Secchi Disk Measurements in Turbid Water

Bowers, D. G.; Roberts, E. Martyn; Hoguane, A. M.; Fall, K. A.; Massey, G. M.; Friedrichs, C. T.

Journal of Geophysical Research: Oceans

Cyswllt i'r cyhoeddiad / Link to publication

30. Apr. 2024

JGR Oceans

Correspondence to:
D. G. Bowers,
d.g.bowers@bangor.ac.uk

Secchi Disk Measurements in Turbid Water

D. G. Bowers[1] , E. M. Roberts[1,2] , A. M. Hoguane[3] , K. A. Fall[4,5], G. M. Massey[4], and C. T. Friedrichs[4]

[1]School of Ocean Sciences, Bangor University, Bangor, UK, [2]Department of Biological Sciences and K.G. Jebsen Centre for Deep Sea Research, University of Bergen, Bergen, Norway, [3]Centre for Marine Research and Technology-CePTMar, Eduardo Mondlane University, Maputo, Mozambique, [4]Virginia Institute of Marine Science, William & Mary, Gloucester Point, VA, USA, [5]US Army Engineer Research and Development Center, Vicksburg, MS, USA

Abstract In the classical theory of the Secchi disk depth, diffuse sunlight falling on the disk is reflected back to the observer's eye along the most direct route, as a beam. The disappearance depth, Z_{SD}, of the disk is then expected to vary inversely with the sum of the beam and diffuse attenuation coefficients: $c + K_D$. Observations presented here show that, in the most turbid waters sampled, the Secchi disk is visible at greater depths (by a factor of up to 4) than predicted by this theory. In these conditions, the disk appears blurry, and it seems likely that some of the light reflected by the disk returns to the eye as diffuse light, photons being scattered one or more times on their journey from the disk surface to the observer. We have modified the theory of the Secchi disk in turbid water to allow for a mixture of beamed and diffuse light contributing to disk visibility. The modified theory corrects the under-estimate of Secchi depths in turbid waters and gives good agreement with observations over a wide range of turbidity. The insight gained allows a more informed interpretation of Secchi disk measurements in turbid water.

1. Introduction

Despite caveats about what it actually measures, the Secchi disk continues to be widely used to give a quick and simple estimate of water clarity. The attraction of a Secchi disk measurement lies in the robustness and ease of use of the equipment. A white (or black and white) disk with a diameter of ~20–30 cm is lowered on a marked line until it is no longer visible and the disappearance depth (the Secchi depth) is noted (Tyler, 1968). The measurement lends itself particularly well to citizen science programs (Busch et al., 2016; Garcia-Soto et al., 2017) which create extensive data sets at low cost. There is also a large archive of Secchi disk measurements, including some time series stretching back several decades, unmatched by other types of water quality data (Gallegos et al., 2011; Kratzer et al., 2003; Sanden & Hakansson, 1996; Wernand, 2011).

The difficulty in interpreting Secchi disk measurements lies in the fact that the disappearance depth depends on two different measures of optical attenuation. Sunlight travels down to the disk as diffuse light. Photons follow a zig-zag path and are attenuated with depth as a function of the diffuse attenuation coefficient K_D (the e-folding length over which irradiance decays with depth; photons are only removed by absorption but scattering increases the path length and so the chance of absorption). Light reflected from the disk travels back to the eye along the shortest route as a straight line, and its passage depends on the beam attenuation coefficient c (the e-folding length for radiance; photons are removed from the beam by both scattering and absorption). The classical theory of the Secchi disk (Duntley & Preisendorfer, 1952; Holmes, 1970; Preisendorfer, 1986; Tyler, 1968; see also the next section of this paper) tells us that the Secchi depth, Z_{SD}, varies inversely as the sum ($c + K_D$) of these two measures of attenuation. That is,

$$Z_{SD} = \gamma/(c + K_D), \tag{1}$$

in which γ is a constant whose value depends on the reflectivity of the disk and the surrounding water as well as the sensitivity of the human eye to contrast (Tyler, 1968). A value of γ about 8 or 9 is commonly used. An alternative theory (Lee et al., 2015) of the Secchi disk has also been proposed. In this paper we will use the classical theory represented by equation (1) but comment on the relevance of the Lee theory in the discussion.

The idea that the light from the disk travels to the eye in a straight line as a beam does not sit comfortably with what we actually see when making Secchi depth measurements in a very turbid estuary. The disk is
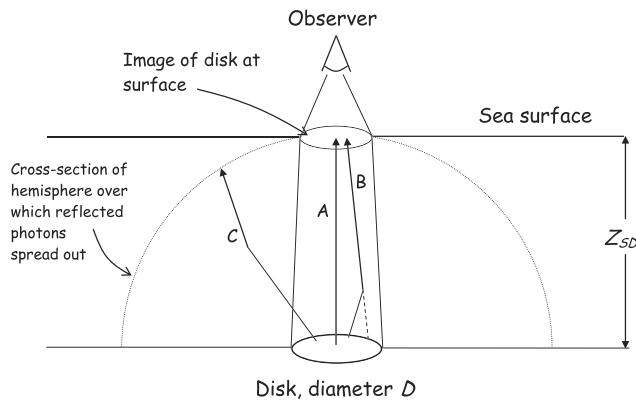
Figure 1. Viewing a Secchi disk in turbid water. Photons reflected by the disk spread out over the surface of a hemisphere. Some travel directly from the disk to the eye following a track such as that labeled A. Others are scattered and follow the indirect track labeled B, appearing at the surface against the background of the disk. Scattered photons contribute to the diffuse light from the disk; they do not preserve any pattern on the disk surface and make the disk look blurry. Most photons follow a track such as C and do not contribute to the disk visibility.

