Optical classifications of the seas in relation to phytoplankton characteristics*

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Optical and bio-optical classifications of natural waters
Diffuse attenuation coefficients for irradiance
Distributions of chlorophyll *a* concentration in the sea

BOGDAN WOŹNIAK
Institute of Oceanology,
Polish Academy of Sciences,
81-967 Sopot
ul. Powstańców Warszawy 55 street

VADIM N. PELEVIN
Shirshov Institute of Oceanology AS USSR,
117-218 Moscow
Krasikowa str. 23

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Abstract

The paper compares and anlyzes the optical and bio-optical classifications of natural marine basins most often quoted in the literature, as well as an attempt to estimate their accuracy. The authors present two original classifications, worked out from statistical analyses of experimental downward irradiance attenuation spectra. The phytoplankton effect and the influence of other optical components on this downward irradiance attenuation is also discussed. A quantitative description of phytoplankton resources in the basin as related to selected components of the light attenuation coefficients in the water column is given.

1. Introduction

The optical properties of marine basins vary in a wide range depending on the concentration of individual optically active components and on their original optical characteristics (Dera, 1983; Jerlov, 1968, 1976). Neverfeatures in common. A number of authors have attempted to classify the optical properties of water masses independently of their depth or general optical properties (*i.e.* taking into account their changes with depth) *e.g.* Baker

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and Smith (1982), Jerlov (1951, 1961, 1968, 1976, 1977, 1978), Jørgensen and Des Marais (1988), Morel (1978, 1982), Pelevin (1985), Pelevin and Rutkovskaya (1977, 1978, 1980), Prieur and Sathyendranath (1981), Rutkovskaya *et al.* (1982), Siegel and Dickey (1987), Simonot and Le Truet (1986), Smith and Baker (1978, 1984). The aim of this paper is to present the existing classifications, to compare them, and to assess their accuracy. The presentation has been limited to the most important and most popular classifications quoted in the literature two original classifications are also discussed.

Classifications are usually developed with respect to the major apparent optical properties of the sea, that is, the spectra of the diffuse attenuation coefficient of the downward irradiance versus depth $K_d(\lambda, z)$ – described by the equation (after Preisendorfer (1961))

$$K_d(\lambda, z) = -\frac{1}{E_d(\lambda, z)} \frac{E_d(\lambda, z)}{dz}, \qquad (1)$$

where

$E_d(\lambda, z)$ – downward irradiance by solar radiation of light wavelength λ at depth z.

The diffuse attenuation coefficients $K_d(\lambda, z)$ are affected on the one hand by the external conditions of the sun's rays penetrating the sea (angular height of the sun, optical properties of the atmosphere and cloud cover, wave motion at the sea surface, *etc.*), and on the other by the inherent optical absorption-diffusion properties of the marine environment – the major factor influencing the propagation of light into the basin. The influence of external factors on the $K_d(\lambda, z)$ coefficients are not usually taken into account. These classifications are therefore less precise as regards the optical properties of surface water than in relation to the deeper water layers, where the effect of the irradiance beam structure is not so noticeable (Dera, 1983; Jerlov, 1976). The general assumption, then, is that the $K_d(\lambda, z)$ coefficients depend mainly on the content and properties of the individual optically active components of sea water. It is common knowledge that the majority of these components (except sea water and inorganic suspensions) ensue from direct or indirect biochemical processes in the phytoplankton (see Vinogradov and Shushkina (1987)). In consequence, a number of statistical relationships exist between phytoplankton content and the resultant optical properties of the basin (Morel, 1978, 1982; Smith and Baker, 1978). Solving this problem constitutes the second major aim of the paper, *i.e.* quantitatively characterizing the phytoplankton effect on light attenuation and the relationship between the phytoplankton content of the water column and the resultant $K_d(\lambda)$ coefficients. It is usual to express the phytoplankton concentration in sea water in terms of the major photosynthetic pigment, chlorophyll *a*. This aim was realized by statistically analyzing the experimental data collected at the Institute of Oceanology of the PAS. The analysis formed a basis for Woźniak's original bio-optical classification of marine basins, more precise and universal than the previous ones.

It is worth mentioning that the problems considered in this paper, related to the optical classification of marine basins and their relationship with selected phytoplankton characteristics are closely connected with the current needs of biology and ecology. For example, many research teams are concentrating their efforts on developing remote optical sensing techniques of measuring primary production in various parts of the World Ocean from satellites (Pelevin *et al.*, 1991). This task requires a careful analysis of the relationship between the major biomass producer – phytoplankton – and the optical properties of the basin directly influencing primary production or determining the structure of the radiance beam issuing from the sea and recorded by satellite scanners (Morel and Berthon, 1989; Smith *et al.*, 1989a,b).

2. Review of optical classifications of natural waters and marine basins

2.1. Jerlov's optical classification of marine basins

Jerlov presented his first classification of the apparent optical properties of various seas as early as 1951; the final version appeared in 1978 (Jerlov, 1951, 1968, 1976, 1977, 1978). He analyzed the experimental spectra of the downward irradiance transmission coefficients in sea water $T_M(\lambda, z) = E_d(\lambda, z)/E_d(\lambda, z = 0)$, in the wavelength range from 310 to 700 nm, measured in various regions of the World Ocean. Jerlov distinguished five types of 'optically clean' ocean basins characterized by optical indexes I, IA, IB, II and III, and nine optical classes of littoral regions with indices from 1 to 9. These classes and the optical types of marine basins differ with respect to the absolute values and spectral distributions of the downward irradiance attenuation coefficients. Examples are given in Table 1 and Figure 1. The data represent the mean values of $K_d(\lambda)$ for the 0–10 m water layer for various classes and optical types of seas and oceans. The complete Jerlov classification (Jerlov, 1978) includes the coefficient of variability with depth. In this respect this classification differs from other classifications presented here, because it considers not the apparent optical properties of certain water masses but of marine basins in general. However, it also suffers from a number of drawbacks. It is discrete, because the optical indices (more precisely, the numbers of the particular types and classes of basins) are discrete, and they are not analytically related to the

Table 1. The spectra of the downward irradiance vertical attenuation coefficients in the 0–10 m water layer, $K_d(\lambda)$ $[10^{-3}\,m^{-1}]$, in various sea and ocean types and classes according to the Jerlov optical classification

Type	Wavelength λ [nm]														
	310	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700
I	15	6.2	3.8	2.8	2.2	1.9	1.8	2.7	4.3	6.3	8.9	23.5	30.5	36	42	56
IA	18	7.8	5.2	3.8	3.1	2.6	2.5	3.2	4.8	6.7	9.4	24	31	37	43	57
IB	22	10	6.6	5.1	4.2	3.6	3.3	4.2	5.4	7.2	9.9	24.5	31.5	37.5	43.5	59
II	37	17.5	12.2	9.6	8.1	6.8	6.2	7.0	7.6	8.9	11.5	26	33.5	40	46.5	61
III	65	32	22	18.5	16	13.5	11.6	11.5	11.6	12	14.8	29.5	37.5	44.5	52	66
1	180	120	80	51	36	25	17	14	13	12	15	30	37	45	51	65
3	240	170	110	78	54	39	29	22	20	19	21	33	40	46	56	71
5	350	230	160	110	78	56	43	36	31	30	33	40	48	54	65	80
7		300	210	160	120	89	71	58	49	46	46	48	54	63	78	92
9		390	300	240	190	160	123	99	78	63	58	60	65	76	92	110

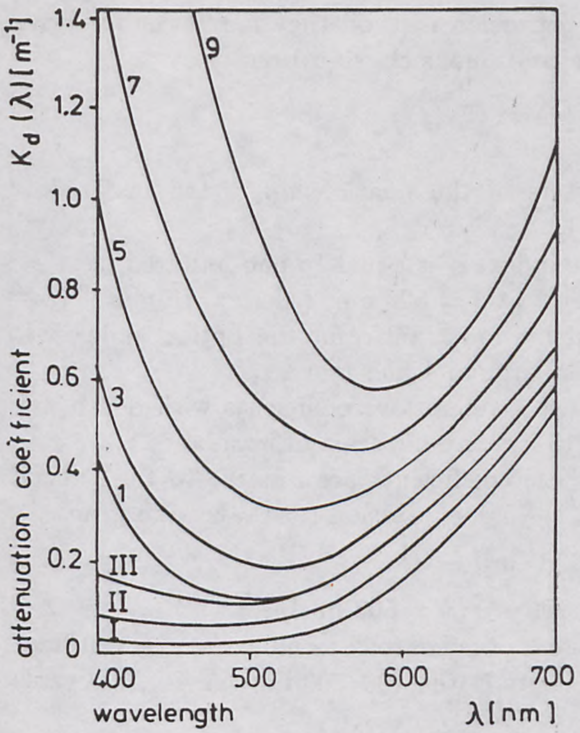

Fig. 1. The spectra of the downward irradiance attenuation coefficients $K_d(\lambda)$; mean values for the surface layer – 0 m to 10 m depth – in various basins, according to the Jerlov classification. Roman and Arabic numerals denote the respective types and optical classes of the seas and the oceans

K_d coefficients. Besides this, our experience indicates that model spectra of attenuation coefficients differ considerably in this classification from experimental spectra of $K_d(\lambda)$. These disadvantages limit the practical applicability of this classification to a significant extent. Considerable progress has been made by the continuous classifications presented below.

