THE SECCHI DISK IN TURBID COASTAL WATERS[1]

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ABSTRACT

Measurements of Secchi disk depth are correlated with beam transmittance (B) in turbid coastal water. Both k (the irradiance attenuation coefficient) and α (the beam attenuance coefficient) can be estimated from the Secchi depth either on an empirical basis or by using the Duntley-Preisendorfer equation of contrast reduction. Such estimates possess relatively large standard errors of estimate.

The effects of the size of Secchi disk and viewing techniques are discussed. An estimate of contrast threshold of the human eye under field conditions has been obtained. A modification of the factor in the Poole and Atkins equation for estimating k from Secchi depth is suggested.

INTRODUCTION

The Secchi disk is perhaps one of the most widely used limnological and oceanographic "instruments," because of its low cost and convenience. Only recently, however, has the meaningfulness of data obtained with the disk, in terms of optical characteristics of water, been examined theoretically. Tyler (1968), using an equation developed by Duntley (1963),[3] showed that the sum of $(\alpha + k)$ could be estimated with a Secchi disk and that if k were measured independently by means of an irradiance meter values of α could then be estimated, provided that certain optical properties of the water, Secchi disk, and observer are known.

Tyler, after selecting reasonable values for the characteristics of disk, water, and sensitivity of the eye of an observer, examined some data obtained by Callaway and McGary (1959) on *Manning* cruise 36 to compare theory with experimental results. The results of this comparison were not completely satisfying because a number of assumptions had to be made that could not be evaluated properly; nevertheless, conditions for the use of the Secchi disk were elaborated and certain observational techniques suggested. It is one of the purposes of this communication to report the results of field observations designed to examine some of the problems raised by Tyler in his examinations of the *Manning* data.

The Duntley-Preisendorfer equation

$$C_R = C_0 e^{-(\alpha + k \cos \theta) R} \tag{1}$$

describes the attenuation of contrast of a submerged object along an inclined path of sight. C_R is the apparent contrast of an object against its background, R is the length of the path of sight in water, α and k are the attenuation coefficients for collimated and diffuse light, respectively, and C_0 is the inherent contrast of the object against its background.

When observations are made along a vertical path, equation (1) reduces to

$$C_R = C_0 e^{-(\alpha + k) R}, \tag{2}$$

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[3] According to Dr. S. Q. Duntley (personal communication) the equation referred to in his 1963 paper was the result of collaborative effort with Dr. R. W. Preisendorfer, who at the time of this collaboration was an undergraduate student working with Dr. Duntley. Dr. Duntley suggests that this equation be referred to as the Duntley-Preisendorfer equation.

which is applicable to Secchi disk observations (Tyler 1968). A value of 0.0066 was selected by Tyler as a reasonable value for C_R. This is the value for the liminal visual contrast for circular targets in air multiplied by 2 to obtain the threshold of conscious sighting. C_0 is determined from the reflectance of the Secchi disk and the reflectance ratio (r) of the water (Tyler 1968). α and k are determined from measurements with a beam transmittance or alpha (α) meter and a relative irradiance or k meter (Jerlov 1968).

METHODS

The optical instrumentation used here consisted of a relative irradiance meter (k meter) and a 1-m-path-length beam transmittance meter. In Goleta Bay, both instruments were filtered to yield a photopic response (i.e., Weston barrier layer cells with Wratten No. 102 filters). At Ellwood, the beam transmission observations were made using a Wratten No. 61 (green) filter rather than the Wratten No. 102.

The Secchi disk measurements were made following the suggestions of Tyler (1968): 1) the depth of disappearance of the disk was estimated with (and without) an immersed viewer to reduce glare and refraction effects; 2) all observations were made on the sunny side of the boat; 3) measurements were made only when the line supporting the disk was vertical.

The diameter of the Secchi disk routinely used was 12 inches (0.3 m). This diameter was selected arbitrarily for its ease of transportation and use rather than for any optical considerations. The disk was painted with flat white paint (3M brand, No. 101-A-10) having a measured reflectance when dry of 84%. When it was immersed in pure water, the reflectance increased to 93% (D. Webb, personal communication).

