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Spectral daylight irradiance and light transmittance in natural waters measured by means of a Secchi Disc only

by

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Abstract

The Secchi Disc is a practical and fairly reliable means for measuring downwelling quanta irradiance (350-700 nm), spectral downwelling irradiance, spectral light transmittance and spectral irradiance ratio, respectively, in the euphotic zone of all natural waters.

Introduction

The Secchi Disc was introduced in the optical oceanography in 1865 as a means to determine the transparency of the sea (for historical details see Collier, Finlayson and Cake, 1968). Later the Secchi Disc was adopted by the marine biologists in order to measure the depth of the euphotic zone defined as the depth at which 1% of the surface quanta irradiance is found. This depth Z_q (1%) is dependent on the inherent optical properties of the sea water, the state of the sea and the surface light conditions. However, for much practical biological work the depth of the euphotic zone might be considered constant (Højerslev, 1974a, b) independent of the surface light conditions.

The relationship between the Secchi Disc depth $\underline{D}$ (i.e. the depth in meters where the Secchi Disc disappears from sight and Z_q (1%) in its most simple form can be written:

$$Z_q\,(1\%) = A \cdot D \qquad (1)$$

where $\underline{A}$ is a dimensionless constant. Quite often another relationship involving the average vertical attenuation coefficient for the downwelling quanta irradiance $< K_q >$ and D is given in the oceanographic literature namely

$$< K_q > = B/D \ m^{-1} \qquad (2)$$

where B is another dimensionless constant equal to $\ell n\ 100/A = 4.6/A$.

The Secchi Disc method as practiced is simple. The procedure is as follows:

1) Measure the depth in meters where the Secchi Disc disappears. This depth will be D.

2) Calculate $Z_q(1\%)$ from a chosen value of the constant A. The choice of value is virtually only dependent on the water mass and the surface light conditions.

3) Assume a $K_q(Z)$ independent of depth = $< K_q >$.

4) Calculate the downwelling quanta irradiance from the relation

$$q(Z)\% = 100 \exp(-K_q(Z) \cdot Z) .$$

The method is seemingly arbitrary. The human eye is involved; we have to decide upon a value for A and finally assume a constant $K_q(Z)$ which is normally not the case. Now, the latter objection has recently been overcome by Jerlov (1977) since he has established functional relationships between $Z_q(1\%)$ and $Z_q(3\%)$, $Z_q(10\%)$ and $Z_q(30\%)$, i.e. the depth of the 1%, 3%, 10% and 30% levels for the downwelling quanta, respectively. Accordingly, knowing $Z_q(1\%)$ from a Secchi Disc measurement the variation of $K_q(Z)$ with depth can be taken into account unless the water mass is highly stratified which might be the case in upwelling areas, in plankton blooms, where fresh water run-out encounters sea water etc.

The crucial point is, however, the choise of the factor B (or A) in equation (2). Poole and Atkins (1929) show from data gathered in the English Channel that B = 1.7 . Clarke (1941) found the same value in waters east of the Caribbean region and south of the Bermuda region. Graham (1966) found in the North Eastern Pacific by a somewhat different approach that B varies between 0.3 and 1.6 . As stated by Steemann Nielsen (1975): "It is clear that a constant value for the factor B cannot be correct for all water types". He gives a value for B equal to 1.85 valid in Danish coastal waters.

Duntley (1963) has discussed the Secchi Disc theory in detail. He gives the equation

$$C_Z = C_0 \exp(-(c + K)Z) \qquad (3)$$

which describes the attenuation of the contrast of a submerged object along the vertical downward directed path of sight. C_0 is the inherent contrast of the object just below the surface as seen by the observer, C_Z is its apparent contrast at depth Z, c is the attenuation coefficient and K is the vertical attenuation coefficient for radiance. In order to arrive at equation (3) monochromatic and unpolarized light in a horizontally stratified water mass having an infinite depth is assumed. (Practically, the claim of "infinite depth" means depths greater than 3 times the Secchi Disc depth D . Observations made at smaller depths might be affected by the albedo from the bottom leading to erroneous results. - Holmes, 1971). Furthermore, it is assumed that the vertical attenuation coefficients for the radiance at all depths and coming from all directions have the same constant value. This assumption involves implicitely that the presence of the Secchi Disc in a water mass does not disturb the surrounding light field.

Although some of the above mentioned assumptions are rather unrealistic for surface layers it can nevertheless be concluded that equation (3) is useful to interpret the problems concerning the Secchi Disc.

