Papers

Underwater light field and spectral distribution of attenuation depth in inland and coastal waters*

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KEYWORDS
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Abstract

The daily variations in the underwater irradiance spectra at different depths were determined using a combination of in situ data and model calculations. The spectra of the attenuation depth (relevant in optical remote sensing) were derived from these data. The results are presented for four Estonian lakes (Koorküla Valgjärv,

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Võrtsjärv, Harku, and Peipsi) and for coastal waters of the Baltic Sea (Pärnu Bay, Gulf of Riga).

1. Introduction

The underwater light field (spectral, vertical and spatial/temporal variation of irradiance) is a relevant factor in optical, biological and remote sensing studies of water bodies. Phytoplankton photosynthesis proceeds using available quantum irradiance in the water; the spectral composition of underwater irradiance is also essential for the growth and dynamics of underwater organisms, including bottom plants (Platt & Sathyendranath 1988, Sathyendranath et al. 1989, Smith et al. 1989, Schofield et al. 1990, Kyewalyanga et al. 1992, Kirk 1994, Sosik 1996, Arst et al. 2008a).

The main object of interest in remote sensing is the irradiance backscattered from the water column and forming one part of the upwelling radiation recorded with satellite sensors (Sathyendranath 1986, Kirk 1994, Kutser et al. 2001, Dekker et al. 2001, Mueller 2002). However, the data on the downwelling irradiance in the water are also of interest for optical remote sensing because they allow the spectra of the attenuation depth z_{att} to be determined. This parameter shows the thickness of the layer from which 90% of the signal recorded by satellite sensor originates.

The main objectives of the present study were: (a) to investigate the optical properties of different water bodies, and calculate the spectral, vertical and diurnal variations of the planar quantum irradiance in the water; (b) to calculate the spectral distribution of the corresponding attenuation depth.

2. Material and methods

Our study contains the results of model calculations, whereby the initial data were taken from in situ measurements made from May to August in 2007 and 2008. The sampling stations were located in the following Estonian water bodies: two small lakes (Koorküla Valgjärv and Harku), two large lakes (Peipsi and Võrtsjärv), and a coastal area of the Baltic Sea (Pärnu Bay and the Gulf of Riga). Figure 1 shows the location of the sampling stations, and Table 1 lists the morphometric data and some other parameters of the four lakes. We used the data of outdoor and laboratory measurements corresponding to these sampling stations. Our results were obtained in 2007–2008, except the measurements for L. Peipsi, which were carried out only in 2008. The measurements in Pärnu Bay (10 sampling stations) and in the Gulf of Riga (2 stations) were made in 2007. In the present study, we took into consideration the results obtained at two stations in Pärnu Bay and one station in the Gulf of Riga (see Figure 1 and Table 2).

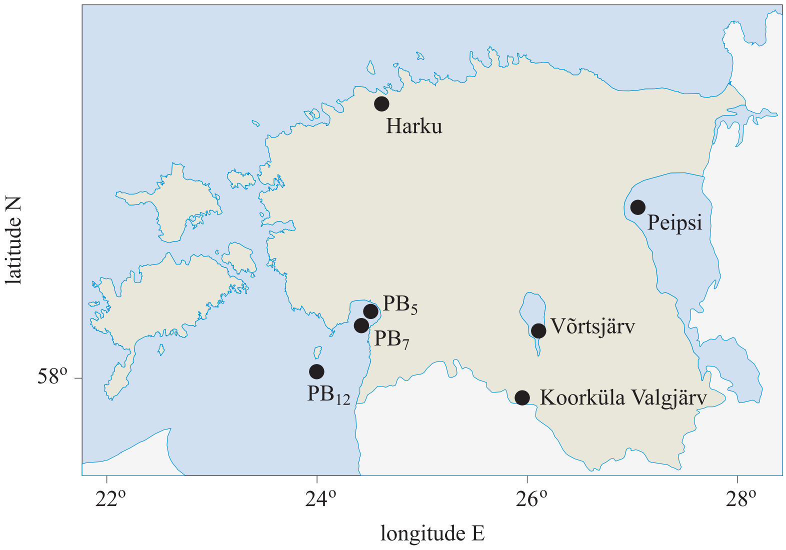


Figure 1. Location of sampling stations in Estonian waters

Table 1. Morphometric data, geographical coordinates of the sampling stations in lakes, the corresponding minimum and maximum values of Secchi depth z_{SD} and diffuse attenuation coefficient of light $K_{\mathrm{d,\ PAR}}$ in the photosynthetically active region (PAR, 400–700 nm) (Arst et al. 2008a,b, Paavel et al. 2008b)

Parameter	L. Peipsi	L. Võrtsjärv	L. Koorküla Valgjärv	L. Harku
trophic level	eutrophic	eutrophic	oligotrophic	hypertrophic
area [km^2]	2611	270	0.44	1.64
mean depth [m]	8.3	2.8	8.5	2.0
location of station	58°52′N 26°57′E	58°13′N 26°06′E	57°54′N 25°52′E	59°24′N 24°37′E
z_{SD} [m]	0.4–4.2	0.3–1.6	2.8–5.3	0.1–1.0
$K_{\mathrm{d,\ PAR}}$ [m^{-1}]	0.7–2.6	1.5–3.8	0.4–0.9	2.5–7.7

Incident solar irradiance was recorded from morning to evening on all the lakes, but this kind of data is not available for Pärnu Bay or the Gulf of Riga. In L. Võrtsjärv we used a Yanishevsky pyranometer (Kondratyev 1965) placed on the roof of a building very near to the coastal station in Võrtsjärv. For L. Peipsi we obtained the necessary data from the actinometric station in Tiirikoja (on the western coast of the lake, close to the sampling station). We measured the incident irradiance on L. Harku and L. Koorküla Valgjärv using an LI-192 SA quantum sensor (LI-COR).