The Secchi disk viewer had a plate glass window of 7×9 inches (0.175×0.225 m). The interior of the viewer was painted flat black and a rubber gasket shielded the observer's eyes from ambient light.

The Goleta Bay observations were made in that portion of the bay immediately east of the Santa Barbara campus in water depths ranging from 6–22 m. A 16-ft (4.9 m) Boston Whaler was equipped with a 5-ft (1.5 m) boom for relative irradiance measurements. All measurements of relative irradiance and Secchi depths were made between 0900 and 1045 PDT. The beam transmittance measurements are averages from two or three samples collected with a plastic sampler at the surface and at or above the depth of Secchi disk disappearance. These measurements were made 1.5–3 hr after the *in situ* measurements.

The Ellwood data came from a Signal Oil Co. pier located about 8 km west of the Santa Barbara campus in water 8–10 m deep.

Relative irradiance values (downwelling and upwelling) at selected depths (generally at 1-m intervals) were obtained while the instrument was lowered and raised from the maximum depth sampled, separate observers making the measurements on each lowering and raising cycle. The irradiance attenuation coefficient (k) was calculated using natural logarithms from the average of two irradiance readings taken at the depth of Secchi disk disappearance and those obtained in air above the sea surface. The immersion effect (Smith 1969) was not noticeable below 0.5–0.75-m depth and essentially the same k value would have been obtained by using a best-fit line through all of the underwater irradiance values obtained below this.

RESULTS AND DISCUSSION

Secchi (Cialdi 1866) showed that in relatively clear water the depth of disappearance of a large diameter disk was always greater than that of a small disk (Z_{SD}, 16–40 m). A series of determinations of Z_{SD} was made at Ellwood for disks of 20-, 30-, and 51-cm diam, with and without the Secchi disk viewer, to evaluate whether this effect would be as marked in turbid water. The data together with the mean and standard deviations show that Z_{SD} does not vary significantly between the various disk diameters at the 2.0 sigma level (Table 1). These data and those from Goleta

TABLE 1. *Depth in meters (Z_{SD}) of disappearance of different diameter Secchi disks with and without an underwater viewer as recorded by two observers in three separate trials, Z_{SD} estimated to nearest 0.25 m. Ellwood pier*

		20 cm		30 cm		51 cm	
Trial	Observer	No viewer	Viewer	No viewer	Viewer	No viewer	Viewer
1	a	5.00	5.50	5.50	5.25	5.50	5.25
	b	4.75	5.00	5.25	5.50	5.00	5.25
2	a	5.00	5.25	5.00	5.25	5.25	5.25
	b	5.00	5.25	5.00	5.25	5.00	5.25
3	a	5.00	5.25	5.00	5.25	5.25	5.25
	b	4.75	5.00	5.00	5.25	5.00	5.00
Mean depth (m)		4.92	5.21	5.12	5.29	5.17	5.21
SD (σ)		0.12	0.17	0.19	0.09	0.19	0.09

Bay (Table 2) also show no significant difference in Z_{SD} with the viewer.

The failure of the viewer to affect Z_{SD} was not expected. Glare and refraction certainly effectively reduce the contrast between the disk and water, and should reduce Z_{SD} (Tyler 1968). Two phenomena may counteract this loss in contrast. Whenever the sea surface is roughened, the disk is illuminated in a pulsating light field (Tyler 1968) rather than one of constant light. This effect, coupled with the slight apparent movement of the disk associated with surface waves, may increase the visibility of the disk by effectively decreasing the threshold of conscious sighting.

It seems probable that Secchi disk diameter, at least in the range used, does not affect Z_{SD} because the Z_{SD} depths are not sufficiently great to cause the angular subtense of the disk to affect the visibility of the disk (*see* Blackwell 1946).

The possibility of estimating both α and k from Secchi disk measurements was suggested by a relationship observed at Ellwood between beam transmittance [from which α is calculated as α = ($\log_e$ 100 − $\log_e$ beam transmittance)/path length (m)] and Secchi depth (Z_{SD}) (Fig. 1), and by the intuitive feeling that at least in local inshore turbid coastal water a relationship might exist between α and k. This idea is not supported by theory (equations 1 and 2) which considers α and k as individual variables whose *sum* is inversely proportional to Z_{SD} under simplifying conditions (*see* equation 5). However, since biologists may not require the high degree of precision and accuracy required by optical oceanographers, it seemed possible that estimates of α and k useful to biologists might be obtained from Z_{SD}, theory notwithstanding. Such indirect estimates would naturally have relatively large standard errors of estimate but these might be acceptable in certain types of study.