2.2. The Pelevin and Rutkovskaya optical classification of marine basins

The Pelevin and Rutkovskaya classification (1977, 1978; Rutkovskaya *et al.*, 1982; Pelevin, 1985) is one of the first attempts to develop a continuous optical classification. It concerns water masses in the euphotic zone irrespective of the depth, not marine basins in general. It is based on over 500 experimental $K_d(\lambda)$ spectra, recorded in various regions of the Atlantic, Pacific and Indian Oceans. The authors of this classification studied the relationships between the $K_d(\lambda)$ coefficients for various wavelengths from the 400–600 nm region and the light attenuation coefficient $K_d(\lambda = 500 \text{ nm})$ at

$\lambda = 500$ nm. Using the linear regression method they found the following relationship fundamental to the continuous classification:

$$K_d^{10}(\lambda) = A(\lambda) + B(\lambda) \cdot m, \tag{2a}$$

where

$A(\lambda), B(\lambda)$ – empirical parameters of the relationship, listed in Table 2 (columns 2 and 3),

m – optical water type index; it is equal to one hundred light attenuation coefficients at $\lambda = 500$ nm, *i.e.* $m = 100 \cdot K_d^{10}$ ($\lambda = 500$ nm). This definition transforms the optical index into convenient numbers around 1 and more,

$K_d^{10}(\lambda)$ – downward irradiance attenuation coefficients with depth, relative to the base 10 logarithmic scale of irradiance.[1]

Since in this paper the $K_d^{10}(\lambda)$ coefficients are relative to the natural logarithm scale (see equations (3)–(5)), expression (2a) takes the form

$$K_d^{10} = (\lambda)\, 2.3 \cdot [A(\lambda) + B(\lambda) \cdot m], \tag{2b}$$

where the optical index is $m = 100 \cdot K_d(\lambda = 500 \text{ nm})/2.3$.

Equations (2a) and (2b) make it possible to determine the spectral functions of light attenuation coefficients in the 400–600 nm range. As regards the long wave range of the $K_d(\lambda)$ spectrum, the differentiation of the coefficient values is much smaller in practice than in the short wave region. The reason for such behaviour comes from light absorption by water molecules, affecting mainly the attenuation coefficient of red light. For this reason Pelevin and Rutkovskaya suggest that when $\lambda \geq 700$ nm the coefficients $K_d(\lambda)$ should be assumed equal for all water types:

$$K_d(\lambda) \approx 1.2 \cdot a_w(\lambda), \tag{6}$$

where

$a_w(\lambda)$ – generally accepted values of light attenuation in pure water (Popov *et al.*, 1979); the numerical factor 1.2 is the ratio of $K_d(\lambda)/a(\lambda)$ typical for this spectral range, approaching the value of the so-called distribution function of the luminous flux (according to the definition quoted by Preisendorfer(1961)).

[1]According to equation (1), the downward irradiance attenuation coefficient K_d can be expressed as a depth derivative of the natural logarithm of irradiance:

$$K_d(z) = -d \ln E_d(z)/dz. \tag{3}$$

The K_d^{10} coefficients presented by Pelevin *et al.* are defined as derivatives of the base 10 logarithm:

$$K_d^{10}(z) = -\frac{d \log E_d(z)}{dz}. \tag{4}$$

Thus the relationship between the coefficients is:

$$K_d = \ln 10 \cdot K_d^{10} \approx 2.3 \cdot K_d^{10}. \tag{5}$$

Table 2. The list of parameters $A(\lambda)$, $B(\lambda)$, applied in the optical classification of water masses by Pelevin and Rutkovskaya (eqs. (2a) and (2b)) and standard errors σ_k of attenuation coefficient K_d^{10}

λ [nm]	A $[10^{-2}\,m^{-1}]$	B $[10^{-2}\,m^{-1}]$	σ $[10^{-2}\,m^{-1}]$ $m \le 2.5$	$2.5 < m \le 5$	$5 < m \le 10$	$10 < m \le 20$
1	2	3	4	5	6	7
400	−0.88	1.60	0.0	1.0	1.0	2.0
410	−1.08	1.69	0.4	1.0	1.0	1.5
420	−1.05	1.64	0.4	0.5	0.5	1.2
440	−0.85	1.48	0.2	0.3	0.4	0.8
460	−0.67	1.31	0.18	0.25	0.25	0.5
480	−0.48	0.15	0.09	0.15	0.25	0.3
490	-0.12	1.05	0.06	0.2	0.2	0.2
500	0	1	–	–	–	–
520	0.93	0.88	0.08	0.1	0.15	0.3
530	1.1	0.83	0.1	0.2	0.25	0.4
540	1.38	0.78	0.15	0.2	0.4	0.6
560	2.34	0.64	0.3	0.3	0.5	0.8
580	3.6	0.67	0.5	0.5	0.7	1.1
590	5.2	0.71	0.9	0.9	1.2	2
600	7.0	0.89	2	2	2	2

To determine $K_d(\lambda)$ in the 600–700 nm range, the authors used linear interpolation between the relevant values of $K_d(\lambda = 600\ \text{nm})$ obtained in equation (2) and $K_d(\lambda = 700\ \text{nm})$ given by equation (6). Examples of spectra of $K_d(\lambda)$ obtained according to this procedure for various types of sea water of different optical indices m and for all the spectral intervals discussed are given in Figure 2.

Unlike Jerlov's classification, the one proposed by Pelevin and Rutkovskaya is a continuous classification because the optical index m, and in consequence the $K_d(\lambda)$ coefficients, may have arbitrary values. It is useful because the index m is easily determinable, as is the full spectrum of $K_d(\lambda)$, from the attenuation coefficient measured in the field – for example: $K_d(\lambda_1)$ of one wavelength λ_1 from the 400–600 nm range. The values of m are then calculated from the relationships (after transformation of equation (2a) or (2b))

$$m = \frac{K_d^{10}(\lambda_1) - A(\lambda_1)}{B(\lambda_1)} \quad \text{or} \quad m = \frac{K_d(\lambda_1) - 2.3 \cdot A(\lambda_1)}{2.3 \cdot B(\lambda_1)}. \tag{7}$$

In practice, the Pelevin and Rutkovskaya classification gives a much better spectral approximation of the $K_d(\lambda)$ coefficients. This has been verified in experiments in which the mean square deviations σ_k of model coefficients and experimental values were calculated (see columns 4–7 in Table 2). The deviations were relatively small.

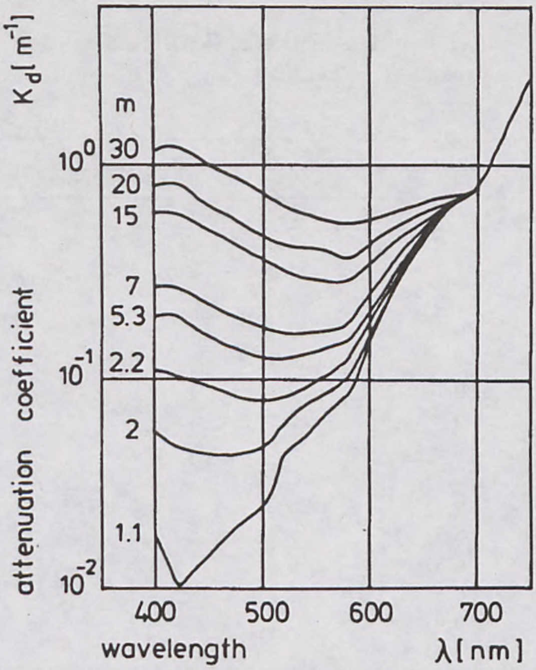

Fig. 2. The spectra of the downward irradiance attenuation coefficients $K_d(\lambda)$ for water of various optical indices m according to the Pelevin and Rutkovskaya classification

2.3. The Smith and Baker bio-optical classification of natural waters

Despite the considerable usefulness of the Pelevin and Rutkovskaya classification, much better from the biological point of view are classifications combining the biological characteristics and optical types of water masses. An early attempt was presented by Smith and Baker, who applied the relationships between the spectra of the downward irradiance attenuation coefficient $K_d(\lambda)$ and chlorophyll a concentration in a sea water Ba (Baker and Smith, 1982; Smith and Baker, 1978, 1984). The total coefficient $K_d(\lambda)$ can be expressed by elements characterizing the particular optically active components of sea water in accordance with the approximate dependence

$$K_d(\lambda) \cong K_w(\lambda) + K_\Delta(\lambda) + K_{pl}(\lambda), \tag{8a}$$

or, taking into account the dependence of K_{pl} on chlorophyll concentration

$$K_d(\lambda) \cong K_w(\lambda) + K_\Delta(\lambda) + k_c(\lambda) \cdot Ba, \tag{8b}$$

where

$K_w(\lambda)$ – contribution to downward irradiance attenuation due to pure water,

$K_{pl}(\lambda)$ – contribution resulting from phytoplankton pigments,

$K_\Delta(\lambda)$ – contribution from optically active admixtures, with the exception of photosynthetic pigments,

$k_c(\lambda)$ – specific light attenuation coefficient of photosynthesic pigments, *i.e.* $k_c(\lambda) = K_{pl}(\lambda)/Ba$.

For the sake of simplicity, the authors took $K_w(\lambda)$ to be the results of measurements of total downward irradiance attenuation in the Sargasso Sea, one of the least polluted natural basins, where optically active substances are practically non-existent. The spectral function of $K_w(\lambda)$ is given in Table 3 (column 2). In the next stage, Smith and Baker statistically analysed the relationship $K_d(\lambda) - K_w(\lambda) = f(Ba)$ at various wavelengths from 350 to 700 nm. The empirical courses of these relationships were approximated by the following broken lines using linear regression methods:

- for $Ba < 1\ \mathrm{mg \cdot m^{-3}}$

$$K_d(\lambda) - K_w(\lambda) = k_{c,1}(\lambda) \cdot Ba, \tag{9a}$$

- for $Ba > 1\ \mathrm{mg \cdot m^{-3}}$

$$K_d(\lambda) - K_w(\lambda) = K_{\Delta,2}(\lambda) + k_{c,2}(\lambda) \cdot Ba, \tag{9b}$$

where

$k_{c,1}$, $k_{c,2}$ – specific coefficients of downward irradiance attenuation by phytoplankton pigments for small ($Ba < 1\ \mathrm{mg \cdot m^{-3}}$) and high ($Ba > 1\ \mathrm{mg \cdot m^{-3}}$) chlorophyll concentrations respectively,

$K_{\Delta,2}$ – contribution of optically active admixtures to the total light attenuation; the authors introduce it for waters with a high chlorophyll content ($Ba > 1\ \mathrm{mg \cdot m^{-3}}$). In waters of low chlorophyll concentration ($Ba < 1\ \mathrm{mg \cdot m^{-3}}$) the effect of admixtures has been neglected, *i.e.* $K_{\Delta,1} = 0$.