Table 2. Location of the sampling stations in Pärnu Bay and in the Gulf of Riga, and some optical properties of the water measured in 2006–2007 (Paavel 2008a)

Parameter	PB5	PB7	PB12
location of station	58°22′N 24°28′E	58°20′N 24°25′E	58°04′N 23°57′E
z_{SD} [m]	0.5–1.7	0.9–1.6	1.5–3.5
$K_{\mathrm{d,\,PAR}}$ [m^{-1}]	0.8–2.0	0.8–1.9	0.7–1.3
remarks	near the mouth of the Pärnu River	in the central part of Pärnu Bay	in the Gulf of Riga near Pärnu Bay

The spectral downwelling planar quantum irradiance (in μmol m^{-2} s^{-1} nm^{-1}) was measured with a BIC-2104 spectroradiometer (Biospherical Instruments Inc., 2003), which has three channels centred at 412, 555 and 665 nm. Such measurements are available only for Lakes Koorküla Valgjärv, Võrtsjärv and Harku; we were unable to carry out BIC-2104 measurements on L. Peipsi or Pärnu Bay. In these latter cases the optical properties of the water were determined from beam attenuation coefficient spectra for filtered and unfiltered water samples (in the 350 –700 nm wavelength range) using laboratory spectrophotometers (Hitachi U1000 and Hitachi U3010).

The values of the underwater planar quantum irradiance for narrow spectral intervals $\Delta\lambda = 10$ nm $q(\Delta\lambda, z)$ at depth z were determined by model calculations according to the equation

$$q(\Delta\lambda, z) = W(\Delta\lambda)(1 - R)q_{\mathrm{PAR}}(z = +0)\exp(-K_{\mathrm{d}}(\Delta\lambda)z), \tag{1}$$

where $W(\Delta\lambda)$ is the contribution of each narrow spectral interval to the PAR irradiance (Bird & Riordan 1986), $q_{\mathrm{PAR}}(z = +0)$ is the incident quantum irradiance in the PAR region [μmol m^{-2} s^{-1}], R is the reflection coefficient of the light and $K_{\mathrm{d}}(\Delta\lambda)$ [m^{-1}] is the diffuse attenuation coefficient for the interval $\Delta\lambda$. Both $K_{\mathrm{d}}(\Delta\lambda)$ and R depend on the solar zenith angle and cloudiness, which can be computed (Ivanov 1978, Kirk 1994). To conclude, the model calculations allow the underwater light field to be described in detail using quite a scarce in situ database.

According to equation (1) we need the values of $K_{\mathrm{d}}(\Delta\lambda)$ for the PAR region. Reinart & Herlevi (1999) developed a model that allows the spectra of K_{d} to be reproduced when its value for one wavelength its known. The corresponding algorithm and a table of the relevant coefficients are presented. Paavel et al. (2006) studied the reliability of this algorithm, elaborating a new and more precise computing system (with the same algorithm but three different reference wavelengths). These reference wavelengths were chosen according to the measuring channels of the BIC-2104 spectroradiometer. Thus, from our BIC-2104 measurements we determined $K_d(\Delta\lambda)$ for channels centred at 412, 555 and 665 nm, and then calculated the diffuse attenuation coefficients for 10th width intervals between 400 and 700 nm using the model by Paavel et al. (2006). We had no BIC-2104 measurements in Pärnu Bay or L. Peipsi, so we derived the spectral values of the diffuse attenuation coefficient from beam attenuation coefficient c data using the model described in Arst et al. (2002) and Arst (2003); in those studies a computing system for estimating the spectra of K_d from the corresponding spectra of c was developed. The basic measurements were made for nine Finnish and nine Estonian lakes (70 spectra altogether) using an underwater spectroradiometer (LI-1800 UW) and laboratory spectrometer (Hitachi U1000) for determining the spectra of $K_d(\Delta\lambda)$ and $c(\Delta\lambda)$ respectively (Arst et al. 2002, Arst 2003). We also determined the spectra of $z_{att}(\Delta\lambda)$ from the $K_d(\Delta\lambda)$ data according to the formula $z_{att}(\Delta\lambda) = 1/K_d(\Delta\lambda)$ (Kirk 1994).