At Ellwood (Fig. 1), beam transmittance (B) and Z_{SD} are significantly correlated ($r = 0.87$, df 79, $p \ll 0.01$), and a linear regression equation expressing this relationship was calculated for values of beam transmission greater than 5% per meter—the accuracy and precision of the alpha meter readings fall off below this value. This equation, $B = 5.3Z_{SD} - 3.4$, has a slope significantly different from zero ($t = 1.53$, df 77, $p \ll 0.01$) but as can be seen from inspection of the data (Fig. 1) the standard error of estimate is large. The considerable scatter is in part due to the inaccuracy resulting from the use of only 1–3 determinations in obtaining average beam transmission values. For Z_{SD} depths of less than 3 m, the average beam transmission was assumed to be equal to the surface value; for Z_{SD} depths of 8–10 m the beam transmission values at the surface, 3, and 5 m were averaged. In all probability a much better relationship would have appeared if more beam transmission values had been available.

This relationship led me to make a series

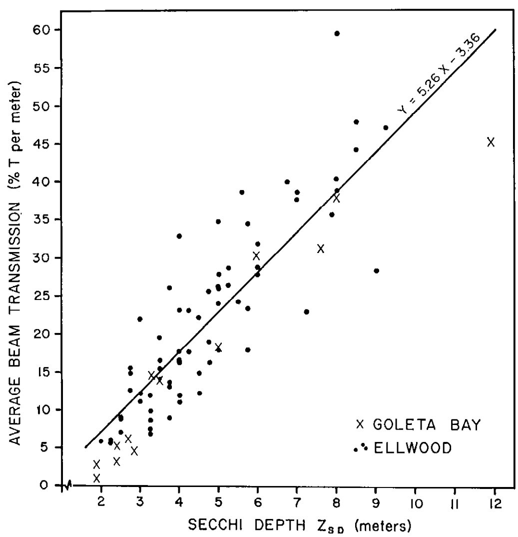

FIG. 1. The relationship between the depth of Secchi disk visibility (Z_{SD}) and average beam transmission of the water above the Secchi depth in the green region of the spectrum.

of measurements of B, k, and Z_{SD} in Goleta Bay to examine in detail empirical relationships between these quantities (Table 2).

As shown above, the Ellwood observations permit the estimation of beam transmission (B) from Z_{SD}. A modified equation based on this Ellwood regression, that is,

$$\alpha = \log_e \frac{100}{5.3 Z_{SD} - 3.4}, \qquad (3)$$

permits the estimation of α directly from Z_{SD}.

In Goleta Bay, the measured values of α and the sum $(\alpha + k)$ are highly correlated ($r = 0.99$, df 12, $p \ll 0.01$) and the regression

$$\alpha = 0.88(\alpha + k) - 0.10 \qquad (4)$$

can be used to estimate k once α has been measured directly or estimated via Z_{SD}. Equation (4) has a slope significantly different from zero ($t = 88.6$, df 11, $p \ll 0.001$). The adequacy with which both α and k can be estimated empirically from Z_{SD} can be judged by examining Fig. 2. In Fig. 2A the measured value of α has been plotted (on the ordinate) against the estimated