not sharply defined but appears rather blurry, as though at least some of the reflected light traveling to the eye is diffuse. Some of the light reflected by the disk, and traveling initially in a direction away from the observer, may be scattered toward the eye (Figure 1, track B). Because this scattered light appears to come from a different part of the disk to that from which it actually originates, it does not faithfully transmit the image of the disk. Instead, it makes the disk appear blurred. This diffuse light does, however, contribute to the brightness of the disk as viewed at the surface and so enhances disk visibility. In these circumstances, we may anticipate that equation (1)—which takes into account only the direct beam—will underestimate the visibility of the disk.

There is some early experimental evidence to suggest that the classical theory of the Secchi disk fails in turbid water. In experiments of disk visibility in water tanks with different concentrations of suspended solids, Timofeeva (1963) found that equation (1) underestimated the Secchi depth in the most turbid conditions. Our aim in this paper is to examine an extensive field data set of Secchi disk observations to see if an adjustment to theory is necessary in naturally turbid water and, if so, the form it should take. The practical benefit of this work is that it will allow for a better informed interpretation of the many measurements of Secchi depth that have been made, and continue to be made, in turbid fresh, estuarine, and coastal water.

2. Theory

The classical theory of the Secchi disk uses the concept of *contrast* between the submerged disk and the surrounding water. Contrast, β, can be defined as

$$\beta = (L_D - L_B)/L_B \tag{2}$$

where L_D is the radiance from the disk and L_B the radiance from the background water. The disk disappears when the contrast falls to a critical value, β_C: at this point, the eye can no longer distinguish between the disk and its background.

The solar irradiance falling on the disk is $E_0 \exp(-K_D z)$ where z is the disk depth, E_0 is the solar irradiance at the sea surface, and K_D is the diffuse attenuation coefficient. In what follows, the water is considered to be optically homogenous between the disk and the surface, so that K_D and all other optical properties are constant. The radiance reflected by the disk vertically upward (at the disk depth) is $L_D = (r_D E_0/\pi) \exp(-K_D z)$ where r_D is the reflection coefficient of the disk. The factor π in this expression comes from the assumption that the reflected photons are distributed uniformly at all angles over the upper hemisphere. The upwelling radiance is then $1/\pi$ times the reflected irradiance, since there are π steradians in a hemisphere (Kirk, 1994). Similarly, the radiance traveling vertically upward from the water surrounding the disk is $L_B = (r_W E_0/\pi) \exp(-K_D z)$ (again at the disk depth) where r_W is the irradiance reflectance of the water body. Substituting these values into equation (2) and canceling the factor $(E_0/\pi)\exp(-K_D z)$ which occurs in every term give

$$\beta = (r_D - r_W)/r_W$$

a quantity known as the *inherent* contrast of the disk. For typical values of $r_D = 0.8$ and $r_W = 0.02$, the inherent contrast will be of order 40 (we note here that the analysis will be somewhat different for a black and white disk, in which the contrast will depend more on the difference between the black and white parts of the disk than on that between the white disk and the water. If the reflection coefficient of the black part of the disk is less than the surrounding water, the inherent contrast of a black and white disk will be greater than an entirely white disk).

As the radiances from the disk and the surrounding water propagate vertically upward as beams of light toward the eye, they are both attenuated. In this case, photons scattered out of or absorbed in the beam

do not make it to a point on the surface in line between the disk and the eye, and the radiance reaching this point is attenuated by a factor $\exp(-cz)$ where c is the beam attenuation coefficient. Light is added to the beams from the disk and its surroundings by backscattering in the water, but, since this happens equally to both beams, the difference in radiance $(L_D - L_B)$ is not affected by the added light. At the surface the difference is

$$L_D - L_B = r_D(E_0/\pi)\exp(-K_Dz)\exp(-cz) - r_W(E_0/\pi)\exp(-K_Dz)\exp(-cz) \quad (3)$$

The contrast between the disk and its surrounding water, when viewed from above the sea surface (and ignoring sun- and sky-light reflected at the surface), is this difference in radiance divided by the background radiance at the surface, namely,

$$\beta = (r_D(E_0/\pi)\exp(-K_Dz)\exp(-cz) - r_W(E_0/\pi)\exp(-K_Dz)\exp(-cz))/(r_WE_0/\pi) = \exp(-(K_D+c)z)(r_D - r_W)/r_W$$

This quantity is known as the *apparent* contrast of the disk. When the disk is at the disappearance depth, the apparent contrast is equal to the critical contrast β_C and so, at the Secchi depth:

$$\exp(-(K_D+c)Z_{SD})(r_D - r_W) = r_W\beta_C \quad (4)$$

from which equation (1) follows:, in which $\gamma = -\log(r_W\beta_C/(r_D - r_W))$. This is the classical solution for the Secchi disk depth. With values of $r_W = 0.02$, $r_D = 0.82$, and $\beta_C = 0.0066$ (Tyler, 1968), $\gamma = 8.7$.

