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# DIFFUSE ATTENUATION COEFFICIENT IN SOME ESTONIAN AND FINNISH LAKES

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**Abstract.** The apparent optical properties – spectral diffuse attenuation coefficient and diffuse attenuation coefficient of photosynthetically active radiation – were estimated in 14 Estonian and Finnish lakes with different trophic state by underwater radiation measurements. Statistical analyses suggest that the main factors influencing vertical attenuation of irradiance are yellow substance and suspended particles (coefficients of determination respectively 45% and 38%), while chlorophyll describes only 13% from its variation. Because of a large amount of optically active substances in our lakes none of the existing optical classifications based on the diffuse attenuation coefficient is totally suitable. Using the statistical methods an analytical expression and its spectral parameters were found, suitable for recreating the diffuse attenuation coefficient spectra of a water body on the basis of the known value of $K_d$(490 nm). This model works with good accuracy (relative error below 10%) if $K_d$(490) ranges from 0.6 to 5.6 $m^{-1}$ (85% of our data collection fell into this range). $K_d$(490) could be used as an optical classification index for clear-water and moderately turbid lakes in Estonia and Finland. However, the lakes with a very high content of yellow substance and extremely turbid ones need a more complicated model.

**Key words:** limnology, optical properties of water, underwater light field.

## INTRODUCTION

The optical properties of water bodies are important for many applications such as primary production (Krause-Jensen & Sand-Jensen, 1998), species composition of the phytoplankton communities (Schanz, 1985), depth distribution of submerged macrophytes (Duarte, 1991), the heat budget of the water body (Fedorov & Ginsburg, 1992), and remote sensing of water surface (Dekker et al., 1995).

A widely used optical property is the diffuse attenuation coefficient ($K_d$), which characterizes the gradient of the vertical decrease of radiation in the water. The values of $K_d$ are useful because: (1) they are easily determined with standard

(and commercially available) instruments (both spectral and broad-band); (2) they generally correlate well with optically active substances in water; (3) they are related to inherent optical properties of water; (4) the depth with enough light for photosynthesis (euphotic depth) is calculable as $4.6/K_d$; (5) they have importance for remote sensing, as 90% of the remotely sensed radiation originates from the layer with a thickness $K_d^{-1}$.

Although optical studies have mostly been directed to open ocean waters, coastal and inland waters have received increasing attention in recent years as they are of high human interest (fresh water supply, recreation, tourism, fisheries). Because of great variability in catchment areas the optical quality of coastal regions of seas and lakes differs fundamentally from that of oceans. For the same reason the optical contrasts between inland waters are also larger than between different regions in the ocean (Morel & Smith, 1974; Kirk, 1980; Horne & Goldman, 1994; Reinart et al., 1998).

Intensive co-operation between the Estonian Marine Institute and the University of Helsinki (Finland) in the field of optical studies in Estonian and Finnish lakes started in 1994. The results obtained are analysed in publications by Arst et al. (1995, 1996, 1998, 1999) and Herlevi et al. (1999). The aim of the present study was to compare the $K_d$ values measured in lakes with those used by other authors in their optical classifications of waters and to consider the possibilities to build some classification of lakes relying on these $K_d$ values. For this we used the diffuse attenuation coefficients determined from spectral and PAR irradiance measurements in 14 Estonian and Finnish lakes of different trophic state.

## OPTICAL CLASSIFICATIONS OF NATURAL WATERS

The general equation used to define $K_d(\lambda)$ follows from exponential decrease of irradiance $E_d(\lambda)$ with depth (far enough from surface and bottom) (Dera, 1992; Mobley, 1994):

$$K_d(\lambda) = -\frac{1}{E_d(z,\lambda)} \frac{\partial E_d(z,\lambda)}{\partial z}, \quad (1)$$

where $E_d(z, \lambda)$ is irradiance at depth $z$.

The most frequently used classification scheme of natural waters based on the spectral shape of $K_d$ was developed by Jerlov (1976). Jerlov's water type I is the clearest and III the most turbid open ocean water. There are also five types of coastal waters (1, 3, 5, 7, and 9), the transparency of the water decreasing with the increasing type number. The wavelength of minimal values of $K_d$ shifts from blue for type I to green for types III and 1 and yellow for the most turbid type 9. Jerlov's measurements were made with broad band colour filters and in some cases are in poor agreement with analogous measurements performed with modern instruments (Mobley, 1994).

Austin & Petzold (1986) used an expanded dataset and re-evaluated Jerlov's types I through III. Their values are recommended over those found by Jerlov (Mobley, 1994) because in the wavelength range 510–680 nm the values obtained by Jerlov for $K_d$ are less than those for the clearest natural water (Smith & Baker, 1981). They found strong relationships between the value of $K_d$ at 490 nm and the value of $K_d$ at some other wavelength:

$$K_d(\lambda) = M(\lambda)\,[K_d(490) - K_w(490)] + K_w(\lambda), \qquad (2)$$

where $K_w(\lambda)$ is the attenuation coefficient of pure water by Smith & Baker (1981). The slope parameter $M(\lambda)$ is tabulated for the spectral region 365 to 700 nm with a 5 nm step. The value of $K_d$ at 490 nm is suggested as a water classification index and it ranges from 0.03 to 0.18 $m^{-1}$. The significance of this classification is that it provides analytical expressions for the spectral nature of the attenuation coefficient. Unfortunately, this model is applicable only for waters with entirely different optical properties than those prevailing in lakes. The spectra of $K_d$ for different water types by Austin & Petzold (1986) and Jerlov (1976) are presented in Fig. 1.