TABLE 2. *Summary of Goleta Bay data*

Date (1969)	Time (PDT)	Weather	Irradiance attenuation coefficient (k)	Beam transmittance (B)	Beam transmittance coefficient (α)	Reflectance ratio for the water (r)	Secchi depth (Z_{SD}) No viewer	Viewer	$(\alpha + k) Z_{SD}$	C_0	C_B
26 Apr	0920	Clear, slight swell	0.587	2.75	3.59	—	1.9	1.9	7.91	—	—
26 Apr	1000	Clear, slight swell	0.289	17.8	1.73	—	5.0	5.0	10.1	—	—
3 May	0920	Slight haze, surface ripple	0.536	4.55	3.09	—	2.75	2.83	10.3	—	—
3 May	1000	Overcast, slight sea	0.683	3.25	3.43	—	2.04	2.39	9.83	—	—
10 May	0920	Hazy, slight sea and swell	0.183	45.2	0.790	—	12.2	11.9	11.6	—	—
10 May	1000	Slight haze, calm	0.332	30.3	1.19	—	5.5	5.95	9.06	—	—
24 May	0900	Clear, calm	0.669	1.0	4.61	0.095	2.0	1.9	10.0	8.79	0.00039
2 Jul	0900	Clear, surface ripple	0.398	14.0	1.96	0.059	3.3	3.5	8.25	14.8	0.0038
2 Jul	1000	Overcast, surface ripple	0.481	6.2	1.79	0.095	2.5	2.7	8.83	8.79	0.0013
8 Jul	0930	Overcast, slight swell	0.289	37.9	0.970	—	7.7	8.0	10.1	—	—
8 Jul	1030	Slight haze, calm	0.565	5.2	1.95	0.086	2.0	2.4	8.4	9.81	0.0018
16 Jul	0905	Clear, surface ripple	0.223	31.3	1.16	0.072	7.4	7.6	10.5	11.9	0.00032
16 Jul	1000	Clear, calm	0.368	14.6	1.92	0.071	3.2	3.3	7.55	12.1	0.00063
		Mean	0.431		2.32	0.080	4.42	4.57	9.42	11.03	0.00139
		SD (σ)	0.161		1.13	0.013	2.97	2.91	1.13	2.24	0.00132

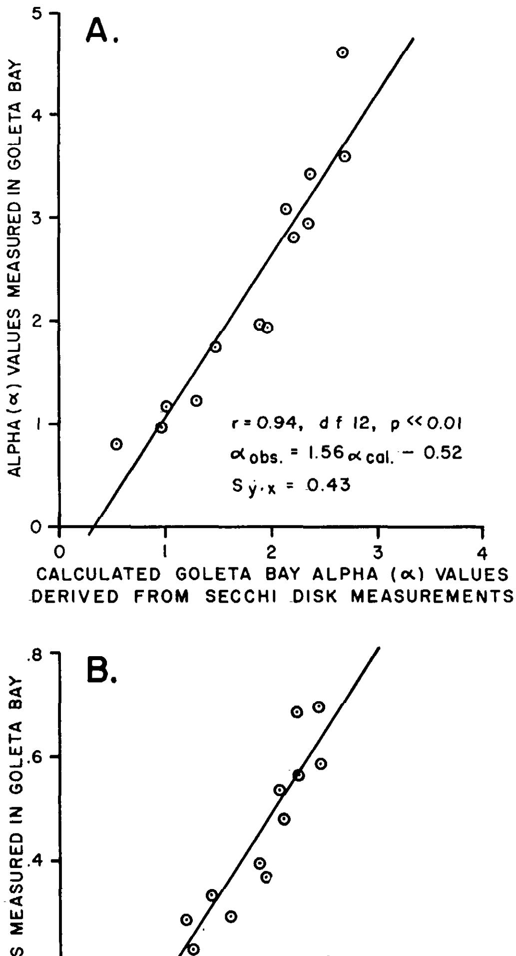

FIG. 2. A. The relationship between the beam transmittance coefficients (α) observed at Goleta Bay and those calculated for Goleta Bay using the Ellwood regression with Goleta Bay Z_{SD} values. B. The relationship between observed attenuation coefficients (k) at Goleta Bay and those calculated for Goleta Bay.

value (on the abscissa), obtained from Secchi measurements via equation (3). In Fig. 2B observed and calculated values of k are presented in similar fashion together with some statistical information concerning the relationship. The estimated k values were calculated from equation (4) using the α values from equation (3). The scatter about both regression lines is moderate and in certain kinds of studies such errors may be acceptable.