3. Results and discussion

The daily variations of the incident irradiance $q_{PAR}(z = +0)$ for Lakes Koorküla Valgjärv (14 May 2007), Võrtsjärv (17 May 2007), Harku (22 May 2008) and Peipsi (27 June 2008) are presented in Figure 2. For better comparison of the properties of the lakes, we have chosen days with small amounts of variable cloudiness. The times in this figure (and afterwards) are given in Eastern European Summer Time (UTC/GMT +3 hours). Figure 2 shows the influence of clouds on $q_{PAR}(z = +0)$ (the jagged outlines of the irradiance curves). The light attenuation in these lakes (spectral and diurnal variations) is compared in Figures 3 and 4. These illustrate the differences of the water properties in these lakes. As far as the lake waters are concerned, the light attenuation in L. Koorküla Valgjärv was rather weak: the picture at 0.2 m hardly differed from that at 0.0 m, and at 1.2 m the irradiance values were about 60% of those at the surface (this decrease also depends on wavelength). L. Peipsi was less transparent: at 1.2 m only ca 40% of the surface irradiance remains. In L. Võrtsjärv the irradiance at 0.4 m was noticeably less than at the surface and at 0.4 m in L. Harku only an imperceptible part of the incident light is still detectable (Figure 4). According to our data, these differences will increase from June to August as a result of the summer phytoplankton bloom in these eutrophic lakes. Figures 3 and 4 also show that the smallest irradiances are in the blue region of spectrum (this is caused by the striking influence of dissolved

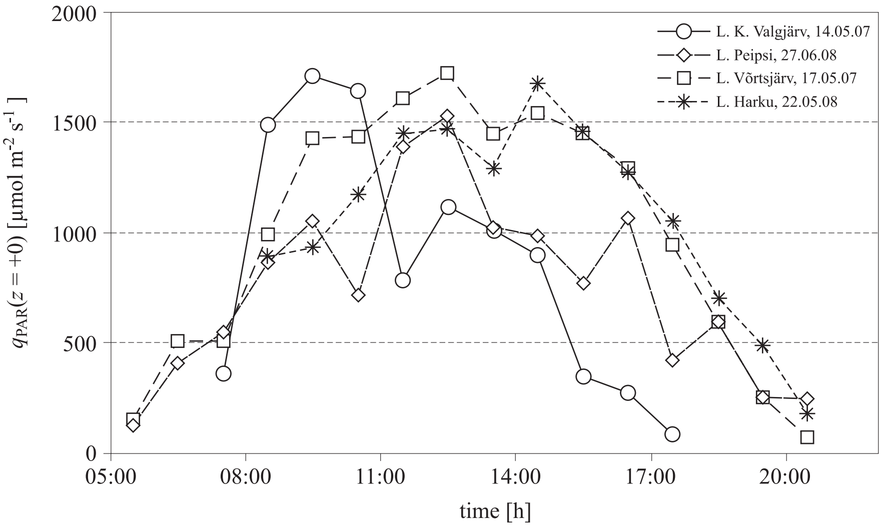


Figure 2. Daily variations in the incident planar quantum irradiance ($q_{\mathrm{PAR}}(z = +0)$) for Lakes Koorküla Valgjärv, Peipsi, Võrtsjärv and Harku. The times are given in Eastern European Summer Time (UTC/GMT +3 hours)

organic matter on light attenuation at wavelengths 400–450 nm). These figures also illustrate the influence of incident irradiance and cloudiness on the underwater light field.

It should be borne in mind that the data in Figures 3 and 4 describe the quantum irradiance at different depths, but not the spectra of the diffuse attenuation coefficient. This coefficient depends to some extent on the solar zenith angle and also on cloudiness (Phillips & Kirk 1984, Kirk 1989, 1994, Reinart et al. 2000, Arst 2003). Two examples are shown in Figures 5 and 6. These estimates were made using the formulas for K_{d} from Kirk (1989, 1994) in the model by Arst et al. (2002), which allows the spectra of K_{d} to be calculated using the spectral values of the beam attenuation coefficient. The results showed that the differences between $K_{\mathrm{d}}(\Delta\lambda,\ 40°)$ and $K_{\mathrm{d}}(\Delta\lambda,\ 57°)$ are from 5.5% to 10%, but between $K_{\mathrm{d}}(\Delta\lambda,\ 40°)$ and $K_{\mathrm{d}}(\Delta\lambda,\ 80°)$ they can rise to 13–20%. The data presented in Figures 3 and 4 were obtained taking into account the dependence of $K_{\mathrm{d}}(\Delta\lambda)$ on the solar zenith angle. However, when the objectives are large-scale calculations of the diurnal or monthly sums of underwater irradiance at different depths, we can ignore the diurnal variability of $K_{\mathrm{d}}(\Delta\lambda)$ (when zenith angles are large, the contribution of incoming solar radiation to diurnal sums of underwater radiation is small) and use the same spectrum of $K_{\mathrm{d}}(\Delta\lambda)$ during the day (the ‘overcast’ spectrum is recommended).

