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Sédiments

Attenuation measurements of monochromatic light in marine sediments

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ABSTRACT

The attenuation coefficients of monochromatic irradiances of wavelengths between 400 and 730 nm were determined for four different types of natural marine sediments. The attenuation coefficients were highly dependent on wavelength and type of sediment, the longest wavelengths penetrating deepest into all four sediments. At 550 nm attenuation coefficients of 1.9 mm^{-1} for sand and 12.2 mm^{-1} for mud were obtained, corresponding to one per cent irradiance depths of 2.40 and 0.38 mm, respectively. The attenuation coefficients showed linear correlation with the concentrations of organic matter and phaeopigments, and less significant exponential correlation with the median grain size and the concentration of silt.

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RÉSUMÉ

Mesures d'atténuation de la lumière monochromatique dans les sédiments marins

L'irradiation en lumière monochromatique, de longueurs d'onde comprises entre 400 et 730 nm, de quatre types de sédiments marins, a donné lieu à une mesure des coefficients d'atténuation. Ces derniers sont étroitement liés à la longueur d'onde et à la nature du sédiment. Les plus grandes longueurs d'onde sont celles qui pénètrent le plus profondément dans les quatre sédiments. A 550 nm, les coefficients d'atténuation sont de $1,9 \text{ mm}^{-1}$ dans le cas du sable et de $12,2 \text{ mm}^{-1}$ dans le cas de la boue, ce qui correspond à 1 % de la profondeur d'irradiation de 2,4 mm de sable et 0,38 mm de boue. On observe une corrélation linéaire entre les coefficients d'atténuation, les concentrations en matière organique et en phaeopigments. La corrélation exponentielle entre les coefficients, la taille moyenne des grains et la concentration en vase est moins significative.

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INTRODUCTION

The microphytobenthos often constitutes a significant part of the nearshore ecosystem as a consumer of inorganic nutrients and producer of oxygen and organic matter.

Since Pomeroy (1959) and Grøntved (1960) introduced methods for determination of the microphytobenthos primary production, an increasing amount of production data has accumulated, most often from different types of

in situ measurements. Gargas (1970) introduced a method for estimation of the actual daily microphytobenthos primary production by measurements of irradiation at the sediment surface, vertical attenuation of irradiance within the sediments, and incubator measurements of microphytobenthos irradiance-production curves.

The incubator technique saves field time, and a large number of samples can be handled, thus reducing the effect of an often inhomogeneous horizontal distribution of the microphytobenthos.

The literature concerning irradiance attenuation by sediments is very small. Perkins (1963), who also reviews earlier investigations, was the first to apply the concept of attenuation coefficients to sediments. He used an artificial light source, neutral and interference filters, and a photoelectric cell covered by sediment layers of different thicknesses. His attenuation coefficients increased from clean white sand to dark muddy soil, especially at shorter wavelengths. He found a marked minimum attenuation at 495 nm wavelength, and his attenuation coefficients increased with decreasing irradiance.

Taylor (1964) and Taylor and Gebelein (1966) used sunlight irradiation, natural sediments of different thicknesses and a pyrhelimeter. Their attenuation coefficients are integral values for the whole spectrum from the ultraviolet to the infrared and were, with few exceptions, roughly correlated with the mean particle size, but not with the concentrations of organic matter or plant pigments. Gomoiu (1967) who used artificial white light and washed sediments obtained similar results.

Fenchel and Straarup (1971) applied a profiling technique by lowering a micro-irradiance-meter into the sediments. Their attenuation coefficients are integral values for four spectral ranges with spectral half-widths of 100 nm or more. In rinsed sand samples, they found the attenuation coefficients related to the grain size distribution of the samples.

MATERIAL AND METHODS

Four types of sediments were collected in February in the Kieler Förde, West-Germany, with a small van Veen grab (0.01 m²) with moveable lids on the upper side. For determination of attenuation coefficients and pigment concentrations, the uppermost 3 mm were sampled from undisturbed sediments within the grab with a tube corer as described by Gargas (1970). For determination of the grain size distribution, the sediment surface was collected with a spoon. Sample IV was collected with a spoon only, because shell fragments made it impossible to use the tube corer.