The parameters of equation (9) are presented in Table 3. This relationship forms the basis of a continuous optical classification in which the chlorophyll concentration Ba is adopted as the optical index of the water type. Examples of $K_d(\lambda)$ spectra determined for a number of basin classes (*i.e.* chlorophyll concentrations) by the application of equation (9) together with experimental curves are given in Figure 3.

Chlorophyll *a* concentration applied as the optical water type index is an important advantage of the Smith and Baker classification. Chlorophyll concentration conveys a lot of information about the complex biological processes taking place in the ecosystem. Thus, the Smith and Baker classification becomes a bio-optical one. However, it has a number of drawbacks;

Table 3. The list of parameters applied in the bio-optical classification of water masses by Smith and Baker (eqs. (9a) and (9b))

λ [nm]	K_w [m^{-1}]	$K_{\Delta,2}$ [m^{-1}]	$k_{c,1}$ [$m^2 (mg Chl)^{-1}$]	$k_{c,2}$ [$m^2 (mg Chl)^{-1}$]
1	2	3	4	5
350	0.059	0.177	0.249	0.066
355	0.055	0.177	0.249	0.066
360	0.051	0.177	0.249	0.066
365	0.045	0.178	0.248	0.063
370	0.044	0.179	0.245	0.061
375	0.043	0.179	0.240	0.058
380	0.040	0.179	0.237	0.055
385	0.036	0.179	0.232	0.053
390	0.031	0.177	0.277	0.051
395	0.029	0.175	0.223	0.050
400	0.027	0.172	0.216	0.049
405	0.026	0.167	0.210	0.048
410	0.025	0.162	0.205	0.047
415	0.024	0.156	0.200	0.046
420	0.024	0.150	0.194	0.045
425	0.023	0.145	0.187	0.044
430	0.022	0.137	0.181	0.042
435	0.022	0.132	0.175	0.041
440	0.022	0.125	0.168	0.039
445	0.023	0.121	0.163	0.038
450	0.023	0.116	0.158	0.037
455	0.023	0.112	0.150	0.036
460	0.023	0.110	0.146	0.034
465	0.023	0.104	0.141	0.033
470	0.023	0.100	0.135	0.031
475	0.022	0.095	0.130	0.030
480	0.022	0.091	0.125	0.029
485	0.024	0.087	0.120	0.027
490	0.025	0.084	0.115	0.026
495	0.027	0.080	0.110	0.025
500	0.029	0.077	0.105	0.024
505	0.033	0.074	0.102	0.022
510	0.037	0.071	0.096	0.021
515	0.043	0.069	0.093	0.020
520	0.048	0.066	0.088	0.019
525	0.050	0.064	0.085	0.017
530	0.050	0.061	0.084	0.016
535	0.052	0.060	0.080	0.015
540	0.055	0.059	0.076	0.014
545	0.059	0.056	0.073	0.013

Table 3. (continued)

λ [nm]	K_w [m^{-1}]	$K_{\Delta,2}$ [m^{-1}]	$k_{c,1}$ [$m^2\,(mg\,Chl)^{-1}$]	$k_{c,2}$ [$m^2\,(mg\,Chl)^{-1}$]
1	2	3	4	5
550	0.063	0.055	0.070	0.012
555	0.067	0.054	0.070	0.011
560	0.071	0.053	0.070	0.011
565	0.074	0.052	0.071	0.010
570	0.077	0.053	0.072	0.009
575	0.082	0.054	0.074	0.009
580	0.088	0.056	0.077	0.008
585	0.099	0.059	0.085	0.008
590	0.107	0.066	0.095	0.007
595	0.121	0.091	0.110	0.007
600	0.131	0.131	0.125	0.007
605	0.146	0.150	0.148	0.007
610	0.170	0.159	0.168	0.007
615	0.188	0.165	0.184	0.006
620	0.212	0.167	0.195	0.006
625	0.244	0.169	0.205	0.006
630	0.277	0.161	0.213	0.006
635	0.300	0.137	0.222	0.007
640	0.327	0.117	0.227	0.007
645	0.339	0.095	0.231	0.008
650	0.336	0.061	0.225	0.009
655	0.337	0.037	0.205	0.011
660	0.390	0.015	0.180	0.012
665	0.425	0.002	0.156	0.014
670	0.460	0.0	0.118	0.015
675	0.485	0.0	0.088	0.016
680	0.510	0.0	0.068	0.015
685	0.540	0.0	0.045	0.014
690	0.570	0.0	0.028	0.011
695	0.600	0.0	0.015	0.008
700	0.630	0.0	0.008	0.004

The most important ones are:

- The relationship of $k_d(\lambda)$ *vs.* chlorophyll concentration, expressed in equation system (9), are non-infinitesimal. Moreover, the $K_d(\lambda)$ values for $Ba = 1\ mg \cdot m^{-3}$ (that is the boundary between the assumed chlorophyll concentration ranges) determined from equations (9a) and (9b) are divergent.

- It has been assumed that the specific coefficients of light attenuation by pigments $k_{c,1}$ = const for $Ba < 1$ mg·m^{-3} and $k_{c,2}$ = const for $Ba > 1$ mg·m^{-3} for both chlorophyll concentration ranges, $Ba < 1$ mg·m^{-3} and $Ba > 1$ mg·m^{-3}, and for given light wavelengths. In fact the coefficients significantly change as the chlorophyll content in water does so (see eq. (13) below).
- Another simplification introduced, similar to the above, was the contribution of other optically active substances K_Δ to the total light attenuation (yellow substances and suspensions with the exception of phytoplankton pigments). Especially in the range of small chlorophyll concentrations it was assumed that $K_{\Delta,1} = 0$. In fact, the photosynthetic pigments are always accompanied by optically active admixtures, and their concentrations, and in consequence their contributions to the total light attenuation, gradually increase when moving from poor basins to biologically flourishing ones.

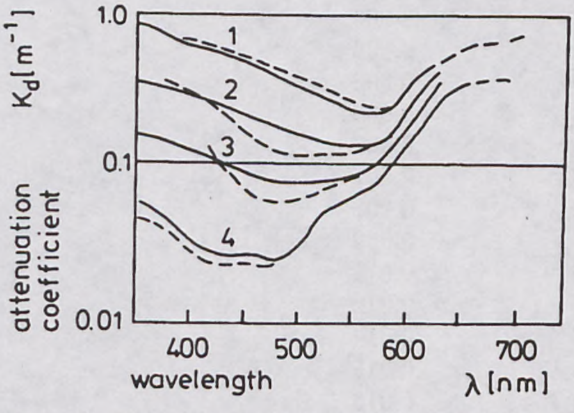

Fig. 3. The spectra of the downward irradiance attenuation coefficients $K_d(\lambda)$ – experimental (broken line) and model (solid line), according to the bio-optical classification by Smith and Baker in water masses of different chlorophyll *a* concentration Ba. The concentration Ba serves as the optical index of the water type. The respective spectra are for: 1 – $Ba = 9.32$ mg·m^{-3}, 2 – $Ba = 2.25$ mg·m^{-3}, 3 – $Ba = 0.44$ mg·m^{-3}, 4 – $Ba = 0.03$ mg·m^{-3}

These disadvantages have been partly removed in the second version of the Smith and Baker classification (Baker and Smith, 1982). Here the relationship between the optical coefficients and the chlorophyll concentration is described in infinitesimal functions. However, another variable has been introduced apart from Ba, *i.e.* the concentration of dissolved organic matter (DOM). The authors admit that this version is based on modest experimental material and requires further verification. Moreover,the practical use of this version is considerably limited by the need to know DOM values.

For these reasons, to fulfil the demands of this study, an original 'single-index' bio-optical classification of natural waters has been prepared by Woźniak, to a large extent free of the drawbacks of the Smith and Baker classification.

2.4. Woźniak's bio-optical classification of natural waters

This classification has not been widely published yet. It is based on the statistical analysis of experimental data (obtained by Woźniak and his co-workers at the Institute of Oceanology of the Polish Academy of Sciences, Sopot) and considers various water masses in natural basins (oceans, seas and lakes) with chlorophyll *a* concentrations ranging from about 0.03 to approximately 60 $mg \cdot m^{-3}$. Thus, it includes nearly all trophic basin types, from oligotrophic to supereutrophic, and it is continuous. The spectral range is from 350 nm to 750 nm. As in the Smith and Baker classification, the chlorophyll *a* concentration Ba is taken to be the water type index. The proposed bio-optical classification is also based on empirical relationships between the coefficients of attenuation and Ba. Several assumptions are similar to those in the Smith and Baker classification: in particular, the general form of the $K_d(\lambda) = f(Ba)$ relationship in equation (8) and the spectrum of light attenuation coefficients in pure water $K_w(\lambda)$ (column 2 in Table 4) are the light attenuation spectra in the Sargasso Sea. By contrast, however, the approximation function (8) in Woźniak's classification has an infinitesimal form (*i.e.* it is based on a single mathematical equation). The parameters K_Δ and k_c have been made variable in relation to Ba. Besides the summary $K_d(\lambda)$ coefficients, the classification is also extended to the spectra of the contributing coefficients: $K_{pl}(\lambda) = k_c(\lambda) \cdot Ba$ – attenuation caused by phytoplankton pigments, and $K_\Delta(\lambda)$ – attenuation resulting from other optical admixtures.

