

LRH: E.A. Steel and S. Neuhauser

RRH: Measuring Water Clarity

A comparison of methods for measuring visual water clarity

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Abstract. Visual water clarity is a primary regulator of biological and ecological functions in both benthic and aquatic systems. We present a large data set, collected under variable field conditions, to compare measurements of visual water clarity between the horizontal black disc, a horizontal Secchi disc, and two more traditional techniques: a vertical Secchi disc and an electronic nephelometer. Readings between the two horizontal discs were nearly equivalent ($\underline{r} = 0.98$). The horizontal discs provided a measure of visibility that was strongly correlated with that of the vertical Secchi disc ($\underline{r} = 0.96, 0.93$). Correlation between measurements made with visual discs and with the electronic nephelometer was high ($-0.86 < \underline{r} < -0.85$) but not as high as among measurements made using the three types of visual disc. The coefficient of variation, a relative indicator of precision, was similar for the three visual methods but higher for the electronic nephelometer. Analyses indicated that there was variation in horizontal disc readings among observers. We recommend the use of horizontal visual discs by trained observers as an inexpensive, practical, and precise tool for measuring visual water clarity.

Key words: visibility, turbidity, light, water clarity, Secchi disc, horizontal black disc.

Visual water clarity is a primary regulator of biological and ecological functions in both benthic and aquatic systems (Gregory 1993, Lloyd et al. 1987, Vinyard and O'Brien 1976). The quality and quantity of underwater light regulate foraging, hunting, and predator avoidance, the behaviors that underlie community dynamics. It has been well documented that fish predation on other fish and on benthic invertebrates can be influenced by visual water clarity (Gregory and Northcote 1993, Vogel and Beauchamp 1999). These effects can filter through multiple levels of the food chain. The trophic cascade theory proposed by Carpenter and Kitchell (1993) suggests that abundance and relative dominance of individual species, such as benthic invertebrates, can be regulated not only by direct predation but also by predation at other levels of the food chain. Decreases in visual water quality are often also associated with increases in suspended sediment, which can have a direct negative effect on survival of benthic invertebrates (Newcombe and MacDonald 1991). Visual water clarity also has a role in regulating primary productivity, the foundation of the benthic food web, which depends on the ability of sunlight to penetrate the water column (Lloyd et al. 1987). Accurate and consistent measurement of visual water clarity is necessary for understanding and predicting relationships between aquatic organisms and the physical parameters of their environment.

In this paper, we compare two newer methods for measuring visual water clarity, the horizontal black disc and the horizontal Secchi disc, with two traditional techniques for measuring related optical properties: the vertical Secchi disc, which measures vertical visual extinction, and the electronic nephelometer, which measures turbidity, a relative measure of light scattering. These comparisons assess the horizontal visual discs with respect to precision, consistency with each other, consistency with traditional measures of related phenomena, consistency among observers, and consistency across weather conditions. By comparing the horizontal black disc, which measures an inherent property of light, to the horizontal Secchi disc, which measures an apparent property of

light, we also assess the practical significance of measuring inherent versus apparent optical properties.

Background

Properties of Light Transmission

Assessment of visual water clarity requires determination of the inherent and apparent properties of light transmission. The inherent ability of a body of water to transmit light is described by the scattering coefficient (b) and the absorption coefficient (a). The scattering coefficient measures the degree to which a beam of light is deviated from its path as it passes through the water; the absorption coefficient describes the degree to which light energy is absorbed as it passes through the water. These optical coefficients are affected by suspended and dissolved constituents. They can be summarized by the beam attenuation coefficient ($c = a + b$). Because these coefficients describe inherent optical properties of water, they are minimally affected by the direction or spectral quality of the light entering the water, by observer variation, or by other external factors. In contrast, apparent optical properties describe the behavior of light in a particular body of water at a particular time. Apparent properties are relevant biologically because they describe the conditions at a fixed place and time, e.g., how well a predator can be detected in the shadows of a rock at dusk; however, dependence on local lighting variation makes them difficult to interpret and extrapolate.