The grain size distribution was determined by sieving the sediments through a series of 15 graded sieves with mesh sizes from 1 mm to 40 µm, and weighing the dried fractions. The content of organic matter was determined by ignition at 540°C of sediment dried at 105°C. The pigment concentrations were determined spectrophotometrically according to the method of Lorenzen (1967). The sediment samples were dried on Whatman GF/C filters with MgCO₃ in darkness, crushed in a mortar, and extracted with 90 % aqueous acetone for 24 hours before centrifugation for 10 minutes at about 4000 rpm.

The optical apparatus for measurements of attenuation is shown in Figure 1. A high energy xenon arc lamp (2.5 kW), illuminated via a dispersion prism, P, the entrance slit of a grating monochromator. The monochromatic light was paralleled by passing the achromatic lens, *l*₆. The diaphragms *S*₁ and *S*₂ limited

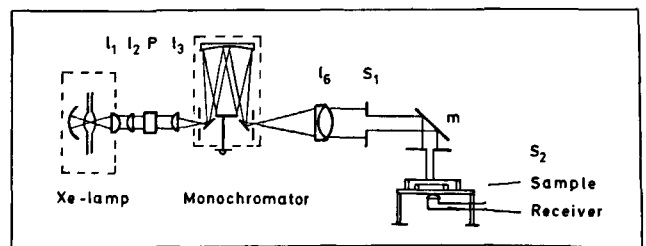


Figure 1

The optical apparatus for measurements of attenuation. For explanation see text.

the diameter of the light beam. The mirror M directed the beam into a vertical direction, so the samples could be positioned horizontally. The light was received by a photodiode, which was selected for good linearity between irradiance and generated current. The diode worked in a closed circuit without bias voltage, and the generated current was measured by means of a digital picoamperemeter. The dependence of the photocurrent of the diode on the beam incident angle was found to be in good agreement with the cosine law. The diode was cemented to the back of a transparent horizontally adjusted plexi-glass table.

Glass bars of 1, 2, or 3 mm thickness were cemented on the bottom of petri-dishes with optical plane bottoms, building the walls of a 40 × 40 mm square. The attenuation layers were prepared by filling the squares with sediment and sliding a glass bar over the walls of the squares. Then the petri-dishes were filled with Whatman GF/C filtered seawater to a fixed level. One petri-dish filled with only filtered seawater was used as reference. Reflection losses between petri-dish and plexi-glass table were avoided by immersion oil.

The attenuation was determined at 50 nm intervals with monochromatic light of 10 nm half-width between 400 and 730 nm and at additional wavelengths in the range of the red chlorophyll absorption peak. Beam diameter was adjusted to 25 mm, the receiver area was 2,5 × 2,5 mm². After a burn-in time of 30 minutes, the radiance of the xenon arc lamp was stable within 2% per hour, so reference measurements only had to be done between each new cycle.

Assuming two attenuation layers, the water above the sediment (index 1) and the sediment (index 2), with constant attenuation coefficients for each layer, the irradiance in the water column above the sediment becomes at constant wavelength

$$E_1 = E_0 P_1 \exp(-K_1 z_1),$$

*E*₁ irradiance at the water depth *z*₁, *E*₀ irradiance above the water surface, *K*₁ attenuation coefficient of water, *P*₁ factor of reflection loss at the air water interface.

In the sediment beneath the water column the irradiance becomes

$$E_2 = E_1(z_1) P_2 \exp(-K_2 z_2),$$

*E*₂ irradiance at the sediment depth *z*₂, *E*₁(*z*₁) irradiance at the sediment surface, *P*₂ factor of reflection loss at the water sediment interface, *K*₂ attenuation coefficient of the sediment.

Table 1

Medium grain size, concentrations of silt, organic matter and plant pigments in the sediment samples from the different water depths. The pigment concentrations are given per m^{-2} and 3 mm sediment depth.

