Standardization of secchi disk measurements, including use of a viewer box

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ABSTRACT: Despite being used by limnologists and oceanographers for over a century, the use of the Secchi disk for estimating water transparency has no agreed-to protocol. Because of this lack of uniformity, and the inherent optical problems with most current Secchi depth procedures, an appeal is made for production of a standardized protocol for Secchi observations. A possible protocol, including the use of a closed-ended viewer box on the sunny side of the boat, is suggested here.

To assist in protocol development, this paper briefly reviews some aspects of optical physics and examines some recent field measurements made by staff of New York City Department of Environmental Protection. These measurements were made using a closed-ended viewer box and are compared with simultaneous naked-eye measurements.

The use of a viewer box increases Secchi depth measurement by removing the interfering effects of water surface glare and glitter. A viewer box also increases between-observer precision. Measurements made both with and without the viewer box are slightly greater on the shady side of the boat than on the sunny side; the latter is the preferred side if Secchi data are to be related to other optical properties. As expected, the difference between viewer box and naked eye measurements increases with increasing wave height but not with increasing illuminance.

INTRODUCTION

The Secchi disk has been around for over a century. Because of its simplicity, it is certainly a useful clarity-estimation tool in a limnologist's armory, but a definitive protocol for its use has not been formalized. Much has been written on the caveats for Secchi disk use and the problems which can lead to measurement uncertainty (e.g., Tyler, 1968; Preisendorfer, 1986; Davies-Colley *et al*., 1993), but in most publications reporting Secchi disk data, these caveats seem to be ignored; certainly they are rarely discussed and the exact field protocol is seldom described.

Tyler (1968) noted that in the first measurements made by Secchi himself, he observed that the depth of visibility varied with the size and whiteness (reflectance) of the disk, sun altitude, disk image dissection by surface refraction of the light path (glitter), and the presence of the ship's shadow. Secchi recommended a wide shadow over the place where the measurement was made in order to reduce glitter. Tyler (1968) pointed out that the methodology for Secchi disk use was never really standardized. Unfortunately, this is still the case.

Tyler (1968) further pointed out that Secchi observations made in the ship's shadow, as is typical in an attempt to reduce surface reflection, means that large reading errors can arise because the disk's viewing path is through a shaded volume of water. This means that certain optical parameters cannot then be calculated and readings cannot be accurately compared.

More recently, Preisendorfer (1986) published "ten laws of the Secchi disk" in both verbal and mathematical form. It is valuable to re-state them here because these fundamental aspects of Secchi disk measurement are still not widely recognized or are ignored. He stated that the depth of disappearance of the disk: 1) varies inversely with the average amount of attenuating material between the surface and the disk; 2) varies inversely with the optical state of the sea surface; 3) varies inversely with the relative amount of reflected luminance of sky in the sea surface compared to the luminance transmitted upward from below the sea surface; 4) varies inversely with the reflectance of the water body; 5) varies directly with its (the disk's) reflectance; 6) varies directly with its diameter; 7) varies directly with sun altitude; 8) varies inversely with the height of the observer above the sea surface; 9) varies inversely with the adaptation luminance (the water background luminance, or brightness); and 10) is larger if the water path of sight between disk and observer is more shadowed. Preisendorfer further stated that "disk readings are dependent on the visual acuity of the observer and his total physiological state at the moment of measurement."

With all of these inherent sources of variance, it is not surprising that Secchi depth measurement has developed a reputation for being "rough" or "semiquantitative" when in fact it is capable of being fairly precise if the above issues are attended to. Tyler (1968) suggested that viewing should occur on the sunny side of the boat to avoid shadowing the light path. Davies-Colley *et al.* (1993) suggested using different sized disks depending on visual range so as to keep the apparent size of the disk roughly constant at the eye of the observer. Furthermore, they recommended allowing the eyes to adapt to the prevailing luminance level of the water by waiting two minutes prior to measurement, and using two observers who should agree within 10%. Although Davies-Colley *et al.* (1993) did not specifically state that one should use a viewing box sealed around the observer's face (to reduce surface glare and glitter) in their Secchi depth method description, they did so for the assessment of black disk clarity, arguably a superior visual clarity index (Davies-Colley (1988)). Use of a viewer box removes many of the problems noted by Preisendorfer, in particular the problems associated with Laws 2, 3, and possibly 8, which together may cause much of the error associated with Secchi depth measurement.