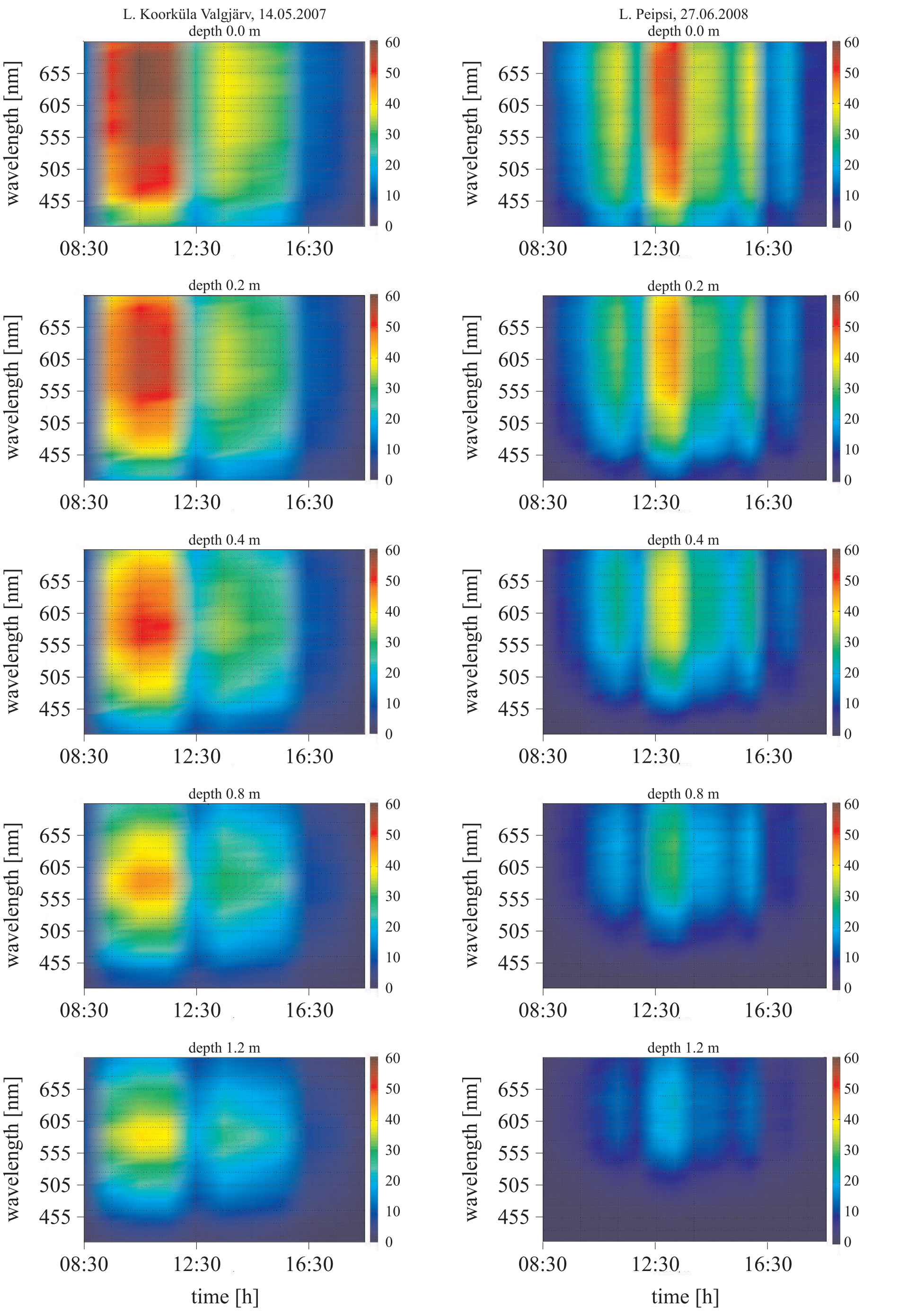


Figure 3. Spectral and diurnal variation in the underwater planar quantum irradiance $q(\lambda,\ z,\ t)$ in L. Koorküla Valgjärv ($K_{\mathrm{d,\ PAR}} = 0.48$) (*continued on next page*)

(**Figure 3.** *continued*) and L. Peipsi ($K_{\mathrm{d,\,PAR}} = 1.03$). The values of $q(\lambda,\ z,\ t)$ are shown in μmol m^{-2} s^{-1} nm^{-1} using the colour scale next to each figure