Photons reflected by the disk will spread out over the surface of a hemisphere centered on the disk (Figure 1). A small proportion of these photons will be reflected directly toward the eye, following a path such as that labeled A in the figure. These are the photons that are considered in the classical theory of the Secchi disk depth described above. Most of the reflected photons leave the disk in a direction away from the eye and follow a path such as that labeled C in Figure 1. These photons never make it to the observer, and we do not need to consider them any further. There is a third category of photon, however, which leaves the disk initially in a direction away from the eye but is then scattered one or more times so as to arrive at the surface within the circular image of the disk at the surface. We have labeled one possibility for this path as B in Figure 1. The photons in this category will travel to the surface as diffuse light: their path length will be increased by scattering, and they will be attenuated by a factor $\exp(-K_Dz)$ in traveling to the surface from a disk at depth z.

If photons are reflected by the disk equally in all directions, the proportion of reflected diffuse light that reaches the surface within the circular image of the disk at the surface (assumed to have the same diameter, D, as the disk) is the area of a circle of diameter D divided by the surface area of a hemisphere of radius z, namely, $(1/8)(D/z)^2$. The reflected irradiance reaching the surface within the image of the disk is then $(1/8)(D/z)^2r_DE_0\exp(-2K_Dz)$ (allowing for diffuse attenuation of irradiance traveling down to the disk and then back to the surface). We can divide this by π to give the contribution the reflected irradiance makes to the radiance from the disk. We can note here that this extra radiance decreases as the square of the disk depth and so is only important at small Secchi depths. The diameter of the disk image at the surface will also decrease as the disk depth increases and further reduce the importance of the diffuse light component. At values of $D/z < <1$ we would expect the classical theory to hold without any need to include the diffuse light component.

To be exact, we should subtract the photons in the direct beam from the reflected irradiance since these have already been counted, but the error in not doing so is a small one. The proportion of reflected irradiance that leaves the disk in the cone traveling directly toward the eye is of order $(1/8)(D/z)^2$ which, for $z/D > 3.6$, is less than 1% and counting the photons in this cone twice makes a negligible difference for Secchi depths greater than about 1 m. In addition, light in the direct beam is scattered on its way to the surface and becomes part of the diffuse light field; this effect becomes greater at small Secchi depths when the water is a more scattering medium. For Secchi depth less than 1 m, with likely beam attenuation and scattering coefficients greater than 10 m^{-1}, fewer than 0.01% of photons will travel from the disk to the surface without being scattered. The rest will be scattered at some point between the disk and the surface and will join the diffuse light traveling upward from the disk.

Allowing for the extra radiance at the surface contributed by the diffuse light traveling upward from the disk, equation (3) becomes

$$L_D - L_B = r_D(E_0/\pi)\exp(-K_Dz)\exp(-cz) + (1/8)(D/z)^2 r_D(E_0/\pi)\exp(-2K_Dz) - r_W(E_0/\pi)\exp(-K_Dz)\exp(-cz)$$
(5a)

And the apparent contrast is

$$\beta = (r_D(E_0/\pi)\exp(-K_Dz)\exp(-cz) + (1/8)(D/z)^2 r_D(E_0/\pi)\exp(-2K_Dz) - r_W(E_0/\pi)\exp(-K_Dz)\exp(-cz))/(r_WE_0/\pi)$$
(5b)

Again equating this to the critical contrast, such that $\beta = \beta_C$ when $z = Z_{SD}$ gives, after some re-arrangement:

$$(r_D - r_W)\exp(-(K_D + c)Z_{SD}) + (1/8)r_D(D/Z_{SD})^2\exp(-2K_DZ_{SD}) = r_W\beta_C$$
(5c)

If the disk reflectance is much greater than the water reflectance ($r_D >> r_W$), we get the following expression for the Secchi depth:

$$\exp(-(K_D + c)Z_{SD}) + (1/8)(D/Z_{SD})^2\exp(-2K_DZ_{SD}) = (r_W/r_D)\beta_C$$
(5d)

In the limit of the Secchi depth being much greater than the disk diameter $(D/Z_{SD}) << 1$ (and assuming $r_D >> r_W$), this equation becomes the same as equation (4) and leads to the classical solution to the Secchi depth problem. Retaining the contribution of diffuse light (the second term on the left of equation (5d), which will always be positive), we can see that $\exp(-(K_D + c)Z_{SD})$ must be smaller than the classical value, since the term on the right is a constant. In other words, the modified Secchi depth is somewhat greater than the value given by equation (1).

There is no simple analytical solution to equation (5d) which gives the Secchi depth in terms of the diffuse and beam attenuation coefficients, but a numerical solution (for given values of K_D and c) is easily obtained. The value of the left-hand side of this equation decreases monotonically as Z_{SD} increases. Starting with a small value of the Secchi depth, Z_{SD} can be increased in increments until the left-hand side falls to the value on the right-hand side of the equation. This gives the adjusted value of the Secchi depth including the effect of the reflected diffuse light on disk visibility.