Vertical Secchi Disc

The Secchi disc is the first recorded method for measuring water clarity (Cialdi and Secchi 1865, Collier et al. 1968, Tyler 1968). The original Secchi disc was an iron circle, 3.73 m in diameter, covered with oiled sailcloth and varnished with white lead (Collier et al. 1968). There have been many variations on the Secchi disc design since that time but the disc in most common current use

is a weighted plastic circle, ~ 20 cm in diameter, patterned with alternating black and white quadrants. The disc is lowered into the water on a graduated line until it is no longer visible, dropped a bit more, and pulled up until it once again becomes visible. Secchi depth, describing the distance of visual extinction, is estimated as the average of the depths at which the disc disappears and at which it reappears. The Secchi depth is a simple, inexpensive, and intuitive indicator of visual water clarity. Secchi depth has two drawbacks. First, it is related to an apparent rather than inherent optical property of water and second, there is no standard protocol for its use (Smith and Hoover 1999, Tyler 1968). Secchi disc readings depend not only on the scattering and absorption coefficients of the body of water of interest, but also on the reflectance of the white areas of the disc, the angle of the sun, and the roughness of the water surface (Preisendorfer 1986). Since one must be able to lower the Secchi disc straight down until it is no longer visible, the utility of the disc is limited to situations where the water is deeper than the Secchi depth and, without use of a boat, to areas without strong currents.

Electronic nephelometer

A common index of water clarity is turbidity, recorded in nephelometric turbidity units (NTU) with an electronic nephelometer. Turbidity describes light scattering, usually centered on an angle of 90° from a perpendicular beam of light. Nephelometers index an inherent optical property of water, the scattering coefficient; however, no universal relationship exists between turbidity in NTU and the scattering coefficient. Turbidity in NTU refers only to the fraction of total scattering that occurs at 90° and there is variability in the ratio of 90° to total scattering between different bodies of water (Davies-Colley 1990). Turbidity in NTU is often used for regulatory purposes to describe changes in visibility in lakes or rivers. Although nephelometers frequently provide data to 2 or 3 significant figures, the readout precision is misleading. Nephelometry has been criticized for

lack of scientific rigor, unrealistic application in environmental standards and regulations, and dependence on Formazin standards (Austin 1973, Davies-Colley and Smith 2001, McCarthy et al. 1974, McCluney 1975, Telesnicki and Goldberg 1995).

Horizontal Black Disc

The horizontal black disc was introduced by Davies-Colley (1988) to provide a measure of visual clarity based on inherent optical properties that can be employed in a wide range of water bodies. The equipment comprises a black disc on a stick, a tape measure, and an underwater viewer. The disc is moved away from the underwater viewer until it is no longer visible (Figure 1). Davies-Colley (1988) suggests recording the distance at which the disc disappears as the measure of visibility. Because the black disc does not reflect light (ideally), this measure of visibility allows one to estimate the beam attenuation coefficient (Duntley 1963). Davies-Colley (1988) provides a mathematical analysis of the optical properties of the horizontal black disc and reports a sample of observations (n=19) from a set of lakes and rivers with a wide-range of optical characteristics; these data were used to calibrate the technique with respect to instrumental measurements of the beam attenuation coefficient.

Horizontal Secchi disc

The horizontal Secchi disc is identical to the horizontal black disc except that the disc is painted with alternating black and white quadrants. Like a traditional vertical Secchi disc, the horizontal Secchi disc measures an apparent optical property of water. It was developed for this study to isolate the effect of measurement orientation (horizontal or vertical) versus the effect of disc reflectivity. Comparing the horizontal Secchi disc to the horizontal black disc allows an assessment of the practical significance of measuring inherent versus apparent optical properties.

In this paper, the effectiveness of the horizontal black disc and horizontal Secchi disc are examined with respect to precision, observer subjectivity, and effects of weather. We consider the correlation between different methods of measuring visual water clarity and assess the precision of each. These analyses build on previous work by considering a large data set collected under variable conditions and by comparing several methods at once.

Methods

The study site was located on the Skagit River near Mount Vernon, in western Washington State. Flow results from a combination of managed releases (Ross, Diablo, and Gorge dams) and natural discharge, including glacial melt. In the Skagit River, unlike many other rivers, water clarity tends to decrease as a result of both high water events and high air temperatures. When air temperatures are high, glacial melt increases the amount of glacial silt in the water, reducing water clarity. Data were collected from February to August 1998. Weather conditions (sun, clouds, or rain) during data collection were recorded.