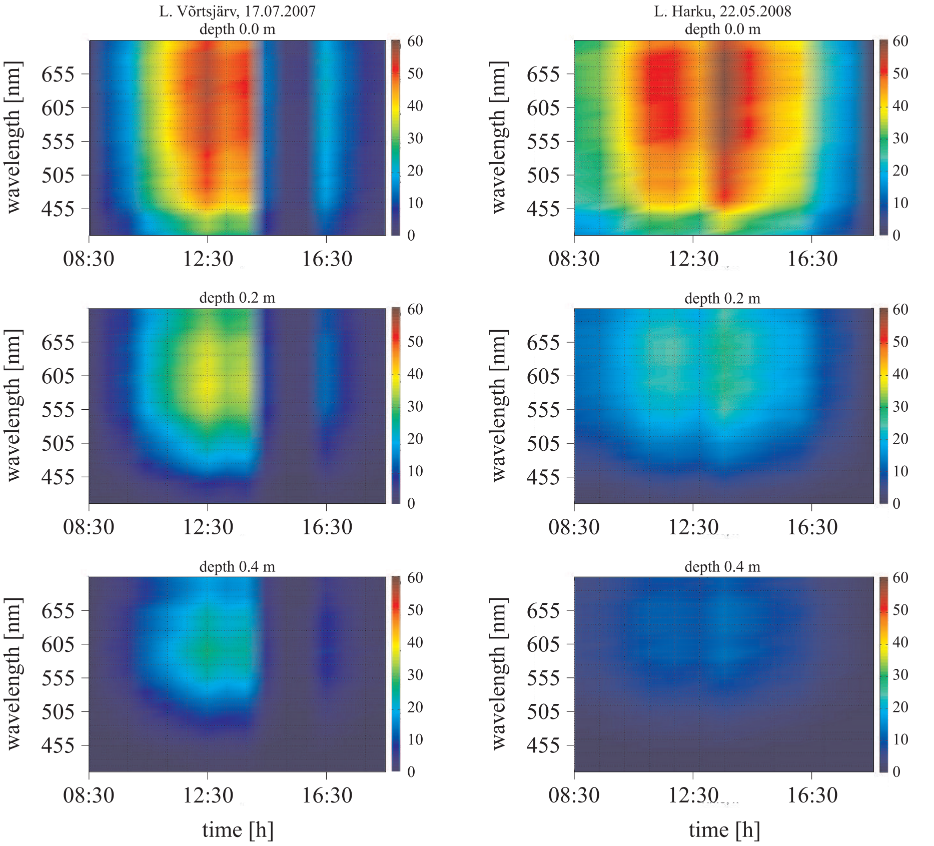


Figure 4. Spectral and diurnal variation in the underwater planar quantum irradiance $q(\lambda,\ z,\ t)$ in L. Võrtsjärv ($K_{\mathrm{d,\,PAR}} = 2.66$) and L. Harku ($K_{\mathrm{d,\,PAR}} = 4.43$). The values of $q(\lambda,\ z,\ t)$ are shown in μmol m^{-2} s^{-1} nm^{-1} using the colour scale next to each figure

The spatial and temporal variabilities of the water parameters were the most marked in Pärnu Bay of all the water bodies investigated. In this region we have no data on the diurnal change of the incoming solar radiation, but we do have the spectra of K_{d} for different stations. Figure 7 shows the differences in $K_{\mathrm{d}}(\Delta\lambda)$ measured at stations PB5, PB7 and PB12 on 24 April and 7 August 2007. As expected, the values of $K_{\mathrm{d}}(\Delta\lambda)$ in the blue region of the spectrum (400–480 nm) in April were substantially higher than those in August: ca 3–4 times higher at station PB5, ca 2–3 times at station PB7

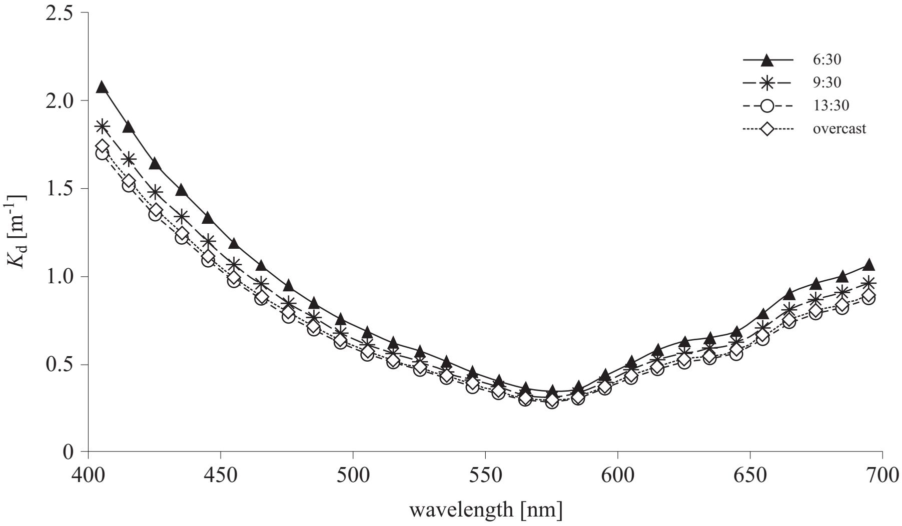


Figure 5. Spectral distribution of the diffuse attenuation coefficient in L. Koorküla Valgjärv at 6:30, 9:30, 13:30 on 14 May 2007 (respective solar zenith angles = 80.6°, 57.1° and 39.6°). The spectrum for overcast sky conditions is also shown

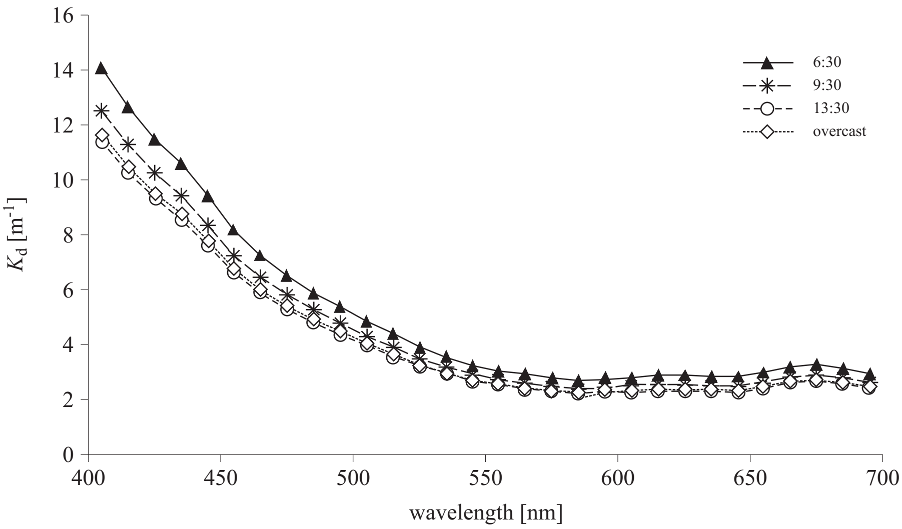
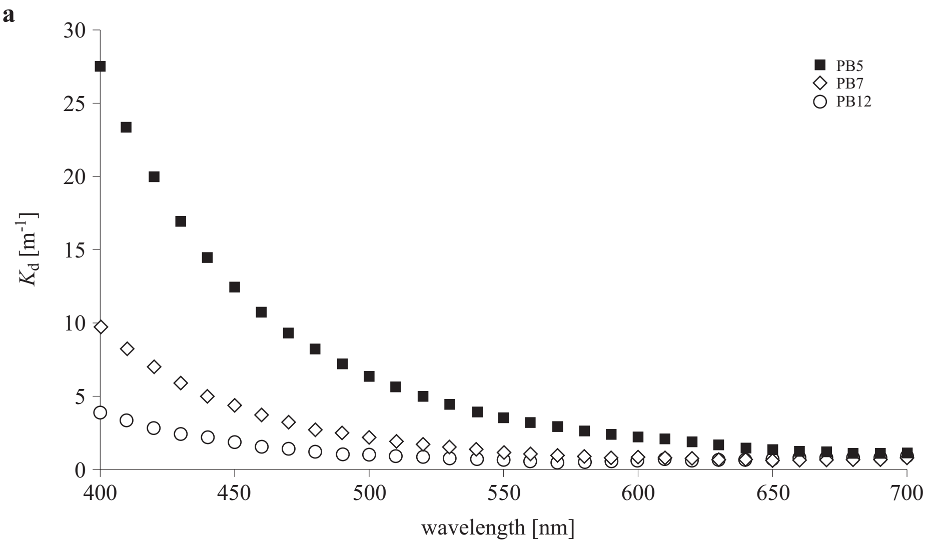