On the basis of biological (concentrations of chlorophyll *a*, $C_{chl}$, and dissolved organic matter, $C_{DOM}$) and spectral measurements in the ocean another classification of nonterrigenous waters was presented by Baker & Smith (1982). From this model $K_d$ spectra corresponding to Jerlov's oceanic water types I to III can be derived as ranging from 0.01 to 0.7 mg $m^{-3}$ for $C_{chl}$ and from 0.01 to 0.03 mg $L^{-1}$ for $C_{DOM}$. If the values of $C_{DOM}$ are increased up to 4 mg $L^{-1}$ and of $C_{chl}$ up to 19 mg $m^{-3}$, the coincidence of $K_d$ spectra with Jerlov's type 9 is reasonably good up to wavelength 550 nm. Some examples are given in Fig. 2 and Table 1.

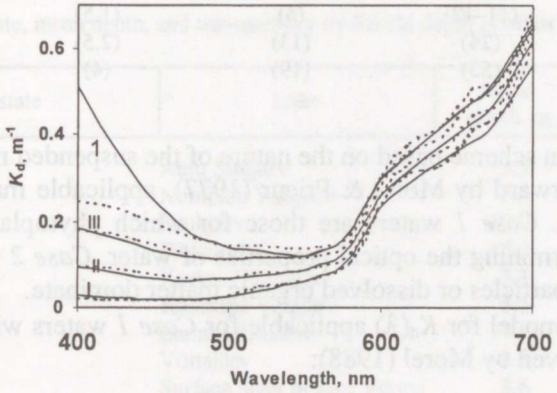


**Fig. 1.** Diffuse attenuation coefficient of oceanic water types I, II, and III and coastal type 1 by Jerlov (1976) (solid line) and the same calculated by Eq. 2 using parameters from Austin & Petzold (1986) (dashed line).

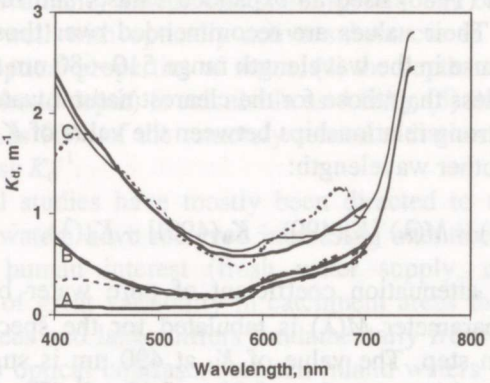


**Fig. 2.** Spectral $K_d$ calculated by Morel (1988) (dashed line), by Baker & Smith (1982) (solid line), and comparable curves of Jerlov's types II, 3, and 9 (thick line). The corresponding concentrations of chlorophyll *a* and dissolved organic matter are presented in Table 1 (rows A, B, C). For case A all these curves overlap.

**Table 1.** Estimated values of the concentrations of chlorophyll *a* ($C_{chl}$) and dissolved organic matter ($C_{DOM}$) by different bio-optical models of the diffuse attenuation coefficient compared with Jerlov's classification

| Jerlov's type | Morel (1988) $C_{chl}$, mg m$^{-3}$ | Baker & Smith (1982) | | Curve in Fig. 2 |
|---|---|---|---|---|
| | | $C_{chl}$, mg m$^{-3}$ | $C_{DOM}$, mg L$^{-1}$ | |
| I | 0–0.01 | 0.01 | 0.01 | |
| II | 0.5 | 0.32 | 0.02 | A |
| III | 1.5–2 | 0.7 | 0.03 | |
| 1 | (2.5–2.75) | 0.5 | 0.75 | |
| 3 | (5–6) | 1 | 1.2 | B |
| 5 | (11–12) | (5) | (1.5) | |
| 7 | (24) | (13) | (2.5) | |
| 9 | (53) | (19) | (4) | C |

A classification scheme based on the nature of the suspended matter within the water was put forward by Morel & Prieur (1977), applicable mainly for remote sensing purposes. *Case 1* waters are those for which phytoplankton plays the main role in determining the optical properties of water. *Case 2* waters are those where inorganic particles or dissolved organic matter dominate.

A bio-optical model for $K_d(\lambda)$ applicable for *Case 1* waters with $C_{chl}$ less than 30 mg m$^{-3}$ was given by Morel (1988):

$$K_d(\lambda) = K_w(\lambda) + X(\lambda)C^{k(\lambda)}, \qquad (3)$$

where $K_w$ is diffuse attenuation coefficient of pure water, $X$ and $k$ are statistically derived functions, tabulated for the spectral range 400–700 nm, every

5 nm. Examples of curves calculated by Eq. 3 are shown in Fig. 2, the respective values of $C_{chl}$ are presented in Table 1.

In Table 1 we present the values of $C_{chl}$ and $C_{DOM}$ estimated from Eq. 3 and from the model of Baker & Smith (1982) choosing the variance which gave similar $K_d$ curves with Jerlov's water types. The coincidence was excellent only for oceanic water types between Morel (1988) and Jerlov (1976) and up to coastal type 3 between Baker & Smith (1982) and Jerlov, therefore some values are in parentheses.

Most bio-optical research has been done for phytoplankton-dominated waters. For *Case 2* waters multicomponental optical models that take into account the relative importance of all major light attenuating components are still under investigation.

Kirk (1980) proposed a crude optical classification for inland waters, using the absorption spectra of the dissolved and suspended fractions of Australian lakes. Often only locally valid relationships between different optical properties and substances in water have been proposed for lakes: Chekhin (1987) for Russian lakes, Eloranta (1978) for Finnish lakes, Koenings & Edmundson (1991) for Alaskan lakes.

