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Optical investigations of CDOM-rich coastal waters in Pärnu Bay

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Abstract. Pärnu Bay in the Eastern Baltic Sea was chosen for studying the spatial-temporal variability of water parameters as an optically complex and semi-enclosed coastal area. The water properties of Pärnu Bay are influenced by the town of Pärnu with its 70 000 inhabitants and by the high inflow from the Pärnu River. The in situ database was collected during the ice-free period of 2006–2007 (11 sampling stations, 10 series of field trips). According to the results, the main factor influencing the light attenuation in the water was coloured dissolved organic matter (CDOM) which overshadows the relationships between the radiation characteristics and organic/inorganic particles. In April and May, when the freshwater discharge of the Pärnu River was highest, the values of $a_{\mathrm{CDOM}}(380)$ were between 4.6 and 31.8 m^{-1}, while in September they varied only within 2.52–10.2 m^{-1}. The concentrations of chlorophyll *a* (including its metabolite phaeophytin *a*) generally ranged from 4 to 12 mg m^{-3} but during algal blooms they rapidly increased to 31.8 mg m^{-3}. The temporal and spatial irregularity of suspended matter concentrations was caused by the loading of unpacked peat at the Pärnu River mouth as well as by undulation and ship traffic in Pärnu Bay. MODIS level 1 data with 250 m resolution were used for illustrative comparison of spatial and temporal variations in the water properties in Pärnu Bay and the Gulf of Riga. An attempt to perform the quantitative analysis with the purpose of estimating the concentrations of different optically significant substances separately gave statistically incorrect results.

Key words: coastal waters, underwater light field, diffuse attenuation coefficient, optically active substances, remote sensing.

INTRODUCTION

Nowadays problems connected with the estimation of the ecological state of seas and inland waters have become especially topical due to increasing industrial and human impact on the aquatic environment. For a comprehensive survey of some water body complex investigations consisting of chemical, hydrophysical, optical and biological measurements are necessary. However, rather essential conclusions may be drawn also on the basis of a certain group of in situ measurements: quite often the complex of data, containing the concentrations of optically significant substances (phytoplankton, coloured dissolved organic matter (CDOM) and suspended matter) as well as the incoming irradiance and diffuse attenuation coefficient, has been collected. These data enable also determination of the underwater irradiance, which is an important factor in forming the phytoplankton productivity. Optical measurements yield information on temporal and spatial variation in optically significant substances, including certain kinds of water pollution.

The advances in ocean colour remote sensing over the decades have made it possible to use remote sensing imagery to produce maps of productivity in the world oceans (Platt & Sathyendranath 1988). Considering the seas and coastal waters, the daily MODIS (onboard the Aqua platform) overpass covers the whole of the Baltic Sea area, which makes it very operative for environmental monitoring. The MODIS/Aqua Level 1 (Top of Atmosphere, TOA) and Level 2 images (including atmospherically corrected water-leaving radiance and chlorophyll *a* concentration) with 250 m spatial resolution are freely available. The MODIS standard algorithm for the diffuse attenuation coefficient of seawater at 490 nm, $K_{\mathrm{d}}(490)$, has been developed using the ratio of water-leaving radiances at 490 and 555 nm (Austin & Petzold 1981; Mueller 2000). $K_{\mathrm{d}}(490)$ gives more accurate results in the Baltic Sea than chlorophyll standard algorithms (Darecki & Stramski 2004; Kratzer et al. 2008). The values of $K_{\mathrm{d}}(490)$ are influenced by all absorbing substances in the water including CDOM, which is often the dominant absorbing compound in these bands.

However, coastal waters are optically complex, characterized by a large variability of optically significant constituents resulting from different biological, chemical and physical processes. This leads to difficulties in the interpretation of satellite data in coastal and inland waters due to several technical and methodological limitations (spatial, spectral and radiometric resolution of the instrument, and the determination of atmospheric correction in multicomponental waters).

Many Estonian coastal regions and inland waters are under strong human impact, and the Baltic is a rather polluted internal sea. The nature of the bays is often influenced by the inflow of rivers that bring along large quantities of CDOM. Small and semi-enclosed Pärnu Bay (in the Eastern Baltic Sea) is under the influence of the town of Pärnu with its 70 000 inhabitants and the high inflow from the Pärnu River. This causes the low transparency of Pärnu Bay water. The bay has been investigated in situ for some years, but the majority of investigations have been conducted in the sphere of hydrology and biology. In the present study the optically complex Pärnu Bay was chosen for in situ measurements with the aim of comprehensive investigation of the temporal-spatial variability of the optical properties of water. We considered it also as a test site for assessing the possibilities of developing remote sensing algorithms for this kind of water. For building and testing a model for interpretation of remote sensing data, however, simultaneous in situ measurements of optically significant substances and radiation characteristics in the water body are needed.

Besides, in situ measurement data have their own, independent value. Firstly, the satellite sensor cannot describe the water state in the conditions of cloudy weather. Secondly, the signal coming into the sensor originates from the surface layer, which is only 20–40 cm thick in case of turbid waters (Secchi disk depth below 0.5 m) (Arst 2003). For this reason the in situ data on the vertical profiles of optically significant substances and underwater irradiance are indispensable.

A database describing the variability of the bio-optical water parameters in Pärnu Bay (and partly in the Gulf of Riga) was collected during 2006–2007 (11 sampling stations, 10 series of field trips). Several correlation relationships between optically significant substances and radiation characteristics were investigated.

MATERIAL AND METHODS

Description of Pärnu Bay

Pärnu Bay is a shallow water basin in the northeastern Gulf of Riga (Fig. 1), which could be divided into an inner and an outer basin. The inner part has approximate measures of 13 km × 14 km, an area of about 190 km^2 and the maximum depth of 7.6 m. The outer part extends down to the southern tip of Kihnu Island, having an area of about 500 km^2 and the maximum depth of about 15 m.

The quality of water and quantity of nutrients in Pärnu Bay depend on the inflow of fresh water from rivers and on the intrusion of water from the Gulf of Riga due to changes in wind direction and water level. Nutrient concentrations in Pärnu Bay are higher than the average level in the Gulf of Riga, as it is a relatively isolated strip of sea. However, in comparison with the general situation of Estonian coastal waters, the bay water has a high quantity of phosphate and a particularly high quantity of nitrogen compounds – consequently, predominantly the environment, which is suitable for primary productivity limited by phosphorus and the light conditions (Tervisekaitseinspektsioon 2009).

