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Helgi ARST, Tiit KUTSER,* Leonardo LAESSON,** and Toomas LUKK**

OPTICAL MEASUREMENTS IN PÄRNU BAY

Abstract. In 1991 a series of optical measurements was carried out in the Pärnu Bay waters. The spectra of the beam attenuation coefficient of light in the water and the radiance factor of the sea in the photosynthetically active region of the solar spectrum were measured. The results obtained together with earlier data enable to estimate the temporal variability of these characteristics in Pärnu Bay. The correlative relationships of the concentrations of chlorophyll *a* and suspended matter in the water with the values of the beam attenuation coefficient and radiance factor were investigated. The relative values of the downward irradiance at several depths as well as the depth of the euphotic zone in Pärnu Bay were computed.

According to our estimations the Pärnu Bay waters are much more turbid than the most turbid water (type 9) of Jerlov's classification. The spectral beam attenuation coefficient has clear seasonal and spatial variability. The measurements of radiance factor of the sea show that during the last decade the amount of substances remarkably absorbing light in the blue region of the solar spectrum has increased in the Pärnu Bay waters. Urgent and fundamental environmental investigations are necessary for realistic ecological prognostication of Pärnu Bay to avoid a potential ecological catastrophe.

Key words: underwater optical measurements, remote sensing, beam attenuation coefficient, radiance factor.

Introduction

Pärnu Bay, one of the most heavily polluted areas near Estonian coast, has been investigated for some years. However, the solar radiation field and the corresponding radiation characteristics in Pärnu Bay waters have been studied insufficiently; well-founded generalizations and prognoses are missing. In 1991 several series of optical measurements were carried out in Pärnu Bay (see Fig. 1 for location of sampling stations). The following characteristics were determined:

1. The spectral values of the beam attenuation coefficient in the region of light spectrum 420—680 nm, measured by the optical device Liki (Arst, Laesson et al., 1989) using water samples taken during three boat trips (May 27, June 6, and October 24) at seven sampling stations in Pärnu Bay. In most cases the water samples were taken at the depths of 0, 2, 5, and 10 m.
2. The spectral values of the radiance factor of the sea in the region 400—680 nm, measured *in situ* by the telespectrometer Pegasus (see about Pegasus in Arst, Miller et al., 1989). The measurements were carried out on May 27 and June 6 in some stations shown in Fig. 1 as well as on the track between stations P1 and P4.
3. The incident integral solar irradiance, measured by a pyranometer placed on the roof of the field base on the shore.

* Estonian Marine Institute, Lai St. 32, EE-0101 Tallinn, Estonia.
** Institute of Thermophysics and Electrophysics, Estonian Academy of Sciences, Paldiski Rd. 1, EE-0001 Tallinn, Estonia.

As known, the beam attenuation coefficient c_λ is determined in the following way:

$$c_\lambda = \frac{-1}{L^*_\lambda} \cdot \frac{dL^{*\prime}_\lambda}{dz}, \tag{1}$$

where L^*_λ is the intensity of the light beam proceeding in some fixed direction in the water; z — the path length travelled by this beam; λ — the wavelength of light (usually L^*_λ is measured in $W \cdot m^{-2} \cdot ster^{-1} \cdot nm^{-1}$, z — in m, and then c_λ will be in m^{-1}). In natural conditions c_λ is measured by means of a special optical device with artificial light source (*in situ* or on the basis of the water samples in laboratory).

The concept of the radiance factor of the sea r_λ is also generally known; when the line of sight is directed to nadir it is described by the following expression:

$$r_\lambda = \frac{\pi L_\lambda(\vartheta=0)}{E_{\lambda,+0}}, \tag{2}$$

where ϑ is the nadir angle of the line of sight, $L_\lambda(\vartheta=0)$ — upwelling radiance from the nadir point (reflected from the water surface and backscattered from the water mass solar radiation), $E_{\lambda,+0}$ — the incident spectral irradiance onto the water surface. Hence, for determining r_λ the measurements of L_λ and $E_{\lambda,+0}$ are needed.

To estimate the connections between optical and other characteristics of the water mass under consideration additional data on the concentrations of chlorophyll and suspended matter were used (these concentrations were determined on the basis of water samples from stations depicted in Fig. 1).