Horizontal discs

The horizontal black disc and the horizontal Secchi disc were used daily from 24 February through 18 August 1998 except for 25 d during which equipment was being repaired or observers were unavailable. The observer crew consisted of 5 primary individuals on rotating, 3-d schedules. One reading was taken each morning from the shaded side of a boat, either as it was drifting downstream or anchored to the shore or to a mid-channel fisheries trap. We used the shaded side of the boat to minimize surface reflection. For both types of disc, the measure of visibility analyzed here was the average of the distance at which the disc disappeared and reappeared. With the black disc method, 3 sizes of disc were used (20 mm, 60 mm, and 200 mm in diameter) depending on

water clarity. This protocol was designed to maintain a relatively constant viewing angle between the periscope and the edges of the black disc at all levels of visibility (Fig. 1) (Davies-Colley 1988). Only 1 size of horizontal Secchi disc (200 mm) was available.

Vertical Secchi disc

A standard 200-mm plastic Secchi disc was used each morning from 8 May to 18 August except for 5 d when crews were unavailable. The vertical Secchi disc was used from the shaded side of a drifting boat to minimize surface reflection and for consistency with the horizontal readings. Because the range of visual water clarity measures at this site did not exceed the depth of the boat's shadow, there was no risk of dropping the target through the shadow of the boat or trap.

Nephelometer

A portable nephelometer (Jenway, model 6035) was used on 11 d during the study period. Each day, 3 independent water grabs were taken within 30 min of each other. Three replicate samples were measured from each water grab, for a total of 9 turbidity readings per day. The turbidity measure reported for any one day was the average of all 9 readings. Coefficient of variation for the 9 replicate measurements ranged from 0.03 – 0.24.

Statistical analysis

Three types of computation are included in the data analysis. The unitless correlation coefficient, r , is used to describe the intensity of association between each pair of methods for measuring water clarity. A value of r close to -1 or 1 indicates a very strong linear correspondence between techniques and suggests that they are measuring the same phenomenon.

The estimated coefficient of variation (CV) is presented for each of the 4 methods of measuring water clarity. The CV is estimated as the sample standard deviation divided by the sample mean. It is a unitless expression of variability in relation to the mean and suggests the relative degree of measurement error one might expect for a particular technique. Statistical tests to compare CV between methods were not possible because the skewness of the data could not be adequately reduced (Zar 1996, p.144).

An analysis of covariance was conducted to detect whether observer pair or weather condition (sun, clouds, rain) had a significant effect on the relationship between each of the horizontal discs and the vertical Secchi disc (Neter et al. 1990). Neither the effect of weather nor observer pair could be estimated directly for any one technique because we lacked an absolute measure or standard for visual water clarity. The analysis of covariance tested whether observer pair or weather condition had a significant effect on the horizontal disc readings given current river conditions, as indexed with the vertical Secchi disc. This analysis will uncover differences in the correlation between measurement techniques under different weather conditions or for different observers; the analysis will not be able to determine with certainty which technique is responsible for the discrepancies.

Results

Comparisons between the 4 methods of measuring visual water clarity

We found consistent patterns over a wide range of conditions; vertical Secchi disc measurements ranged from 15 - 218 cm and horizontal disc measurements ranged from 24 - 329 cm. Correlations were high between the 3 visual methods ($0.93 < r < 0.98$) (Figure 2). Increased scatter at longer sighting ranges suggests that correlation between methods decreases with increasing

water clarity; however, correlation relative to the mean remains constant or decreases slightly as water clarity increases. The relationships between the electronic nephelometer and the visual methods were consistent but less dramatic ($-0.86 < r < -0.85$). Data comparing the visual discs to the electronic nephelometer are presented on log scales to reflect the expected relationship.

Estimated coefficients of variation (CV) for each method are presented in Table 1. Accurate comparisons between methods must use data collected over the same set of days to control for changes in river condition. In Table 1, the CV for each method is calculated using all available data (diagonal elements) and also for subsets of the data representing fewer observation days. Comparisons should be made using the off-diagonal elements representing identical time periods. For example when comparing the black disc and the vertical Secchi disc, one should compare measurements made on the same 86 days; the CV for visual water clarity readings from the black disc on days when the vertical Secchi disc was also used (0.46) should be compared to the CV for data from the vertical Secchi disc taken on days when the black disc was also used (0.57). The CVs for all 3 visual methods are similar. The CVs for the electronic nephelometer are highest in all comparisons.