The Secchi Disc

In the following we consider the case where the observation of the disappearance of the Secchi Disc at Z = D is made from just below the water surface by means of a scuba diver or a viewer. Equation (3) becomes:

$$(c + K)D = \ln \frac{C_0}{C_{Z=D}} \qquad (4)$$

where $C_{Z=D}$, the so-called liminal visual contrast, has the recommended value of 0.0066 (Blackwell, 1946, and National Defense Research Committee, 1946). The inherent contrast of the Secchi Disc just below the water surface C_0 is defined by

$$C_0 = \frac{L_t - L_b}{L_b} \qquad (5)$$

where L_t and L_b are the upwelling nadir radiance for the Secchi Disc and the neighbouring water, respectively. Assuming the Secchi Disc to be a perfect Lambert emitter having a reflectance ρ and the upwelling light field to be uniform, equation (5) can be written

$$\begin{aligned} L_t &= \rho E_d/\pi \\ L_b &= E_u/\pi \end{aligned} \qquad (6)$$

Where E_d and E_u are the downwelling and the upwelling irradiance, respectively. Inserting equation (6) into (4):

$$(c + K)D = \ln \rho \frac{E_d - E_u}{E_u} \Big/ 0.0066 \sim$$

$$\ln \rho \frac{E_d}{E_u} \Big/ 0.0066 = 5.02 + \ln \rho - \ln R \qquad (7)$$

where $R = E_u/E_d$ is the so-called irradiance ratio. Equation (7) demonstrates that the reflectance ρ of the Secchi Disc is of minor importance. Example::

$\rho = 0.9$; $(c + K)D = 4.91 - \ln R$

$\rho = 0.7$; $(c + K)D = 4.66 - \ln R$

Consequently $\rho = 0.8$ is chosen which is leading to:

$$(c + K)D = 4.80 - \ln R \qquad (8)$$

The diameter of the Secchi Disc is normally around 30 cm. The size of the disc has a slight effect when measuring D but not in such a way that a greater diameter automatically involves a greater D . It is true that a decrease in the angular subtense of the Secchi Disc leads to a reduced contrast vision (Blackwell, 1946) but at the same time the assumption stating that the disc must not disturb the surrounding light field should not be violated. As a matter of fact it was found, from experiments that great Secchi Discs used in turbid waters gave a lesser D than did smaller discs.

Equation (8) contains 3 unknowns, i.e. c, K and R . According to all published work concerning the Secchi Disc it is clearly expressed that there are no ways by which the terms c and K can be found separately from downward. Secchi Disc observations (an academic but highly impractical method where both upward and downward observations are involved allows the above-mentioned separation. (Preisendorfer, 1976)). This is, however, not impossible to separate the term (c + K) within reasonable limit of errors into c and K from a single Secchi Disc messurement which is shown both theoretically and experimentally below. The optical model given by Timofeeva (1974) has been applied. This gives the irradiance ratio R (2) and the vertical attenuation coefficient K expressed in terms of the attenuation coefficient c as a function of the photon survival probability b/c - see Table I and Fig. 1. This model allows the left side of equation (8) to be written in terms of c and D so that a calculation of Dc as a function of b/c is now possible. The result of this computation is given in Table II, Case 1, 2nd column. Then an optical model is constructed by assuming that the backscattering b_b can be put equal to 0.02 times the scattering coefficient b and that the irradiance ratio $R = 0.33\, b_b/a$, where $\underline{a}$ is the absorption coefficient. The results from this model are tabulated in Table I where the irradiance ratio R (1) is given as a function of b/c. Like before $\underline{Dc}$ is calculated from equation (8) and the result can be found in Table II, Case 1, 1st column. The average value of $\underline{Dc}$ equals 6.4 for Case 1, i.e. observations made from just below the water surface. It is difficult to check the 2 above mentioned optical models experimentally since only a few direct measurements of $\underline{R}$ versus b/c are made. In Fig. 1 some of the authors own experimental findings from different areas of the sea are included (Højerslev, 1973, 1974a). Considering the uncertainties in these four independent measurements it can be concluded that both models are satisfactory.