3. Observations

To test the ideas of the last section, optical data were obtained from three sites, on three different continents. The Irish Sea is a relatively low turbidity, tidally energetic shelf sea (Krivtsov et al., 2008), located between the islands of Ireland and Great Britain in north-west Europe. The York River is a partly mixed, moderately turbid, estuary in the state of Virginia in the United States (Friedrichs, 2009). The Bons Sinais is a very turbid estuary in Mozambique in south-east Africa (Timba et al., 2014).

3.1. Methods

Secchi disk measurements were made with a 30 cm matt white disk in the Irish Sea and a 20 cm diameter quartered black and white disk in both the York and Bons Sinais estuaries (see Åberg & Rhode, 1942, for a discussion of the benefit of black and white, rather than white disks, in turbid water). Diffuse attenuation coefficients were calculated from radiometer profiles as the vertical gradient of the natural logarithm of downwelling broad-band (400–700 nm) irradiance. In the Irish Sea and York River, the underwater irradiance was scaled by the above-water irradiance to allow for the effects of changing light conditions during the profile. No surface irradiance measurements were available in the Bons Sinais, but surface light conditions were steady during this survey, and measurements were completed quickly. The water was so turbid in the Bons Sinais that obtaining a profile of downwelling irradiance against depth was impossible. Instead, the diffuse attenuation coefficient was determined by just two measurements of irradiance: one as close to the surface as possible and a second at a short distance (typically 20 cm) below the surface. The

Table 1

Summary of Observations

	Irish Sea	York River	Bons Sinais
No. of stations	174	66	6
K_D (m^{-1})			
Minimum	0.06	0.94	9.20
Maximum	1.19	7.06	20.30
Mean	0.40	2.52	15.40
c (m^{-1})			
Minimum	0.42	3.17	n/a
Maximum	8.9	77.20	n/a
Mean	1.74	17.79	n/a
Secchi depth (m)			
Minimum	1.0	0.30	0.15
Maximum	15.0	1.50	0.30
Mean	5.7	0.70	0.20
TSS (mg·L^{-1})			
Minimum	1.60	10.63	200
Maximum	20.38	94.40	350
Mean	15.94	34.24	208

diffuse attenuation coefficient was calculated (using the Lambert-Beer Law) from these two irradiance measurements and the known depth interval between them.

In the Irish Sea, beam attenuation was measured by a transmissometer on the ship's CTD (a SeaTech T1000 transmissometer operating at 660 nm with a 20 cm path length). The CTD was not deployed at all optical stations, and, where beam attenuation was not available, we have calculated scattering and absorption coefficients from the radiometer measurements of reflectance and diffuse attenuation using the results of Monte Carlo models of the underwater light field (Kirk, 1994). The method is identical to that described in Binding et al. (2005). Beam attenuation was then set as the sum of absorption and scattering coefficients at 670 nm. In the York River estuary, beam attenuation was measured using a Laser In-Situ Scattering and Transmissometry instrument Type C (LISST-100X, Sequioa Scientific, WA, USA). Immediately following the collection of Secchi depths and irradiance profiles, the LISST was lowered to a depth of 1–2 m below the surface, and beam attenuation at 670 nm was measured over a 5 cm path length. No beam attenuation measurements were made in the Bons Sinais.

Note that in both the York River and the Irish Sea, the parameters used to calculate the Secchi depth are the diffuse attenuation coefficient averaged over the visible spectrum and the beam attenuation coefficient *at a specific wavelength* in the red part of the spectrum. As the turbidity increases above moderate levels, however, c will become dominated by scattering and will become only weakly dependent on wavelength (Kirk, 1994).

Total suspended solids concentration (TSS) was measured at all stations by collecting near-surface water samples and filtering through pre-weighed GF/F filters. After rinsing in distilled water to remove crystallized salt (Stavn et al., 2009), the filters were then weighed in the laboratory: the increase in weight divided by the volume of water sampled gives TSS in mg·L^{-1}.

The results of the surveys are summarized in Table 1. In terms of the diffuse attenuation coefficient K_D, mean light extinction is about six times greater in the York River than it is in the Irish Sea and a further six times greater in the Bons Sinais than in the York.

3.2. Comparison Between Observed and Theoretical Secchi Depth

We have plotted (Figure 2) the observed Secchi depth in the Irish Sea and York River against the sum of beam and diffuse attenuation coefficients ($c + K_D$) (the Bons Sinais has been omitted from this figure because there are no direct measurements of beam attenuation). With the log-log axes employed in this figure, the classical solution represented by equation (1) predicts that the points should lie along a straight line and we have plotted this line (using $\gamma = 8.7$) on Figure 2. The agreement between the observations and the classical solution is good in the range of Secchi depths between 10 and 1 m, but for Secchi depths less than 1 m, the observations depart from the classical solution in the sense that the Secchi depths are, for the most part, greater than that predicted by equation (1). At the extreme, the prediction underestimates the Secchi depth by a factor of about 4.