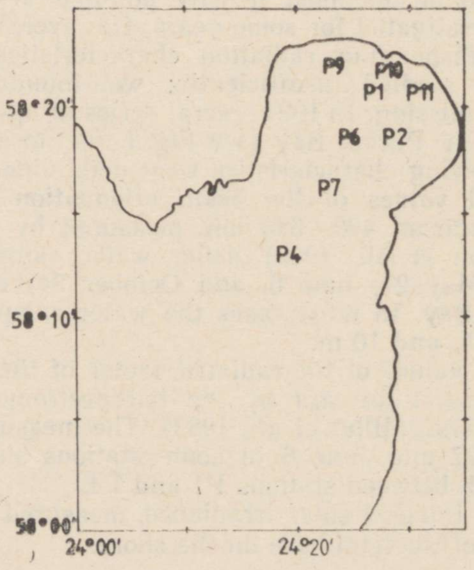

Fig. 1. The sampling stations in Pärnu Bay in 1991 (water samples and telephotometric measurements).

We had at our disposal also some earlier data: (a) the spectra of the beam attenuation coefficient, obtained during the tests of the optical device Liki in 1986—1987 (for some stations shown in Fig. 1); (b) the spectra of the radiance factor, measured on board of the RV *Aju-Dag* by telespectrometer MS-1 in the summer of 1981 and 1982 (Arst et al., 1984).

In 1991 the spring and early summer were predominantly cool and windy. High waves often raised up mud and sand from the bottom of the shallow Pärnu Bay. As a result, in such days the turbidity of the Pärnu Bay waters (which are turbid anyway) increased remarkably. The illumination conditions were ideal (totally clear sky) for telespectrometric measurements only on May 27; the measurements in June were carried out in the conditions of Cu clouds, bringing about frequent changes in the incident irradiance. The autumn measurements (limited only with Liki investigations as for telespectrometric measurements the incident solar radiation flux was too small) were carried out in the conditions of moderate winds. It should be noted that the optical device Liki enables to determine the beam attenuation coefficient both *in situ* and in laboratory.

In 1981—1982 the measurements of the radiance factor were carried out in the conditions of weak wind (2—6 $m \cdot s^{-1}$) and mostly of Ci clouds. We have no data on the weather conditions during the measurements of the beam attenuation coefficient in 1986—1987 (except for the fact that the measurements in February were carried out using the water samples taken from under the ice cover).

Results of the Measurement of Beam Attenuation Coefficient

The results obtained by means of Liki show very low transparency of the water (in some cases, as in the conditions of strong undulation, the water transparency may be extremely low); at the same time, however, the seasonal and spatial variability of the beam attenuation coefficient is clearly expressed.

The variability of the beam attenuation coefficient in the Pärnu Bay waters is remarkably big: its lowest values (0.3—1.5 m^{-1}) were observed in February (under ice cover), highest (19—31 m^{-1}) — in summer under strong winds; the biggest values of c_λ occur in the blue region of the spectra. Some extremal spectra of the beam attenuation coefficient for Pärnu Bay as well as those for other regions of the Baltic are shown in Fig. 2. It should be pointed out that our measurements put the Gotland Deep and Kunda waters respectively to the 5th and 9th type according to the classification suggested by Jerlov (1976). Jerlov's classification distinguishes five types of coastal waters (types 1, 3, 5, 7, and 9); their turbidity increases with the type number. This classification includes no waters more turbid than type 9. However, the values of the beam attenuation coefficient in Pärnu Bay exceed in most cases (sometimes to a great extent) the values corresponding to the 9th type by Jerlov (cf. also Fig. 2). The only exception is the measurement results obtained under ice in February, where the values of c_λ are even smaller than for the Gotland Deep in summer. But here one must take into account the fact that, as a rule, in summer the water is more turbid due to the biological processes in the sea. The values of c_λ for the Gotland Deep region, calculated using Ivanov's data (Иванов, 1975), are remarkably smaller than the summer measurements data in Gotland, and in the blue-green region of spectra even smaller than c_λ values for Pärnu Bay in February.