The cases where the Secchi Disc observations are made from above the water surface at different weather situations are considered, i.e. light reflected from the sea surface into the eye is taken into account. The procedure is in the same way as before and the result can be found in Table II. As one could expect $\underline{Dc}$ demonstrates its maximum = 6.4 when the disappearance of the Secchi Disc is observed from just below the water surface since the contrast sensation of the eye is not disturbed by reflected light from the sea surface. Conversely $\underline{Dc}$ has its minimum value = 5.6 in overcast weather for observations made from above the sea surface since the daylight is relatively low and the reflected light from the sea surface relatively high. However, with sufficient accuracy it can be concluded that

$$D \cdot c \mathrel{\hat{=}} 6 \qquad (9)$$

valid for all waters, all wavelengths and for all observation conditions. This remarkable result has been confirmed experimentally in different waters at different wavelengths - see Figs. 2 and 3. (The transmissometer is built and described by Lundgren, (1976) and the findings in Fig. 3 originate mainly from Malmberg, 1968). This means that if we place say a green glass filter in front of the eye and observe the disappearance of the Secchi Disc through the filter, the attenuation coefficient in the green part of the spectrum is readily computed from c (green) = 6/D (green) within $\pm$ 10%.

Only broad glass filters should be applied for these spectral measurements since the liminal visual contrast $C_{Z=D}$ has been given the constant value of 0.0066. However, $C_{Z=D}$ is dependent on the light intensity at which the observations are performed. Application of narrow interference filters would presume that $C_{Z=D}$ = 0.0066 would be too small.

In order to measure the downwelling quanta irradiance in the spectral range of 350 -700 nm by means of the Secchi Disc equation (8) and Table III shall be applied. The disappearance of the Secchi Disc is for this case observed by means of the naked eye (photopic vision). The irradiance ratio for lux at the sea surface $R(0-, \overline{y_\lambda})$ can be put equal to 0.01 . This is a good choice because observations indicate that R for lux varies only insignificantly from the clearest to some of the most turbid sea waters - see Table III. Furthermore, Tyler et al. (1972) have developed an optical model for natural waters in which R for lux = 0.0095 (Crater Lake). Consequently, we can establish a relation between $D(\overline{y_\lambda})$ observed by the naked eye and $K(\overline{y_\lambda})$ for the vertical attenuation coefficient for the downwelling lux irradiance as done in Table III, last column. From 600 daylight spectra measured by Dr. A. Morel in the most different areas and from Jerlov's (1976) optical classification of oceanic and coastal water masses both the quanta irradiance (350 - 700 nm) q and the lux irradiance $E(\overline{y_\lambda})$ have been computed. Dr. Morel and the author operated with the following equation

$$q = H(Z)\,E(\overline{y_\lambda})^{h(Z)}$$

and by a 'best fit' procedure we were able to give values for H and h versus depth. It was found that for all water types a specified $E(\overline{y_\lambda})$ would give q within $\pm$ 20% inside the euphotic zone. This is a sufficient accuracy for the present purpose.

The above-mentioned work forms the main basis for preparing the Tables IV and V, respectively, which give the quanta irradiance and the lux irradiance as a function of the Secchi Disc depth D when measured by means of the naked eye. These tables are as mentioned earlier based upon an assumed fixed value of $R(0-, \overline{y_\lambda}) = 0.01$.

If we measure with both a white and a black Secchi Disc (the black shall preferably be a light trap) it is possible to make spectral measurements of c, K, and R, respectively. Only the final results from observations made just below the water are presented - see Table II, Case 1:

$$\begin{aligned} D \cdot c &= 6.4 \quad \text{(as before)} \\ K &= 5/d - 6.4/D \\ R &= 120\, e^{-5D/d} \end{aligned} \qquad (10\,a, b, c)$$

Here, D and d are the depths of disapperance of the white and the black Secchi Disc, respectively. From equations (10 a, b, c) we obtain the very useful approximation

$$R = 0.3\, e^{-6\frac{K}{c}}$$

valid at least in the euphotic zone of all waters and valid for all wavelengths. From Fig. 1 it is seen that the approximation is in good accordance with the experimental findings.

The findings given in equations (10a, b, c) have been extended to comprise of the Cases 2-6, which, however, will not be presented here.

Conclusions

For all water masses, all weather situations and all wavelengths the following practical results have been achieved:

1) $c = 6/D$

2) $K = 5/d - 6/D$

3a) $R = 120\, e^{-5D/d}$

3b) $R = 0.3\, e^{-6\frac{K}{c}}$

where D and d are the Secchi Disc depths of the white and the black disc, respectively. c, K and R are the attenuation coefficient, the vertical attenuation coefficient for the downwelling irradiance and the irradiance ratio, respectively. The spectral observations are made by observing through the appropriate broad glass filters.