Figure 6. Spectral distribution of the diffuse attenuation coefficient in L. Võrtsjärv at 6:30, 9:30, 13:30 on 17 May 2007 (respective solar zenith angles 79.7°, 56.5° and 39.2°). The spectrum for overcast sky conditions is also shown

and 1.6–1.8 times at station PB12. This can be explained by the maximum content of dissolved organic matter in spring, which is most noticeable at



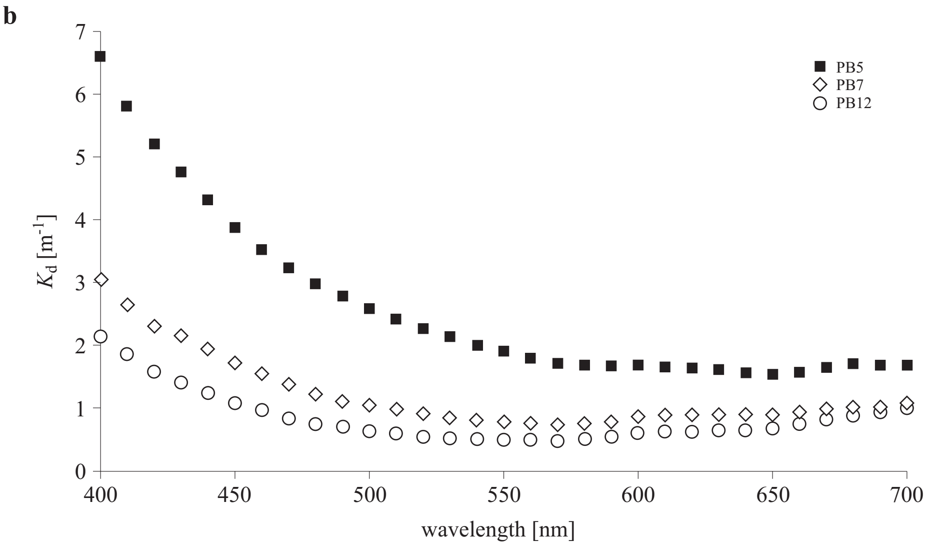


Figure 7. Spectral distribution of the diffuse attenuation coefficient at stations PB5, PB7 and PB12: on 24 April 2007 (a), on 7 August 2007 (b)

the station near the mouth of the Pärnu River. The seasonal change of $K_d(\Delta\lambda)$ at two stations, PB5 and PB12, is characterised in Figure 8. At station PB5 this change corresponds to the decrease in the dissolved organic matter content towards autumn (except in the red region of the spectrum); at station PB12 the sequence of the curves was irregular and was probably influenced by the variability of the phytoplankton during the summer.