## MEASUREMENTS AND METHODS

### Investigated lakes

We used the data from underwater light measurements in 14 Estonian and Finnish lakes made in 1995 and 1997. These data reveal a high variability in water properties of the studied lakes. A detailed description of these lakes was given by Arst et al. (1996, 1999). The trophic state of the lakes is shown in Table 2.

**Table 2.** Trophic state, mean depth, and transparency by Secchi depth of lakes under investigation

| Trophic state | Lake | Mean depth, m | Secchi depth, m |
|---|---|---|---|
| Alkalitrophic | Äntu Sinijärv | 3.5 | Bottom seen |
| Oligotrophic | Nohipalu Valgjärv | 5.4 | 3.5–6.7 |
| | Paukjärv | 10.0 | 5 |
| | Päijänne | 15.0 | 3.5–5.9 |
| Mesotrophic | Kurtna Nõmmjärv | 3.1 | 2.5–4.5 |
| | Koorküla Valgjärv | 8.5 | 2.9–4.8 |
| | Lammi Pääjärvi | 14.4 | 1.6–3.0 |
| Eutrophic | Võrtsjärv | 2.8 | 0.15–1.0 |
| | Surface layer of lake Verevi | 3.6 | 1.5–3.8 |
| | Vesijärvi | 6.6 | 1.2–3.7 |
| Hypertrophic | Tuusulanjärvi | 3.1 | 0.3–0.9 |
| Dyseutrophic | Uljaste | 2.2 | 1.1–3.4 |
| Dystrophic (reddish-brown water) | Nohipalu Mustjärv | 3.9 | 0.4–0.75 |
| | Valkeakotinen | 3.0 | 0.8–1.1 |

**Measurements of optically active substances**

For $C_{chl}$ measurements, suspended particles were collected on Whatman glass fibre filters (GF/C). Pigments were extracted with ethanol and analysed spectrophotometrically by standard methods. The concentration of suspended matter ($C_s$) was determined by dry weight after filtration of the water through cellulose acetate filters (Sartorios, pore diameter 0.45 μm). Beam attenuation coefficient of the filtered water was measured with a spectrophotometer Hitachi U1000 (Oriola OY, Espoo, Finland) in the wavelength range 350–700 nm. The measured spectra were converted to the "effective" concentration of yellow substance, $C_{y,e}$, in mg $L^{-1}$ using the following equation:

$$C_{y,e} = 1.06 c_f (350), \quad (4)$$

where $c_f$ is the beam attenuation coefficient of the filtered water at $\lambda = 350$ nm (Mäekivi & Arst, 1996). $C_{y,e}$ characterizes the optical influence of dissolved organic matter and its numerical value may be different from $C_{DOM}$ determined by chemical methods. The relative transparency ($Z_{Secchi}$, m) was measured in all lakes with a standard white Secchi disc.

**Radiation measurements**

The depth profiles of downwelling and scalar irradiance in the PAR region (in μmol $m^{-2}$ $s^{-1}$) were measured using LI-COR quantum sensors LI-192 SA (cosine sensor) and LI-193 SA (spherical sensor). The advantages and shortcomings of these types of devices and benefits of using scalar irradiance sensors instead of cosine collectors for measuring PAR in water are discussed by Jewson et al. (1984), Bowling & Tyler (1985), Kirk (1994), and others. These devices have an almost ideal quantum response between 400 and 700 nm.

The spectral distribution of underwater irradiance was measured with a spectroradiometer LI-1800 UW, which measures in the range 300–850 nm with a resolution of 2 nm (W $m^{-2}$ $nm^{-1}$). For a comparison of PAR and spectral measurements, the results obtained in W $m^{-2}$ $nm^{-1}$ were converted into quanta $m^{-2}$ $s^{-1}$ by multiplying with $\lambda/hc_0$. The value of $h$ (Planck's constant) is $6.6255 \times 10^{-34}$ J s, $c_0 = 2.9979 \times 10^8$ m $s^{-1}$ (velocity of light in vacuum) and $\lambda$ is the wavelength (in nm). Integrating over the wavelength in the range of 400–700 nm and replacing 1 μmol $m^{-2}$ $s^{-1}$ = $6.022 \times 10^{17}$ quanta $m^{-2}$ $s^{-1}$, the value of PAR in μmol $m^{-2}$ $s^{-1}$ was obtained also from spectral data. Changes in underwater irradiance caused by variation of incident irradiance (due to cloud cover) were taken into account following the method of Virta & Blanco-Sequeiros (1995), which involves simultaneous use of recorded air pyranometer LI-200 SA (400–1100 nm) data.

To determine the averaged over depth values of the attenuation coefficient from spectral [$K_d(\lambda)$] and integral data in the PAR region ($K_{d,PAR}$, $K_{o,PAR}$), a

similar method was used for both cases: irradiance values at any depth were fitted by least-squares to a straight line on a semilog plot, the slope of which gives $K_{d,o}$. If necessary, additional smoothing by moving average over 6 nm was done. For making the results from different devices comparable, mostly the values of $K_d$ for the 0.5–2 m layer were used in the present study. Only in case of very high attenuation (irradiance values beyond the sensitivity limit) a thinner layer was used. Higher than 5 $m^{-1}$ $K_{d,PAR}$ values were removed from the dataset used for correlation analyses (all together 4 values), because they coincided with bad measurement conditions (overcast weather, brownish water) and the error can be as high as 50%. Due to spectral variation of sensitivity of LI-1800 UW no data of shorter wavelength was used if $K_d(490)$ exceeded 7.6 $m^{-1}$.