The relationships of the respective light attenuation coefficients *vs.* the chlorophyll concentration are described by the following equations

- summary coefficient

$$K_d(\lambda) = K_w + Ba \cdot [D_1(\lambda) \cdot e^{-a_1(\lambda) \cdot Ba} + k_{d,n}(\lambda)], \tag{10}$$

- phytoplankton pigment coefficient

$$K_{pl}(\lambda) = Ba \cdot [C_2(\lambda) \cdot e^{-a_2(\lambda) \cdot Ba} + k_{c,n}(\lambda)], \tag{11}$$

- optically active admixtures

$$\begin{aligned} K_\Delta(\lambda) &= K_d(\lambda) - [K_w(\lambda) + K_{pl}(\lambda)] = Ba \cdot [C_1(\lambda) \cdot e^{-a_1(\lambda) \cdot Ba} - \\ &+ C_2(\lambda) \cdot e^{-a_2(\lambda) \cdot Ba} + k_{d,n}(\lambda) - k_{c,n}(\lambda)]. \end{aligned} \tag{12}$$

The empirical parameters in these relationships are $C_1(\lambda)$, $C_2(\lambda)$, $a_1(\lambda)$, $a_2(\lambda)$, $k_{d,n}(\lambda)$ and $k_{c,n}(\lambda)$. The last and the last but one parameters are

Table 4. The list of parameters applied in the Woźniak bio-optical classification of water masses (eqs. (10)–(12))

λ [nm]	K_w [m^{-1}]	a_1 [m^3(mg Chl)$^{-1}$]	C_1 [m^2(mg Chl)$^{-1}$]	$k_{d,n}$ [m^2(mg Chl)$^{-1}$]	a_2 [m^3(mg Chl)$^{-1}$]	C_2 [m^2(mg Chl)$^{-1}$]	$k_{c,n}$ [m^2(mg Chl)$^{-1}$]
1	2	3	4	5	6	7	8
350	0.059	0.301	0.260	0.0875	3.83	0.0117	0.0161
360	0.051	0.293	0.217	0.0866	3.92	0.0177	0.0171
370	0.044	0.294	0.181	0.0839	2.57	0.0267	0.0187
380	0.040	0.357	0.163	0.0821	2.09	0.0325	0.0233
390	0.031	0.419	0.146	0.0803	2.00	0.0476	0.0280
400	0.027	0.422	0.139	0.0750	1.95	0.0603	0.0307
410	0.025	0.497	0.135	0.0714	1.85	0.0823	0.0333
420	0.024	0.535	0.131	0.0696	1.82	0.0888	0.0360
430	0.022	0.585	0.118	0.0678	1.73	0.0856	0.0375
440	0.022	0.621	0.110	0.0669	1.72	0.0899	0.0383
450	0.023	0.555	0.105	0.0625	1.70	0.0862	0.0373
460	0.023	0.489	0.0946	0.0589	1.62	0.0866	0.0344
470	0.023	0.503	0.0866	0.0527	1.60	0.0798	0.0320
480	0.022	0.504	0.0779	0.0508	1.49	0.0727	0.0293
490	0.025	0.510	0.0772	0.0464	1.54	0.0683	0.0264
500	0.029	0.607	0.0670	0.0419	1.62	0.0627	0.0233
510	0.037	0.592	0.0598	0.0386	1.84	0.0528	0.0213
520	0.048	0.587	0.0605	0.0339	2.00	0.0431	0.0197
530	0.050	0.691	0.0575	0.0303	2.00	0.0370	0.0167
540	0.055	0.604	0.0506	0.0300	1.91	0.0318	0.0137
550	0.063	0.512	0.0437	0.0286	1.89	0.0239	0.0122

Table 4. (continued)

λ	K_w	a_1	C_1	$k_{d,n}$	a_2	C_2	$k_{c,n}$
[nm]	[m^{-1}]	[m^3(mg Chl)$^{-1}$]	[m^2(mg Chl)$^{-1}$]	[m^2(mg Chl)$^{-1}$]	[m^3(mg Chl)$^{-1}$]	[m^2(mg Chl)$^{-1}$]	[m^2(mg Chl)$^{-1}$]
1	2	3	4	5	6	7	8
560	0.071	0.462	0.0426	0.0258	1.59	0.0158	0.0115
570	0.077	0.381	0.0290	0.0250	2.56	0.0126	0.0112
580	0.088	0.395	0.0238	0.0241	3.47	0.00901	0.0113
590	0.107	0.362	0.0186	0.0241	3.58	0.00681	0.0111
600	0.131	0.331	0.0173	0.0232	3.89	0.00492	0.0107
610	0.170	0.301	0.0161	0.0223	3.94	0.0370	0.0104
620	0.212	0.313	0.0152	0.0232	4.01	0.00190	0.0106
630	0.277	0.421	0.0185	0.0232	4.09	0.00148	0.0107
640	0.327	0.421	0.0216	0.0233	5.07	0.00064	0.0120
650	0.336	0.346	0.0164	0.0241	5.40	0.00050	0.0150
660	0.390	0.347	0.0141	0.0258	–	0	0.0213
670	0.460	0.173	0.00938	0.0267	–	0	0.0251
675	0.485	0.173	0.00425	0.0269	–	0	0.0260
680	0.510	–	0	0.0258	–	0	0.0250
690	0.570	–	0	0.0190	–	0	0.0182
710	1.002	–	0	0.0044	–	0	0.0044
720	1.374	–	0	0.0014	–	0	0.0014
730	1.852	–	0	0.0004	–	0	0.0004
740	2.436	–	0	0.00007	–	0	0.00007
750	3.020	–	0	0.00001	–	0	0.00001

the boundary values of the specific light attenuation coefficients ($k_{d,n}(\lambda)$ – the attenuation due to all components except water, and $k_{c,n}(\lambda)$ – that due to phytoplankton pigments). The real values of the coefficients in super-eutrophic basins ($Ba \gg 1\ \mathrm{mg \cdot m^{-3}}$ or $Ba \to \infty$) approach these boundary values.

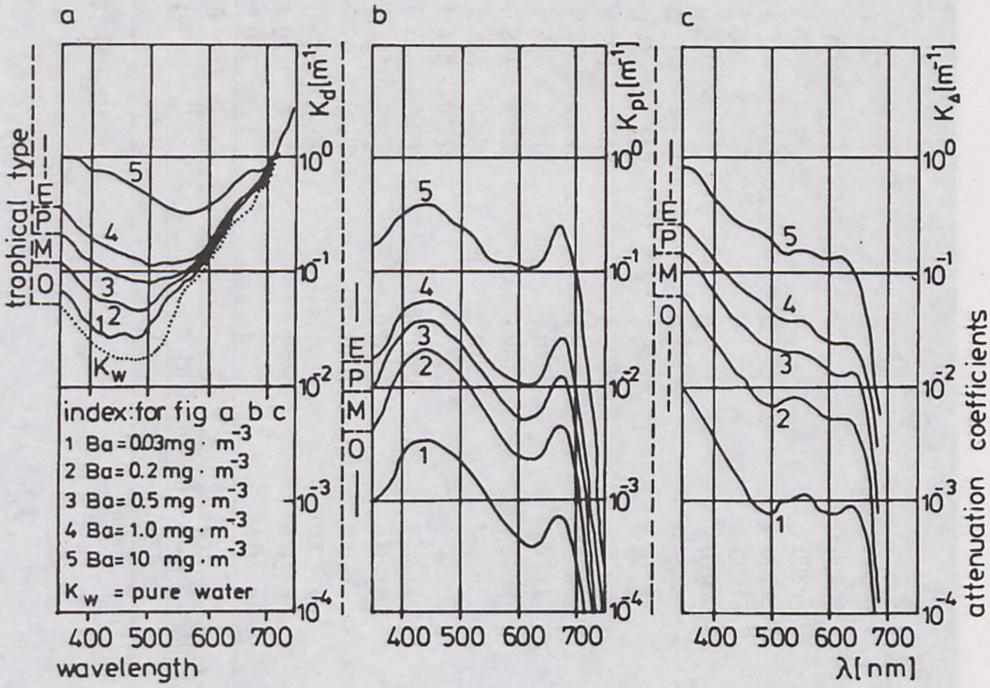

Fig. 4. The spectra of the downward irradiance attenuation coefficients according to the Woźniak bio-optical classification: a – total attenuation $K_d(\lambda)$, b – attenuation by phytoplankton $K_{pl}(\lambda)$, c – attenuation by other optically active substances, *i.e.* yellow substances and suspensions $K_\Delta(\lambda)$, with the exception of phytoplankton. O – oligotrophic sea ($Ba(0) < 0.2\ \mathrm{mg \cdot m^{-3}}$, M – mesotrophic sea ($0.2 < Ba(0) < 0.5\ \mathrm{mg \cdot m^{-3}}$), P – intermediate sea: meso-eutrophic ($0.5 < Ba(0) < 1.0\ \mathrm{mg \cdot m^{-3}}$), E – eutrophic sea ($Ba(0) > 1.0\ \mathrm{mg \cdot m^{-3}}$)

These empirical parameters were determined after a statistical analysis of

- approximately 850 experimental $K_d(\lambda)$ spectra in relation to the chlorophyll concentration Ba,
- about 250 approximated[2] $K_{pl}(\lambda)$ spectra in relation to the chlorophyll concentration Ba.