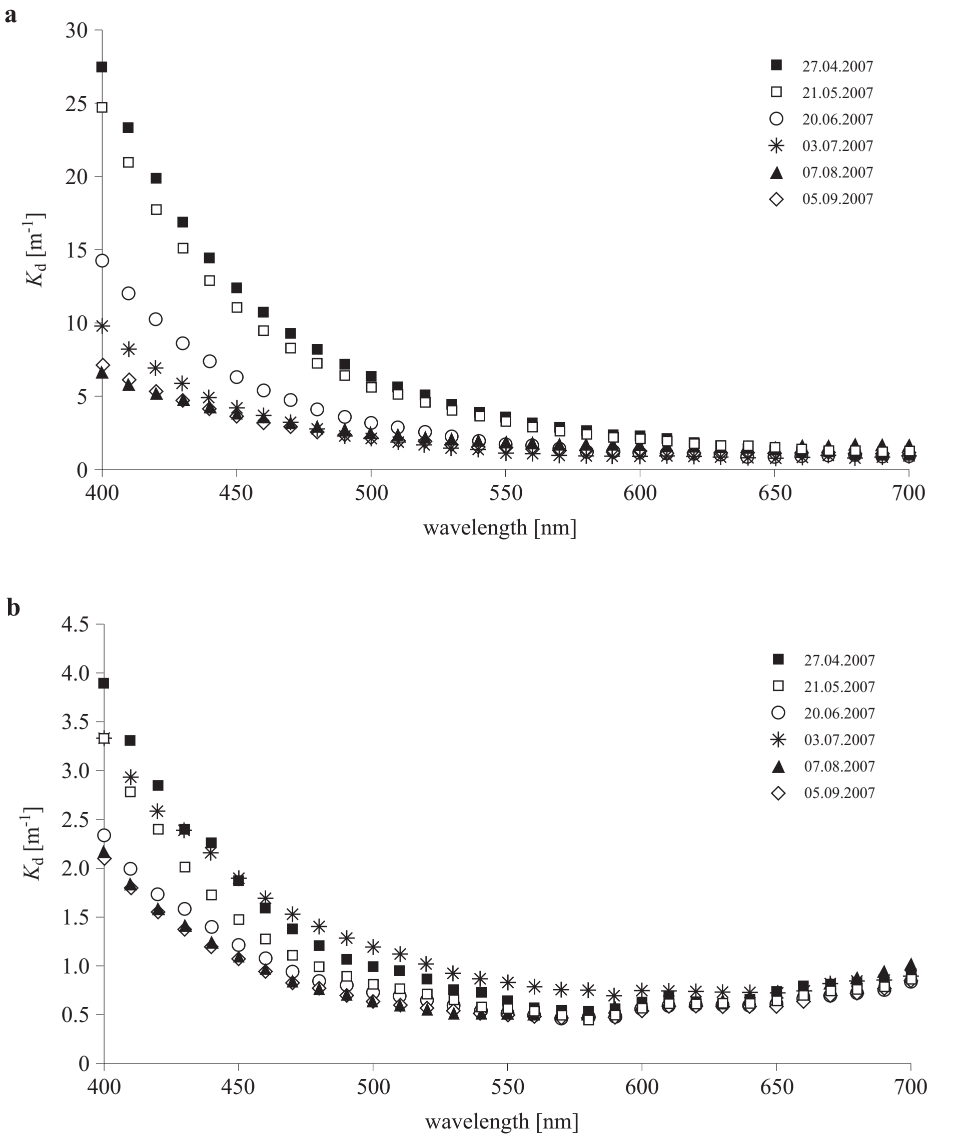


Figure 8. Spectral distribution of the diffuse attenuation coefficient at different times during summer 2007: station PB5 (a), station PB12 (b)

From the point of view of remote sensing it is important to know not only the values of the attenuation depth for the PAR region, but also its spectral distribution. Figure 9 shows these spectra for all six water bodies on different dates in May. We can conclude that the satellite sensor is able to acquire information in Lakes Võrtsjärv and Harku only from the 0.2–0.3 m layer and at wavelengths exceeding 500 nm. At the coastal station in

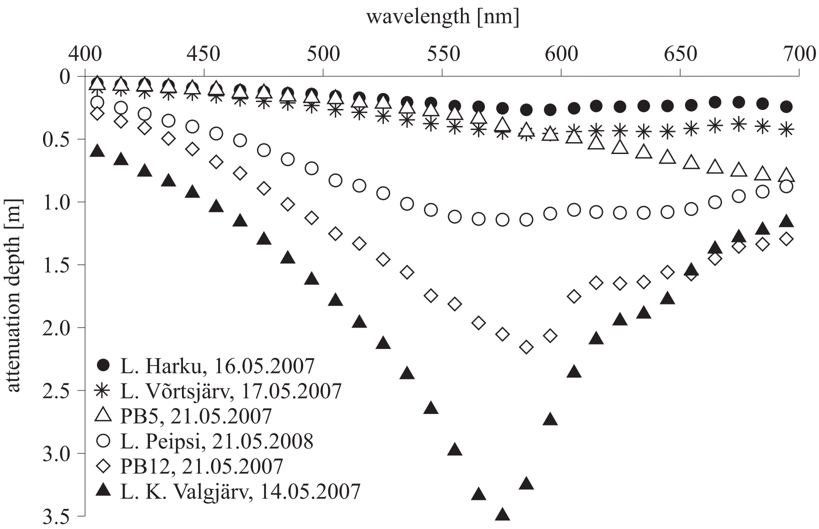


Figure 9. Spectral distribution of the attenuation depth in different water bodies (only the results for May are shown)

Pärnu Bay (PB5) the values of $z_{\text{att}}(\lambda)$ in the region of 570–700 nm were ca 0.6–1.0 m, but in the blue region of the spectrum they were very low owing to the high concentration of coloured dissolved organic matter (CDOM) entering the bay from the River Pärnu. In May 2008 $z_{\text{att}}(\lambda)$ in L. Peipsi was ca 0.9–1.2 m (525–700 nm). The situation was much better in the Gulf of Riga (station PB12) and especially in L. Koorküla Valgjärv. In the latter case information was attainable even from a depth of 3.5 m (Figure 9). Most of the investigated water bodies showed the maximum $z_{\text{att}}(\lambda)$ in the region 550–600 nm, except Pärnu Bay (PB5), where $z_{\text{att}}(\lambda)$ reached a maximum in the 600–650 nm band. The value of $z_{\text{att}}(\lambda, \max)$ was ca 3.5 m in L. Koorküla Valgjärv, 2.2 m in the Gulf of Riga (PB12), 1.4 m in L. Peipsi, 0.6 m in Võrtsjärv and 0.25 m in L. Harku.

