until recently oligotrophic, but are now slightly eutrophicated. Chlorophyll played the smallest role in light attenuation in lakes Nohipalu Mustjärv (3%) and Kurtna Nömmejärv (5%). The latter is a flow-through lake with a rather high water transparency (2.4–4.5 m) due to abundant submerged macrophyte vegetation.

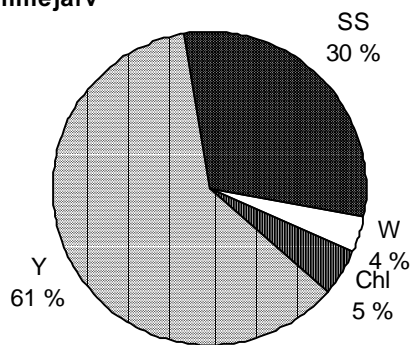
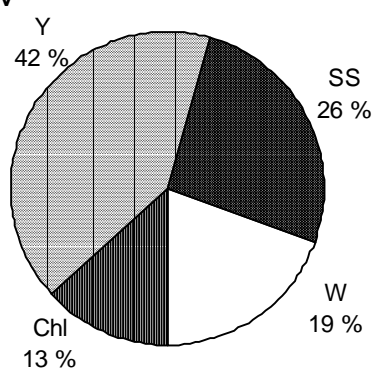
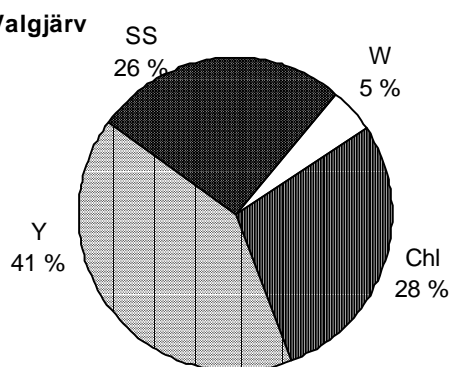
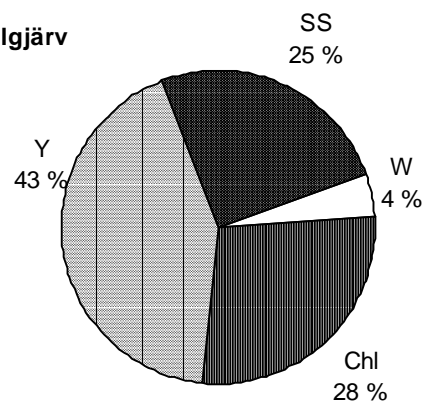
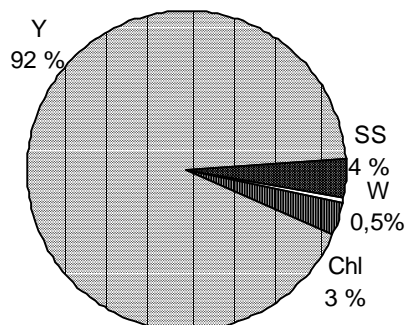
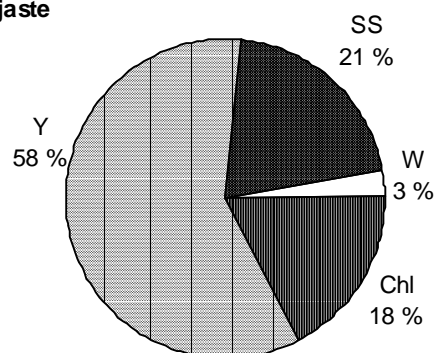
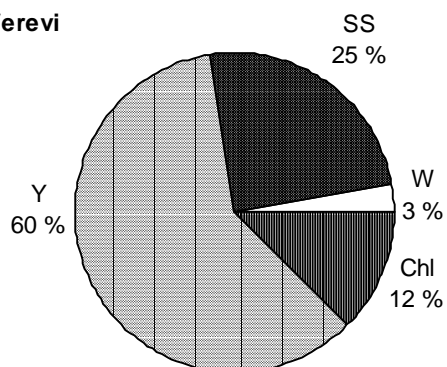
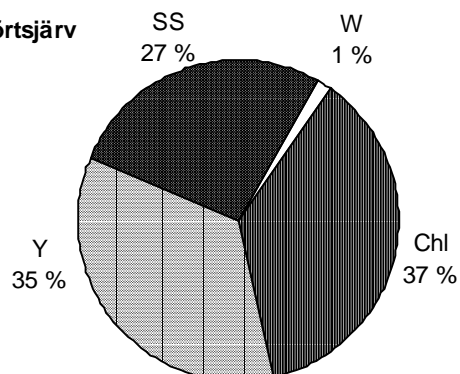
K. Nõmmejärv**Ä. Sinijärv****K. Valgjärv****N. Valgjärv****N. Mustjärv****Uljaste****Verevi****Võrtsjärv**

Fig. 1. Contribution of optically active substances to overall attenuation of PAR in the euphotic layer of studied lakes.