The Pärnu River accounts for approximately 80% of the inflow to Pärnu Bay, bringing annually 2 km^3 of fresh water to the bay, although the volume of the inner basin is only 1 km^3 (Suursaar & Tenson 1998). The average river flow rate is 64 m^3 s^{-1}, which varies considerably during the year. Maximum rates remain in

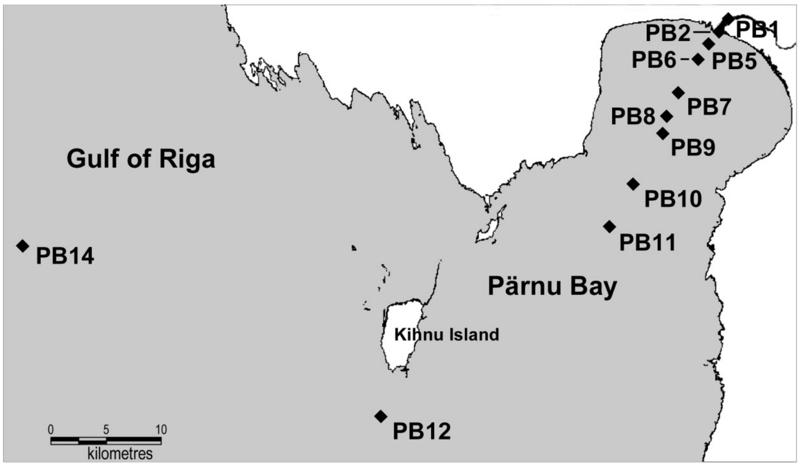

Fig. 1. Pärnu Bay as part of the Gulf of Riga in the Baltic Sea (the mouth of the Pärnu River is also shown). The sampling stations are marked by dark diamonds.

the range of 220–330 $m^3\ s^{-1}$, but minimum rates are approximately 100 times smaller – in the range of 3.5 to 4.7 $m^3\ s^{-1}$ (BERNET 2000). Due to this fact the salinity of water in Pärnu Bay is low, only 3–5 in comparison with the salinity of 4.5–6 of the Gulf of Riga (Tervisekaitseinspektsioon 2009).

The characteristic bay bottom type is fine sand, with only occasional stony areas. Due to the effect of waves and currents the water always contains particles of soft bottom sediments. Additional suspended matter is brought also by the Pärnu River waters. More specifically, large quantities of peat dust are directed to ditches and to the Sauga River and from there to the Pärnu River with drainage water from peat excavation areas. Peat dust reaches the bay also in the course of loading unpacked peat at the mouth of the river.

Measurement methods

Optical monitoring of Pärnu Bay and the Gulf of Riga was carried out at 11 sampling stations (Table 1 and Fig. 1) during the ice-free period in 2006–2007. The study programme involved both in situ measurements and collection of water samples for subsequent laboratory analyses.

Water samples were collected from the surface layer (0.2 m) with a standard water sampler and stored in the dark and cold for less than 7 h before filtering. The concentrations of chlorophyll *a* and phaeophytin *a* were analysed in duplicate by filtration of water samples (0.5–1 L) through Whatman GF/F-filters. Pigments were extracted from the filters in 90% ethanol at 75 °C for 5 min and measured spectrometrically, both before and after acidification with dilute hydrochloride acid (ISO 1992). Eventually, the determined absorbance values were converted, respectively, to chlorophyll *a* and phaeophytin *a* concentrations. For the sake of simplicity, the sum of concentrations is from now on abbreviated to C_{ph}. The concentration of total suspended matter, C_s, was measured gravimetrically after filtration of the same amount of water through pre-weighed and precombusted (103–105 °C for 1 h) filters (ESS 1993). The attenuation coefficients of light, $c^*(\lambda)$ and $c_f^*(\lambda)$, were determined, respectively, from unfiltered and filtered water samples. The variable $c^*(\lambda)$ was obtained as the difference $c(\lambda) - c_d(\lambda)$, where $c(\lambda)$ and $c_d(\lambda)$ are the beam attenuation coefficients for natural and distilled water, respectively.

Table 1. Sampling stations in Pärnu Bay (field trips were carried out from April to September in 2006–2007)

Station	Latitude N, °	Longitude E, °	Number of trips
PB1	58.386	24.489	8
PB2	58.376	24.476	9
PB5	58.367	24.457	10
PB6	58.354	24.442	10
PB7	58.326	24.410	9
PB8	58.306	24.392	2
PB9	58.293	24.388	1
PB10	58.251	24.342	2
PB11	58.216	24.305	8
PB12	58.059	24.952	7
PB14	58.2	23.4	3

Both fresh and saline waters contain also varying concentrations of dissolved organic material (DOM), the optically active fraction of which, known as CDOM, plays a great role in the attenuation of irradiance in the water. Due to the fact that in natural waters CDOM is a rather indeterminate mixture of dissolved organic substances, it is extremely difficult to determine individual organic compounds therein by analytical methods (Dera 1992). In the present study the amount of CDOM was characterized by its absorption coefficient at 380 nm, $a_{CDOM}(380)$. Unfortunately, with spectrometers such as Hitachi U1000 we cannot directly measure $a_{CDOM}(\lambda)$, but attenuation coefficient spectra of filtered water, $c^*_f(\lambda)$. The variable $c^*_f(\lambda)$ is not identical to $a_{CDOM}(\lambda)$ because some very small inorganic particles and colloids also pass through the filter and the water may remain a scattering medium even after filtration. However, the differences are small, about 2–8% (Sipelgas et al. 2003).

The depth profiles of planar downwelling irradiance ($q_d(z)$) in the water column were measured using a LI-192 SA sensor (LI-COR, Inc., 1984). This device has an almost ideal quantum response over 400–700 nm (photosynthetically active region of the spectrum, PAR). We used the results of the underwater quantum irradiance for estimating the widely used diffuse attenuation coefficient, K_d(PAR) (Dera 1992; Kirk 1994; Arst 2003). The coefficient K_d(PAR) characterizes the averaged (over a water column) vertical decrease in natural light in the PAR. For these calculations irradiance values were plotted against depth (for the 0.1–3 m layer) and K_d(PAR) was found as the exponent of the least-squares regression line through these point.