4) The downwelling quanta irradiance (350 - 700 nm) is obtained from a measurement of D with the naked eye (photopic vision) and Tables IV or V are then used.

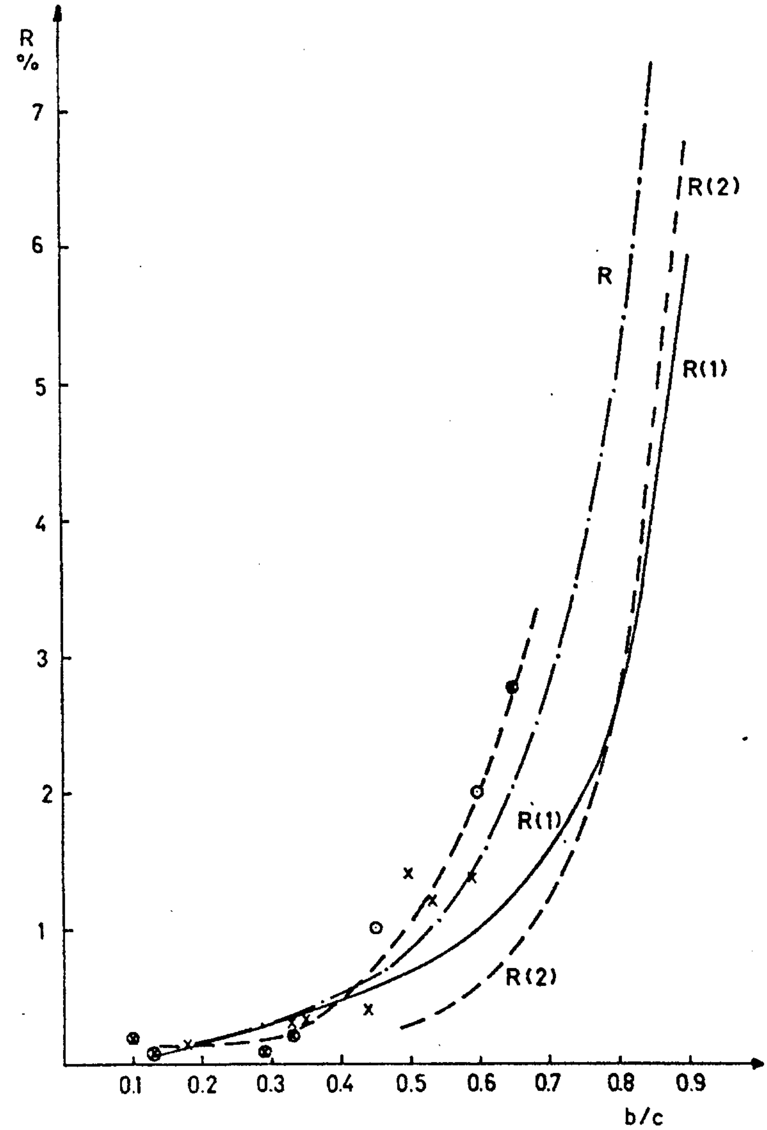

Fig. 1. Irradiance ratios E_u/E_d versus the photon survival probability b/c. For further explanation see Table I.

⊗ Western Mediterranean (Højerslev, 1973)

x Baltic (Højerslev, 1974a)

⊙ The Belts (Højerslev, in prep.)

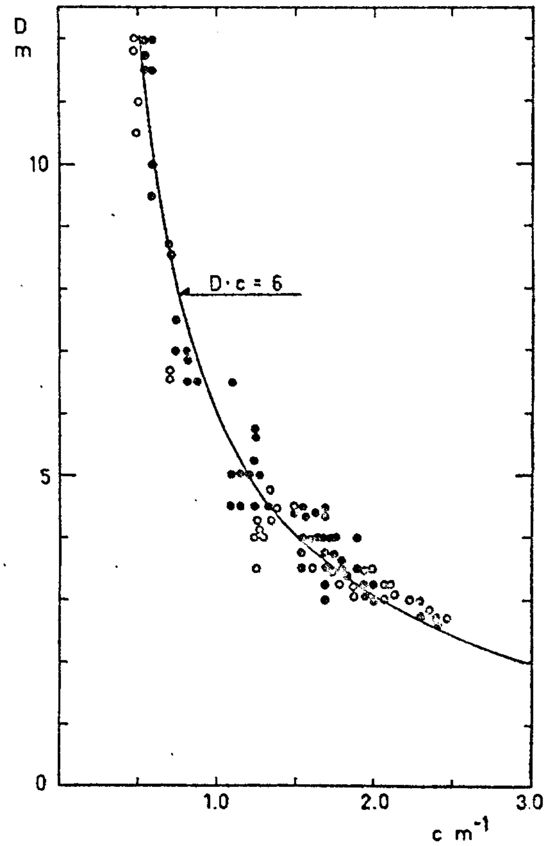

Fig. 2. Spectral Secchi Disc depths D versus spectral attenuation coefficients c:

- ⊙ refer to measurements of the parameters D, c in the green part of the spectrum ~ 525 nm by using VG9 glass filters (Schott and Genossen) in both the transmissometer and in the Secchi Disc measurements.
- o refer to measurements in the same way as above of D, c in the red part of the spectrum ~ 655 nm by using RG1 glass filters and finally
- ● refer to measurements of D, c in the blue part of the spectrum ~ 465 nm by using a glass filter combination of GG5 and BG12.

All the points are obtained in Danish waters at different surface light conditions. Three different Secchi Discs have been applied with diameters around 20, 30 and 100 cm, respectively. Sometimes observations were made from deck; at other occasions they were made just below the water surface by means of a viewer. No significant difference in the observed values from one type of a measurement to another could be observed.

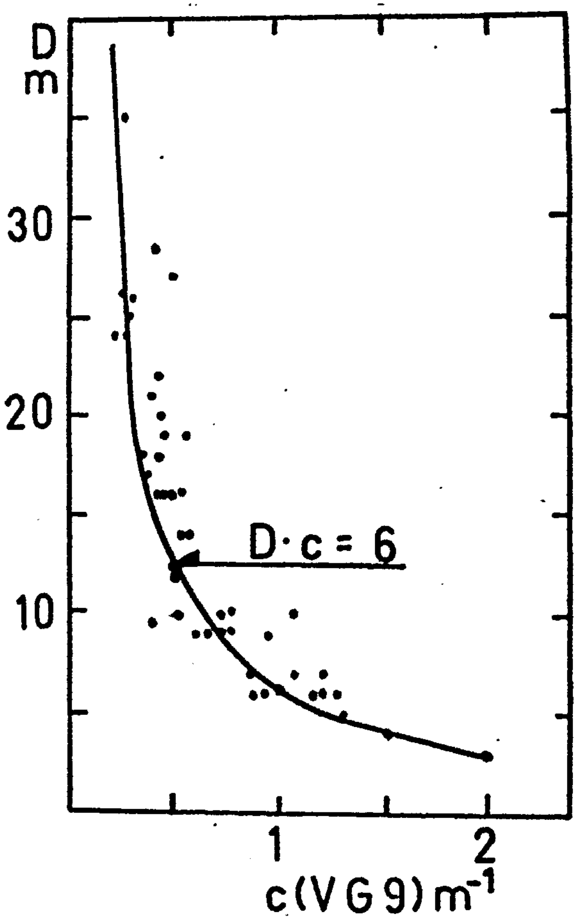

Fig. 3. Secchi Disc depths D measured by means of the naked eye (photopic vision) versus the attenuation coefficient in the green part of the spectrum ~525 nm. The measurements are all carried out in Icelandic waters.