Figure 10 shows the spectra of z_{att} for different months (in L. Peipsi, at both Pärnu Bay stations and at the one in the Gulf of Riga). The greatest temporal variation in $z_{\text{att}}(\lambda)$ in all the lakes was recorded in L. Peipsi (Figure 10a). There, the attenuation depth reached a maximum in June; obviously CDOM and the spring phytoplankton bloom in May and the summer bloom in July–August diminished the values of $z_{\text{att}}(\lambda)$. The values of z_{att} in L. Harku were small throughout the summer, and the attenuation depth in L. Võrtsjärv reached a minimum in June and August. At the coastal station in Pärnu Bay (PB5) the attenuation depth fell to a minimum (especially in the blue region of the spectrum) in April–May, when the CDOM concentration was high (inflow from the River Pärnu). It is possible

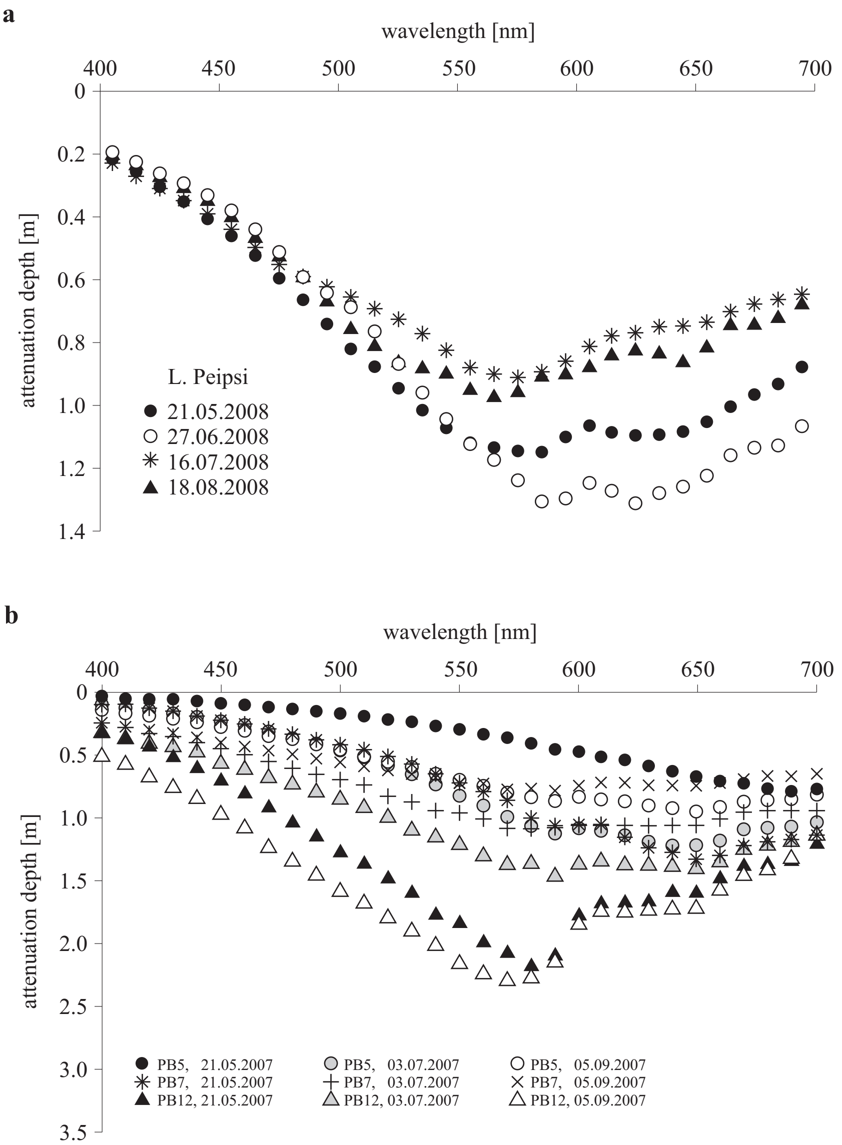


Figure 10. Spectral distribution of the attenuation depth in different months: in L. Peipsi (a), in Pärnu Bay and in the Gulf of Riga (stations PB5, PB7 and PB12)(b)

that the spring algal bloom in the sea also has some influence. From July to September the phytoplankton bloom at station PB7 conspicuously reduces $z_{att}(\lambda)$ in the 570–700 nm region. The curves in Figure 10a show a contrast between the spectrum for May in PB5 (minimum $z_{att}(\lambda)$) and the spectra for May and September in PB12 (maximum $z_{att}(\lambda)$). The other curves do not differ very much from each other. The strong influence of CDOM on the spectra of underwater irradiance and attenuation depth in the lakes and in Pärnu Bay is readily discernible – both were small in the blue region of the spectrum (Figures 3–4 and 9–10).

There is a good reason for investigating the spectral values of the attenuation depth because satellite sensors receive information only from certain spectral channels. Knowing the spectral distribution of $z_{\mathrm{att}}(\lambda)$, we can choose the channels suitable for each water body. But apart from hyperspectral radiometers, the field of manoeuvre with satellite spectral channels is rather restricted. HYPERION is one of the satellites with a hyperspectral sensor (Giardino et al. 2007), the satellite CHRIS has 62 spectral channels in the 411–997 nm range (Mannheim et al. 2004, Van Mol et al. 2004) and the satellite MERIS (Bricaud et al. 1999) has 9 channels in the visible region of the spectrum.

Acknowledgements

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