A semi-empirical model described in Arst et al. (2002) and Arst (2003) allows estimation of the spectra of the diffuse attenuation coefficient, $K_d(\lambda)$, on the basis of measured $c^*(\lambda)$. From these results the spectra of the attenuation depth ($z_{att}(\lambda)$) can be determined using the relationship $z_{att}(\lambda) = 1/K_d(\lambda)$. This parameter shows the thickness of the surface layer from which 90% of radiation received by satellite sensors originates. Precisely, the spectral values of z_{att} are needed due to remote sensing sensors working in separate wavebands.

RESULTS

In situ and laboratory measurements

The minimum and maximum values of the optical characteristics measured in Pärnu Bay in 2006 and 2007 are presented in Table 2. The spatial variations in optically active substances (except for total suspended matter, whose concentrations are connected with ship traffic, i.e. resuspensions of sediments form the bottom) measured in the transect from the Pärnu River mouth towards the open parts of Pärnu Bay are shown in Fig. 2. Some examples on the seasonal change in C_{ph}, C_{s} and $a_{\mathrm{CDOM}}(380)$ for stations PB5 and PB11 in Pärnu Bay during 2007 are shown in Fig. 3. The spectral distributions of the attenuation depth at two stations, PB5 and PB12, are described in Fig. 4.

Our database showed both spatial and temporal variation in the water properties in Pärnu Bay. The Pärnu River brings large amounts of CDOM into the bay from the surrounding peat excavation areas, which makes the water close to river inflow brownish and usually less transparent than the water in deeper parts of Pärnu Bay. At the present study typical Secchi depth values near the coast (between stations PB1 and PB6) were below 1 m, while in the outer basin and in the Gulf of Riga z_{SD} was always higher than 1.4 m (Table 2). That spatial behaviour of the optical parameters $c^*(\mathrm{PAR})$ and $K_{\mathrm{d}}(\mathrm{PAR})$ had an almost similar pattern – decrease from the northeastern part of the bay towards its southwestern part. The concentrations of C_{ph} generally ranged from 4 to 12 mg m^{-3}, however, during the vernal algal bloom in April 2007 the exceptional maximums (25.5–31.8 mg m^{-3}) were observed at stations PB6, PB7, PB11 and PB12 (Fig. 2A). The amount of suspended matter in the water was mostly between 8 and 14 g m^{-3}. Extremely high values of C_{s} (from 23.2 to 49.0 g m^{-3}) at stations PB5–PB7 were influenced by the loading of unpacked peat at the mouth of the river on 2 August 2007. However, the variations in the concentration of total suspended matter were also caused by ship traffic, i.e. resuspension of sediments form the bottom. As expected, there was also a very pronounced decrease in CDOM from the river mouth towards the offshore stations in Pärnu Bay and the Gulf of Riga. In April and May, when freshwater discharge by the Pärnu River was highest, the values of $a_{\mathrm{CDOM}}(380)$ were between 4.6 and 31.8 m^{-1}, while in September $a_{\mathrm{CDOM}}(380)$ varied only from 2.52 to 10.2 m^{-1} (Fig. 2B).

The seasonal behaviour of water parameters at different stations was to some extent even opposite (Fig. 3). The higher vernal $a_{\mathrm{CDOM}}(380)$ values at station PB5 compared to those at offshore station PB11 resulted from intensive inflow from the Pärnu River to the bay. The chlorophyll *a* (including its metabolite phaeophytin *a*) concentration at both stations increased towards late summer, however, at station PB11 intensive algal bloom occurred also in April. During spring and summer the concentrations of the total suspended matter at station PB5 varied generally between 4.7 and 5.6 g m^{-3}, but by the beginning of September the value of C_{s} had risen up to 13.5 g m^{-3}. The slightly higher values of C_{s} (10.2 g m^{-3}) on 20 June 2007 were caused by yacht racing in the transect PB1–PB6. In the Pärnu Bay outer basin the concentrations of total suspended matter were somewhat higher – from 8.6 to 12.7 g m^{-3}.

In order to estimate the values and variability of the attenuation depth z_{att}, first the $K_{\mathrm{d}}(\lambda)$ spectra were

Table 2. Minimum and maximum values of water characteristics measured in Pärnu Bay during the ice-free period in 2006–2007. The denotation *N* in the last row is the number of individual results of each water parameter

Station	z_{SD}, m	$c^*(\mathrm{PAR})$, m^{-1}	$K_{\mathrm{d}}(\mathrm{PAR})$, M^{-1}	C_{ph}, mg m^{-3}	C_{s}, g m^{-3}	$a_{\mathrm{CDOM}}(380)$, m^{-1}
PB1	0.6–1.6	3.0–6.5	1.4–2.3	5.7–12.4	3.9–10.9	7.8–31.8
PB2	0.6–1.2	3.2–6.5	1.6–2.3	6.7–17.6	3.8–14.1	7.5–31.8
PB5	0.5–1.5	3.1–6.5	1.1–2.0	6.6–15.1	3.7–26.7	5.5–31.4
PB6	0.4–1.5	3.3–4.6	0.8–1.8	5.2–31.8	9.9–49.0	2.9–14.1
PB7	0.8–1.7	1.7–5.6	0.8–1.9	2.6–30.4	8.7–23.2	2.2–11.4
PB8	1.5	1.5–3.7	0.8–1.0	2.8–6.6	9.4–11.2	2.2–5.0
PB9	1.7	2.8	0.78	2.7	8.9	4.2
PB10	2	1.8–2.0	0.83	2.1–6.7	9.4–9.8	2.4–4.0
PB11	1.3–3.1	1.0–2.5	0.5–1.6	1.5–25.5	8.0–14.7	2.3–5.8
PB12	1.5–3.5	0.8–2.1	0.6–1.2	5.6–28.2	7.8–13.4	2.3–3.9
PB14	2.3–4.3	0.8–1.4	–	3.2–12.0	7.4–17.5	2.1–2.6
N	58	60	33	67	67	65