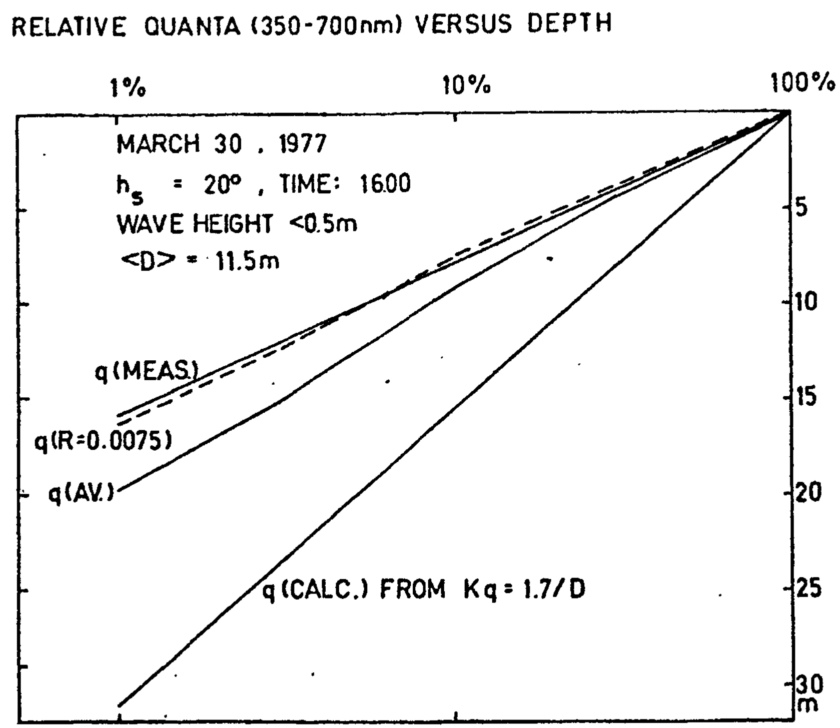

Fig. 4. q (meas.): Relative quanta irradiance (350-700nm) versus depth in the Arkona Basin.

q (av.): Relative average quanta irradiance (350-700 nm) obtained from a conventional Secchi Disc measurement by using Table IV directly.

q (calc.): Relative quanta irradiance (350-700 nm) calculated from the almost classical relation $K_q = 1.7/D$ and assuming a constant vertical attenuation coefficient in the euphotic zone.

q (R = 0.0075): Relative quanta irradiance (350-700 nm) calculated from a measured irradiance ratio R for photopic vision $R(o-,\overline{y_\lambda})$ in the Baltic and by using Tables II and V, respectively. From Table II Case 4 was applied i.e. Dc = 6.25 leading to DK ~ 3 and for such a case Table V is applicable.

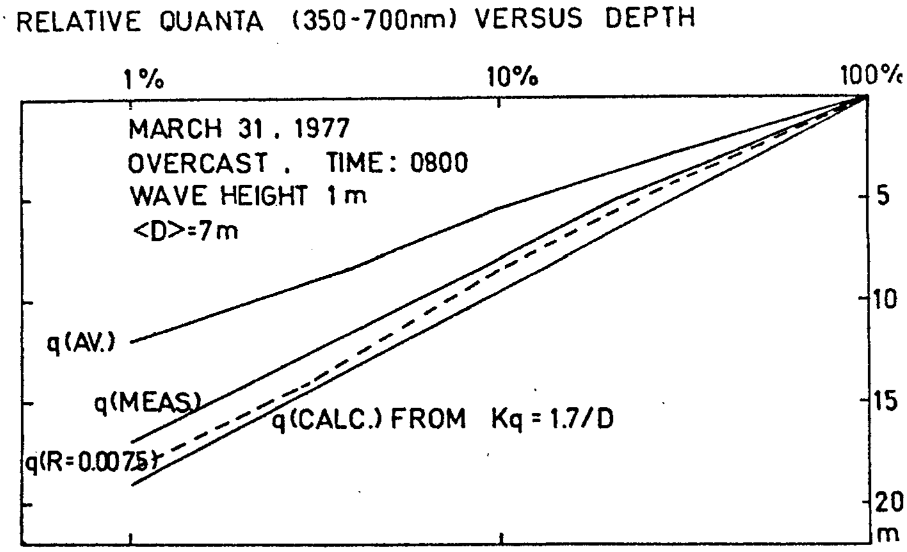

Fig. 5. Same explanation as in Fig. 4 with the exception that q(R = 0.0075) is calculated from Table, II Case 2, i.e. Dc = 5.6 and DK ~ 2.3. For this case (overcast) Table IV shall be used.