Sample No.	Water depth (m)	Medium grain size (μm)	Silt ($<40 \mu m$) (% of DW)	Organic matter (% of DW)	Chl. <i>a</i> ($mg \cdot m^{-2}$)	Phaeopigm. ($mg \cdot m^{-2}$)	Total chl. <i>a</i> ($mg \cdot m^{-2}$)
I	0.7	260	0.140	0.5	44.1	0	44.1
II	2	205	1.056	0.5	48.7	9.3	58.0
III	10	105	33.450	5.5	23.0	44.6	67.6
IV	4	90	43.205	9.2	50	80	130

If the thickness of the water layer in the reference chamber is equal to the water layer above the sediment in the water-sediment sample, the ratio between the two measurements becomes

$$\ln(E_2/E_1) = -K_2 z_2 + \ln P_2 \quad (1)$$

However, with thicknesses of 1-3 mm and grain sizes up to 0.5 mm, the surface roughness at the water sediment interface and the sediment glass interface cannot be neglected in thickness determinations. So the sediment thickness must be written

$$z_{2i} = d_i - (d_{gs} + d_{ws}),$$

$d_i = 1, 2, \text{ or } 3 \text{ mm}$ determined by the glass walls, d_{gs} mean value of the interface roughness glass sediment, d_{ws} mean value of the interface roughness water sediment.

Then (1) will be transformed into

$$-\frac{\ln(E_{2i}/E_1)}{K_2} = d_i - \left(d_{gs} + d_{ws} + \frac{\ln P_2}{K_2} \right) \quad (2)$$

As the three samples of each sediment type are treated in the same manner, the roughness of the surfaces can be assumed to be equal and the parenthesis of (2) is a constant c_2 for one sediment type at constant wavelength.

The measured values E_{2i}, E_1 then must fit (2) for each d_i and the fitting gives the values K_2 and c_2, c_2 , being of no interest. The fitting was done with a logarithmic fitting programme.

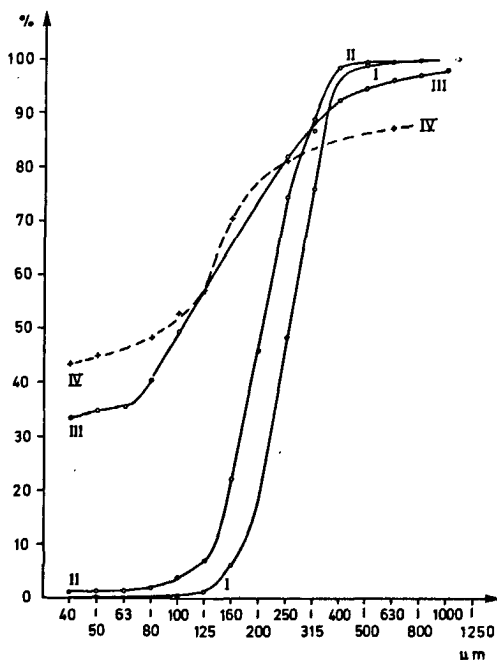


Figure 2
Grain size distribution of the sediment samples.

RESULTS

The grain size distribution of the sediment samples is shown in Figure 2. Sample I consisted of well sorted medium sand without any visible organic particles. Sample II consisted of rather well sorted fine sand with a few floccy particles. Some of the sand grains were coated with iron or manganese. Sample III had a grey brownish colour. It consisted mainly of finer particles, light brown and black faecal pellets of 0.3 to 1 mm length, and floccy material from decaying pellets. A slight smell of H_2S was observed. Sample IV was floccy with a black greyish colour. It contained many small shell fragments and many black or brown pellets of 0.1 to 1 mm length, and of varying stability.

The concentrations of organic matter, phaeopigments, and silt (particles smaller than $40 \mu m$) increased with sample number, while the concentration of chlorophyll *a* in sample III was about half the concentration of the others (Table 1).

The calculated coefficients of the irradiance attenuation are given in the Figures 3 *a* and 3 *b*, the corresponding optical 1% depths according to

$$z_{0.1} = -\ln(0.01)/K_\lambda,$$

are given in Table 2.

Table 2

The one per cent irradiance depths in millimeters of the sediment samples at various wavelengths.