The approximation was carried out by non-linear methods. The parameters calculated for various light wavelengths are presented in Table 4. The spectral courses of the total $K_d(\lambda)$ coefficient and the contributing $K_{pl}(\lambda)$ and

$K_\Delta(\lambda)$ coefficients in water masses of various chlorophyll concentrations Ba, derived from equations (10) – (12), are illustrated in Figure 4. The variability ranges of the particular coefficients in the given trophic types of basins are also presented.

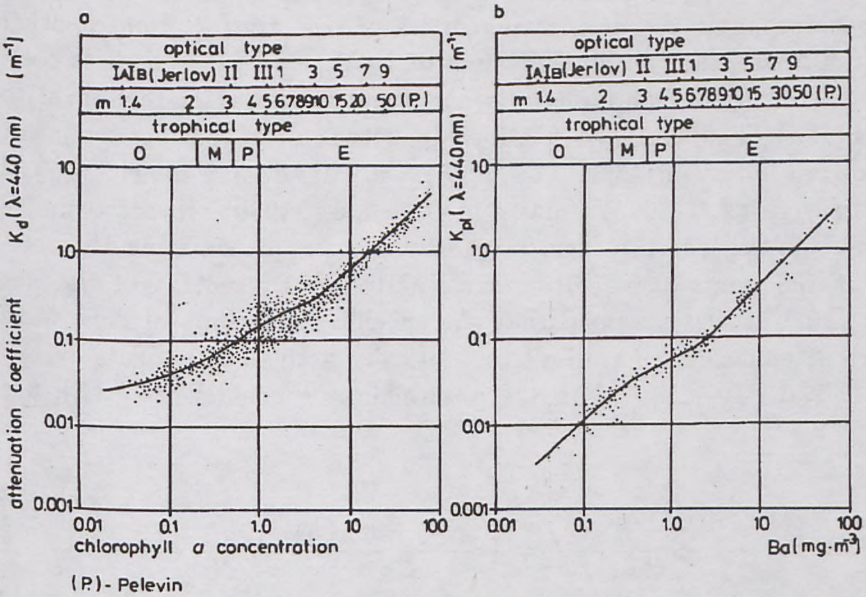

Fig. 5. Experimental interrelations between chlorophyll a concentration Ba, in water masses of various and oceans: a – total coefficient of downward irradiance attenuation $K_d(\lambda) = 440$ nm), b – component $K_{pl}(\lambda = 440$ nm) – coefficient of light attenuation by phytoplankton. Solid lines denote functions approximated by equations (10) (Fig. a) and (11) (Fig. b). O – oligotrophic sea ($Ba(0) < 0.2$ mg $\cdot$ m^{-3}, M – mesotrophic sea ($0.2 < Ba(0) < 0.5$ mg $\cdot$ m^{-3}), P – intermediate sea: meso-eutrophic ($0.5 < Ba(0) < 1.0$ mg $\cdot$ m^{-3}), E – eutrophic sea ($Ba(0) > 1.0$ mg $\cdot$ m^{-3})

Practice has proved that equations (10)–(12) give a good approximation of the experimental functions of the particular coefficients versus chlorophyll a concentration at a particular light wavelength: this is shown in Figure 5 for the K_d and K_{pl} coefficients displayed at $\lambda = 440$ nm. This emerges from the justified physical sense of these approximation functions. It is particularly obvious when $K_{pl}(\lambda) = f(Ba)$. According to equation (11), the specific coefficient of light attenuation by phytoplankton pigments $k_c = K_{pl}/Ba$ is equal to

$$k_c(\lambda) = \frac{K_{pl}(\lambda)}{Ba} = C_2(\lambda) \cdot e^{-a_2(\lambda) \cdot Ba} + k_{c,n}(\lambda). \tag{13}$$

This means that the $k_c(\lambda)$ coefficients have the highest values in oligotrophic water masses of low chlorophyll concentration, where the pigment accompanying chlorøphyll (*i.e.* other chlorophylls, carotenoids and phycobylines) make a significant contribution to the general pigment concentration in the photosynthetic apparatus of oligotrophic phytocoenoses, which was proved statistically by Woźniak and Ostrowska (1990a). Following the increase in chlorophyll *a* concentration in water, the contribution of other pigments decreases, and so do the values of $k_c(\lambda)$. Thus, the smallest coefficient is lowest in eutrophic phytocoenoses and is approximately equal to $k_c(\lambda) \approx k_{c,n}(\lambda)$. The averaged relationship between the specific coefficient of light absorption by phytoplankton $k_c(\lambda) = a_{pl}(\lambda)/Ba$ and the chlorophyll *a* content (Woźniak, 1989; Woźniak and Ostrowska, 1990b) reveal a similar behaviour. As regards the form of the function approximating the relationship of the summary coefficients $K_d(\lambda)$ to the concentration Ba (see equation (10)), it was assumed that the specific coefficients of downward irradiance attenuation $k_d(\lambda)$ of all the optically active components except water, qualitatively identical to the phytoplankton coefficients $k_c(\lambda)$, are equal to

$$\begin{aligned} k_d(\lambda) &= \frac{K_d(\lambda) - K_w(\lambda)}{Ba} = \frac{K_{pl}(\lambda) + K_\Delta(\lambda)}{Ba} = \\ &= C_1(\lambda) e^{-a_1(\lambda) \cdot Ba} + k_{d,n}(\lambda). \end{aligned} \quad (14)$$

The introduction of this analogy results from the correlation between the concentration of various optical components and chlorophyll *a* content (Woźniak, in preparation). The statistical distribution of these compounds gives rise to the significantly scattered distribution of experimental points in the diagram of $K_d(\lambda)$ versus Ba, as compared to the case of $K_{pl}(\lambda)$ versus Ba (Figs. 5a and 5b). Finally, the approximation function of the $K_\Delta(\lambda) = f(Ba)$ relationship (see equation (12)) emerges as the difference between equations (10) and (11).

The precision and accuracy of the Woźniak classification were verified experimentally by using 200 sets of experimental data on the measured spectra of the total downward irradiance attenuation coefficients $K_d(\lambda)$, the component spectra of the phytoplankton attenuation coefficients determined indirectly (from measurements of absorption *in vivo* or in acetone extracts) $K_{pl}(\lambda)$, and the measured concentrations of chlorophyll *a* Ba. The data recorded in various sea types and at different depths of the euphotic zones in these basins. Using the experimental Ba results, the model spectra of total light attenuation and attenuation by phytoplankton were obtained

Table 5. Experimental verification of the Woźniak bio-optical classification of water masses

Spectrum type	Bio-optical type of basin	Ba range [$mg \cdot m^{-3}$]	Parameter	Wavelength [nm]								
				< 420	420 ÷ 460	460 ÷ 500	500 ÷ 540	540 ÷ 580	580 ÷ 620	620 ÷ 660	660 ÷ 700	> 700
$K_d(\lambda)$	Oligotrophic	< 0.2	$< \varepsilon_k >$ [%]	+16	+14	+12	+12	+8	+2	0	-7	–
			σ_ε [%]	±30	±28	±22	±20	±18	±25	±24	±20	–
	Mesotrophic	0.2 ÷ 0.5	$< \varepsilon_k >$ [%]	–5	–10	–10	–11	–8	+7	+2	-7	–
			σ_ε [%]	±41	±23	±20	±21	±13	±10	±18	±18	–
	Intermediate	0.5 ÷ 1	$< \varepsilon_k >$ [%]	–7	+7	–7	–3	–3	+1	–3	–6	–
			σ_ε [%]	±48	±48	±41	±37	±31	±14	±26	±16	–
	Eutrophic	> 1	$< \varepsilon_k >$ [%]	+9	+9	+10	+7	+6	–4	0	+4	–
			σ_ε [%]	±28	±30	±29	±19	±21	±14	±26	±19	–
$K_{pl}(\lambda)$	Oligotrophic	< 0.2	$< \varepsilon_k >$ [%]	+9	+9	+9	+8	+3	+4	+3	–1	+7
			σ_ε [%]	±35	±30	±21	±20	±19	±21	±18	±18	±45.
	Mesotrophic	0.2 ÷ 0.5	$< \varepsilon_k >$ [%]	–10	–10	–8	0	–2	–4	+1	–3	–3
			σ_ε [%]	±42	±29	±16	±16	±19	±14	±18	±16	±42
	Intermediate	0.5 ÷ 1	$< \varepsilon_k >$ [%]	–11	–8	–4	–4	–2	–4	–3	–3	–4
			σ_ε [%]	±45	±28	±26	±23	±25	±22	±26	±15	±60
	Eutrophic	> 1	$< \varepsilon_k >$ [%]	+14	+14	+16	+3	+4	+7	+6	+6	+5
			σ_ε [%]	±18	±28	±20	±20	±20	±22	±28	±17	±41

NB: $< \varepsilon_k >$ – systematic error,
σ_k – statistical error.

from equations (10) and (11). These spectra were compared with the experimental curves, which led to the respective relative errors $\varepsilon_k(\lambda)$ at various wavelengths

$$\varepsilon_k(\lambda) = \frac{K_{cal}(\lambda) - K_{meas}(\lambda)}{K_{meas}(\lambda)}, \tag{15}$$

where

$K_{meas}(\lambda)$ – measured values of the $K_d(\lambda)$ or $K_{pl}(\lambda)$ coefficients,
$K_{cal}(\lambda)$ – calculated values of the coefficients.