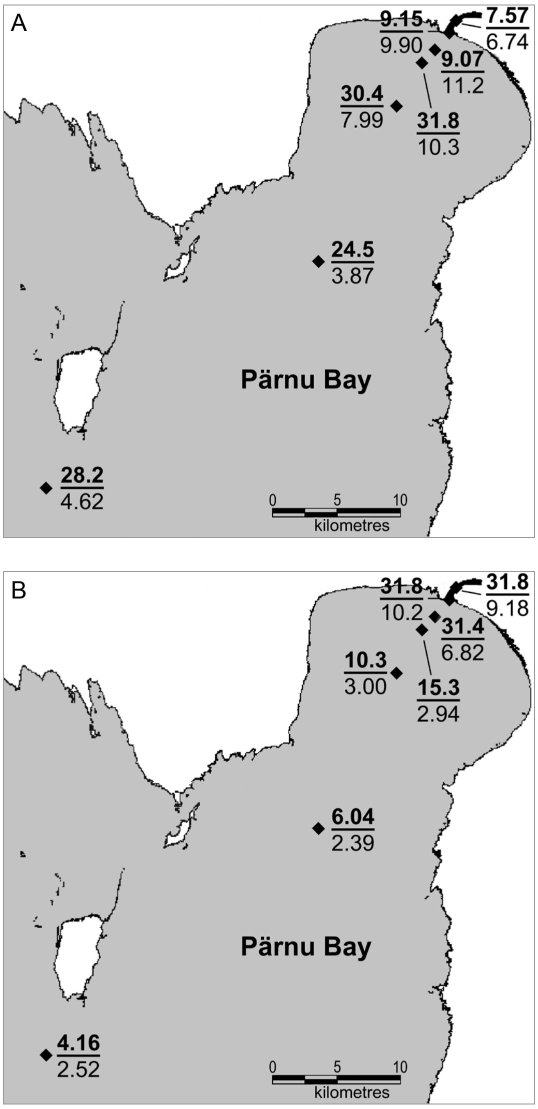

Fig. 2. Spatial variation in optical parameters in Pärnu Bay (upper numbers are the results obtained on 27 April 2007, the lower numbers those obtained on 5 September 2007): (A) for C_{ph}, (B) for $a_{CDOM}(380)$.

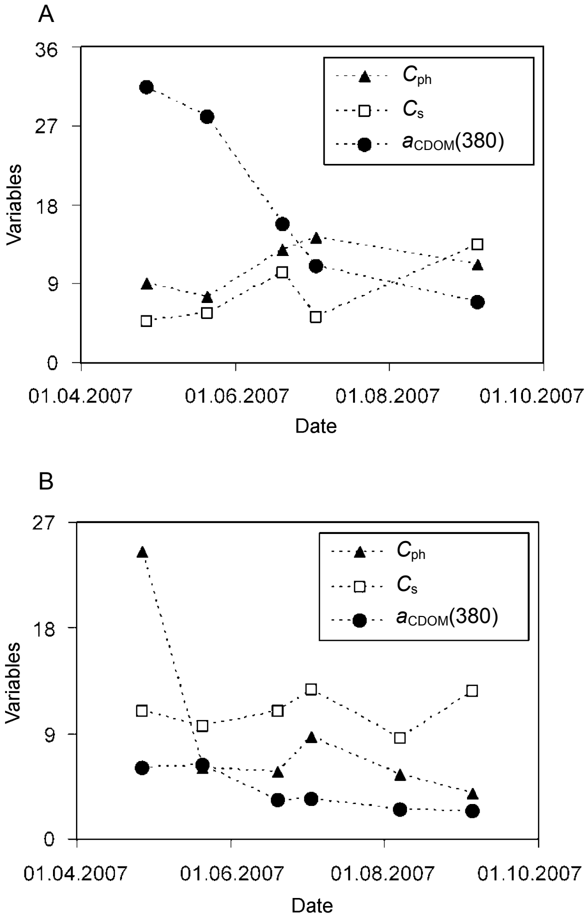

Fig. 3. Variation in chlorophyll *a* (including phaeophytin *a*), suspended matter and CDOM during 2007: (A) station PB5, (B) station PB11.

calculated from measured $c^*(\lambda)$ by using a semi-empirical model described in Arst et al. (2002). Subsequently, the corresponding attenuation depth spectra were determined by using the relationship $z_{att}(\lambda) = 1/K_d(\lambda)$. Our computation results for stations PB5 and PB12 (respectively, in the fluvial region and in the Gulf of Riga) are shown in Fig. 4. The data of $z_{att}(\lambda)$ permit us to draw some important conclusions about the possibilities of using optical remote sensing. We can see that at station PB12 remote sensing yields information from the surface layer down to 2.3 m, but at station PB5 only from the upper 0.34–0.8 m (Fig. 4). As the thickness of the informative layer varies also with wavelength, the colour indices and other water optical parameters of remote sensing spectra would be most effective if they were chosen at the wavelengths corresponding to maximum values of attenuation depth.

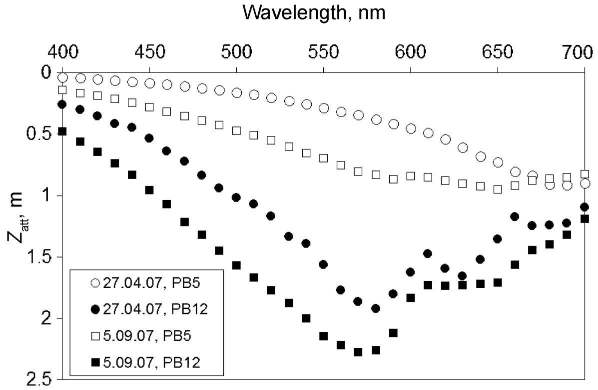

Fig. 4. Spectral variation in the attenuation depth in two stations (PB5 and PB12) in April and September 2007.

Table 3. Values of $K_d(490)$ (in m^{-1}) determined in the region of Pärnu Bay from in situ measurements in 2006–2007. The stations where the number of field trips was less than 6 were left out

Date	Station						
	PB1	PB2	PB5	PB6	PB7	PB11	PB12
31.05.2006	3.83	3.78	3.62	2.24	–	–	–
20.06.2006	–	3.24	1.91	1.90	1.60	0.77	–
31.07.2006	6.44	–	2.28	1.99	1.09	–	–
24.04.2007	7.11	7.32	7.20	3.55	2.46	1.53	1.06
21.05.2007	–	6.72	6.43	3.10	2.70	1.75	0.88
20.06.2007	4.22	4.17	3.63	2.15	2.53	0.93	0.79
3.07.2007	2.44	2.52	2.43	1.85	1.52	1.33	1.29
5.08.2007	2.16	2.42	2.78	–	1.13	0.92	0.70
5.09.2007	2.22	2.63	2.35	1.98	1.89	1.31	0.69

As is known, the MODIS standard algorithm for the diffuse attenuation coefficient of seawater at 490 nm ($K_d(490)$) is widely used for describing the spatial variation in the water properties. Table 3 shows the results of in situ measurements of $K_d(490)$ at most of the sampling stations.