There is a cluster of points indicated on Figure 2 in which the observed Secchi depth is less than 1.5 m and for which the observed depth is *less* than the predicted value. These points (six of them) are all from the same survey—an anchor station on the York River on 13 April 2016—and we have no explanation as to why they should be anomalous. The boat was anchored for the observations which could have made difficulty measuring the Secchi depth if the current was strong but that was not the case on this occasion and there were other anchor stations in the data set. It is also not apparent that there was anything special about the particles on this occasion. Chlorophyll concentrations were higher than average, but not exceptionally so and not the highest levels in the record.

There is only one adjustable parameter in equation (1), namely, the factor γ in the numerator. This factor depends, in turn, on the sensitivity of the human eye to contrast and the reflection coefficients of the disk
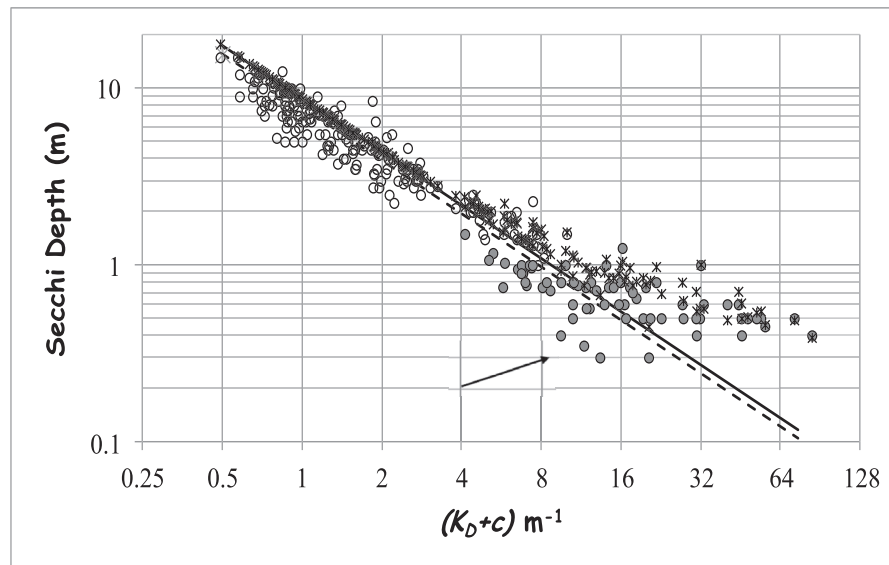
Figure 2. Secchi depth plotted against the sum ($K_D + c$) of the diffuse and beam attenuation coefficients. The straight lines show the relationship expected from the classical theory, equation (1), for two values of γ (8.7 continuous line and 7.8 dashed line). Open circles are observations in the Irish Sea and gray-filled circles in the York River. These depart from the theoretical line at Secchi depths less than about 1 m. Asterisks show the predictions of the modified theory, represented by equation (5) in the text. There is a group of points indicated by an arrow in which the observed Secchi depth is less than that predicted. These points are all from the same cruise in the York in April 2013 and are commented on in the text.

and of the water. We can see no reason why the sensitivity of the eye or the reflection coefficient of the disk will be different in very turbid water. The reflection coefficient of the water itself, however, may increase because the high concentration of suspended matter scatters light. Tyler (1968) obtained $\gamma = 8.7$ using a value of water reflectance of 2%, a reasonable figure for open waters, but a value likely to be an underestimate in particle-rich estuary waters. Repeating Tyler's calculation with a water reflectance of 5% reduces γ to 7.8. This relatively small change is because γ depends on the logarithm of the reflectance. Changing γ to 7.8 produces a marginal shift in the theoretical line on Figure 2 and cannot explain the departure of the observations from the theory at low Secchi depth. The upper reaches of an estuary such as the York River will contain high levels of dissolved colored material (CDOM) introduced by the freshwater flow into the estuary. CDOM absorbs light strongly in the blue part of the spectrum (Bricaud et al., 1981), and its effect on beam attenuation will be largely missed by a transmissometer operating in the red. In these waters, it is likely therefore that the measurements of beam attenuation are an underestimate of the spectrally averaged value. Since the theoretical value of the Secchi depth depends inversely on beam attenuation, this means that the predicted Secchi depth will tend to be an overestimate of the observed value. We observe Secchi depths in the most turbid waters which are greater than those predicted by theory and the presence of CDOM cannot account for that.

The modified theory represented by equation (5) can be used to calculate the Secchi depth if the beam attenuation, diffuse attenuation coefficient, and Secchi disk diameter are known. The solution, for a given disk size, no longer depends uniquely on the sum ($K_D + c$) but also depends on the value of K_D at the location. We have added the predictions of equation (5) as points marked with an asterisk to Figure 2. The solution is very similar to that of the classical theory for Secchi depths greater than about 1 m, but at lower Secchi depths the modified theory departs from the classical theory and successfully captures the behavior of the observations.

3.3. Secchi Depths and Water Clarity

One of the principal uses of the Secchi disk is to provide an estimate of the transparency of the sea to sunlight. As the Secchi depth decreases, the diffuse attenuation coefficient increases, and this inverse

relationship constrains the value of the product $K_D Z_{SD}$. A constant value of this product, typically in the range 1.4–1.5 (Kirk, 1994), is often used to make a rough estimate of the diffuse attenuation coefficient from Secchi depth measurements.