In the next stage of verification, the mean error $< \varepsilon_k(\lambda) >$ and standard deviation $\sigma_\varepsilon(\lambda)$ were calculated, separately for each trophic type. The results are given in Table 5. The mean error $< \varepsilon_k(\lambda) >$ is the measure of the systematic error of the classification verified. On the other hand, the standard deviation $\sigma_k(\lambda)$ is the measure of the random (statistical) errors of this classification. The values presented in Table 5 are relatively small and comparable with the measurement accuracy of the coefficients $K_d(\lambda)$ and $K_{pl}(\lambda)$. This means that Woźniak's classification is to a great extent correct and practicable.

3. Comparison of spectral optical properties of natural waters according to various classifications

The spectral optical properties of natural waters determined on the basis of various classifications differ in some respects and are similar in others. This is illustrated in Figure 6. The curves represent model spectra of the coefficients of total downward irradiance attenuation in sea water $K_d(\lambda)$ obtained from Woźniak's classification versus the relevant spectra obtained from the classifications by Jerlov (Fig. 6a), Pelevin and Rutkovskaya (Fig. 6b) and Smith and Baker (Fig. 6c), as well as experimental spectra (Fig. 6d). To facilitate the comparison, the $K_d(\lambda)$ spectra of similar $K_d(\lambda = 500 \text{ nm})$ values were selected in the case of the Woźniak and the Pelevin and Rutkovskaya classifications, or the spectra were chosen for the same chlorophyll *a* concentrations (when comparing the $K_d(\lambda)$ spectra from the Woźniak classification with the Smith and Baker classification or with experimental $K_d(\lambda)$ spectra).

The picture shows similar shapes of the spectra from all four classifications analyzed, and bears a considerable resemblance to the experimental spectra. This is evidence for their considerable correctness, the more so that the discrepancies between the model curves in various classifications ensue from the individual selection of the tested experimental material, experimental errors and different methods of statistical approximation of the data.

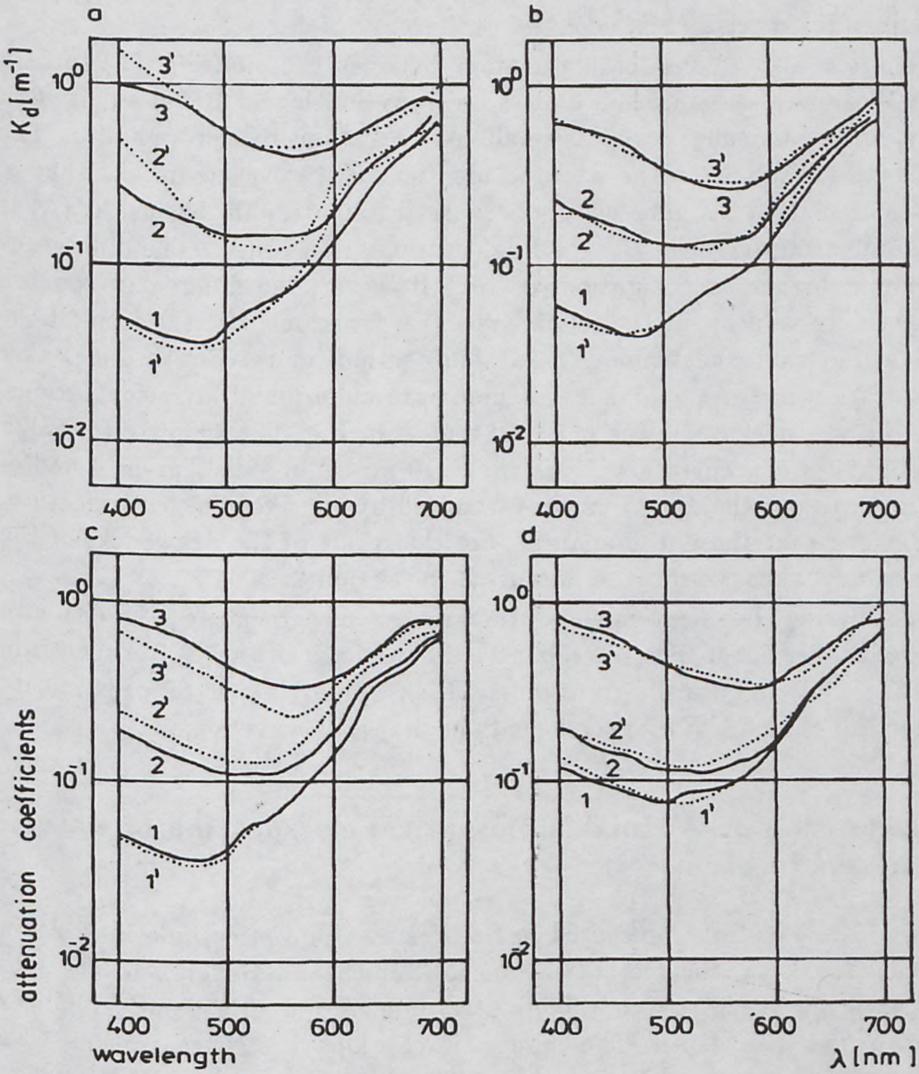

Fig. 6. Comparison of the spectra of the total coefficients of downward irradiance attenuation $K_d(\lambda)$ obtained by Woźniak's classification (solid lines) with the following spectra (broken lines): a – Jerlov's classification, b – Pelevin and Rutkovskaya's classification, c – Smith and Baker's clasification, d – experimental examples. The respective optical indexes are: in Figure a: 1÷3, $Ba = 0.11$ mg·m^{-3}, $Ba = 1.8$ mg·m^{-3}, $Ba = 13$ mg·m^{-3}; 1′ ÷ 3′ Jerlov indices IB, 1, 7; in Figure b: 1÷3 $Ba = 0.45$ mg·m^{-3}, $Ba = 1.6$ mg·m^{-3}, $Ba = 7.4$ mg·m^{-3}; 1′ ÷ 3′ Pelevin and Rutkovskaya indices $m = 2$, $m = 5.3$, $m = 15$; in Figure c in both cases: 1÷3 and 1′ ÷ 3′ $Ba = 0.1$ mg·m^{-3}, $Ba = 1.0$ mg·m^{-3}; in Figure d in both cases: 1÷3 and 1′ ÷ 3′ $Ba = 0.5$ mg·m^{-3}, $Ba = 1.0$ mg·m^{-3} and $Ba = 10$ mg·m^{-3}

The greatest analogy occurs between the model spectra of Woźniak and those of Pelevin and Rutkovskaya (Fig. 6b). They also closely resemble the experimental spectra (Fig. 6d).

There is also a considerable analogy between the model $K_d(\lambda)$ spectra from Woźniak's classification and those from Smith and Baker's (Fig. 6c). They agree particularly well at small concentrations of chlorophyll *a*. The similarities result from the adopted identical $K_w(\lambda)$ spectrum, *i.e* that of light attenuation by pure water, because in oligotrophic basins $K_w(\lambda)$ is the dominating factor in the total light attenuation $K_d(\lambda)$. The differences appear at higher concentrations of Ba. However, the differences concern the absolute values, not the relative spectral functions, *i.e.* the form of the light attenuation spectrum. The absolute values in the Smith and Baker classification are either higher (for moderate chlorophyll *a* concentrations, *e.g.* $Ba = 1\ \mathrm{mg \cdot m^{-3}}$ – see curves 2 and 2' in Fig. 6c) or lower (for high chlorophyll *a* concentrations, *e.g.* $Ba = 10\ \mathrm{mg \cdot m^{-3}}$ – see curves 3 and 3' in Fig. 6c) than the $K_d(\lambda)$ values estimated by the Woźniak classification. We believe that these discrepancies are the result of the drawbacks of the Smith and Baker classfication discussed in Section 2.

The Jerlov classification shows the greatest disagreement (Fig. 6a) with other classifications. The discrepancies in the form of the $K_d(\lambda)$ spectrum appear mainly in optically contaminated seas. Jerlov's spectra also indicate higher values of the $K_d(\lambda)$ coefficients in the short wave region.

4. Extension of Woźniak's bio-optical classfication of water masses to basins

The classifications presented in Section 2 – the optical one by Pelevin and Rutkovskaya, the bio-optical one by Smith and Baker, and the bio-optical by one Woźniak – characterize water masses of certain optical indices regardless of their depth. The changes in chlorophyll *a* concentration serve as the optical index in bio-optical classifications. It is well established that the chlorophyll *a* concentration alters with depth, so the light attenuation coefficients correlated with Ba alter accordingly. Experimental examples of such changes in chlorophyll *a* concentration $Ba(z)$, and in the $K_d(\lambda =$ 500 nm, $z)$ coefficient at a selected wavelength of 440 nm are illustrated in Figure 7.

To make the optical classifications of water masses applicable to the characterization of light transmission into the sea it was necessary to consider the changes of the relevant optical indices with depth, *i.e.* chlorophyll *a* concentration changes with depth.