Measurements were carried out twice per year, in May or June and in August, mostly around noon (to avoid the changes of $K_d$ due to different solar zenith angles). We used 40 measurement series to determine $K_{d,PAR}$, 46 series for $K_{o,PAR}$, and 49 for spectral $K_d$.

## DIFFUSE ATTENUATION COEFFICIENT OF PAR

If more definite data are lacking, the most exact method to characterize water with respect to the energy available for photosynthesis is the use of the term of total quanta between 400 and 700 nm. As the quantum sensors for the PAR region are commercially available and easy to use, we are interested in finding out relationships between the total quanta results and other bio-optical parameters (including the concentrations of optically active substances) in the upper layer of lakes.

The values of $K_d$ for different lakes together with the concentrations of optically active substances are presented in Fig. 3. The values of $C_{y,e}$ and $C_{chl}$ are comparable with those used in the model by Baker & Smith (described above) only in lakes Äntu Sinijärv and Paukjärv. The model by Baker & Smith leaves out the influence of the suspended matter on $K_d$, but in our lakes $C_s$ values ranged from 1.5 to 37.5 mg $L^{-1}$. Therefore, different combinations of substances are responsible for light attenuation in different lakes and it is not surprising that correlations between some individual optically active substance and $K_{d,PAR}$ were relatively small. The lowest value of the correlation coefficient $R$ was found between $K_{d,PAR}$ and $C_{chl}$ ($R = 0.36$); for $K_{d,PAR}$ and $C_s$ (0.62), and $C_{y,e}$ (0.67) it was remarkably higher. This confirms that the lakes under consideration do not belong to the *Case 1* waters and for a complete description of their bio-optical properties multicomponental models are needed.

The $K_{d,PAR}$ values varied from 0.2 $m^{-1}$ in Äntu Sinijärv to 7.2 $m^{-1}$ in Nohipalu Mustjärv (Fig. 3). These values are not comparable with clear water (e.g. $K_{d,PAR} \sim 0.08$ $m^{-1}$ in the Gulf of California), but are in the same range as those of many other inland water bodies (Kirk, 1994).

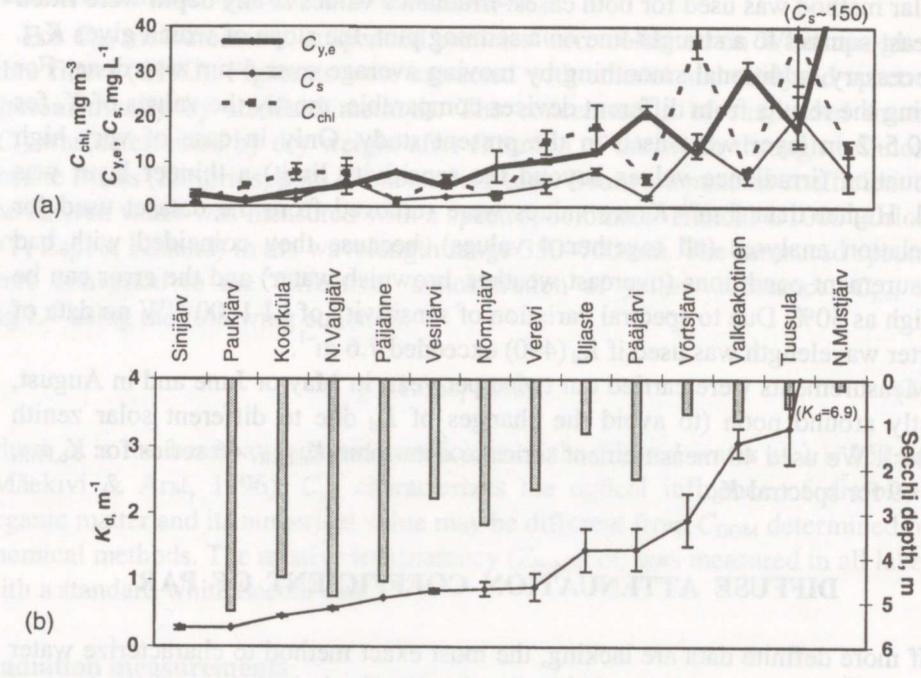


**Fig. 3.** (a) Averaged concentrations with standard deviation of optically active substances for each lake measured in 1995 and 1997. (b) Diffuse attenuation coefficient $K_{d,PAR}$ (lakes are connected with a line) and transparency by Secchi disc (columns) for the same lakes. Shortened names of lakes are used in the figure. (Lines connect separate lakes only for better appreciation.)

It was found that the connections between $K_{d,PAR}$ and $Z_{Secchi}$ can be expressed by the power function:

$$Z_{Secchi} = 2.14 K_{d,PAR}^{-0.87}, \quad R^2 = 0.66, \quad N = 38, \quad p < 0.05. \tag{5}$$

Our data show that in the case of high attenuation ($K_{d,PAR} > 4.6$ m$^{-1}$) Secchi depth is very weakly sensitive to changes in the properties of water.