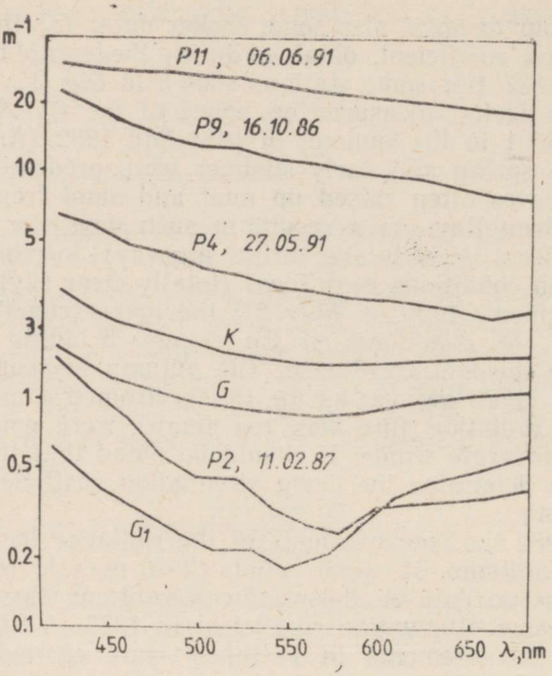

Fig. 2. The minima and maxima of the beam attenuation coefficient spectra in Pärnu Bay for cool (stations P2 and P9) and warm (stations P4 and P11) seasons. For comparison the typical c_λ spectra in Kunda Bay (K) and Gotland Deep (G) polygons in the Baltic determined by measurements in August 1987, and c_λ spectrum for the Gotland Deep region (G_1) computed on the basis of data by Ivanov (Иванов, 1975) are shown.

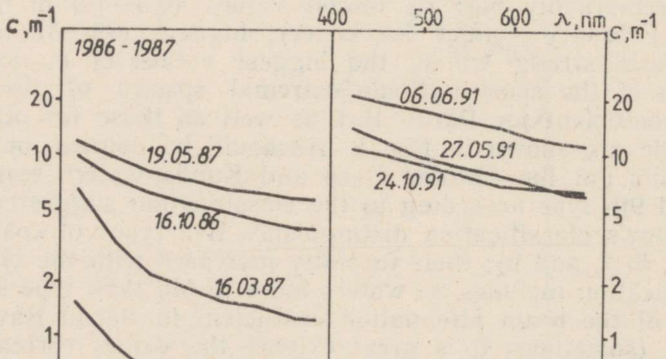

Fig. 3. The spectra of the beam attenuation coefficient, determined on the basis of the water samples taken from measurement station P2 in 1986—1991.

The spectra of c_λ measured in different months at station P2 are presented in Fig. 3. This figure illustrates the conclusion obtained on the basis of the whole data set: the beam attenuation coefficient in the Pärnu Bay waters has a remarkable seasonal run, with minima in mid-winter and maxima in summer, whereas the annual amplitude is rather large (differences up to 50 times). This run is indubitably caused mainly by biological processes in the sea (their activity is periodically very high in summer). In addition, as was mentioned above, in shallow Pärnu Bay the values of c_λ may be considerably bigger because of the strong undulation, raising up sand and mud from the bottom. The strong wind and high waves are obviously the reason for the high values of c_λ on June 6, 1991: on two previous days, on June 4 and 5, the wind velocity was more than 15 $m \cdot s^{-1}$, on June 6 the wind was somewhat weaker (8—10 $m \cdot s^{-1}$), but there was still a remarkable amount of different optically active substances in the water. Measurements of suspended matter confirm this: on June 6, its concentration exceeded 1.5—3.4 times the values for May 27 (except for station P10 near the mole).

All the values of c_λ measured in 1991 exceed those of 1986—1987 (see also Fig. 3). However, for 1991 we have no data for winter and early spring, which gave the lowest values of c_λ in 1986—1987. Thus, we cannot prove that the turbidity of the Pärnu Bay waters increased remarkably over the years of 1986—1991. For determining the long-time trend of the beam attenuation coefficient in Pärnu Bay a larger data set (frequent and regular measurement series for different months and years, desirably in the conditions of weak wind) is needed.

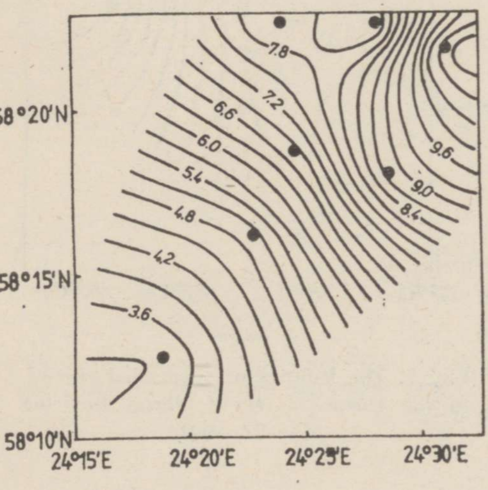

Fig. 4. The isolines of the beam attenuation coefficient (wavelength 540 nm) in the surface layer of Pärnu Bay determined on the basis of measurements on May 27, 1991.