Weather and observer effect on horizontal disc readings

Weather did not have a significant effect on the relationship between the horizontal Secchi disc and the vertical Secchi disc ($p=0.24$), but it did have an effect on the relationship between the horizontal black disc and the vertical Secchi disc ($p=0.01$) (Figure 3). The effect of rain is demonstrated by a different relationship, as described by the slope of the line, between the horizontal black disc and the vertical Secchi disc for measurements taken during rainy versus sunny or cloudy conditions. The statistical significance of this effect may occur because no readings were taken on rainy days with clear waters.

Observer pair was significant in explaining the relationship between both the horizontal black disc and the vertical Secchi disc ($p < 0.01$) and between the horizontal Secchi disc and the vertical Secchi disc ($p < 0.01$). Each line describes a slightly different relationship to the vertical disc readings for horizontal disc readings taken by different observer pairs (Figure 4).

Discussion

Overall, the 3 visual discs performed similarly. All 3 techniques were highly correlated and the relative variability of the methods was comparable. Neither measurement orientation nor disc color had a dramatic effect on recorded visual water clarity. The absolute difference between techniques was least for the lowest levels of water clarity, suggesting that there may be increased measurement error when the water is clear. Horizontal discs become somewhat more difficult to use as water clarity increases because longer sight ranges are required. At long sight ranges, small movements of the periscope can cause the observer to lose sight of the target.

On average, vertical Secchi depth was somewhat shorter than either of the horizontal measures of visibility as expected. Both (Gordon and Wouters 1978) and (Hojerslev 1986) report that Secchi depth, Z_{SD} , is approximately equal to $6/c$, where c is the beam attenuation coefficient. Black disc visibility, y_{BD} , is equal to $4.8/c$ (Davies-Colley 1988). We would therefore expect black disc visibility, y_{BD} , to equal $(4.8/6)Z_{SD}$ or $0.8 Z_{SD}$. The fitted regression line between horizontal black disc visibility and vertical Secchi depth was 0.85 and between horizontal Secchi disc visibility and vertical Secchi depth was 0.77 (Figure 2).

The similarity in performance between the horizontal black disc and the 2 Secchi discs is somewhat surprising because the horizontal black disc measures inherent optical properties of water and the 2 Secchi discs measure only apparent properties of water. Both types of Secchi disc reading

should depend on variations in the light field caused by the height of the sun, shadows, and light scattering from surface roughness, as well as on the visual acuity of the observer (Preisendorfer 1986); therefore one might expect more variability in the data resulting from these techniques. We suggest further studies under an even wider range of conditions before concluding that there is no practical significance to measuring inherent versus apparent properties of water.

Because the water was very deep in our study area and we had access to a boat, we were able to take all the visual readings by viewing the discs against water rather than against cobbles or boulders. In very shallow waters, where the disc is necessarily viewed against the stream bottom rather than against deeper water, one should be careful to measure the visual extinction of the black disc against water rather than against the riverine background. This might be accomplished by observing the extinction of the top of the disc rather than the areas of the disc that are in front of cobbles or other substrate. There might be situations where the use of a black and white disc could help control for variability in the optics of stream substrate. When using a black and white disc, one can measure the visual extinction of the black part of the disc against the standard of the white quadrants. For comparability with other measures of visual water clarity, measurements with a black and white disc should be calibrated to measures with a black disc taken in similar waters.

All 3 visual disc readings were strongly correlated with turbidity (NTU); however, the CV of the turbidity readings (NTU) was higher (less precise) than that of the visual discs. The high relative variability is dramatic because each turbidity measurement represents the average of 9 readings with the same instrument. While replicate readings are fairly standard, turbidity measurements that represent fewer readings would be expected to have an even higher relative variability. Our results suggest that electronic turbidity readings provide a false sense of precision as readouts are often displayed to several significant digits. Turbidity readings are sensitive to imperfections in the glass

measuring cell, time since the sample was agitated, polishing of the glass, and other details in the measurement process (McCluney 1975, Telesnicki and Goldberg 1995). Smith et al. (1997) found a similar relationship between turbidity and water clarity as measured with the horizontal black disc. The strength of the relationship between turbidity in NTU and visual water clarity results from the dependence of both measures on the concentration of suspended solids and the imprecision of the relationship is due to variability in the light scattering character of the suspended matter (Smith et al. 1997).

In the analysis of the effect of weather, the difference between sunny and cloudy skies did not have a significant effect on the water clarity measurement. The horizontal discs performed equally well under variable ambient light conditions, suggesting that the effects of sun angle or cloudiness on measures of the apparent versus inherent optical properties of water are not dramatic.