Scalar irradiance diminishes with increasing depth in a similar manner with downwelling irradiance. These two diffuse attenuation coefficients have a strong correlation corresponding to the following regression equation:

$$K_{o,PAR} = 0.91(\pm 0.01) K_{d,PAR}, \quad R^2 = 0.96, \quad N = 38, \quad p < 0.05. \tag{6}$$

Equation 6 has practical importance allowing computation of $K_{o,PAR}$ from known $K_{d,PAR}$ (or vice versa). Comparing the attenuation coefficients determined from the PAR sensors' data with those calculated for the PAR range from the spectral data $K_d$ (400–700), we found that the correlation coefficient was a little

higher for $K_{o,PAR}$ ($R = 0.94$; $N = 44$) than for $K_{d,PAR}$ ($R = 0.91$; $N = 38$). The slope parameter for $K_{o,PAR}$ was ~1, while $K_{d,PAR}$ exceeded the corresponding $K_d$ (400–700) value in average 1.06 times. As spectral composition of radiation in water differs remarkably from that used for the calibration of the device (LI-COR..., 1990), the readings need a special correction (this problem is important and worth to be investigated in the future). Results from flat LI-192 SA are very sensitive to small deviations from the vertical position of the device, which may occur during measurements on windy days when the surface of waters is rough (the device LI-192 SA is small and light). Spherical LI-193 SA and heavy LI-1800 UW give much more stable data. Nevertheless, the coincidence of the diffuse attenuation coefficients obtained by the two different devices was quite good.

## SPECTRAL DIFFUSE ATTENUATION COEFFICIENT

All optically active components affect irradiance in a different manner, therefore the spectral $K_d$ could give much more information about the underwater light field than the broad-band $K_d$. One example for each lake was chosen to show the variability among our lakes (Fig. 4).

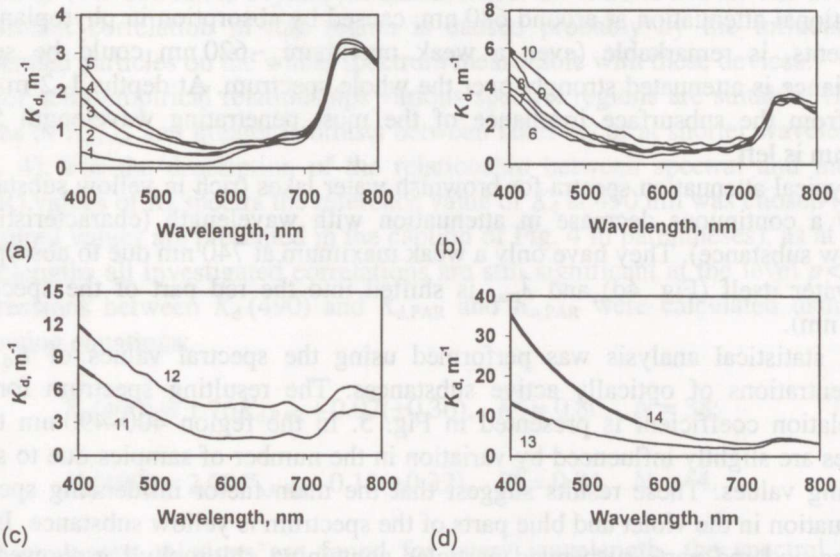


**Fig. 4.** Measured diffuse attenuation coefficients in clear lakes (a, b), turbid lakes (c), and brownish water lakes (d). Thick part of some spectra was calculated by Eqs. 8 and 9 using parameters from Table 3 to recover missing values. 1, Äntu Sinijärv ($K_d(490) = 0.14$ m$^{-1}$); 2, Paukjärv (0.53 m$^{-1}$); 3, Nohipalu Valgjärv (0.68 m$^{-1}$); 4, Koorküla Valgjärv (0.92 m$^{-1}$); 5, Vesijärvi (1.1 m$^{-1}$); 6, Päijänne (1.13 m$^{-1}$); 7, Uljaste (1.42 m$^{-1}$); 8, Verevi (1.36 m$^{-1}$); 9, Kurtna Nõmmjärv (2.04 m$^{-1}$); 10, Lammi Pääjärvi (2.72 m$^{-1}$); 11, Võrtsjärv (4.0 m$^{-1}$); 12, Tuusulanjärvi (4.2 m$^{-1}$); 13, Valkeakotinen (5.6 m$^{-1}$); 14, Nohipalu Mustjärv (16.3 m$^{-1}$).

Lake Äntu Sinijärv is exceptionally clear (curve 1 in Fig. 4a) and its whitish bottom is well visible. A small amount of dissolved organic matter originating from the shore brings about an increase in the attenuation in the violet and blue parts of the spectrum, but the main attenuating factor is water itself. The irradiance that penetrates to the deepest layers is in the range of 540–550 nm ($\lambda_{max}$). Because of multiple reflection from the bottom and water surface, the measurement results probably underestimate the real attenuation and the application of any models described previously would not be reasonable, as they were developed for an optically infinite case.

Diffuse attenuation coefficient spectra for lakes comparable with Jerlov's water types 5–9 are also presented in Fig. 4a (curves 2–5). The $\lambda_{max}$ values varied from 560 to 578 nm. For these spectra the highest attenuation in the red part of the spectrum is characteristic.

The curves of the attenuation coefficients exceeding those for type 9 by Jerlov are presented in Fig. 4b, curves 6–10. The reason of high attenuation can differ from lake to lake (in Lake Lammi Pääjärvi it is yellow substance, but in Lake Verevi also phytoplankton is important). The irradiance is attenuated quickly from both ends of the spectrum and notably less in the region 580–680 nm.