Regression analysis

We used a linear regression program Microsoft Data Analysis. The determination of coefficients and significance of various combinations of parameters are presented in Table 4. It turned out that for $c^*(\mathrm{PAR})$ vs z_{SD} and $K_d(\mathrm{PAR})$ vs z_{SD} the best regression was nonlinear:

$$c^*(\mathrm{PAR}) = 3.72 z_{\mathrm{SD}}^{-1.02}, \qquad (1)$$

where $R^2 = 0.793$ and $p < 0.0001$;

$$K_{\mathrm{d}}(\mathrm{PAR}) = 1.48 z_{\mathrm{SD}}^{-0.75}, \qquad (2)$$

where $R^2 = 0.655$ and $p < 0.0001$.

According to the results, the main factor influencing the light attenuation in water was CDOM. It overshadows the relationships between the radiation characteristics and organic/inorganic particles. A surprisingly weak relationship between the concentrations of C_{ph} and C_{s} could probably be explained by a significant contribution of mineral particles in the total suspended matter. There were some additional negative regressions, all containing the suspended matter mentioned above (C_{s} vs a_{CDOM}, $c^*(\mathrm{PAR})$ vs C_{s} and $K_d(\mathrm{PAR})$ vs C_{s}). The reason for this is temporal and spatial irregularity of C_{s}, caused by loading unpacked peat at the mouth of the Pärnu River, undulation and ship traffic.

Due to the facts that ocean colour sensors SeaWiFS and MODIS provide $K_d(490)$ as standard Level 2 product (http://oceancolor.gsfc.nasa.gov/) and this parameter is also widely used for describing the water properties, we studied its regressions with $a_{\mathrm{CDOM}}(380)$, C_{Chl} and C_{s} (all obtained from in situ measurements in 2006–2007). The numerical values of $K_d(490)$ were calculated from measurements of $c^*(490)$ by using a special model developed in Arst et al. (2002). The results of the regression analysis are presented in Tables 5 and 6. For recognition of the cases with negative correlation in these tables the values of R are presented (instead of R^2). Despite the small number of regression points, these results allow of some useful conclusions. It is clear that in Pärnu Bay the values of $K_d(490)$ are strongly influenced by CDOM that overshadows the actual relationship between $K_d(490)$ and C_{ph}. In some cases it has led even to negative correlation coefficients for $K_d(490)$ vs C_{ph} (Tables 5 and 6). These results support the opinion that (a) in CDOM-rich coastal waters the spatial distribution of $K_d(490)$ allows determination of the corresponding values of $a_{\mathrm{CDOM}}(380)$ with high accuracy and (b) in these waters $K_d(490)$ is unsuitable for estimating C_{ph} and C_{s}. However, in case of remote sensing measurements we can derive $a_{\mathrm{CDOM}}(380)$ from $K_d(490)$ only when the satellite values of $K_d(490)$ are reliable enough.

MODIS level 1 data with 250 m resolution were used for illustrative comparison of spatial and temporal variations in the water properties in Pärnu Bay and the Gulf of Riga (Fig. 5). According to these results, the water properties in Pärnu Bay are very variable and differ markedly from those in the open area of the Gulf of Riga. Obviously, optically significant substances vary in higher levels inside the bay and all relative concentrations are decreasing outside the Pärnu Bay area. An attempt to perform quantitative analysis with the purpose of estimating the concentrations of different optically active substances separately gave statistically incorrect results.

DISCUSSION

We compared our in situ measurement data with some others (different time periods, different sampling stations). In Arst et al. (1993, 1994) three field trips to the Pärnu Bay inner basin (8 sampling stations) were carried out in May, June and October in 1991. During summer months the values of C_{chl} were in the range of 3.9–12.9 mg m^{-3}. This means that generally the chlorophyll concentrations were in a good accordance with the present study, but due to the vernal algal bloom in April in 2007 our maximum values of C_{chl} were much higher. In the present study the concentration of suspended matter ranged from 3.7 to 49 g m^{-3} (all measurements), while on 6 June 1991 the values of C_{s} were between 11 and 38 g m^{-3}. This fact proves once more the temporal and spatial irregularity of suspended matter, which is influenced by undulation and ship traffic in the bay. Similarly to our investigation, the beam attenuation coefficient decreased from the river mouth towards the open parts of Pärnu Bay, but the absolute values of c^*_{PAR} were noticeably higher (at stations close to the coast even up to 20 m^{-1}). This implies increase in the water transparency from the year 1991 to 2007.

Another database for describing the bio-optical properties of Pärnu Bay on 5–6 June 2001 is also available (L. Sipelgas, pers. comm. 2002). The measurements were carried out at two depths (0 and 2 m) at 10 stations over the whole Pärnu Bay (from the mouth of the Pärnu River to the station with the coordinates 58°10′N and 24°17′E). The values of C_{chl}, C_{s}, c^*(PAR) and $a_{\mathrm{CDOM}}(380)$ varied, respectively, in the ranges 28–133 mg m^{-3}, 4.4–14.4 g m^{-3}, 2.7–9.4 m^{-1} and 5.3–20.5 m^{-1}. Extraordinarily high chlorophyll *a* concentrations, mainly at the stations in the inner basin of the bay, were obviously caused by strong phytoplankton bloom. Secchi depth varied between 0.75 and 2.5 m and K_{d}(PAR) from 0.8 to 2.1 m^{-1}. The results lead to a conclusion that during the past decades the optical properties of Pärnu Bay have been almost unchanged, however, the comparison is complicated due to a large variability of these properties in time and space.