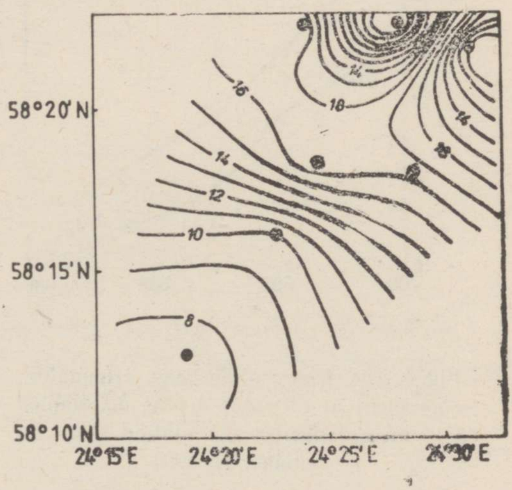

Fig. 5. The isolines of the beam attenuation coefficient (wavelength 540 nm) in the surface layer of Pärnu Bay determined on the basis of measurements on June 6, 1991.

The beam attenuation coefficient has also clearly expressed horizontal variability in Pärnu Bay with c_λ values decreasing from near-coastal zone toward the open sea. As an example, Figs. 4 and 5 depict the isolines of $c(\lambda=540\ nm)$ for May 27 and June 6. The vertical changes of the beam attenuation coefficient are mostly rather small (up to 10%); yet, in some cases a thin layer of clearer (or more polluted) water was observed at different depths. One such case is shown in Fig. 6.

Table 1

Concentrations of chlorophyll *a* and suspended matter measured in Pärnu Bay in 1991 simultaneously with the optical measurements

Sampling station	Chlorophyll *a*, $mg \cdot m^{-3}$			Suspended matter, $mg \cdot l^{-1}$		
	May 27	June 6	Oct. 24	May 27	June 6	Oct. 24
P1	—	—	1.55	—	33.0	11.5
P2	5.50	11.40	2.70	14.5	28.0	13.5
P4	4.60	3.85	4.45	10.0	15.0	17.5
P6	5.05	12.90	3.35	11.0	37.0	14.0
P7	4.65	5.55	3.45	10.5	19.5	15.0
P9	12.80	12.90	2.25	13.5	37.0	12.0
P10	3.90	8.30	1.75	11.0	11.0	11.5
P11	10.50	10.40	5.55	14.0	38.0	17.0

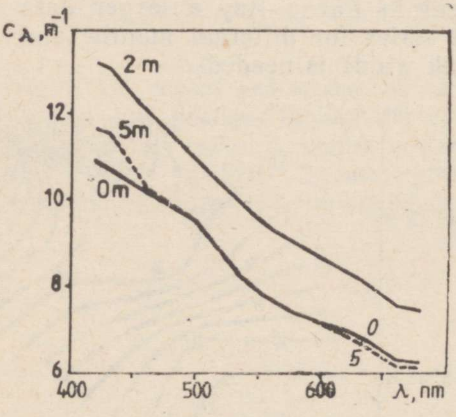

Fig. 6. The spectra of the beam attenuation coefficient at different depths determined by measurements at station P2 on October 24, 1991.

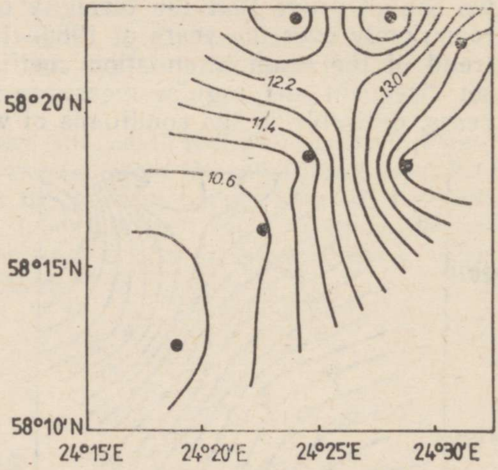

Fig. 7. The isolines of suspended matter in the surface layer of Pärnu Bay on May 27, 1991.