Lakes Võrtsjärv and Tuusulanjärvi (Fig. 4c), which are shallow and rich in phytoplankton, form a separate group. In these lakes the attenuation in the violet and blue parts of the spectrum typically exceeds the attenuation in the red part. Additional attenuation at around 680 nm, caused by absorption in phytoplankton pigments, is remarkable (even a weak maximum ~620 nm could be seen). Irradiance is attenuated strongly over the whole spectrum. At depths 1–2 m only 1% from the subsurface irradiance of the most penetrating wavelength 590–650 nm is left.

Typical attenuation spectra for brownish water lakes (rich in yellow substance) show a continuous decrease in attenuation with wavelength (characteristic of yellow substance). They have only a weak maximum at 740 nm due to absorption by water itself (Fig. 4d) and $\lambda_{max}$ is shifted into the red part of the spectrum (710 nm).

A statistical analysis was performed using the spectral values of $K_d$ and concentrations of optically active substances. The resulting spectrum for the correlation coefficient is presented in Fig. 5. In the region 400–490 nm these curves are slightly influenced by variation in the number of samples due to some missing values. These results suggest that the main factor influencing spectral attenuation in the violet and blue parts of the spectrum is yellow substance. In the orange and red parts suspended particles containing chlorophyll *a* showed the highest correlation with spectral attenuation. Water transparency is correlated negatively with spectral attenuation – higher $Z_{Secchi}$ values corresponded to lower attenuation, with $R$ ranging from 0.6 to 0.8. These not very high values can be explained by simultaneous influence of many factors (including weather and the sensitivity of the human eye). The comparable low correlation of $K_{d,PAR}$ (as well as $K_{o,PAR}$) in the regions 400–500 and 680 nm shows that broad-band sensors

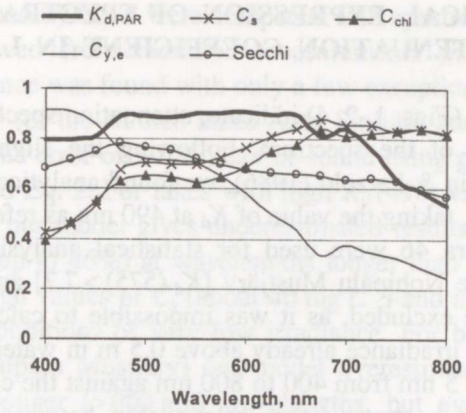


**Fig. 5.** Correlation coefficient ($R$) ($p<0.05$) between $K_d(\lambda)$ values estimated from spectral measurements and values of concentrations of optically active substances, $K_{d,PAR}$ and Secchi depth ($-R$ value) for each wavelength interval of 5 nm.

are not very sensitive to changes in irradiance in some narrow spectral region (weak absorption by yellow substance or absorption peak of chlorophyll). The region of 700–800 nm is beyond the sensitivity of LI-192 SA and LI-193 SA, and significant correlation in this region is caused probably by the influence of suspended particles on the whole spectrum measurable with these devices.

For semi-empirical relationships various spectral regions are suitable. Higher values of $K_{d,PAR}$ and greater contrasts between lakes occur at shorter wavelengths (Fig. 4). For the description of the relationship between spectral and integral (PAR) values of $K_d$ spectra the reference value of $K_d$ at 490 nm was chosen (some measured values are presented in the caption of Fig. 4 in parentheses), as at these wavelengths all investigated correlations are still significant at the level $p<0.05$. Regressions between $K_d$ (490) and $K_{d,PAR}$ and $K_{o,PAR}$ were calculated using the following equations:

$$K_d(490) = 1.76K_{d,PAR} + 0.07(\pm 0.36), \quad R^2 = 0.80, \quad N = 38;$$
$$K_d(490) = 2.00K_{o,PAR} - 0.13(\pm 0.32), \quad R^2 = 0.84, \quad N = 44. \tag{7}$$

If analogous relations are found for every wavelength, the spectral $K_d$ is roughly estimable from known values of broad-band attenuation coefficients. Using Eq. 7 and the analytical expression of spectral diffuse attenuation coefficient described in the following part of this paper, all spectra of $K_d$ can be calculated by known values of broad-band attenuation coefficients (or even by Secchi depth). This could be useful if we have no spectrophotometric data available or for converting the PAR measurements into spectral values.

## ANALYTICAL EXPRESSION OF SPECTRAL DIFFUSE ATTENUATION COEFFICIENT IN LAKES

As all examples (Figs. 1, 2, 4) indicate, attenuation spectra behave in a regular fashion over most of the spectrum. Following the slightly modified method introduced by Austin & Petzold (1986), we found analytical expression for lakes under investigation, taking the value of $K_d$ at 490 nm as reference value. From 49 measured $K_d$ spectra 46 were used for statistical analysis. Both spectra from extremely dark lake Nohipalu Mustjärv [$K_d(575) > 7.7$] and one spectrum from Tuusulanjärvi were excluded, as it was impossible to calculate $K_d(490)$ due to high attenuation of irradiance already above 0.5 m in water. From the plot of all $K_d$ values for every 5 nm from 400 to 800 nm against the corresponding value of $K_d(490)$, we found a strong linear relationship between these two variables (correlation coefficient was higher than 0.8 over the whole spectrum, significance $p<0.05$). The slope parameter $M(\lambda)$ and the intercept $I(\lambda)$ for all 81 wavelengths were based on fitting by the least squares technique a linear equation of the form:

$$K_d(\lambda) = I(\lambda) + M(\lambda) K_d(490). \tag{8}$$

Using values of these parameters (in Table 3 the values are presented with a 10 nm step) the entire spectrum of $K_d$ could be found by the reference value of $K_d$ at 490 nm. The unknown value of $K_d$ at the wavelength $\lambda_2$ is calculable from the known $K_d$ at any other wavelength $\lambda_1$ by applying Eq. 8 twice:

$$K_d(\lambda_2) = I(\lambda_2) + [K_d(\lambda_1) - I(\lambda_1)] \frac{M(\lambda_2)}{M(\lambda_1)}. \tag{9}$$

This procedure is useful for determining the missing $K_d$ values at shorter wavelengths, which often happens in lakes with brownish water.