For comparison of the results obtained in the river mouth areas in Pärnu Bay with those from the other water bodies we chose the Kymijoki and Porvoonjoki estuaries (both rivers discharge into the Gulf of Finland). However, we had a rather small database collected on 9 and 12 August 2005 as well as on 13–14 June 2006. In the Kymijoki the measurements were carried out in a transect, which starts with the coordinates 60°27′N and 26°28′E and ends at the station with coordinates 60°23′N and 26°33′E. In the Porvoonjoki the respective coordinates were 60°22′N and 25°40′E, and 60°20′N and 25°38′E. As expected, a pronounced decrease in CDOM from the river mouths towards the offshore stations was observed also in Finnish estuaries. In August 2005 the values of $a_{\mathrm{CDOM}}(380)$ were between 3.7 and 7.4 m^{-1} in the Porvoonjoki, while in the Kymijoki the $a_{\mathrm{CDOM}}(380)$ varied only from 5.2 to 6.4 m^{-1}. In June 2006 the absorptions by CDOM in both estuaries were in the range 5.9–11.3 m^{-1}. According to these values, Finnish estuaries, are to some extent different from Pärnu Bay. They are less ‘yellow’ (the maximum of $a_{\mathrm{CDOM}}(380)$ differs about 2.5 times). However, sometimes similar values of $a_{\mathrm{CDOM}}(380)$ were observed: in June 2006 Pärnu Bay gave $a_{\mathrm{CDOM}}(380)$ between 2.4 and 12.6 m^{-1}, in June 2005 in the Porvoonjoki estuary this variation was 5.9–11.3 m^{-1}. Except for the phytoplankton blooms, the chlorophyll concentration in Pärnu Bay was generally below 12 mg m^{-3}. At the stations of the estuary of the Porvoonjoki it was considerably higher (in June 2006 from 8.7 to 30.4 mg m^{-3} and in August 16.2–19.9 mg m^{-3}). In the Kymijoki estuary the values of C_{ph} varied between 10.2 and 14.2 mg m^{-3}. The amount of suspended matter in the water was almost similar in all three regions – in Pärnu Bay the values of C_{s} were mostly between 8 and 14 g m^{-3} and in Finnish estuaries they ranged from 8.1 to 17.5 g m^{-3}.

The ENVISAT satellite, which carries the medium resolution imaging spectrometer (MERIS) sensor, was launched on 1 March 2002. The MERIS sensor characteristics have been developed according to optically complex water properties, making it the first sensor for monitoring the multicomponental waters. MERIS (like other earth observation satellite sensors) has high measurement frequencies, passing over the regions of interest each day and greatly increasing the chances of obtaining useful cloud-free images. The full resolution (~300 m) data provide the high spatial resolution available from a satellite sensor, whereas new developments for optically complex (Case-2 Regional, Boreal Lakes, Eutrophic Lakes) processors are still going on. The new processors have additional products such as downwelling irradiance attenuation coefficient, absorption coefficients of phytoplankton, CDOM, and a coefficient of all particles after bleaching and scattering (Doerffer & Schiller 2008). To illustrate spatial variation in water properties, MERIS image from 6 July 2002, which is a good example for characterizing the situation in Pärnu Bay, is presented in Fig. 6. Using MERIS standard products, we can observe very complex spatial distribution of the water properties, which could not be visualized by in situ measurements. Clearly visible is a highly turbid water area (Fig. 6 top left) flowing out of the bay. This feature is notable on the suspended matter and CDOM products, but not on the algal_2 product. The high amount of CDOM in Pärnu Bay overshadows the signal of chlorophyll *a*, which leads to invalid reflectances used for calculating chlorophyll *a* product algal_2. As different times of measurements and different parameters were used, the quantitative comparison of Figs 5 and 6 is impossible. However, in both figures the multi-coloured Pärnu Bay region, different from that in the open part of the Gulf of Riga, is clearly seen.

Kutser et al. (2009) analysed the results of remote sensing investigations by a satellite sensor Advanced Land Imager (ALI) in the eastern part of the Baltic Sea.