There is confusion as to how the Secchi depth is measured. For example, Verschuur (1997) took the depth at which the disk was "just visible" in contrast to Effler (1989) who used the distance at which the disk just disappears, and Davies-Colley *et al*. (1993) who recommend the average depth between the disk just disappearing and then reappearing, as do Wetzel and Likens (1991). The latter authors recommend use of an all-white 20cm disk, whereas Davies-Colley *et al*. (1993) suggested a matte white disk or a black and white quadrant disk. The white portion's reflectance also needs to be considered for accurate work. Because results will differ depending on the method used, there is clearly a need to standardize even these ‘simple’ aspects of the measurement.

A further concern is that so much effort (and cost) goes into obtaining Secchi depth measurements and such great importance may be placed on them, when there is no standardization of methods and much potential error associated with current practice.

This paper uses Secchi disk depth measurements taken by technical staff from New York City’s Department of Environmental Protection during the normal field program to illustrate problems of measurement. Measurements were obtained on the shady and sunny side of a boat, both with a viewer box and with the naked eye, in order to examine the differences. Also examined is the precision based on variation between different observers, and whether use of a viewer box can, indeed, improve precision as expected from Laws 2 and 3.

METHODS

The viewing disk was a “conventional” 20cm black and white quadrant disk (Wildco); the reflectance of the white portions was not measured. The viewing box (Davies-Colley *et al*., 1997), modified here by improving the face seal to allow for better exclusion of extraneous light, and the addition of handles to make the observations and measurement easier, was kindly supplied by the National Institute of Water and Atmospheric Research, New Zealand, where viewers of this type have been used for many years for black disk clarity observation (e.g., Davies-Colley, 1988; Smith and McBride, 1990; Smith *et al.*, 1997).

Observations were made between July and September 1997 during a normal field sampling run on New York City’s Delaware reservoirs, viz., Pepacton, Neversink, Rondout, and Cannonsville, in the Catskill Park region of New York State. Up to six sites per reservoir were visited between approximately 09:00 and 13:00h. Because the regular field program has severe time constraints, Secchi depth measurement was relatively quick (probably the norm for measurements of this type); they are simply part of a time-constrained routine field operation during which many other measurements are made. When using the viewer box, the time allowed for eye accommodation to the water light field was only about 30s at best. Wherever possible, two observers made independent measurements but on 40% of occasions only a single observer was available. In the former cases there was no deliberate collusion between observers to ensure that observer differences could be assessed; measurements were written into the field log as they were made and were not repeated even if large differences between observers (up to 30%) were recorded. The Secchi depth recorded was the mean of the disappearance/reappearance depths (Davies-Colley *et al.* (1993); Likens and Wetzel (1991)); all sighting ranges were made from the bottom of the viewer box (which was immersed in the water to just a few cm) to the face of the Secchi disk so that only the water optical path length was measured. For 39 sets of measurements (i.e., 25% of the total), because of overcast conditions or fog, there is likely to be little or no distinction between the “sunny” and “shady” sides of the boat; in these cases the ‘sunny’ side was taken to be the south side.

At all sites, visual assessments were made for wind speed, cloud cover, and wave height. Irradiance measurements were made as an indication of ambient lighting conditions (Li-Cor Model LI-193SA Spherical Quantum Sensor) at arm’s length from the boat, just above the water surface.

RESULTS AND DISCUSSION

The data set includes 156 sets of Secchi depth measurements, roughly evenly spread over the four reservoirs. Each set consists of four data points: sunny and shady side of boat measurements with a viewer box (coded VB), and with the naked eye (NE). There are 57 comparison sets between observers. Three sets of observations were excluded from the original dataset; in one instance there was an obvious recording error and in the other two, very rapidly changing weather conditions (in particular, wave action) resulted in unreliable measurement pairs.