Table 2

Values of correlation coefficients obtained on the basis of data for Pärnu Bay in 1991

Correlations	Correlation coefficient		
	May 27	June 6	Oct. 24
Chlorophyll vs suspended matter	0.19	0.78	0.48
c (λ=440) vs chlorophyll	0.47	0.75	0.33
c (λ=540) vs chlorophyll	0.49	0.72	0.13
c (λ=440) vs suspended matter	0.77	0.67	0.22
c (λ=540) vs suspended matter	0.87	0.66	0.16

The concentrations of chlorophyll *a* and suspended matter, measured simultaneously with the optical measurements, are presented in Table 1. The correlative relationships between these concentrations and the beam attenuation coefficient are characterized in Table 2. The values of the correlation coefficient vary within wide limits, from 0.13 to 0.87. The best correlations are observed on June 6, and also between suspended matter and $c(\lambda=540\ \mathrm{nm})$ on May 27.

The isolines of suspended matter concentrations measured in the surface layer of Pärnu Bay on May 27 (Fig. 7) show a remarkable similarity with those of $c(\lambda=540\ \mathrm{nm})$ on the same date (Fig. 4).

We made an attempt to estimate also the influence of the yellow substance upon the spectra of the beam attenuation coefficient in Pärnu Bay. For this purpose we compared our c_λ spectra (normalized to 540 nm) with those obtained assuming that the only optically active substance in the water was suspended matter (data taken from the monograph by Jerlov, 1976). The results show that Jerlov's spectra are always much plainer than the c_λ spectra for Pärnu Bay, whereas the big values and rapid increase of c_λ in the blue region of the spectrum evidently indicate the presence of a great amount of yellow substance in the Pärnu Bay waters. As an example, the above-mentioned spectra for station P4 are shown in Fig. 8.

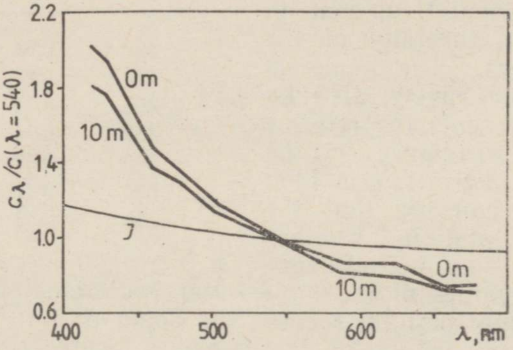

Fig. 8. The spectra of the beam attenuation coefficient obtained on May 27, 1991 at station P4. *J* is the spectrum of c_λ determined assuming that the only optically active substance in water is suspended matter (data from Jerlov, 1976). All spectra are normalized to 540 nm.

The values of the beam attenuation coefficients do not allow of immediate computation of the downward irradiance in the water; to do this, the values of the diffuse attenuation coefficient are needed. As known:

$$E_\lambda(z)=E_{\lambda,-0}\exp\left(-\int_0^z K_{\mathrm{d},\lambda}(\zeta)\,\mathrm{d}\zeta\right), \qquad (3)$$

where $E_\lambda(z)$ is the downward spectral irradiance at the wavelength λ in the depth z; $E_{\lambda,-0}$ — the downward spectral irradiance just beneath the water surface; $K_{\mathrm{d},\lambda}(\zeta)$ — the spectral diffuse attenuation coefficient of solar light in the water at the depth ζ.

Assuming that $K_{\mathrm{d},\lambda}$ does not depend on the depth:

$$E_\lambda(z)=E_{\lambda,-0}\exp(-K_{\mathrm{d},\lambda}z). \qquad (4)$$

The downward integral irradiance at the depth z is:

$$E(z) = \int_{\lambda_1}^{\lambda_2} E_\lambda(z)\,d\lambda, \quad (5)$$

where the whole solar spectrum lies between the wavelengths λ_1 and λ_2.

To compute the values of $K_{d,\lambda}$ we used the approximate expression $K_{d,\lambda} \approx \gamma_\lambda c_\lambda$, where the coefficient γ_λ depends on the wavelength of light and to some extent also on the turbidity of the water. We assumed that for the Pärnu Bay waters the values of γ_λ were close to those determined for Kunda Bay on the basis of simultaneously measured $K_{d,\lambda}$ and c_λ values (data collected in 1987 to 1990). The values of γ_λ obtained using these data are presented in Table 3.