We can, in general, express attenuation coefficients (and hence the predicted Secchi depth) as theoretical functions of the suspended solids concentration if c and K_D are written in suitable form. We can write:

$$c = a + b = (a_W + a^*TSS) + b^*TSS \tag{6}$$

$$K_D = a/\mu = (a_W + a^*TSS)/\mu \tag{7}$$

in which a_W is the absorption coefficient of water without suspended solids, a^* and b^* are, respectively, absorption and scattering by unit concentration of suspended solids, and μ is the mean cosine of the angle the diffuse photons make with the vertical. We could add a component of absorption due to CDOM and chlorophyll to these equations if necessary, but in the first-order solution that follows we ignore these in comparison to absorption by TSS. We also note that the specific optical properties of particles may vary with their origin and type (Bowers et al., 2014). Proceeding with a first-order calculation, the absorption coefficient of pure water varies from 0.02 m^{-1} in the blue part of the spectrum to 0.50 m^{-1} in the red (Morel & Prieur, 1977); we use a representative value of $a_W = 0.2$ m^{-1} in the calculations that follow. Bowers and Binding (2006) showed that, for mineral particles, a^* typically varies with wavelength from about 0.02 to 0.06 m$^2 \cdot$g^{-1}, and we have used $a^* = 0.04$ m$^2 \cdot$g^{-1} to represent a spectral mean figure. The specific scattering coefficient was set to $b^* = 0.4$ m$^2 \cdot$g^{-1} following Bowers and Binding (2006). In turbid water, in which irradiance can be expected to be almost totally diffuse, the mean cosine μ of the downward-traveling photons will have a value close to 0.7 (Kirk, 1994), and this was the figure we used. We assume that the values of a^* and b^* do not vary strongly as a function of TSS composition among the samples used in this study. This is a reasonable first approximation given that the general form of the solution which follows is not sensitive to the exact values of these parameters.

Figure 3 shows the expected variation of the product $K_D Z_{SD}$ with TSS for the classical theory of the Secchi depth (equation (1)). It follows from equation (1) that the product $K_D Z_{SD}$ depends inversely on the ratio c/K_D of beam to diffuse attenuation coefficients. As the suspended solids load increases, scattering of light becomes more important, and the ratio c/K_D increases. Accordingly, classical theory predicts that $K_D Z_{SD}$ decreases monotonically with the TSS concentration as shown by the continuous line in Figure 3. In the case of the modified theory (equation (5)), the Secchi depth increases above the classical value at high suspended solids load, and $K_D Z_{SD}$ plotted against TSS becomes a U-shaped curve. The curves for two commonly used Secchi disk diameters, 20 and 30 cm, have been added to Figure 3. The product $K_D Z_{SD}$ is greater for the larger disk because this reflects more diffuse light back to the surface.

We have also plotted on Figure 3 the observed values of the product $K_D Z_{SD}$, now including the data in the Bons Sinais estuary in Mozambique for which observations of Secchi depth, K_D, and TSS are available. The observations follow all three theoretical curves up to a suspended load of between 10 and 20 mg·L^{-1}, but at higher turbidity the observed value of the product increases, as predicted by the modified theory. There is a broad minimum value of $K_D Z_{SD}$ in the range 1–2 in the midrange of turbidity (i.e., $5 <$ TSS < 50 mg·L^{-1}) commonly observed in coastal waters, but the product takes on a higher value at both higher and lower suspended load.

4. Discussion

It must be acknowledged that it is difficult to measure small Secchi depths precisely, especially when there is a chop on the water surface. There is a great deal of scatter in the observations shown in Figures 2 and 3. This is partly because of errors in measuring a Secchi depth precisely but also, we think, because of changes in the optical properties of the particles from site to site and from time to time. Nevertheless, the coherence in the trend of the observations supports the central idea of this paper. In turbid estuary or coastal waters, in which the Secchi depth is less than about 1 m or the suspended solids load greater than about 20 mg·L^{-1}, the classical theory of the Secchi disk underestimates the disappearance depth. We believe that this happens because, in these conditions, some of the light reflected by the disk travels to the eye diffusely,
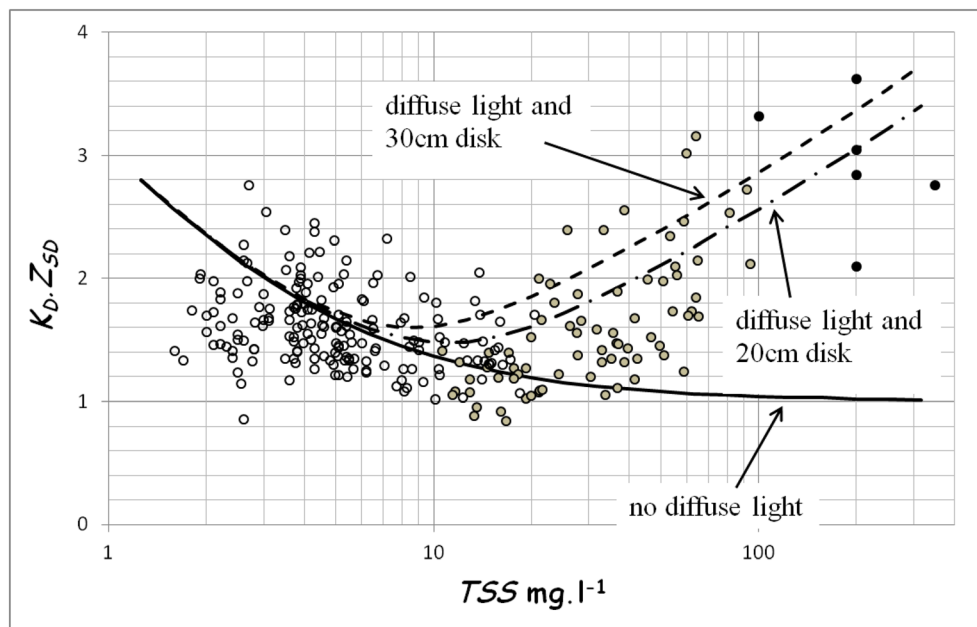
Figure 3. The product $K_D Z_{SD}$ of the diffuse attenuation coefficient and Secchi depth plotted against the concentration of total suspended solids TSS. Open circles show observations in the Irish Sea, gray in the York River and black in the Bons Sinais estuary. The continuous line shows the expected variation according to the classical theory in which no diffuse light contributes to disk visibility. The other two curves show the results for the modified theory of disk visibility described in this paper for a 30 cm diameter disk (dashed curve) and a 20 cm diameter disk (dash-dot curve).