Summary statistics for all measurements are presented in Table 1. Statistics for the individual reservoirs can be obtained from Smith and Hoover (1999). The data set includes measurements made on overcast days when there was likely to be little or no difference in illumination between the 'sunny' and shady' sides of the boat: overcast day data were included in the overall dataset because there was no significant difference ($P < 0.10$; Kolmogorov-Smirnov two sample test) between sunny and overcast conditions data. Overcast conditions are operationally defined as irradiance <1000μmol m^{-2} s^{-1} (PAR), supported by field observation of what constituted overcast conditions and an absence of shadowing. For all five datasets (i.e., the combined data and the four reservoirs) the coefficient of variation (CV) is very uniform between all types of Secchi depth measurement. Thus the distributions about the means are very similar, however the central tendencies of each are somewhat different: ShadyVB (overall mean = 4.68m) > SunnyVB (4.54m) >ShadyNE (4.07m) > SunnyNE (3.94m). The overall mean difference between ShadyVB and ShadyNE is 0.61m which translates to an average increase of 13% in viewer box measurements over naked eye observations. On the sunny side of the boat the difference is 0.60m (15%). The overall mean difference between the "conventionally" measured ShadyNE and the "more correctly" measured SunnyVB is 0.47m (12%). Use of the viewer box produces greater measured transparency on both the shady and sunny side of the boat. An increase is to be expected, of course, because the viewer box eliminates water surface glare and glitter.

TABLE 1. Summary Secchi depth (m) statistics for the reservoirs combined. SunnyNE and ShadyNE, and SunnyVB and ShadyVB. (NE = naked eye, VB = viewer box.)

	SunnyNE	SunnyVB	ShadyNE	ShadyVB
All reservoirs combined (*n*=156)				
Minimum	1.10	1.10	1.00	1.10
Maximum	7.00	7.55	7.15	8.12
Mean	3.94	4.54	4.07	4.68
Median	3.59	4.39	3.72	4.52
Coeff of variation %	39.3	39.4	41.1	40.1

What may be a surprise is that ShadyVB is greater than SunnyVB, and ShadyNE is greater than SunnyNE (Cannonsville is an exception here where the means of both pairs of measurements are the same). That ShadyNE measurements were greater than SunnyNE measurements may be partly explained by some reduction in surface glare in the shade. But this does not explain the difference when using the viewer box (i.e., ShadyVB compared with SunnyVB) where water surface glare and glitter have been eliminated. The reason for this difference is more fundamental and is probably a consequence of the different luminance on both sides of the boat. At least part of this difference can be explained as follows: the disk's disappearance/reappearance distance occurs at a particular threshold contrast of the light from the white disk face *versus* the light from the water backscattering. Contrast is defined (Tyler 1968) as:

$$C = (B_d - B_b)/B_b, \qquad (1)$$

where B_d and B_b are the disk and background water luminances, respectively. As the disk is lowered into the water, B_d reduces because of attenuation of light reflected by the disk on its way up to the surface through the intervening water until, at extinction, $C = C_{threshold}$. The water background luminance is obviously higher on the sunny side of the boat than on the shady side; therefore, from the definition of contrast, it follows that the contrast will be greater on the shady side of the boat at any given water depth provided the disk is in sunlight. Hence, Secchi depth will be greater on the shady side of the boat (R.J. Davies-Colley, NIWA, New Zealand, pers. comm.). This is in accordance with Preisendorfer's Law 10.

Because most data sets are not normally distributed, non-parametric statistics were employed to examine differences between the four sets of Secchi depth measurements for each of the reservoirs (Table 1). Wilcoxon signed-rank tests on paired differences between measurements for all reservoirs combined and all individual reservoirs show highly significant differences (normally $P < 0.05$, and in many instances $P < 0.0005$) between all data sets except for Cannonsville Reservoir where no difference was found between SunnyNE and ShadyNE, and between SunnyVB and ShadyVB ($P > 0.10$)—see Smith and Hoover (1999).

Individual pairs of results (VB vs NE) are plotted separately in Figure 1 for both sunny side and shady side of the boat measurements. There is a strong correlation in both cases $r = 0.97$ and 0.96, respectively, $n = 156$). For comparison, the 1:1 relationship is shown. A log-log plot is employed to emphasize the observation that the *percentage* difference (~ 15%) between measurement pairs changes little with transparency, although in the shade a very weak but statistically significant downward trend was found for the value (ShadyVB–ShadyNE)x100/ShadyNE) with increasing ShadyNE—$P < 0.05$, $r = 0.19$, $n = 156$. The reason for this apparent weak trend in the shade is not clear.