The Duntley-Preisendorfer equation can be rewritten as follows:

$$Z_{SD}(\alpha + k) = 2.3 \log_{10}(C_0/C_R). \quad (5)$$

Values of C_0 can be calculated for 6 Goleta Bay stations (Table 2). This quantity together with the measured values of Z_{SD}, k, and α permit the calculation of C_R, the sensitivity of the eye of the observer. A mean value of 0.0014 was obtained at these stations, with an SD of 0.0013 (Table 2). As far as I can determine this is the first field estimation of this value obtained with untrained observers (cf. Blackwell 1946). This value is reasonable in view of Blackwell's (1946) results, although it is greater (i.e., a less sensitive observer) than the value selected by Tyler (1968). The very large standard deviation associated with this mean value is not unexpected, since the nature of the Duntley-Preisendorfer equation is such that C_R is extremely sensitive to variations in C_0, α, and k.

At these 6 stations, the mean value for the ratio $2.3 \log_{10}(C_0 : C_R)$ equals 8.9 and was calculated using the mean values of C_0 and C_R at the 7 stations. This value is not too different from the mean value of 9.4 of the product $Z_{SD}(\alpha + k)$ obtained at all 13 Goleta Bay stations (Table 2) and is an independent confirmation of the validity of the Duntley-Preisendorfer equation.

By using 8.9 as the best estimate of $2.3 \log_{10}(C_0 : C_R)$ we can calculate the sum $(\alpha + k)$ from Z_{SD} at each of the 13 Goleta Bay stations. A highly significant correlation ($r = 0.97$, df 12, $p \ll 0.01$) exists between the values of $(\alpha + k)$ calculated in this manner and those actually measured in Goleta Bay (*see also* Tyler 1968). From this calculated sum α can be calculated via equation (4), and k is next determined from the difference between $(\alpha + k)$ and α. A comparison of the calculated values of α and k with those measured in Goleta Bay is presented in Fig. 3; since 6 sets of

TABLE 3. *Calculated values of* kZ_{SD}, *the depth to which 1% of the ambient visible radiation reaches, and the factor relating the 1% depth to* Z_{SD} *in the Goleta Bay data*

k	Z_{SD}	kZ_{SD}	% surface irradiance at Z_{SD}	1% irrad.* depth (m)	1% depth Z_{SD}
0.587	1.9	1.115	32.1	7.84	4.1
0.289	5.0	1.445	22.6	15.92	3.2
0.536	2.83	1.517	23.6	8.58	3.0
0.683	2.39	1.632	21.2	6.74	2.8
0.183	11.9	2.178	10.9	25.2	2.1
0.332	5.95	1.975	19.8	13.86	2.3
0.669	1.9	1.271	27.2	6.88	3.6
0.398	3.5	1.393	25.7	11.6	3.3
0.481	2.7	1.300	27.6	9.56	3.5
0.289	8.0	2.312	11.7	15.9	2.0
0.565	2.4	1.356	23.6	8.14	3.4
0.223	7.6	1.695	19.2	20.6	2.7
0.368	3.3	1.214	29.0	12.5	3.8
	Mean	1.57			3.06
	Median	1.44			3.2

* Calculated as follows: $1/k^{(2.3)(2)}$.

α and k values were used in the calculation of C_R, I have indicated on the graph those values used.

The standard deviations (i.e., S_{yx} of α and k) in the latter regressions (Fig. 3) are comparable with those obtained using the empirical method (Fig. 2). Both methods yield moderate standard errors. Such errors may be acceptable to investigators wishing to make rough estimates of visibility, α, or k.

Some of the results of the Goleta Bay investigation were applied to the data obtained at Ellwood. A value of 9.4 was used for the constant value of the product $Z_{SD}(\alpha + k)$, which was then divided by measured values of Z_{SD} to calculate corresponding values of $(\alpha + k)$. Equation (4) then was used to estimate α, and these estimates correlated significantly with the measurements of α ($r = 0.89$, df 77, $p \ll 0.001$). For Secchi depths of 4–12 m, this process yields α values close to those of equation (3), which was derived from the original Ellwood regression.