	λ/nm						
	400	450	500	550	600	650	700
Sample I	1.67	1.88	2.08	2.40	2.66	2.79	2.99
Sample II	1.08	1.21	1.33	1.58	1.73	1.83	1.96
Sample III	0.50	0.52	0.55	0.58	0.60	0.61	0.63
Sample IV		0.30	0.34	0.38	0.39	0.40	0.42

The attenuation coefficients are highly dependent on the type of sediment and increase with increasing content of organic matter and decreasing medium grain size. The linear correlation between irradiance attenuation and concentration of organic material and phaeopigments, and the exponential correlation between organic material and medium grain size, are significant at the 1 and the 2% level, respectively (Table 3). The covariation between the concentrations of phaeopigments and organic material may be due to the time of the year at which the sediments were collected. Especially in shallower water, phaeopigments are often absent from sediments relatively rich in

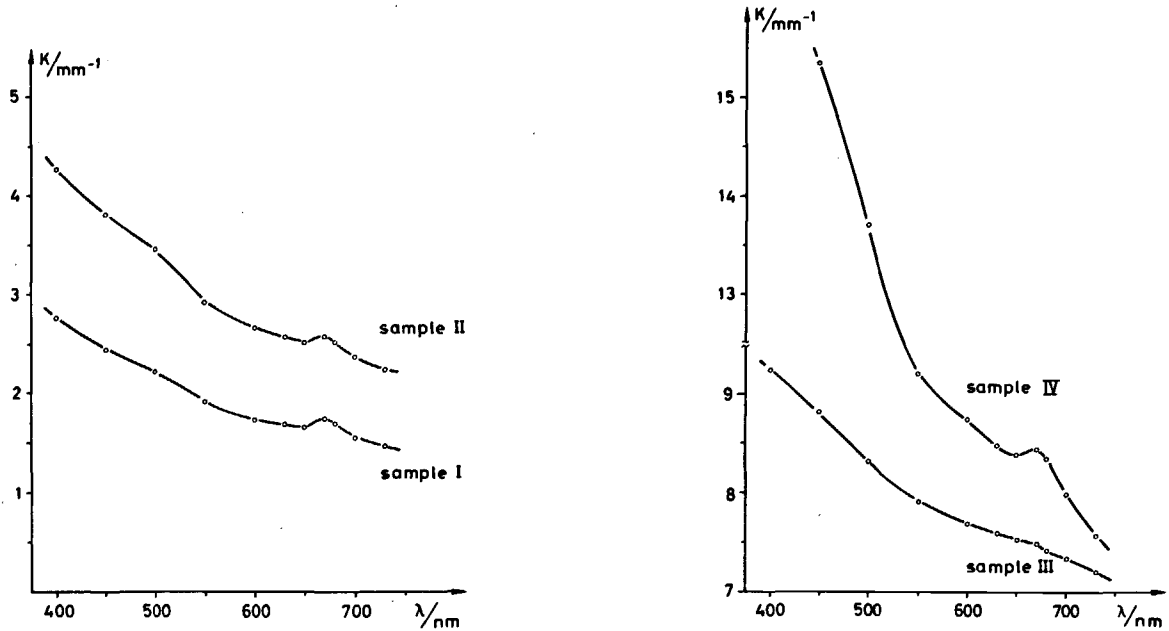


Figure 3
Coefficients of irradiance attenuation versus wavelength. a) sample I and sample II. b) sample III and sample IV.

Table 3

Matrix of linear correlation coefficients for the attenuation at 550 nm wavelength and different characteristics of the sediments. The attenuation at other wavelengths gives nearly identical correlation coefficients.

	Medium grain size	Log _e grain size	Particles <40 μm	Organic matter	Log _e organic matter	Chl. a	Phaeopigm.	Total chl. a
Medium grain size	1.000							
Log _e grain size	0.995	1.000						
Particles <40 μm	-0.961	+0.983 (**)	1.000					
Organic matter	-0.922	-0.954	+0.983 (**)	1.000				
Log _e org. matter	-0.960	-0.982 (**)	0.999 (*)	0.974	1.000			
Chl. a	0.329	0.307	-0.287	-0.112	-0.332	1.000		
Phaeopigm.	-0.933	-0.957	0.970	0.994 (*)	0.958	-0.052	1.000	0.958
Total chl. a	-0.788	-0.818	0.837	0.918	0.810	0.281	0.944	1.000
K ₅₅₀	-0.923	-0.950	0.968	0.995 (*)	0.955	-0.040	1.000 (*)	0.948

(*) Significant at the 1 % level (P < 0.01).

(**) Significant at the 2 % level (P < 0.02).

organic material during periods of vigorous microphyto-benthos growth (Nielsen, 1976). Figure 4 shows the attenuation coefficient, K, at 550 nm wavelength versus the content of organic material. When the organic content is extrapolated to zero, the attenuation cuts the axis between 1 mm⁻¹ and 3 mm⁻¹, dependent on the composition of the inorganic component of the sediment and the content of silt.