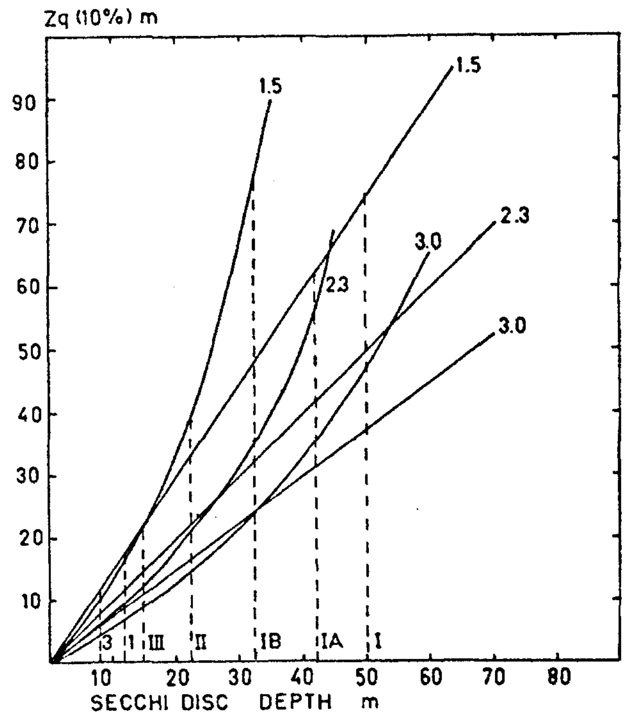

Fig. 6. The depths of the 10% level for the downwelling quanta irradiance (350-700 nm) versus the Secchi Disc depth D measured by means of the naked eye. The three straight lines termed 1.5, 2.3 and 3.0, respectively, refer to different rather crude optical models where i) $K = 1.5/D$, ii) $K = 2.3/D$ and III) $K = 3/D$ for the downwelling quanta irradiance at all depths. The three curved lines having the same numbers as above refer instead to more elaborate optical models where a relationship between the downwelling quanta irradiance (350 - 700 nm) and the downwelling lux irradiance have been established from about 600 daylight spectra measured in different natural sea waters (for further details see the text and Tables IV and V) Near the abcissa axis is included Jerlov's (1976) optical classification of water masses with respect to downwelling quanta irradiance. The five oceanic types I, IA, IB, II and III respectively, and the two coastal types 1 and 3, respectively, are depicted.

Table I.

Irradiance ratios E_u/E_d, average cosine E/E_o and vertical attenuation coefficient for downwelling irradiance K as a function of photon survival probability b/c.

b/c	R	R(1)	R(2)	E/E_o	K m^{-1}
0.1	0.0011	0.00073	-	0.97	0.93·c
0.2	0.0018	0.00165	-	0.94	0.85·c
0.3	0.0030	0.0028	-	0.91	0.77·c
0.4	0.0051	0.0044	-	0.88	0.68·c
0.5	0.0082	0.0066	0.0030	0.83	0.60·c
0.6	0.015	0.0099	0.0058	0.80	0.50·c
0.7	0.027	0.0154	0.012	0.75	0.40·c
0.8	0.050	0.026	0.027	0.67	0.30·c
0.9	0.096	0.059	0.067	0.53	0.19·c

$R \sim 0.3\, e^{-6 \cdot \frac{K}{c}}$ (the author's suggestion)

$R(1) = 0.33 \frac{b_b}{a}$ where $b_b = 0.02\, b$ (Jerlov, 1976 and Prieur, 1976)

$R(2) = f\,(b, c, z \to \infty)$ (Timofeeva, 1972)

Table II.

The product of the Secchi Disc depth D and the attenuation coefficient c as a function of the photon survival probability b/c at different surface daylight conditions.

	D · c calculated											
case	1		2		3		4		5		6	
b/c	R(1)	R(2)	R(1)	R(2)	R(1)	R(2)	R(1)	R(2)	R(1)	R(2)	R(1)	R(2)
0.1	6.2	-	4.2	-	4.9	-	5.3	-	5.6	-	6.0	-
0.2	6.0	-	4.4	-	5.1	-	5.5	-	5.7	-	6.0	-
0.3	6.0	-	4.6	-	5.2	-	5.6	-	5.8	-	6.0	-
0.4	6.1	-	4.8	-	5.5	-	5.8	-	5.9	-	6.1	-
0.5	6.1	6.6	5.0	5.1	5.6	5.8	5.9	6.2	6.0	6.4	6.1	6.6
0.6	6.3	6.6	5.3	5.3	5.9	6.0	6.1	6.3	6.2	6.5	6.3	6.6
0.7	6.4	6.6	5.6	5.6	6.1	6.2	6.3	6.4	6.4	6.5	6.4	6.6
0.8	6.5	6.4	5.9	5.9	6.3	6.3	6.4	6.4	6.5	6.4	6.5	6.5
0.9	6.4	6.2	6.0	6.0	6.3	6.2	6.4	6.3	6.4	6.3	6.4	6.3
Average values	6.3	6.5	5.6	5.6	6.0	6.1	6.2	6.3	6.1	6.4	6.2	6.5

Case 1: Observations made from just below the water surface.
$(c + K)\ D = 4.80 - \ln R$

Case 2-6: Observations made above the water surface

Case 2: Overcast
$(c + K)\ D = 8.17 - \ln (1 + 28R)$

Case 3: E_d sky/E_d sun = 1:3 (low sun or cloudy)
$(c + K)\ D = 9.56 - \ln (1 + 114R)$

Case 4: E_d sky/E_d sun = 1:10 (high sun)
$(c + K)\ D = 10.58 - \ln (1 + 313R)$

Case 5: E_d sky/E_d sun = 1:20
$(c + K)\ D = 11.22 - \ln (1 + 600R)$

Case 6: E_d sky/E_d sun = 1:100
$(c + K)\ D = 12.79 - \ln (1 + 2878R)$

Table III.