**Table 3.** Values of intercept $I(\lambda)$ ($\pm 0.04$) and slope parameter $M(\lambda)$ ($\pm 0.01$) for analytical expression of $K_d(\lambda)$ by Eq. 8

| λ, nm | $I(\lambda)$ | $M(\lambda)$ | λ, nm | $I(\lambda)$ | $M(\lambda)$ | λ, nm | $I(\lambda)$ | $M(\lambda)$ |
|---|---|---|---|---|---|---|---|---|
| 400 | 0.58 | 2.20 | 540 | –0.10 | 0.68 | 680 | 0.31 | 0.43 |
| 410 | 0.52 | 2.00 | 550 | –0.11 | 0.64 | 690 | 0.40 | 0.38 |
| 420 | 0.44 | 1.79 | 560 | –0.13 | 0.61 | 700 | 0.53 | 0.33 |
| 430 | 0.37 | 1.66 | 570 | –0.14 | 0.58 | 710 | 0.72 | 0.32 |
| 440 | 0.28 | 1.56 | 580 | –0.12 | 0.56 | 720 | 1.04 | 0.32 |
| 450 | 0.22 | 1.37 | 590 | –0.06 | 0.53 | 730 | 1.62 | 0.33 |
| 460 | 0.18 | 1.24 | 600 | 0.00 | 0.52 | 740 | 2.36 | 0.35 |
| 470 | 0.11 | 1.14 | 610 | 0.03 | 0.51 | 750 | 2.80 | 0.32 |
| 480 | 0.06 | 1.06 | 620 | 0.08 | 0.50 | 760 | 2.86 | 0.31 |
| 490 | 0.00 | 1.00 | 630 | 0.10 | 0.47 | 770 | 2.87 | 0.29 |
| 500 | –0.04 | 0.93 | 640 | 0.12 | 0.45 | 780 | 2.78 | 0.28 |
| 510 | –0.07 | 0.87 | 650 | 0.16 | 0.43 | 790 | 2.61 | 0.26 |
| 520 | –0.08 | 0.80 | 660 | 0.21 | 0.43 | 800 | 2.45 | 0.26 |
| 530 | –0.09 | 0.74 | 670 | 0.26 | 0.44 | | | |

The results obtained by Eq. 8 were compared with spectral curves of $K_d(\lambda)$ for different lakes derived from radiation measurements *in situ*. In general a satisfactory coincidence was found with only a few exceptions. If $K_d(490)$ values are less than 0.6 $m^{-1}$ (of the studied lakes Äntu Sinijärv and Paukjärv) then the best results (within the error of ±10%) can be found using parameters by Austin & Petzold (1986) and Eq. 2. For lakes with high $K_d(490)$ values (5.7–7.5 $m^{-1}$ in Lake Tuusulanjärvi) our model gives underestimated results in comparison with the measured ones (up to 46%) at wavelengths longer than 600 nm. The reason may be extremely high values of $C_s$ (about 40 mg $L^{-1}$) and also the measurement error of $K_d$ in the conditions of very low irradiance. For brownish water lakes (Valkeakotinen, Nohipalu Mustjärv) our model overestimates (up to 50%) the real attenuation at longer (>600 nm) wavelengths, but even in this case this model can be used for draft extrapolation of missing data in the violet and blue regions of the spectrum (Eq. 9). For such extreme cases more data are needed and probably another algorithm could be used, based on some previous knowledge about optical properties of these lakes.

A comparison of the measured and calculated values showed that the coincidence was good if $K_d(490)$ values ranged from 0.6 to 5.6 $m^{-1}$ (Fig. 6). Relative error was the highest around 680 nm being ~10% over the whole spectrum.

A plot of the series of modelled $K_d$ spectra according to different $K_d(490)$ values in the range 0.5 to 5.5 is shown in Fig. 7. Only two curves (with the values of $K_d(490)$ 0.63 and 1.08 $m^{-1}$) are comparable with Jerlov's most turbid water types 7 and 9, with little differences in the violet and red parts of the spectrum. The other spectra in Fig. 7 describe much more turbid waters than any water type

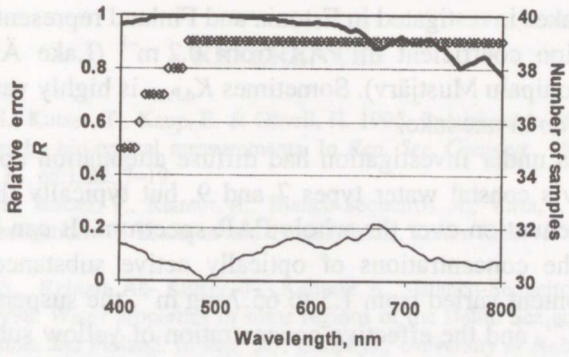


**Fig. 6.** Results of algorithm (Eq. 8, Table 3) validation: thick line, correlation coefficient ($R$) between measured and modelled $K_d$ using the reference $K_d(490)$ in the range 0.6–5.6 $m^{-1}$ at any wavelength interval of 5 nm; solid line, relative error of modelled $K_d$. Diamonds show the number of cases used for comparison.