More than a half of light attenuation could be accounted for by yellow substance in lakes Nohipalu Mustjärv (92%), Kurtna Nõmmejärv, Verevi and Uljaste (all about 60%). Yellow substance seems to be the dominating optically active component in most Estonian lakes, as it caused more than 40% of the total light attenuation even in transparent lakes Äntu Sinijärv, Nohipalu Valgjärv and Koorküla Valgjärv, in which the yellowish colour is hardly visible. In L. Võrtsjärv the contribution of yellow substance to the overall light attenuation was the smallest, but still made up one third of it. In Australian lakes listed by Kirk (1994) 7.5–60.4% of photosynthetic quanta were absorbed by the soluble fraction.

It was impossible to calculate the euphotic holding capacity for suspended solids, because their optical effect is, besides their concentration, strongly dependent on their composition, particle size and surface properties of the particles. Calculated mean contribution of particulate matter to light attenuation varied from 4% in L. Nohipalu Mustjärv to 30% in Kurtna Nõmmejärv. In shallow L. Võrtsjärv, where high phytoplankton production and sediment resuspension cause high turbidity of water, the actual amount of suspended solids was rather high (Table 1). However, its contribution to the attenuation remained in the medium range and was overcome by that of chlorophyll and yellow substances. The role of chlorophyll-less particles is very high in L. Kurtna Nõmmejärv, which receives partly technogenic waters pumped out from neighbouring oil-shale mines that turn the lake into a settling basin (Sagris, 1987).

Due to several concessions made in the physical exactness of the methodology, the results are rather rough estimates, which nevertheless are consistent with our present understanding of the status of the investigated lakes. We consider the method still valuable, as it offers a simple way to formalize and compare the wide range of optical properties of surface waters that is needed for better understanding their bioproduction potential.

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References

- Baker, K.S. and R.C. Smith, 1982. Bio-optical classification and model of natural waters. 2, *Limnol. Oceanogr.*, **27**, 500-509.
- Dera, J., 1992. *Marine physics*. PWN, Warszawa, Elsevier, Amsterdam - Oxford - New-York - Tokyo, 516 pp.
- Højerslev, N.K., 1980. On the origin of yellow substance in the marine environment, *Univ. Copenhagen Inst. Phys., Oceanogr. Rep.*, **42**, 39-56.

- Lorenzen, C.J., 1967. Determination of chlorophyll and pheopigments: Spectrophotometric equations, *Limnol. Oceanogr.*, **12**, 343-346.
- Mäekivi, S. and H. Arst, 1996. Estimation of the concentration of yellow substance in natural waters by beam attenuation coefficient spectra, *Proc. Estonian Acad. Sci.*, **45**, 108-123.
- Nõges, P. and T. Nõges, 1998. Stratification of Estonian lakes studied during hydro-optical expeditions in 1995-97, *Proc. Estonian Acad. Sci.*, **47**, 108-123.
- Sagris, A., 1987. Mõningate Kurtna järvestiku järvede veebilansist. In: M. Ilomets (Ed.), *Kurtna järvestiku looduslik seisund ja selle areng*, Valgus, Tallinn, 144-148.
- Sakamoto, M. and K. Hogetsu, 1963. Spectral change of light with depth in some lakes and its significance to the photosynthesis of phytoplankton, *Pl. Cell Physiol.*, **4**, 187-198.
- Steemann-Nielsen, E. 1962. On the maximum quantity of plankton chlorophyll per surface unit of a lake or the sea, *Int. Revue ges. Hydrobiol. Hydrogr.*, **47**, 333-338.
- Talling, J.F., R.B. Wood, M.V. Prosser and M. Baxter, 1973. The upper limit of photosynthetic productivity by phytoplankton: evidence from Ethiopian soda lakes, *Freshwat. Biol.*, **3**, 53-76.
- Tilzer, M.M., 1987. The productivity of phytoplankton and its control by resource availability. A review. In: H.D. Kumar (Ed.), *Phycotalk*, Bavaras Hindi University, Varanasi.
- Williams, P.J.le B. and N.W. Jenkinson, 1980. A simple and inexpensive 4-p light collector and two designs for a light meter for light attenuation studies, *Freshwat. Biol.*, **10**, 491-496.