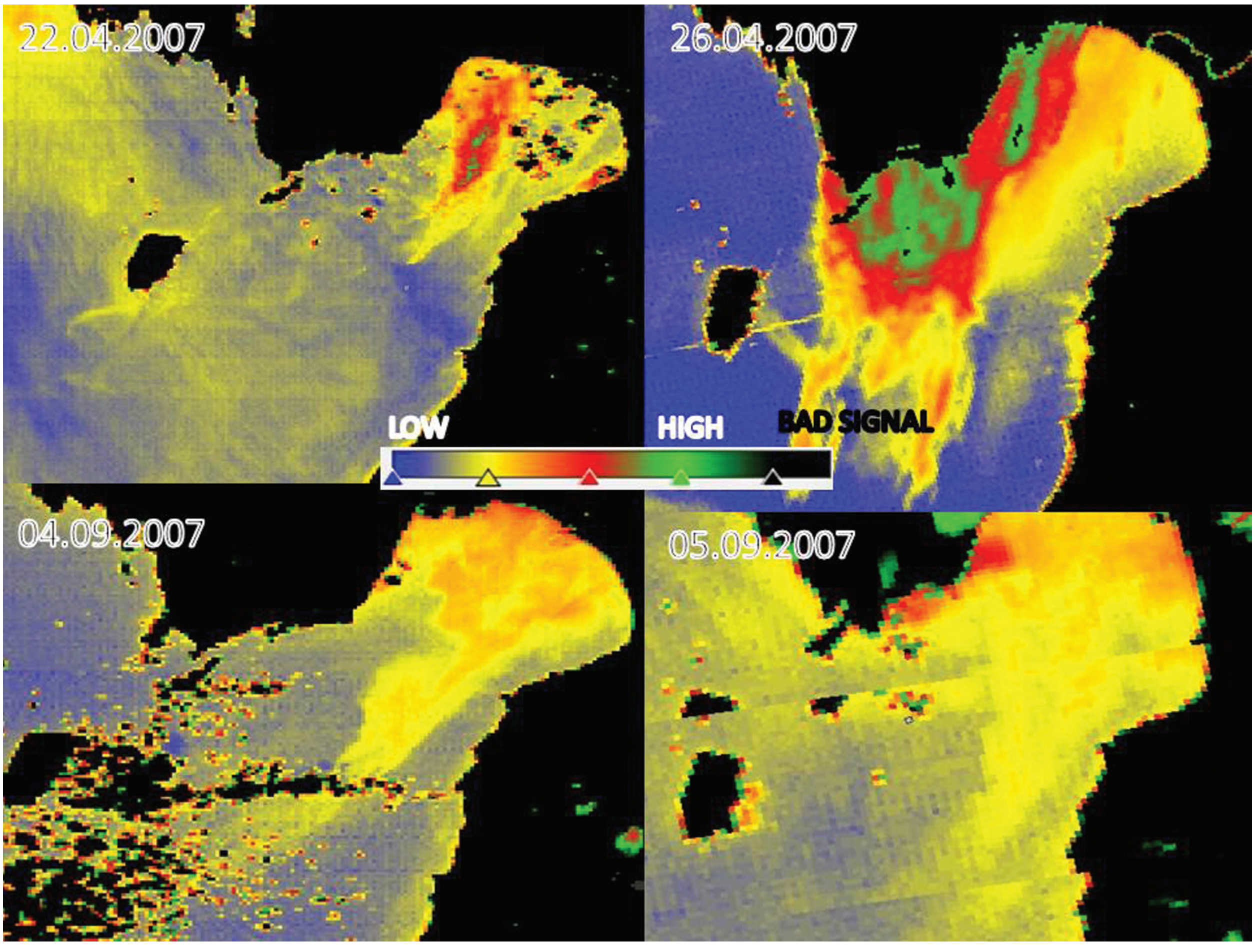

Fig. 5. MODIS Aqua 250 m resolution images over Pärnu Bay showing the spatial variation in the mixture of the three optically significant substances (CDOM, phytoplankton and suspended matter). Bad signal is defined as quality mask over land and clouds.

Table 4. Determination coefficients (R^2) and significance (p) of the linear regressions obtained for several bio-optical parameters of Pärnu Bay

Regression	R^2	p	Comments
C_{ph} vs C_s	0.077	0.028	
C_{ph} vs a_{CDOM}	0.022	0.247	
C_s vs a_{CDOM}	0.268	<0.0001	Negative
c^*(PAR) vs C_{ph}	0.035	0.143	
c^*(PAR) vs C_s	0.029	0.188	Negative
c^*(PAR) vs a_{CDOM}	0.662	<0.0001	
K_d(PAR) vs C_{ph}	0.110	0.084	
K_d(PAR) vs C_s	0.029	0.386	Negative
K_d(PAR) vs a_{CDOM}	0.568	<0.0001	
c^*(PAR) vs K_d(PAR)	0.745	<0.0001	

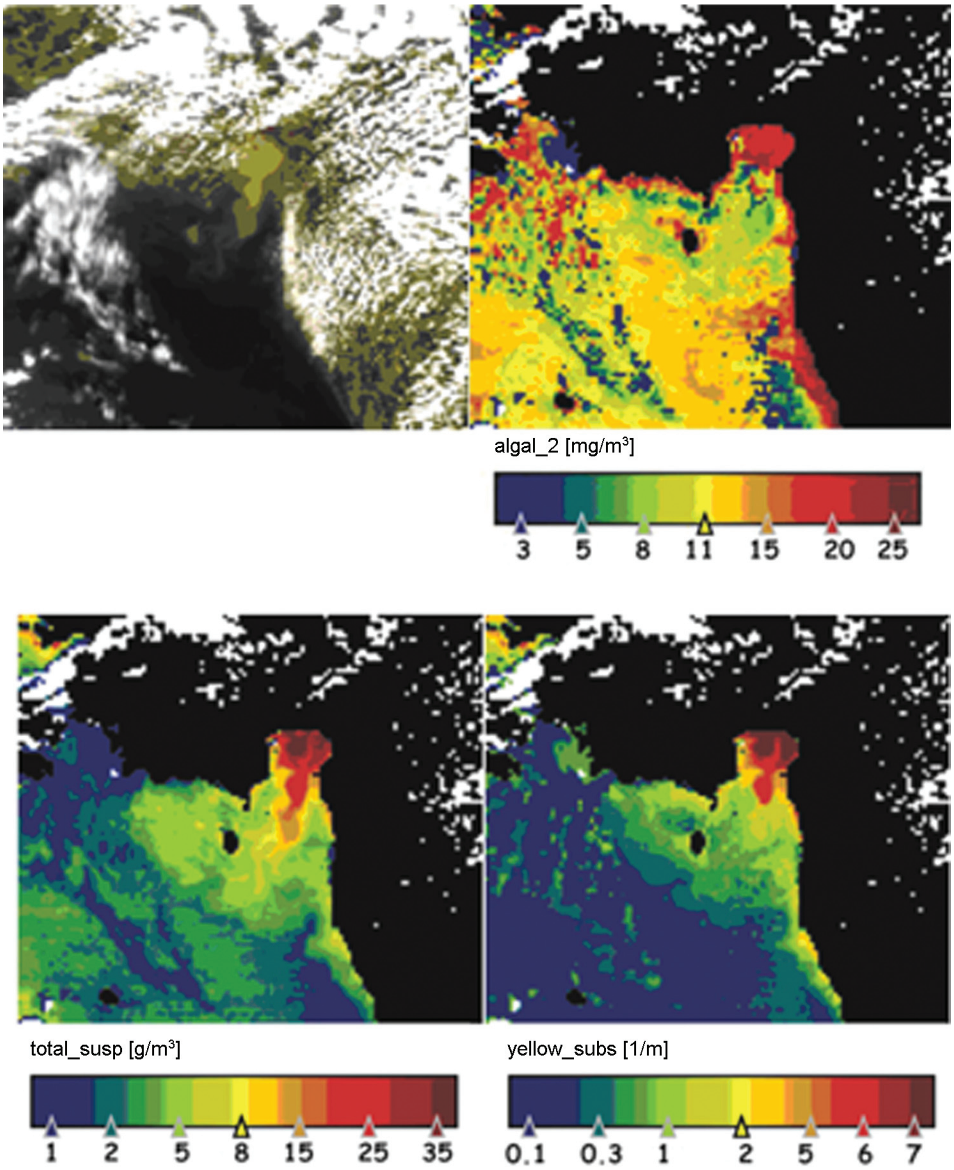

Fig. 6. MERIS L1 image (top left) and three water products for chlorophyll *a* in multicomponential waters (algal_2), suspended matter (total_susp) and CDOM (yellow_subs) on 6 July 2002 in Pärnu Bay.