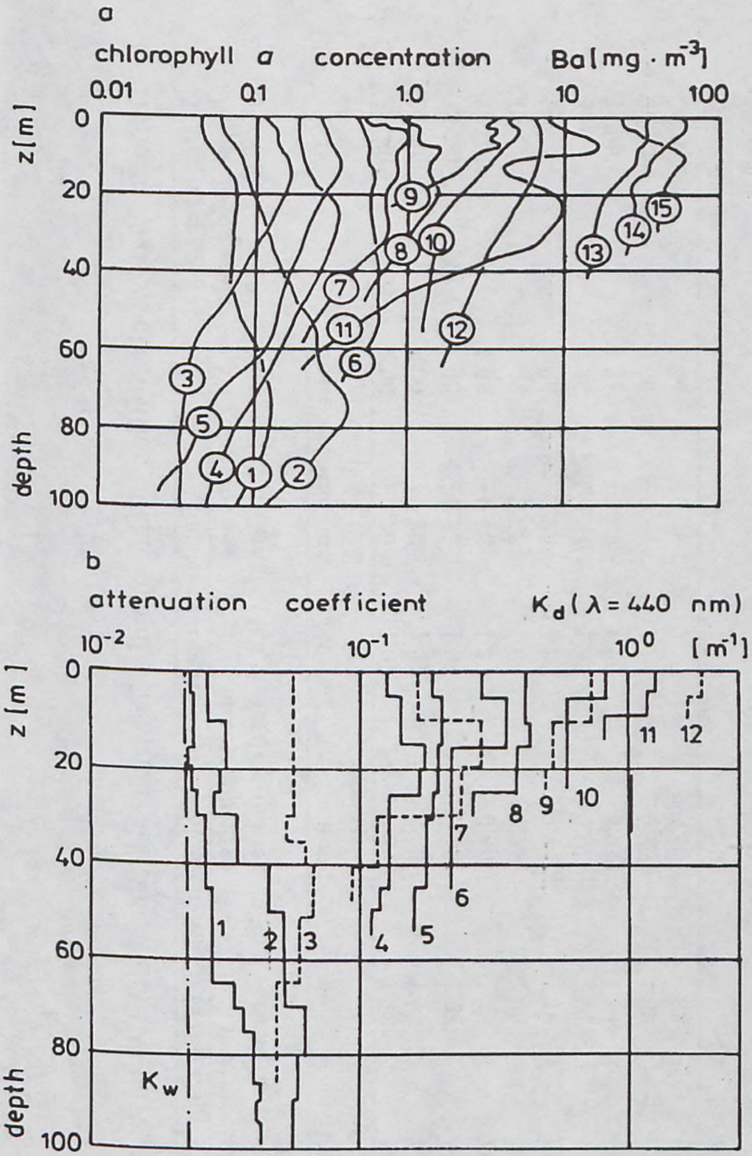

Fig. 7. Examples of experimental vertical profiles: a – chlorophyll *a* concentration *Ba*: 1 – central Indian Ocean, 2÷5 –central Atlantic Ocean, 6÷7 – Atlantic Ocean – the Ezcura Gulf, 8÷11, 13 – the Baltic Sea and the Gulf of Gdańsk, 12, 14, 15 – the Black Sea and the Gulf of Burgas; b – coefficient of downward irradiance attenuation at 440 nm $K_d(\lambda = 440$ nm): 1, 2 – the Indian Ocean (around Mauritius), 3 – the Atlantic Ocean (the Canary Islands), 4 – the Atlantic Ocean (Antarctic), 5, 8 – the Baltic Sea (the Gdańsk Deep), 6, 9 – the Black Sea (the Gulf of Burgas), 7 – the Baltic Sea (the Gotland Deep), 10, 11 – the Gulf of Gdańsk, 12 – Puck Bay. K_d values averaged in 5 m water layers

Table 6. Vertical distribution of chlorophyll *a* in various sea types (after Woźniak, in preparation)

Water layer in transmission scale T_M [%]	Relative concentration of chlorophyll *a* $Ba(T_M)/Ba(z=0)$ [dimensionless]							
	Oligotrophic sea $Ba(0) < 0.2$ mg·m^{-3}		Mesotrophic sea $0.2 \leq Ba(0) < 0.5$ mg·m^{-3}		Intermediate sea meso- and eutrophic $0.5 \leq Ba(0) < 1$ mg·m^{-3}		Eutrophic sea $Ba(0) \geq 1$ mg·m^{-3}	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
90–60	1.06	±0.20	1.07	±0.17	1.18	±0.28	1.12	±0.33
60–30	1.09	±0.39	1.21	±0.34	1.22	±0.42	1.18	±0.38
30–20	1.45	±0.65	1.31	±0.48	1.27	±0.42	1.24	±0.39
20–10	1.54	±0.76	1.37	±0.46	1.45	±0.45	1.20	± 0.49
10–5	2.02	±1.46	1.66	±0.78	1.39	±0.44	1.16	±0.60
5–3	2.06	±1.25	1.63	±0.74	1.30	±0.79	1.08	±0.49
3–1	2.06	± 1.16	1.57	±0.91	1.21	±1.00	1.03	±0.44
1–0.5	1.31	±0.85	1.26	±0.98	1.14	±0.39	0.94	±0.50
0.5–0.1	0.65	±0.41	1.17	±0.85	1.09	±0.29	0.81	±0.51
0.1	0.44	±0.38	0.79	±0.40	0.83	±0.26	0.67	±0.51
Number of analyzed experimental distributions	165		105		85		598	

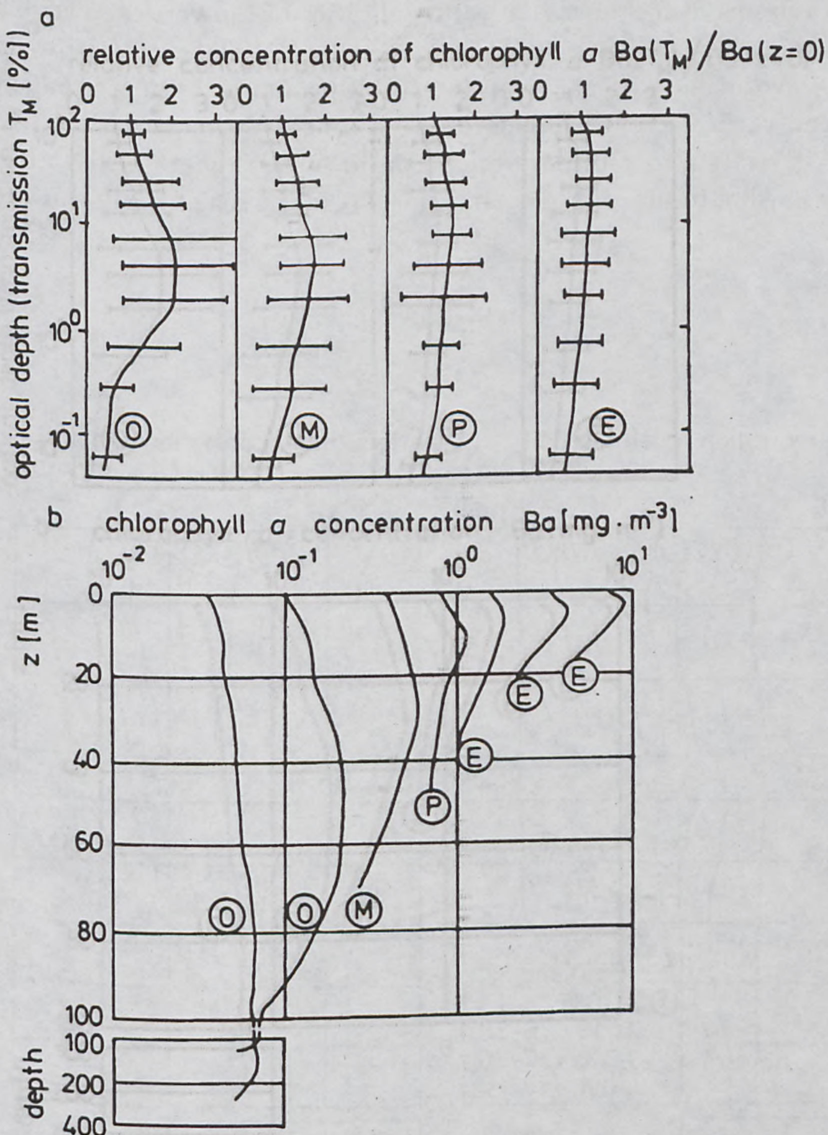

Fig. 8. Statistical distribution of vertical profiles of relative chlorophyll *a* concentration $Ba(T_M)/Ba(z=0)$ in typical basins: O – oligotrophic sea ($Ba(0) < 0.2$ mg·m^{-3}, M – mesotrophic sea ($0.2 < Ba(0) < 0.5$ mg·m^{-3}), P – intermediate sea: meso-eutrophic ($0.5 < Ba(0) < 1.0$ mg·m^{-3}), E – eutrophic sea ($Ba(0) > 1.0$ mg·m^{-3}). Optical depth expressed on the scale of PAR irradiance transmission into the basin. Horizontal segments denote the standard deviation of the relative chlorophyll *a* concentrations (a); examples of hypothetical vertical profiles of absolute chlorophyll *a* concentrations *Ba* in the marine basins of different trophisms (Woźniak and Ostrowska, 1990a) (b).