Our results suggest that observer pair does influence the horizontal black disc and horizontal Secchi disc readings. While some variation in the fitted relationship between horizontal and vertical observations by different observer pairs could be explained by variation in the vertical Secchi disc measurements, at least a part of the observer effect is likely due to variation in horizontal disc readings between observer pairs. Differences between observers in vision or in skill at operating the horizontal discs could lead to variation in readings. The horizontal discs require patience in handling a large buoyant periscope while keeping the target in the line of sight as well as coordination between the person looking through the periscope and the person holding the target. Higher data variability associated with greater distances between the periscope and the target suggests that operator skill might be particularly important as water clarity increases. Potential for observer variation to influence results indicates that training and cross-validation are important components of initiating in-field use of the horizontal discs.

We recommend the use of horizontal discs by trained observers for measuring visual water clarity. Horizontal discs are the best and most precise option for many riverine studies due to the impracticality of vertical discs in shallow streams or fast currents and the problems associated with electronic nephlemetry. Multiple readings are recommended in clear water where accurate visual readings may be more difficult. Theory suggests that the horizontal black disc is preferable to the horizontal Secchi disc, but there was no difference between techniques for the field conditions under which we made our observations. Measurement with visual discs, though subjective, provides more precise and more immediately useful results than measurements made from electronic nephometers.

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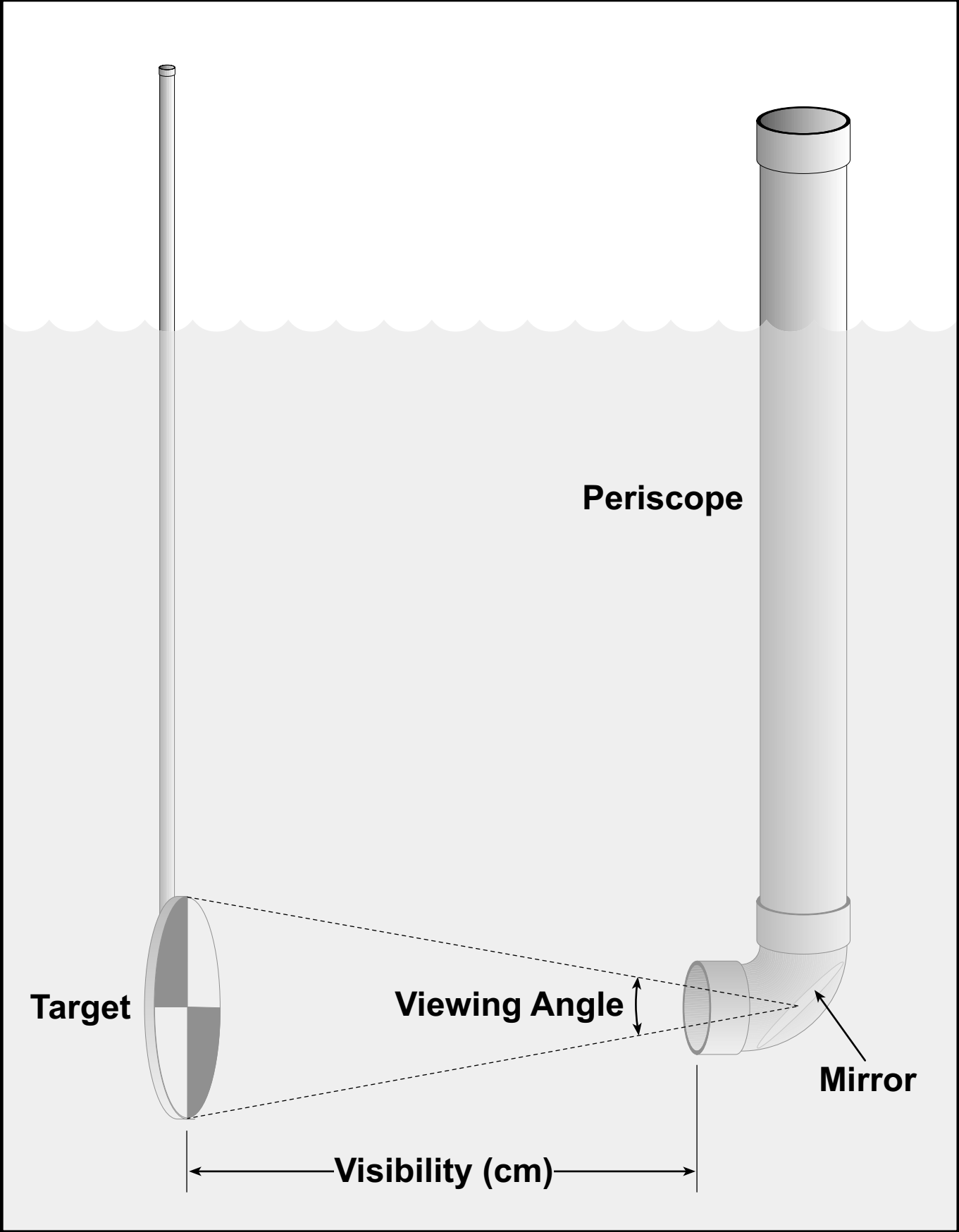
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Table 1: Coefficients of variation (CV) describing the relative variability of each method of measuring water clarity over various subsets of the data. Each row includes CV for one method of measuring water clarity; columns represent different subsets of days for which the CV was calculated. Diagonal elements of the matrix are the CVs calculated using all available data for that method. Comparisons are only appropriate using the off-diagonal elements in which two methods are compared across identical subsets of days.