The Goleta Bay data suggest that the Poole and Atkins (1929) formula for estimating k from Z_{SD} ($k = 1.7/Z_{SD}$) yields k values that are too high, at least in turbid water. The product of kZ_{SD} for Goleta Bay (Table 3) yields a mean value of 1.57. Because of two rather high values of the product a better estimate of central tendency is the median. This has a value

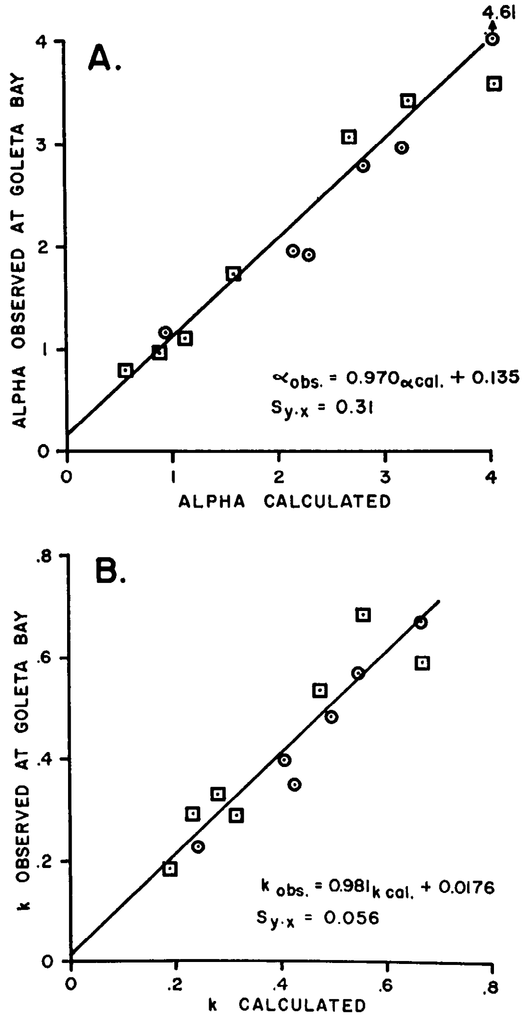

FIG. 3. The relationship between calculated and observed beam transmittance coefficients (α) and calculated and observed irradiance coefficients (k) in Goleta Bay. A. The calculated values of α obtained with the Duntley-Preisendorfer equation using mean values for C_0 and C_R from 6 stations obtained in Goleta Bay. B. The calculated values of k obtained by the difference between $(\alpha + k)$ and α (*see text*). Values on graph in circles were used in the calculation of 2.3 $\log_{10}$ $(C_0 : C_R)$.

of 1.44 (Table 3). Thus, in turbid water 1.44 is probably a more appropriate factor than 1.7 in estimating k from Z_{SD}. If equation (4) is used to derive a formula for k from the sum $(\alpha + k)$ computed from $9.4/Z_{SD}$, the result is $k = (1.13/Z_{SD}) + 0.10$, which seems to describe the observations even better.

It is common practice for primary productivity workers to estimate the depth of the euphotic zone, that is, the depth reached by 1% of the ambient radiant energy, by multiplying Z_{SD} by 3. As can be seen in the last column of Table 3 the mean of the factor relating Z_{SD} with the 1% depth is close to 3. It is also true in Goleta Bay that this factor is negatively correlated with Z_{SD} ($r = -0.795$, df 12, $p \ll 0.01$). These data suggest that a factor of something like 3.5 might be most appropriate in water with a Z_{SD} of less than 5 m and a factor of the order of 2.0 for water with a Z_{SD} between 5 and 12 m. It is quite possible that this relationship is fortuitous, since no explanation of the relationship is apparent. Further study is warranted with a wider range of Z_{SD} values than was available for this study.

SUMMARY

1. A statistically significant relationship between the Secchi depth (Z_{SD}) and beam transmittance (B) in the green region of the spectrum exists in a turbid inshore marine region.

2. In water with a Z_{SD} of about 5.1 m, no significant difference in Z_{SD} was noted with disks of 20-, 30-, or 51-cm diam. Furthermore, the use of a viewer placed immediately below the sea surface did not increase Z_{SD} significantly.

3. Alpha and k can be estimated from Z_{SD} either in a completely empirical manner or by combining the Duntley-Preisendorfer equation with regressions obtained in this investigation. A value of 0.0014 ± 0.0013 for C_R was obtained. These methods yield values of α and k that have moderately large standard errors but may be acceptable in certain kinds of work.

4. A value of 1.44 is suggested as a suitable substitute for the 1.7 proposed by Poole and Atkins for determining k from Z_{SD} in turbid water.

5. The relationship between Z_{SD} and the 1% optical depth merits additional study.

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