The bio-optical classification of natural waters by Woźniak has been extended to basins using the statistical regularities of the vertical distribution of chlorophyll *a* in the sea published earlier by Woźniak and Ostrowska (1990a) and Woźniak (in preparation) (see Table 6 and Fig. 8). These papers present mean vertical profiles of chlorophyll a concentration in various marine basins in relation to depth or optical depth. Optical depth in the latter case is expressed in terms of the transmission T_M in the sea of the downward

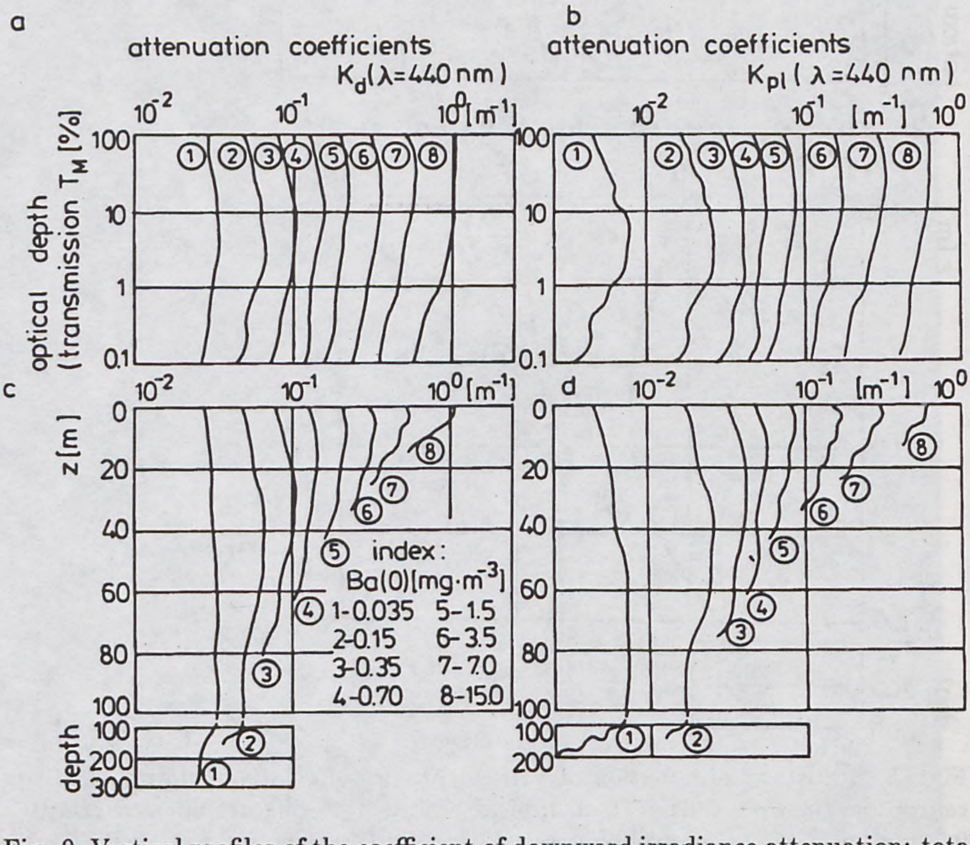

Fig. 9. Vertical profiles of the coefficient of downward irradiance attenuation: total (K_d) and by phytoplankton (K_{pl}), for light of a wavelength $\lambda = 440$ nm in various bio-optical basins characterized by the surface chlorophyll *a* concentration $Ba(0)$ according to the Woźniak bio-optical classification. K_d and K_{pl} changes presented in relation to the optical depth expressed by the irradiance transmission coefficient in the sea T_M and in relation to the actual depth z: a – K_d versus T_M, b – K_d versus z, c – K_{pl} versus T_M, d – K_{pl} – versus z

irradiance, integral in the PAR[3] spectral range. Applying these data and using equations (10) – (12) the vertical distributions of the total $K_d(\lambda, z)$ and of component $K_{pl}(\lambda, z)$ and $K_\Delta(\lambda, z)$ – the coefficients of light attenuation – are determined for various bio-optical sea types. The surface concentration of chlorophyll a $Ba(z = 0)$ is the main input data and the index of sea type. Examples of vertical profiles of $K_d(\lambda) = 440$ nm, z) in various seas, related to actual and optical depths, are shown in Figure 9.

The figure shows that the model vertical profiles match the experimental profiles of light attenuation coefficients (Fig. 7b). It is obvious that the coefficient changes with depth follow the chlorophyll changes (Figs. 7a and 8). The figure indicates the occurrence of certain levels with maximum light attenuation, corresponding to the levels of maximum chlorophyll concentration. Above and below these maxima the values of the light attenuation coefficient decrease. Hence, as with chlorophyll, the location of the attenuation maximum changes according to the trophic type of the basin. The attenuation maxima attain the greatest depths in oligotrophic seas, and as the trophism of the basin increase they approach the surface.

5. Final remarks

For biological practice the authors of this paper recommend Pelevin and Rutkovskaya's optical classifications or Woźniak's bio-optical classification. The arguments presented in Sections 2 and 3 against the other classifications show their more limited applicability. The Jerlov classification is 'discrete', while the major drawbacks of the Smith and Baker classification are the discontinuity of the approximation functions of the light attenuation coefficients K_d (total), K_Δ (a component related to yellow substances and suspensions, but not pigments), K_{pl} and k_c (components related to ordinary and specific attenuation by phytoplankton pigments) in relation to chlorophyll a concentration. These classifications do not agree so well with the experimental data.

Particular attention is drawn to Woźniak's bio-optical classification. It takes into account the spectra of the total light attenuation coefficient $K_d(\lambda)$, and its components $K_w(\lambda)$ $K_{pl}(\lambda)$ and $K_\Delta(\lambda)$. In the version extended to marine basins it additionally includes the coefficient changes with depth. This classification reveals a feature important from the biological point of view, *i.e.* its double bio-optical character. The index of the basin type, *i.e.* the surface concentration of chlorophyll a – $Ba(z = 0)$, enables

[3]PAR – photosynthetic available radiation. In oceanological measurements PAR ranges from 400 nm to 700 nm.

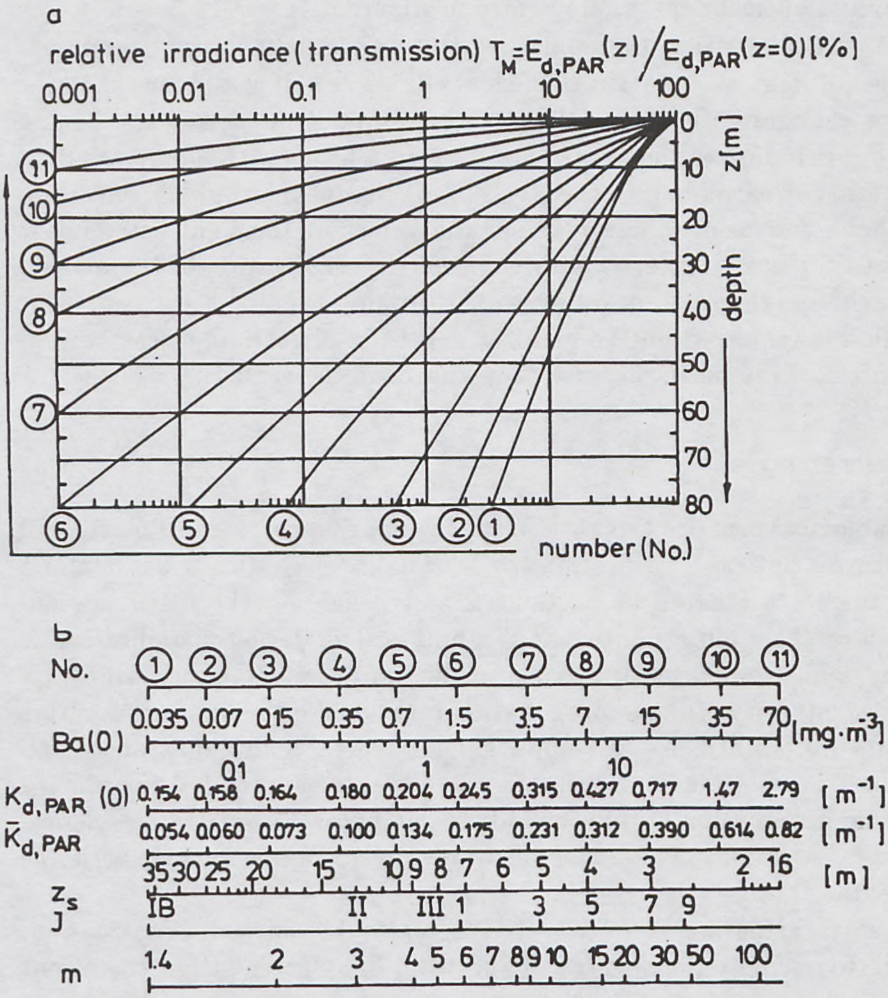

Fig. 10. Vertical profiles of the relative downward irradiance in the PAR range (400–700 nm) $T_M(z) = E_{d,\mathrm{PAR}}(z)/E_{d,,\mathrm{PAR}}(z=0)$ in various types of seas according to the Woźniak bio-optical classification of basins (a). A diagram for the approximate determination of the optical index (Number – No.) with the application of various parameters: $Ba(0)$ – surface concentration of chlorophyll a; $K_{d,\mathrm{PAR}}$ – coefficient of $E_{d,\mathrm{PAR}}$ irradiance attenuation near the surface; $\overline{K}_{d,\mathrm{PAR}}$ – mean coefficient of $E_{d,\mathrm{PAR}}$ irradiance attenuation in the 0–30 m layer; z_s – Secchi disc visibility; J – basin type according to Jerlov; m – Pelevin and Rutkovskaya's optical index (b)

both the vertical profiles of the light attenuation coefficient (and consequently· an estimation of the underwater irradiation in the PAR range) and the vertical profiles of chlorophyll *a* concentration to be obtained. The features presented have played an important role in the creation of the algorithm for determining·primary production by satellite sensing[4]. In addition, the charts of chlorophyll *a* distribution in the surface water layers of various seas and oceans published by Krey and Babenerd (1976) and Mordasowa (1976) (see also Woźniak and Ostrowska, 1990a) may also be applied as indicators of a particular bio-optical basin type in the World Ocean.

Finally, we present a practical diagram for a rough estimation of the bio-optical type of a basin and the relative vertical distribution of PAR downward irradiance in the sea – Figure 10. Figure 10a illustrates the vertical distributions of the total downward irradiance from 400 nm to 700 nm in various bio-optical basin types. They were obtained from the spectral and vertical distributions of $K_d(\lambda, z)$ obtained from the extended Woźniak classification. Figure 10b shows the possibility of determining the bio-optical basin type from factors other than chlorophyll concentration $Ba(z = 0)$, *e.g.* the Jerlov or Pelevin and Rutkovskaya indices and other parameters. The diagram has been constructed from analogies between the various optical classifications (see Section 3) and the relationship between the optical parameters.

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[4]See our article: Pelevin *et al.* (1991) in this volume.

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