	Data available for			
	Horizontal	Horizontal	Vertical Secchi	Electronic
	black disc	Secchi disc	disc	nephelometer
Horizontal black disc	0.5610 (n=156)	0.5387 (n=140)	0.4637 (n=86)	0.4084 (n=10)
Horizontal Secchi disc	0.5298 (n=140)	0.5214 (n=148)	0.5264 (n=77)	0.3796 (n=9)
Vertical Secchi disc	0.5661 (n=86)	0.5371 (n=77)	0.5661 (n=98)	0.4813 (n=11)
Electronic nephelometer	0.6018 (n=10)	0.6696 (n=9)	0.6344 (n =11)	0.6344 (n=11)

Figure Legends

Figure 1: Horizontal disc for measuring water clarity.



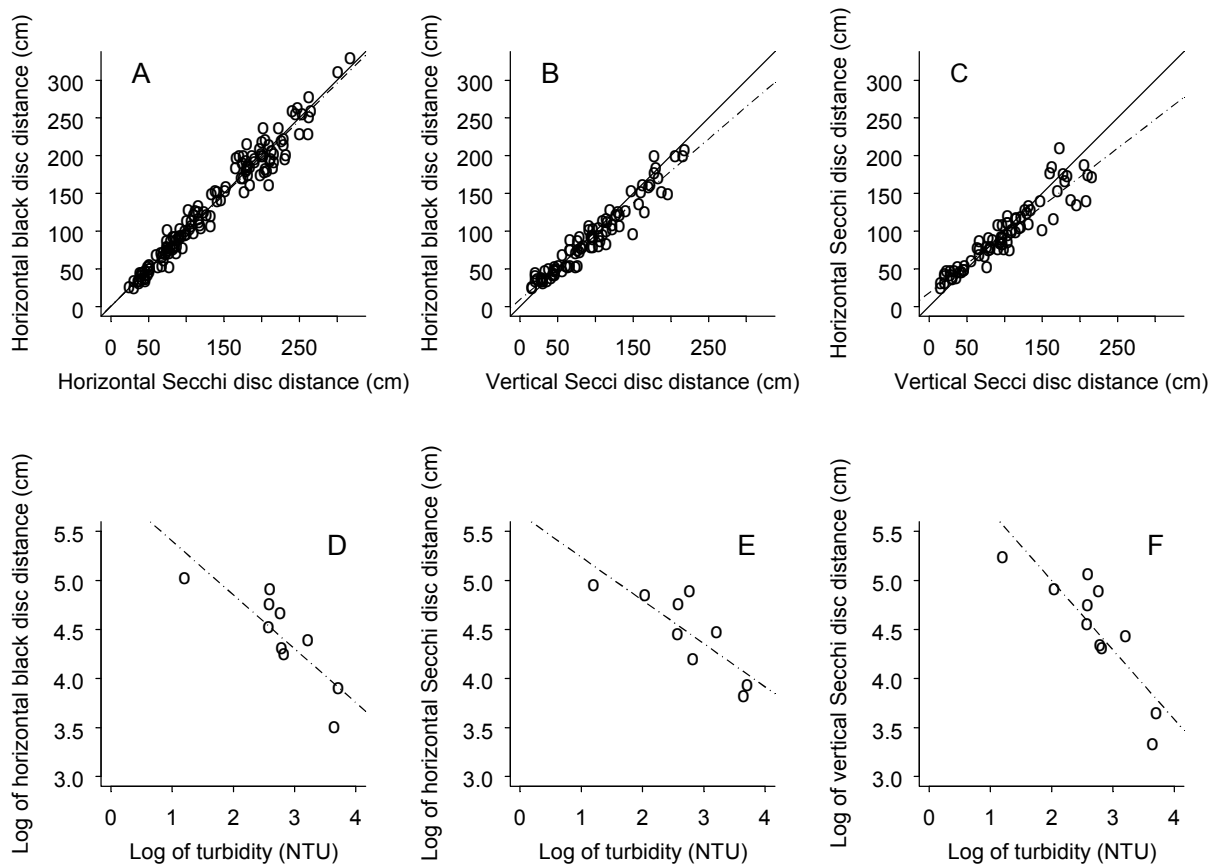


Figure 2: The relationships of (a) the horizontal black disc distance (cm) and the horizontal Secchi disc depth (cm) ($r = 0.98$) (b) the horizontal black disc distance (cm) and the vertical Secchi disc depth (cm) ($r = 0.96$), (c) the horizontal Secchi disc distance (cm) and the vertical Secchi disc depth (cm) ($r = 0.93$), (d) log horizontal black disc distance (cm) and log turbidity in NTU ($r = -0.86$), (e) log horizontal Secchi disc distance (cm) and log turbidity in NTU ($r = -0.85$), and (f) log vertical Secchi disc depth (cm) and log turbidity in NTU ($r = -0.86$). The lines in panels (a)-(c) represent a 1:1 relationship.