Table 3

Relation $\gamma_\lambda = K_{d,\lambda}/c_\lambda$, computed on the basis of simultaneously measured $K_{d,\lambda}$ and c_λ values in Kunda Bay (1987—1990)

λ, nm	γ_λ	λ, nm	γ_λ
420	0.91	560	0.36
440	0.73	580	0.36
460	0.62	600	0.37
480	0.54	620	0.39
500	0.47	640	0.42
520	0.41	660	0.46
540	0.38	680	0.49

Using the values of γ_λ from Table 3 and pyranometric data for determining E_0 and $E_{\lambda,+0}$ the approximate vertical profiles of the downward irradiance in the Pärnu Bay waters were computed. In doing so the independence of c_λ (and consequently, of $K_{d,\lambda}$) from the depth was assumed and the averaged (by depth) values of c_λ were used. The results of these computations confirm once again high turbidity of the Pärnu Bay waters. The same is demonstrated expressively also by Table 4, which presents the relative values of solar irradiance in the photosynthetically active region (400—700 nm). One can see that the location of the station, weather conditions, and season influence considerably the values of the underwater radiation, but in most cases a very small amount of light reaches the depth of 1 m. On the basis of these data also the values of the euphotic depth z_e were computed. According to Chekhin (Чехин, 1987) z_e is the depth where the downwelling irradiance is 0.75 $J \cdot cm^{-2} \cdot h^{-1}$ and below this depth the amount of solar light is insufficient to trigger the process of photosynthesis. The obtained results show that at noon on May 27, 1991, the euphotic depth at station P4 was 1.9 m and at station P9 0.75 m; on June 6 it was 0.75 and 0.3 m, respectively.

Table 4

Relative values of the downward irradiance (%) reaching the depth z in the spectral region 400—700 nm (the irradiance just below the water surface is taken equal to 100%)

z, m	March 16, 1987	May 27, 1991		June 6, 1991	
	P2	P4	P9	P4	P9
0.1	86	74	47	52	21
0.5	47	20	2.5	3.2	0.04
1.0	25	5.1	0.1	0.1	0.00

The spectra of the radiance factor r_λ, determined by means of the telespectrometric measurements in Pärnu Bay, show the features typical of the turbid waters: the spectral maximum in the green-red region, the minimum in the blue region of the spectra. Though the data set at our disposal was small, we tried to investigate correlative relationships between the radiance factor and the concentrations of chlorophyll *a* and suspended matter as well as to determine the corresponding regression formulae. It was found that from the numerous characteristics determined on the basis of the spectra of the radiance factor (Афонин and Кравцов, 1985) high values of correlation coefficients are given by a few, here denoted by X_1, X_2, and X_3:

$$X_1 = \frac{r(\lambda=530) - r(\lambda=600)}{r(\lambda=600)}. \tag{6}$$

Characteristic X_1 is appropriate for computing the concentrations of chlorophyll as well as suspended matter; the correlation coefficients are respectively 0.80 and 0.86.

$$X_2 = \frac{r(\lambda=565) - r(\lambda=610)}{r_{\max}}, \tag{7}$$

and

$$X_3 = \frac{\int_{405}^{455} r_\lambda \, d\lambda \times \int_{655}^{675} r_\lambda \, d\lambda}{\int_{465}^{615} r_\lambda \, d\lambda}. \tag{8}$$

Characteristic X_2 gives the greatest value of the correlation coefficient for chlorophyll ($R=0.92$), X_3 — for suspended matter ($R=0.87$).

Using the values of X_1, X_2, and X_3 one can calculate the concentrations of chlorophyll and suspended matter on the basis of the radiance factor. Comparison of the obtained values with the concentrations determined from the samples in laboratory shows that the mean difference for chlorophyll is 15% (differences lie in the range of 6—22%) and for suspended matter — 18% (differences in the range of 0.1—31%). So, in spite of the fact that the obtained results should be considered as preliminary (taking into account the rather small number of optical measurements), one may conclude that the estimation of the concentrations of the optically active substances in the turbid waters on the basis of the telespectrometric measurements seems promising.