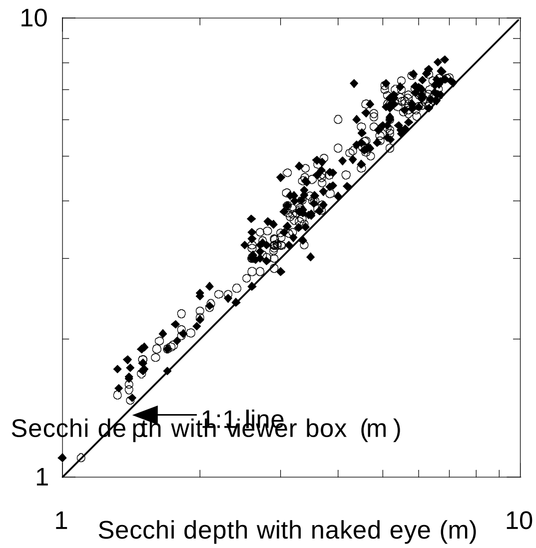

Figure 1. Relationship between Secchi depth measurements made with the aid of a viewer box and the naked eye. The open and closed symbols refer to measurements made on the sunny and shady side of the boat, respectively.

For paired measurements (VB–NE) made on each side of the boat, the difference seems to depend upon wave action, as expected. Figure 2 shows the relationship between (SunnyVB–SunnyNE), plotted as % relative difference with respect to SunnyVB, and wave height. The relationship is highly significant ($P < 0.01$; $r = 0.45$; $n = 156$) with wave height explaining 20% of the variance in % relative difference . A similar relationship was found for the shady side of the boat comparison ($P < 0.01$; $r = 0.49$; $n = 156$). The plot intercepts (at around 9% for both) show a 'residual' effect (i.e., with zero wave action). This is probably due to sky reflection on naked eye assessment and appears independent of side of boat. Plots of pairs of measurements, i.e., VB–NE, against wave height for both sides of the boat have intercepts at 0.45m.

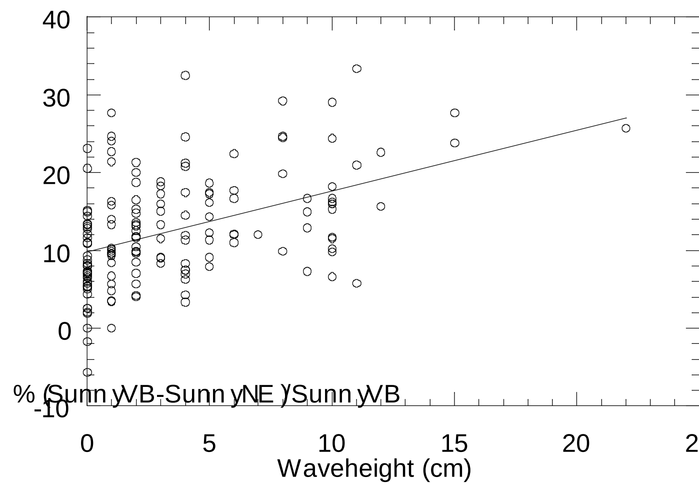

Figure 2. The effects of wave height on the relative difference in Secchi depth measurement with and without a viewer box on the sunny side of the boat, i.e., 100x(SunnyVB–SunnyNE)/SunnyVB.

We found no overall relationships between the same pairs of Secchi measurements, i.e., (SunnyVB–SunnyNE) and (ShadyVB–ShadyNE), and scalar irradiance *(P* > 0.10), confirming that absolute lighting is not relevant (i.e., absolute irradiance does not affect contrast). This was also the case when data were partitioned into calm (wave height #1 cm) and disturbed water conditions (*n* = 62 and 94, respectively). The calm water data are not significantly different from the disturbed water data (two sample Kolmogorov-Smirnoff test; *P* > 0.10).

Table 2 presents the paired comparison data between two observers (not always the same). For all reservoirs combined, the percent difference between observers (a measure of precision) ranges from zero to 30%, with viewer box differences being considerably less on average than those with the naked eye. Use of the viewer box would be expected to improve precision because of the removal of surface glare and glitter. However, it is noteworthy that even the greatest average difference (for ShadyNE) is only 7.6% indicating that even here the precision is better than that of many physical and chemical analytical methods in water quality. Precision might be improved for both VB and NE methods if collusion had occurred between observers, i.e., if the paired measurements had deviated by more than say 5 or 10%, then measurements would have been repeated to see if precision could be improved. This is the protocol recommended by Davies-Colley *et al.* (1993) for black disk observations for which a precision of 3.7% was reported by Davies-Colley and Close (1990), slightly smaller than our means of 4.2 (in sun) and 4.6 (in shade) *without* collusion. This protocol would be expected to eliminate some of the gross errors which occur from time-to-time. The percent differences are independent of water transparency, and relatively large differences can be found over the whole range (see Figure 3, which, by way of example, depicts shady side of boat data). There are fewer gross differences when using the viewer box—only 4% of ShadyVB measurements had a difference of >10%, whereas 10% of ShadyNE measurements exceeded a 10% difference.