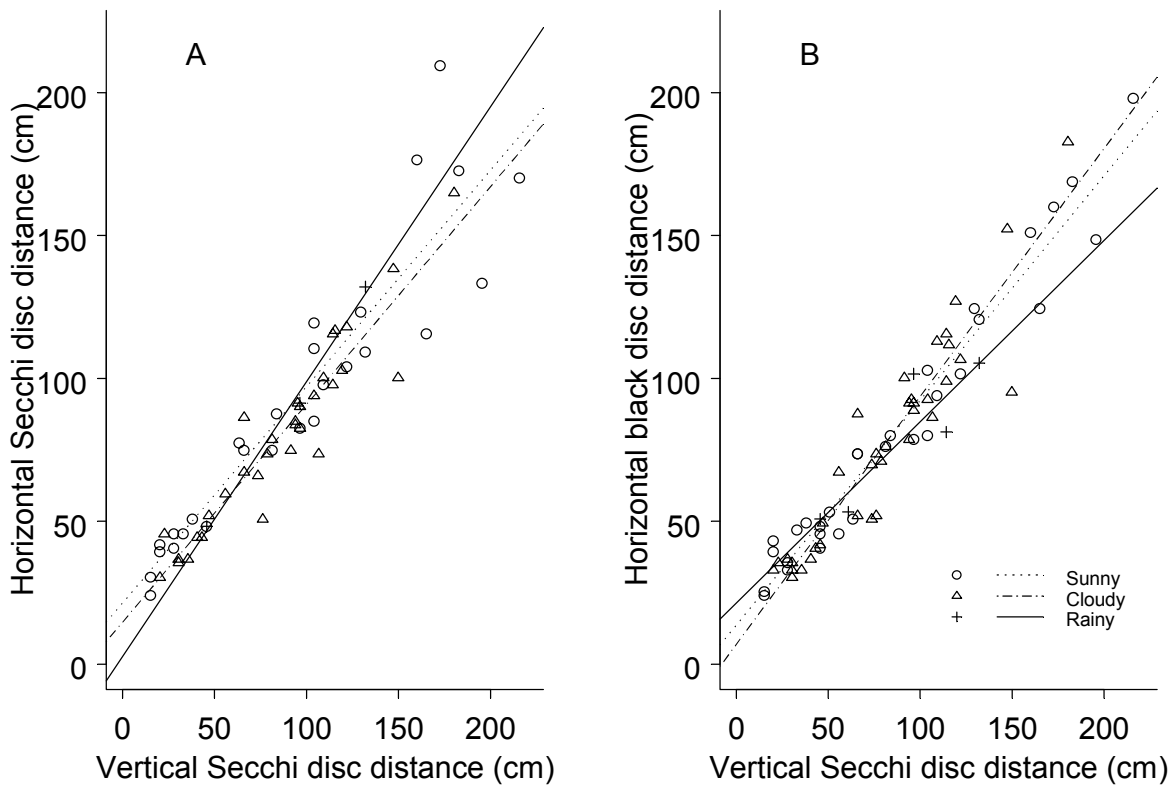


Figure 3: The relationship between (a) measurements of water clarity taken with the horizontal black disc and the vertical Secchi disc and between (b) measurements of water clarity taken with the horizontal Secchi disc and the vertical Secchi disc across three weather indicators. Plotting characters identify weather at each observation as s=sunny, c=cloudy or r=rainy. The dotted line describes the least squares regression for sunny days. The dashed line describes