In all samples (Fig. 3), the attenuation is highest for blue light and decreases nearly constantly with increasing wavelength with exception of the selective absorption at 670 nm, which is caused by the chlorophyll a and phaeopigment absorption peak. The increase ΔK at 670 nm amounts to

$$\Delta K_I = 0.16 \text{ mm}^{-1}, \quad \Delta K_{II} = 0.13 \text{ mm}^{-1},$$

$$\Delta K_{III} = 0.08 \text{ mm}^{-1} \quad \text{and} \quad \Delta K_{IV} = 0.34 \text{ mm}^{-1}$$

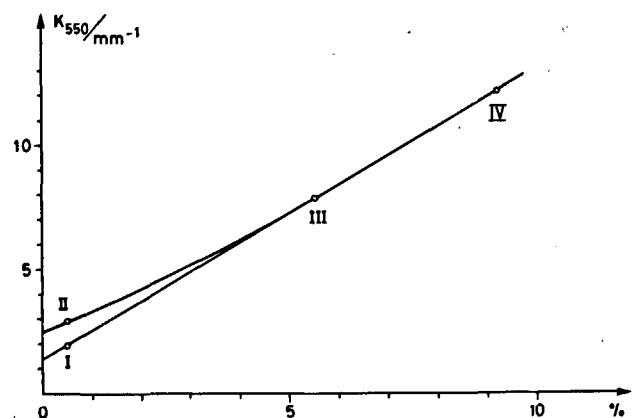


Figure 4
The attenuation coefficient at 550 nm wavelength versus the concentration of organic material (per cent of dry weight) in the sediment samples.

and should according to the equations of Lorenzen (1967) be proportional to

$$\Delta K \sim (C_{\text{phaco}} + 1,7 C_{\text{chl } a})$$

C concentrations in $\text{mg} \cdot \text{m}^{-3}$.

In this respect the correlation coefficient of our data was 0,924.

However, regarding the total attenuation, the absorption by chlorophyll *a* is less important, even in sample I it causes less than 10% of the attenuation of the red light of 670 nm wavelength.

DISCUSSION

The data presented above are in agreement with the results of Fenchel and Straarup (1971) who found that red light penetrates deepest and the blue light shortest into the sediment, irrespective of sediment type, and the attenuation coefficients increase with decreasing median grain size. However, the influence of wavelength and sediment type is much more pronounced in our data (cf. Figs. 3, 5 and 6), and may be caused by a higher content of silt in our samples. On the other hand, a broad band light spectrum, as used by Fenchel and Straarup (1971), tends to smooth the dependence of the attenuation on wavelength.

Our results concerning the spectral attenuation differ markedly from those given by Perkins (1963). The sharp attenuation minimum at about 500 nm was not observed. Though the albedo of the samples he investigated was not considered, the minimum and the maxima in his data cannot be explained by this.

When considering the attenuation of light for an organic matter content extrapolated to zero (Fig. 4) our data approximates to that of Fenchel and Straarup (1971), whose data has been used to prepare Figures 5 and 6.

Figure 5 shows the attenuation coefficient of rinsed quartz sand of 200 μm medium grain size, and Figure 6 shows the attenuation of rinsed quartz sand versus grain size at 400 nm wavelength, and a half-width of about 100 nm.

The attenuation of the sand is slightly influenced by the wavelength and more pronouncedly by the grain size. For a medium grain size diameter of 260 μm (sample I) one would from Figure 6 expect $K_1 = 1.6 \text{ mm}^{-1}$ at $\lambda = 400 \text{ nm}$ and, according to Figure 5, $K_1 = 1.35 \text{ mm}^{-1}$ at $\lambda = 550 \text{ nm}$. This value is in good agreement with the extrapolated value of $K_1 = 1.4 \text{ mm}^{-1}$ (Fig. 4). If the organic content of sample II is extrapolated to zero then $K_{\text{II}} = 2.5 \text{ mm}^{-1}$, a relatively high value caused by the amount of fine particles present.