TABLE 2. Secchi depth summary statistics for % difference between pairs of samplers (i.e., the modulus of the difference/mean of the pair of observations).

	SunnyNE	SunnyVB	ShadyNE	ShadyVB
All reservoirs combined (*n*=57)				
Minimum	0.0	0.0	0.0	0.6
Maximum	22	20	30	19
Mean	6.9	4.2	7.6	4.6
Median	5.9	3.0	6.4	3.5

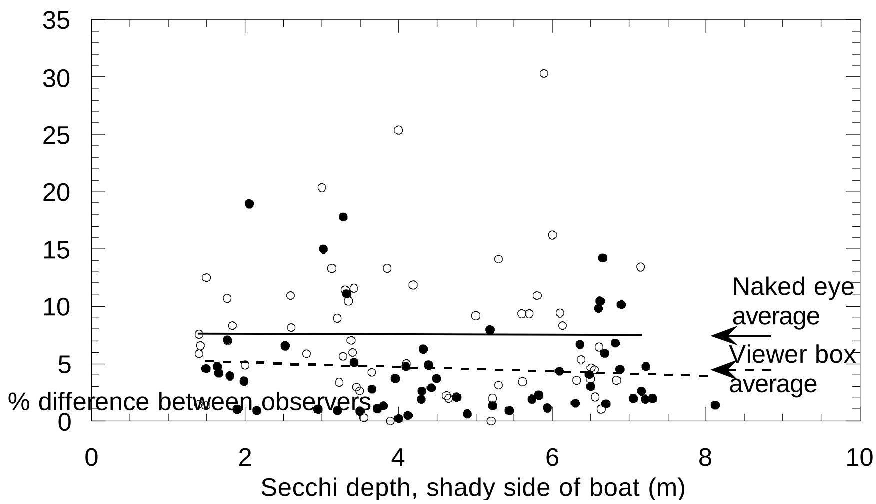

Figure 3. Relationship between percent difference between observers and Secchi depth measurement on the shady side of the boat, using a viewer box and the naked eye. The open symbol and solid regression line, and the closed symbol and dotted regression line, refer to naked eye and viewer box measurements, respectively.

CONCLUSIONS

We have shown that use of a closed-ended viewer box increases Secchi depth measurement by removing the interfering effects of surface water glare and glitter. A viewer box also increases between-observer precision. Measurements made both with and without the viewer box are slightly greater on the shady side of the boat than on the sunny side. As expected, the difference between viewer box and naked eye measurements increases with increasing wave height but not with increasing illuminance.

Secchi depth, although potentially a somewhat precise measurement, as presently measured breaks many optical principles enunciated by, for instance, Preisendorfer (1986). For the best quality work, there is a need to:

1) Standardize the point to which the measurement is made; i.e. just above disk disappearance, at disk disappearance, at disk reappearance, or the *mean of the last two*.

2) Determine whether one measurement is acceptable and whether, if *more than one observer*, they should *collaborate* to improve precision and eliminate gross errors.

3) Measure on the *sunny* rather than the shady side of the boat.

4) *Use a viewer box closed at the water end*, and specify what is an appropriate eye acclimation time to the illuminance of water space light field.

5) Determine what the disk should look like, for instance, should it be all-white or have black-and-white quadrants, and what should be the reflectance of the white portion. Also, what the size should be, 20 cm or *dependent on the visual clarity of the water,* as suggested by Davies-Colley *et al.* (1993).

The favored options by the author of this paper are italicized.

Because of these concerns, it is incumbent upon international limnologists, and perhaps oceanographers, to standardize the Secchi depth measurement procedure. Perhaps the National Water Quality Monitoring Council could take a lead here, for example, by convening an international working group.

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