Relations between Secchi Disc depths D observed with a naked normal human eye and the attenuation coefficients c and K, respectively, for different daylight conditions and different observation techniques. The irradiance ratio for photopic vision at the surface $R(0-, \overline{y_\lambda})$ is assumed equal to 0.01 for all natural sea waters since $R(0-, \overline{y_\lambda})$ Sargasso ~ 0.012 and $R(0-, \overline{y_\lambda})$ Baltic ~ 0.0075 (for instance Lundgren and Højerslev, 1971; Højerslev 1974)

Case No	Remarks	(c + K) · D	D · c	D · K
1	Observations made just below the water surface	9.4	6.4	3.0
2	Observations made above the water surface; overcast	7.9	5.6	2.3
3	Observations made above the water surface; low sun or cloudy	8.8	6.05	2.75
4	Observations made above the water surface; intermediate or high sun	9.15	6.25	2.9
5	E_d, sky/E_d, sun = 1:20	9.25	6.25	3.0
6	E_d, sky/E_d, sun = 1:100	9.4	6.35	3.05
Average values		9.0	6.15	2.85

Table IV.

The depths of selected quanta levels Z_q as a function of the Secci Disc depth D for low sun or overcast. Included is the depth of the 10%-level for the downwelling lux irradiance versus D.

Assumption:

$K(\overline{y_\lambda}) = 2.3/D(\overline{y_\lambda})$ between the 100%-level and the 10%-level for the downwelling lux irradiance $\equiv E_d(\overline{y_\lambda})$.

Note: The depth of the 10%-level for $E_d(\overline{y_\lambda})$ = D.

D	Z_q m				lux
m	Z_q(30%)	Z_q(10%)	Z_q(3%)	Z_q(1%)	Z(10%)
5	1.92	3.90	6.44	8.49	5
6	2.29	4.69	7.74	10.21	6
8	3.04	6.25	10.31	13.61	8
10	3.76	7.81	12.89	17.01	10
12	4.55	9.52	15.71	20.73	12
14	5.44	11.48	18.94	25.00	14
16	6.26	13.33	21.99	29.03	16
18	7.21	15.52	25.61	33.80	18
20	8.20	17.86	29.47	38.90	20
22	9.08	20.00	33.00	43.56	22
25	10.60	23.81	39.29	51.86	25
30	13.26	30.93	51.03	67.37	30
35	16.25	39.77	65.62	86.62	35
40	19.08	49.38	81.48	107.55	40

Table V.

The depths of selected quanta levels Z_q as a function of the Secchi Disc depth D for an intermediate to a high sun and blue sky. Included is the depth of the 10%-level for the downwelling lux irradiance versus D.

Assumption:

$K(\overline{y_\lambda}) = 3/D(\overline{y_\lambda})$ between the 100%-level and the 10%-level for the downwelling lux irradiance $\equiv E_d(\overline{y_\lambda})$.

D	Z_q m				lux
m	Z_q(30%)	Z_q(10%)	Z_q(3%)	Z_q(1%)	Z(10%)
5	1.48	3.00	4.95	6.53	3.83
6	1.77	3.59	5.92	7.82	4.60
8	2.34	4.79	7.90	10.43	6.13
10	2.89	5.95	9.82	12.96	7.67
12	3.48	7.19	11.86	15.66	9.20
14	4.03	8.39	13.84	18.27	10.74
16	4.65	9.73	16.05	21.19	12.26
18	5.20	10.96	18.08	23.87	13.81
20	6.01	12.78	21.09	27.83	15.33
22	6.58	14.07	23.22	30.64	16.89
25	7.76	16.82	27.75	36.63	19.17
30	9.61	21.30	35.15	46.39	23.00
35	11.55	26.28	43.36	57.24	26.81
40	13.63	31.95	52.72	69.59	30.67
45	16.07	39.20	64.68	85.38	34.50
50	18.19	46.18	76.20	100.58	38.33

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