the least squares regression for cloudy days and the solid line represents the regression for rainy days.

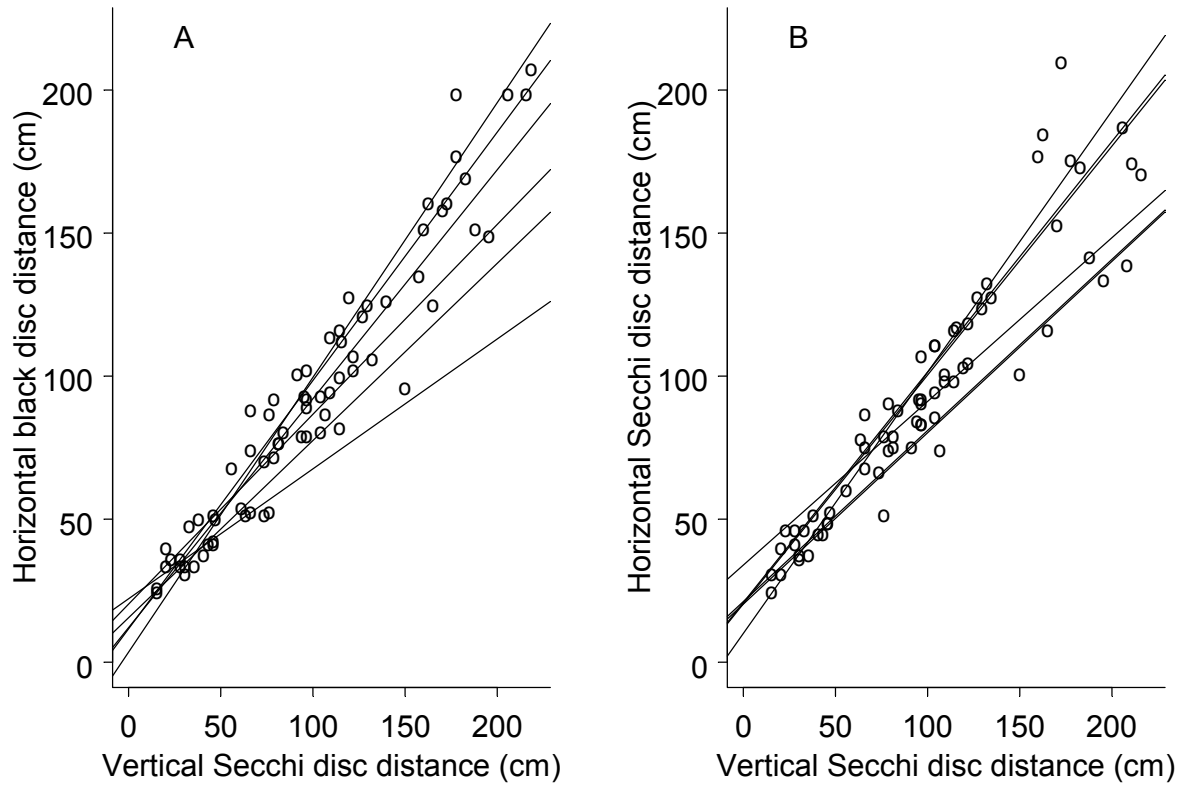


Figure 4: The relationship between (a) measurements of water clarity taken with the horizontal black disc and the vertical Secchi disc and between (b) measurements of water clarity taken with the horizontal Secchi disc and the vertical Secchi disc for six different pairs of observers. Lines represent least squares regression relationships for each observer pair.