The attenuation in pure sands is mainly caused by multiple scattering and less by absorption and particles in the $<5 \mu\text{m}$ size region cause the increase of the attenuation at decreasing wavelengths because of the increasing scattering efficiencies of particle sizes and shape irregularities in the order of magnitude of the applied wavelength.

With increasing concentrations of organic material, the attenuation coefficients increase due to increasing

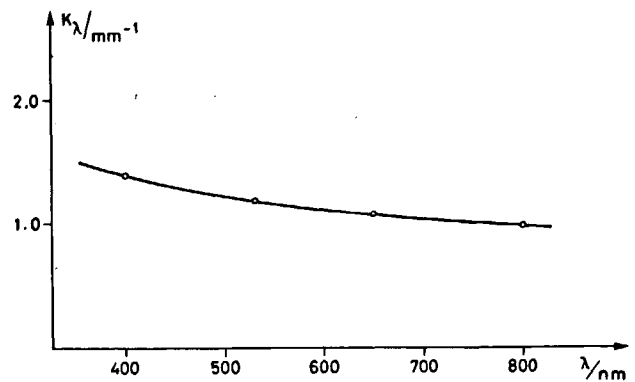


Figure 5

The attenuation coefficient of rinsed quartz sand of 200 μm medium grain size versus wavelength (based on the results of Fenchel and Straarup, 1971).

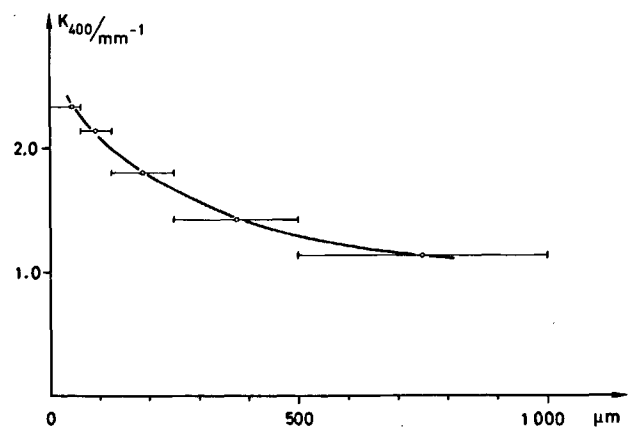


Figure 6

The attenuation coefficient of rinsed quartz sand versus grain size at 400 nm wavelength (based on the results of Fenchel and Straarup, 1971).

absorption by the organic materials other than chlorophyll *a*. Indeed Fenchel and Straarup (1971) found that only a smaller part of the light is absorbed by "living chlorophylls", even in sediments rich in chlorophylls.

Newell (1970) demonstrates that generally an exponential correlation exists between median grain size and concentrations of organic nitrogen and carbon in natural marine sediments. The correlation is most significant for organic nitrogen, because this mainly originates from the bacteria population attached to the surfaces of the sediment particles, whereas the organic carbon also originates from organic debris. In our samples, the covariation between the concentrations of phaeopigments, organic matter and particles smaller than 40 μm indicates that the small particles consisted mainly of decaying organic material and algae. Assuming a carbon/chlorophyll *a* ratio of 50 and an organic matter/carbon ratio of 2 (Lørgensen 1979), about 22% of the organic material of samples I and II and 3% of samples III and IV was made up of living algae. A substantial part of the rest of the organic material in samples III and IV must have originated from litter particles including decaying faecal pellets, which were found in considerable numbers. The exponential

correlation between the median grain size and organic matter content was significant only at the 2% level, a result in agreement with Newell (1970).

When applying the incubator method for determination of the microphytobenthos primary production, it is not convenient to measure the irradiance attenuation of the sediment samples directly. However, the present preliminary results indicate that it may be possible to determine the irradiance attenuation from measurements of the concentration of organic matter or, when this is low, from measurements of the grain size distribution.

With increasing sediment depth, the spectral composition of the day light changes from a maximum irradiance at about 480 nm towards a longer wavelength and a smaller band width. With increasing depth, the irradiance at the sediment surface in coastal marine

waters changes towards green light, blue and red light being attenuated more rapidly (Jerlov, 1976). Therefore, it seems reasonable at all water depths to use the attenuation coefficient of green light (e. g. 550 nm) as an average value for the sediments attenuation of the irradiance penetrating to the sediment surface.

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