photons being scattered one or more times on passage from the disk to the sea surface. The extra light enhances the visibility of the disk but also blurs the image. A modified theory of the Secchi depth in very turbid water, which allows for the diffuse light and contains no adjustable parameters, explains the enhanced disk visibility.

We mentioned in the introduction the alternative theory of the Secchi disk depth proposed by Lee et al. (2015). According to this theory, the inverse of the Secchi depth is approximately equal to $K_D min$, the minimum value of K_D in the spectrum. In very turbid waters, in which all colors except the most penetrating ones are quickly filtered out, $K_D min$ approximates to K_D for PAR. This happens because the spectrum of downwelling light becomes very narrow, centered on the most penetrating color, and the spectral mean K_D converges on the minimum value. The theory then predicts that product of Z_{SD} and K_D approaches a value of 1 in the most turbid waters. This does not accord with Figure 3, and so this theory cannot help us in this case.

The value of this work is that it allows better informed interpretations of Secchi depths in very turbid waters such as those found in estuaries and some coastal waters. The Secchi disk is often used to estimate important ecological parameters, such as the depth at which solar irradiance falls to 1% of its surface value (a rough indicator of the lower limit of the photic zone—Tett, 1990). The 1% depth is always equal to $4.6/K_D$. If, as is commonly the case, $Z_{SD} \approx 1.5/K_D$, the 1% depth will be about three times the Secchi disk depth—a useful rule of thumb. In this work, however, we have shown that in very turbid estuaries and coastal locations, the relationship between Secchi depth and K_D is closer to $Z_{SD} \approx 3/K_D$. The depth of the photic zone will then be only about one and a half times the Secchi depth.

Diffuse photons from the disk approaching the sea surface at an oblique angle will undergo total internal reflection on the underside of the water surface. This will cause a (probably small) reduction in the diffuse light from the disk that makes it to the eye of the observer, but it is something that we have not accounted for in this paper. It would be possible to make an adjustment for this effect in the case of a perfectly flat water surface, assuming that the diffuse light approaches the surface from below at all angles and removing the photons that are traveling at an angle shallow enough to be reflected back down from the surface. The likely impact of this correction could be investigated in further work, as could the effect of surface waves on the

refraction of the diffuse light at the surface.A consequence of the modified theory, represented by equation (5), is that the diameter of the disk, D, affects the disappearance depth in turbid water. Large disks are more visible than small ones. This is not the case with the classical theory, in which the disk is effectively a point source and its size does not matter. It is also the case with the modified theory that the height of the observer above the surface becomes a factor (since this affects the size of the image of the disk).

In view of this, the disk diameter and observer's height should be noted in observations of Secchi depths in turbid water. Intriguingly, it is possible that this fact will allow us to squeeze more information from Secchi disk measurements. If, for example, two different diameter disks are used at a single station in turbid water, the larger one should be visible at a slightly greater depth. Equation (5) can then be written twice, as two simultaneous equations and solved (after some manipulation) for both c and K_D. This trick could only be pulled off in turbid waters.

It is quite likely that Secchi depths cannot be measured precisely enough to get reliable figures for c and K_D using different sized disks. More realistically, we need careful measurements of c, K_D, and Z_{SD} in turbid waters to test the modified theory of the Secchi disk proposed here.

References

Åberg, B., & Rhode, W. (1942). Über die Mileufactoren in einigen südschwedischen Seen. *Symbolae botanicae Upsalienses*, *5*(3), 256.