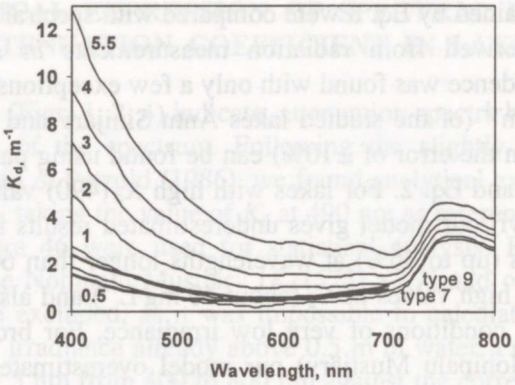


**Fig. 7.** $K_d(\lambda)$ calculated by Eq. 8 using parameters from Table 3, according to different values of $K_d(490)$ (numbers in figure); thick lines represent type 7 and 9 by Jerlov (1976).

by Jerlov. The value of $K_d(490)$ could be used as a classification index for clear-water and moderately turbid lakes in Estonia and Finland. This model describes satisfactorily 85% of all spectra measured by us.

## CONCLUSIONS

1. The existing optical classifications of natural waters proposed by different authors are suitable for describing the *Case 1* waters (by Morel) and give quite coinciding results for the open ocean. For multicomponental waters these models give mostly different results, the coincidence occurring only in some cases.

2. Fourteen lakes investigated in Estonia and Finland represent the variation of diffuse attenuation coefficient of PAR from 0.2 $m^{-1}$ (Lake Äntu Sinijärv) to 7.2 $m^{-1}$ (Lake Nohipalu Mustjärv). Sometimes $K_{d,PAR}$ is highly variable during the warm season even in one lake.

3. Some lakes under investigation had diffuse attenuation coefficient spectra similar to Jerlov's coastal water types 7 and 9, but typically the lakes showed much higher attenuation over the whole PAR spectrum. It can be explained by the values of the concentrations of optically active substances in lakes: the chlorophyll *a* content varied from 1.3 to 65.7 mg $m^{-3}$, the suspended matter from 1.5 to 37.5 mg $L^{-1}$, and the effective concentration of yellow substance from 3.2 to 100 mg $L^{-1}$. These data together with the analysis of the contribution of each substance in the spectral attenuation of light in the water show that these lakes obviously do not belong to Morel's *Case 1* waters, but being multicomponental, their attenuation coefficients are influenced by a concrete combination of different optically active substances in the water.

4. As a large number of lakes have diffuse attenuation coefficients exceeding Jerlov's most turbid coastal water type 9 and due to a greater contribution of yellow substance in the light attenuation compared with that in the sea, there is an urgent need for an optical classification of the lake waters.

5. Using the statistical methods an analytical expression and its spectral parameters were found, suitable for re-creating the diffuse attenuation coefficient spectra of some water body on the basis of the known value of $K_d(490)$. This method works with good accuracy (relative error below 10%) if $K_d(490)$ ranges from 0.6 to 5.6 $m^{-1}$ (this is 85% from our data collection). $K_d(490)$ could be used as a classification index for clear-water and moderately turbid lakes in Estonia and Finland. However, the lakes with a very high content of yellow substance or extremely turbid ones need a more complicated model.

6. Widely used LI-COR broad-band PAR sensors LI-192 SA and LI-193 SA give results that are in rather good coincidence with respective values calculated from the spectral data of LI-1800 UW. However, because the spectral composition of light in the water differs remarkably from that used for the calibration of LI-COR sensors, their response to irradiance with different spectral composition needs additional investigation.

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# DIFUUSSE KIIRGUSE NÕRGENEMISKOEFITSIENT MÕNES EESTI JA SOOME JÄRVES

Anu REINART ja Antti HERLEVI

Veealuse kiiritustiheduse mõõtmiste põhjal on leitud spektraalsed ja fotosünteetiliselt aktiivse kiirguse vertikaalsed nõrgenemiskoefitsiendid neljateistkümnes erineva toitelisusega Eesti ja Soome järves. Statistilise analüüsi alusel on kiirguse nõrgenemine neis järvedes tingitud peamiselt kollasest ainest ja heljumist (determinatsiooni koefitsient vastavalt 45 ja 38%), klorofüll *a* kirjeldab ainult 13% nõrgenemiskoefitsiendi muutlikkusest. Nõrgenemiskoefitsiendil põhinevad vee optilised klassifikatsioonid ei ole üldiselt järvede puhul rakendatavad, sest optiliselt aktiivsete ainete kontsentratsioon on neis suhteliselt suur. Ainult selgeveelistes järvedes on kiirguse nõrgenemine võrreldav Jerlovi klassifikatsiooni kõige hägusamate vetega. Seetõttu on statistilise analüüsiga leitud difuusse kiirguse spektraalse nõrgenemiskoefitsiendi analüütiline avaldis ja selle spektraalsed parameetrid lainepikkuse 490 nm alusel (täpsusega 10%, kui $K_d(490)$ on vahemikus 0,6–5,6 $m^{-1}$). Saadud avaldis võib olla kasulik nõrgenemiskoefitsiendi spektris puuduvate väärtuste arvutamiseks. Empiirilisi seoseid kasutades saab määrata ligikaudse nõrgenemiskoefitsiendi spektri integraalsetest kiirgusmõõtmistest või isegi Secchi ketta läbipaistvuse järgi. $K_d(490)$ väärtust võiks kasutada kui puhaste ja keskmiselt hägusate Eesti ja Soome järvede klassifikatsiooni indeksit.