Table 5. Correlation characteristics ($K_d(490)$ vs different optically significant substances) obtained at sampling stations PB5, PB7 and PB11 in 2006–2007. The station PB5 is located close to the shore (near the pier), PB7 in the central part of Pärnu Bay and PB11 in the western part of the bay, close to the Gulf of Riga

Regression	PB5, $N = 9$		PB7, $N = 8$		PB11, $N = 7$	
	R	p	R	p	R	p
$K_d(490)$ vs $a_{CDOM}(380)$	0.971	<0.0001	0.792	0.019	0.799	0.031
$K_d(490)$ vs C_{Chl}	–0.176	0.650	0.618	0.102	0.486	0.268
$K_d(490)$ vs C_s	–0.491	0.180	0.683	0.062	0.244	0.597

Table 6. Correlation characteristics ($K_d(490)$ vs different optically significant substances) obtained on 27 April 2007 and 5 September 2007 in Pärnu Bay (all stations together)

Regression	27.04.2007		05.09.2007	
	R	p	R	p
$K_d(490)$ vs $a_{CDOM}(380)$	0.999	<0.0001	0.794	0.01
$K_d(490)$ vs C_{Chl}	–0.897	0.006	0.741	0.022
$K_d(490)$ vs C_s	–0.874	0.01	0.366	0.419

The conclusion was that optical properties of the Baltic Sea are dominated by CDOM. Strong absorption of light by CDOM at shorter wavelengths is probably the main reason why standard chlorophyll *a* retrieval algorithms fail in the Baltic Sea. Thus, according to this study, CDOM dominates not only in Pärnu Bay, but also in many coastal regions of the Baltic.

CONCLUSIONS

During the ice-free period in 2006–2007 Pärnu Bay was characterized by marked spatial and seasonal variation in the water properties. A very pronounced decrease in CDOM occurred from the river mouth towards the offshore stations in Pärnu Bay and the Gulf of Riga. In April and May, when freshwater discharge of the Pärnu River was highest, the $a_{\mathrm{CDOM}}(380)$ values were between 4.6 and 31.8 m^{-1}, whilst in September $a_{\mathrm{CDOM}}(380)$ varied only from 2.52 to 10.2 m^{-1}. Phytoplankton contributed to light attenuation of seawater primarily during algal bloom periods, when C_{ph} increased rapidly from its general values of 4–12 mg m^{-3} to its vernal peak of 25.5–31.8 mg m^{-3}. The temporal and spatial irregularity of C_{s} was caused by the loading of unpacked peat at the mouth of the Pärnu River as well as by undulation and ship traffic in the bay.

The results of correlation analysis (data obtained in situ) showed that the main factor influencing light attenuation in the water is CDOM. It overshadows the relationships between the radiative characteristics and organic/inorganic particles. In some cases it has led even to negative correlation coefficients for $K_{\mathrm{d}}(490)$ vs C_{ph}.

Due to the variability of the water properties, Pärnu Bay seems to be an interesting subject of investigations by optical remote sensing. However, in summer the spectral values of the attenuation depth in the inner basin of the bay were mostly below 1 m (especially in the blue–green region of the spectrum) and only in autumn the values $z_{\mathrm{att}}(\lambda) > 1.5$ m were observed. Also the values of $K_{\mathrm{d}}(490)$ that are often used in satellite results analysis are strongly influenced by CDOM, which overshadows the actual relationship between $K_{\mathrm{d}}(490)$ and C_{ph}.

The main conclusions concerning the interpretation of the satellite data in CDOM-rich coastal waters are: (a) the spatial distribution of $K_{\mathrm{d}}(490)$ allows determination of the corresponding values of $a_{\mathrm{CDOM}}(380)$ with a high accuracy; (b) in these waters $K_{\mathrm{d}}(490)$ is unsuitable for estimating C_{Chl} and C_{s}. However, in case of remote sensing measurements we can derive $a_{\mathrm{CDOM}}(380)$ from $K_{\mathrm{d}}(490)$ only when the satellite values of $K_{\mathrm{d}}(490)$ are reliable enough. Thus, the remote sensing investigation of Pärnu Bay is still problematic and new algorithms are necessary.

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Optilised mõõtmised lahustunud orgaanilise aine rikastes Pärnu lahe rannikuvetes

Birgot Paavel, Helgi Arst, Liisa Metsamaa, Kaire Toming ja Anu Reinart

Veekogu omaduste ajalis-ruumilise muutlikkuse uurimise objektiks oli Pärnu laht, mis on optiliselt keerukas, vähese veeläbipaistvusega ja osaliselt suletud rannikuala Läänemere idaosas. Pärnu lahte mõjutab nii Pärnu linnaelanike tekitatav antropogeenne koormus kui ka tugev vee sissevool Pärnu jõest. Aastate 2006–2007 jäävabal perioodil koguti *in situ* mõõtmiste teel arvestatava suurusega andmebaas Pärnu lahe optiliste omaduste kohta (11 mõõtejaama, 10 seeriat välitöid). Saadud tulemused näitavad vee parameetrite olulist ajalis-ruumilist muutlikkust. Veealuse valgusvälja formeerumisel oli suurim tähtsus värvilisel lahustunud orgaanilisel ainel (VLOA), mis varjutas kiirguskarakteristikute seoseid vees sisalduva fütoplanktoni ja heljumiga. Selgesti joonistus välja VLOA kontsentratsiooni vähenemine alates Pärnu jõe suudmealast suunaga Liivi lahele. Aprillis-mais ületasid VLOA neeldumiskoefitsiendi ($a_{\mathrm{VLOA}}(380)$) väärtused jõesuudme läheduses 30 m^{-1}, septembris olid need väärtused vahemikus 2,52–10,2 m^{-1}. Harilikult oli fütoplanktoni kontsentratsioon vahemikus 4–12 mg m^{-3}, kuid veeõitsengute perioodil olid need väärtused mõnes mõõtmisjaamas kuni 31 mg m^{-3}. Vees sisalduva heljumi puhul esines selle kontsentratsioonide märgatav ruumiline ja ajaline irregulaarsus, mille põhjustas osaliselt turba laadimine alustele ning elav laevaliiklus Pärnu lahes. Pärnu lahe ja sellega külgneva Liivi lahe omaduste illustreerimiseks kasutati satelliitandmeid (MODIS level 1 lahutusvõimega 250 m).