Binding, C. E., Bowers, D. G., & Mitchelson-Jacob, G. (2005). Estimating suspended sediment concentrations from ocean colour measurements in moderately turbid water; the impact of variable particle scattering properties. *Remote Sensing of Environment*, *94*(3), 373–383. https://doi.org/10.1016/j.rse.2004.11.002

Bowers, D. G., & Binding, C. E. (2006). The optical properties of mineral suspended solids: A review and synthesis. *Estuarine, Coastal and Shelf Science*, *67*(1-2), 219–230. https://doi.org/10.1016/j.ecss.2005.11.010

Bowers, D. G., Hill, P. S., & Braithwaite, K. M. (2014). The effect of particulate organic content on the remote sensing of marine suspended sediments. *Remote Sensing Environment*, *144*, 172–178. https://doi.org/10.1016/j.rse.2014.01.005

Bricaud, A., Morel, A., & Prieur, L. (1981). Absorption by dissolved organic matter of the sea (yellow substance) in the UV and visible domains. *Limnology and Oceanography*, *26*(1), 43–53. https://doi.org/10.4319/lo.1981.26.1.0043

Busch, J. A., Bardaji, R., Ceccaroni, L., Friedrichs, A., Piera, J., Simon, C., et al. (2016). Citizen Bio-Optical observations from coast and ocean and their compatability with ocean colour satellite measurements. *Remote Sensing*, *8*(11), 879. https://doi.org/10.3390/rs8110879

Duntley, S.Q. and Preisendorfer, R.W. (1952) The visibility of submerged objects. MIT Visibility Laboratory Final Report N5ori-07864

Friedrichs, C. (2009). York River physical oceanography and sediment transport. *Journal of Coastal Research*, *SI57*, 17–22. https://doi.org/10.2112/1551-5036-57.sp1.17

Gallegos, C. L., Werdell, P. J., & McClain, C. R. (2011). Long-term changes in light scattering in Chesapeake Bay inferred from Secchi depth, light attenuation and remote sensing measurements. *Journal of Geophysical Research*, *116*, C00H08. https://doi.org/10.1029/2011JC007160

Garcia-Soto, C., Van der Meesen, G.I., Busch, J.A., Delany, J., et al. (2017) Advancing Citizen Science for coastal and ocean research. European Marine Board Poition Paper 23. ISBN 978-94-92043-30-6

Holmes, R. W. (1970). The Secchi disk in turbid coastal zones. *Limnology and Oceanography*, *15*(5), 688–694. https://doi.org/10.4319/lo.1970.15.5.0688

Kirk, J. T. O. (1994). *Light and photosynthesis in aquatic systems*. Cambridge: University Press.

Kratzer, S., Buchan, S., & Bowers, D. G. (2003). Testing long-term trends in turbidity in the Menai Strait, North Wales. *Estuarine, Coastal and Shelf Science*, *56*(2), 221–226. https://doi.org/10.1016/S0272-7714(02)00159-2

Krivtsov, V., Howarth, M. J., Jones, S. E., Souza, A. J., & Jago, C. F. (2008). Monitoring and modelling of the Irish Sea and Liverpool Bay: An overview and SPM case study. *Ecological Modelling*, *212*(1-2), 37–52. https://doi.org/10.1016/j.ecolmodel.2007.10.038

Lee, Z. P., Shang, S., Hu, C., Du, K., Weidemann, A., Hou, W., et al. (2015). Secchi disk depth: A new theoretical mechanistic model for underwater visibility. *Remote Sensing of Environment*, *169*, 139–149. https://doi.org/10.1016/j.rse.2015.08.002

Morel, A., & Prieur, L. (1977). Analysis of variations in ocean colour. *Limnology and Oceanography*, *19*, 591–600.

Preisendorfer, R. W. (1986). Secchi disk science: Visual optics of natural waters 1. *Limnology and Oceanography*, *31*(5), 909–926. https://doi.org/10.4319/lo.1986.31.5.0909

Sanden, P., & Hakansson, B. (1996). Long term trends in Secchi depth in the Baltic Sea. *Limnology and Oceanography*, *41*(2), 346–351. https://doi.org/10.4319/lo.1996.44.2.0346

Stavn, R. H., Rick, H. J., & Falster, A. V. (2009). Correcting the errors from variable sea salt retention and water hydration in loss on ignition analysis: Implications for studies of estuarine and coastal waters. *Estuarine, Coastal and Shelf Research*, *81*(4), 575–582. https://doi.org/10.1016/j.ecss.2008.12.017

Tett, P. (1990). *The photic zone. P59-87 of light and life in the sea*. Cambridge: Cambridge University Press.

Timba, I. L., Nehama, F. P. J., & Mazzilli, S. (2014) Propagação de onda de maré no Estuário dos Bons Sinais. VIII Conferencia Cientifica UEM, Universidade Eduardo Mondlane, Maputo, Mozambique, https://www.researchgate.net/profile/Fialho_Nehama/

Timofeeva, V. A. (1963) Determination of the absorption and scattering coefficients of light in turbid media by means of white disks. Izv. Akad. Nauk SSSR, Ser.Geophys., pp. 621–625. (Translation. Volume unknown)

Tyler, J. E. (1968). The Secchi disk. *Limnology and Oceanography*, *13*(1), 1–6. https://doi.org/10.4319/lo.1968.13.1.0001

Wernand, M. R. (2011). Poseidon's paintbox: Historical archives of ocean colour in global-change perspective. PhD thesis, Utrecht University