We had at our disposal also the results of some telespectrometric measurements carried out in 1981—1982 from board of the RV *Aju-Dag* in Pärnu Bay, all together nine spectra (see also Arst et al., 1984). Comparison of these data with the results obtained in 1991 shows a general similarity of the configuration of spectral curves, but the values of the radiance factor are prevailingly higher in 1981—1982 than those at the same stations in 1991. Differences in the backscattering of light but also different illumination conditions may be the reason.

The radiance factor spectra determined in stations P4 and P11 in 1982 and 1991 are depicted in Fig. 9 as an example. In general, the spectra of 1982 and 1991 coincide rather well; yet the spectra of 1991 show a stronger influence of yellow substance (in the blue region of the spectrum the r_λ values decrease with the decreasing of wavelength). Fig. 9 depicts also the spectrum of the radiance factor regarded as typical for Pärnu Bay by Pelevin (Пелевин, 1978; measurements carried out in 1975). In this spectrum the minimum near 440 nm, caused by the absorption of light by chlorophyll, is clearly shown; evidently also the influence of yellow substance is smaller than in the case of the later measurements (in the range 400—440 nm the radiance factor decreases with the increase of wavelength). This suggests that during the last decade the amount of substances remarkably absorbing light in the blue region of the spectrum (e.g. yellow substance, oil) has increased in the Pärnu Bay waters.

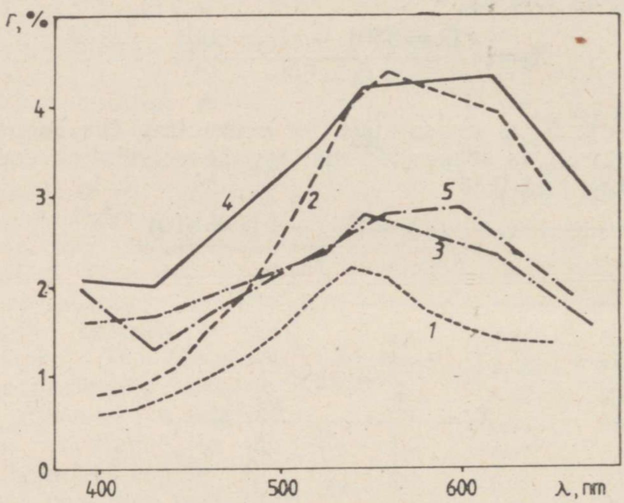

Fig. 9. Spectra of the radiance factor in Pärnu Bay: *1* and *2* — measured on May 27, 1991 at stations P4 and P11; *3* and *4* — measured at station P4 on July 26, 1982 and at station P11 on July 31, 1982, respectively; *5* — the spectrum of r_λ typical for Pärnu Bay, determined by Pelevin in the spring and summer of 1975 (Пелевин, 1978).

Comparison of the values of the radiance index $X_4 = r(\lambda=432)/r(\lambda=547)$ determined for Pärnu Bay in 1981—1982 and 1991 with those for the Skagerrak waters (Arst et al., 1984) is presented in Table 5. As known, an increase in water turbidity brings about a decrease in the index X_4. However, we cannot prove that the double decrease of X_4 during the last decade in Pärnu indicates a firm and drastic trend, because there is a possibility that the low values of X_4 in 1991 were partly caused by weather conditions (in 1981—1982 weak winds predominated, in 1991 — strong or moderate winds).

Table 5

Averaged values and the range of variability of the radiance index $X_4 = r(\lambda=432)/r(\lambda=547)$

Characteristic	Skagerrak 1981	Pärnu Bay 1981—1982	Pärnu Bay 1991
$\bar{X}_4$	1.19	0.61	0.26
ΔX_4	1.12—1.43	0.48—0.94	0.16—0.30

Research Needs

To sum up the discussion above we can say that Pärnu Bay is probably in a poor ecological state. Urgent and profound environmental investigations are needed to give well-founded ecological prognoses and work out recommendations to avoid a potential ecological catastrophe of Pärnu Bay. As regards optical investigations a more expansive measurement programme is necessary: measurements of the diffuse attenuation coefficient and the vertical profiles of solar irradiance in the sea should be added for computing the values of the downward photon flux and euphotic depth (both are of great importance from the aspect of the investigation of the process of photosynthesis and primary production). Taking into account the remarkable spatial variability of the optical characteristics in Pärnu Bay a bigger number of sampling stations is needed. Investigations of the solar heating of the water in different parts of the bay in spring and early summer against the background of the actinometric data are also of certain interest.

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Presented by J.-M. Punning, D. Sc.

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