A Comparison of Methods for Measuring Water Clarity

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Abstract

The horizontal black disc (Davies-Colley 1988) was introduced as a method for measuring water clarity that can be employed in shallow streams and fast-moving rivers. We provide a large data set, collected under variable field conditions, to compare measurements between the horizontal black disc and 2 more traditional measures of water clarity: a vertical Secchi disc and an electronic turbidimeter. We introduce a fourth technique, the horizontal Secchi disc, to isolate the effect of measurement orientation (horizontal or vertical) versus the effect of disc color. Results indicate that the horizontal black disc provides a consistent measure of visibility that is strongly correlated with both the vertical (ρ = 0.96) and horizontal Secchi discs (ρ = 0.98). Correlation between the visual discs and the electronic turbidimeter was high ($-0.8601 < \rho < -0.8489$) but not as high as within the 3 types of visual disc. The estimated coefficient of variation, a relative indicator of potential measurement error, was similar for the 3 visual methods but higher for the electronic turbidimeter. There was variation in horizontal disc readings between observers. Presence or absence of rain had an effect on the horizontal black disc readings.

Key Words: water clarity, black disc, Secchi disc, turbidity, light, visibility

Introduction

Light is a primary regulator of biological and ecological functions in aquatic systems (Vinyard and O'Brien 1976, Breitburg 1988, Barrett *et al.* 1992, Gregory 1993, Gregory and Northcote 1993, McAlary and McFarland 1993). Foraging, hunting, and predator avoidance are critical processes regulated by the quality and quantity of underwater light. Light can be measured or described in several ways, for example water clarity, visibility or turbidity. Variations in water clarity may determine the balance between predator and prey in a particular system or at a particular time, and may be key in explaining individual behaviors, species interactions, and community dynamics.

Underwater light is a function of both the solar radiation entering the water and the inherent and apparent optical properties of the body of water (Williams 1970). The inherent ability of a body of water to transmit light is described by the scattering coefficient and the absorption coefficient. The scattering coefficient reflects the degree to which a beam of light is refracted as it passes through the water column; the absorption coefficient describes the degree to which light energy is absorbed as it passes through the water column. These optical coefficients are affected by total suspended solids (TSS), water color, and water chemistry. They can be summarized by the beam attenuation coefficient; the beam attenuation coefficient is the sum of the scattering and absorption coefficients. Because these coefficients are inherent optical properties of water, they are not affected by the angle or quality of the light entering the water, by observer variation, or by other external factors. In contrast, apparent optical properties describe the perceived optical qualities of water at a specific location and time. Apparent properties may be particularly 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 variation makes them subjective and difficult to measure.

In this paper, two similar and relatively new methods for measuring visibility, the horizontal Secchi disc and the horizontal black disc, are compared with each other and with 2 traditional techniques, the vertical Secchi disc and the electronic turbidimeter.

Four methods for measuring water clarity

The Secchi disc was 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 iterations of the Secchi disc since that time but the disc in most common current use is a weighted plastic circle, approximately 30 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. Light penetration is estimated as the average of the depths at which the disc disappears and at which it reappears. The Secchi disc is a simple, inexpensive, and intuitively reasonable indicator of water clarity. The Secchi disc is, however, less precise than other techniques because it measures apparent rather than inherent optical properties of water. Secchi disc readings reflect not only the scattering and absorption coefficients of the body of water of interest, but also the reflectance of the white areas of the disc, the angle of the sun, and the roughness of the water surface (Preisendorfer 1986). The utility of the Secchi disc is limited to situations where the water is deep and there are no strong currents.

A second common measure of water clarity is turbidity, recorded in nephlometric turbidity units (NTU) with an electronic turbidimeter. Turbidity in NTU describes the degree to which a sample of water interferes with the perpendicular transmission of a beam of monochromatic light. Turbidimeters measure an inherent optical property of water; however, it is not possible to estimate the scattering coefficient directly from NTU. Turbidity in NTU refers only to the fraction of 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 index TSS. Although turbidimeters frequently provide data to 1 or 2 decimal points, the precision of this method has been questioned. Nephlometry has been criticized for lack of scientific precision, unrealistic application in environmental standards and regulations, and dependence on Formazin standards which are not reliable at high turbidity levels (Austin 1973, McCarthy *et al.* 1974, Telesnicki and Goldberg 1995).

The horizontal black disc was introduced by Davies-Colley (1988) to provide an accurate and cost effective measure of visibility that can be employed in oceans, lakes, large rivers, and shallow streams. The device consists of a black disc on a stick and a periscope, sealed with thick, clear, plastic on one end. The disc and the covered end of the periscope are placed close together underwater, then pulled apart until the disc is no longer visible through the periscope (Fig. 1). The distance at which the disc disappears is recorded as the measure of visibility. Because the black disc does not scatter light, this measure of visibility allows one to estimate the beam attenuation coefficient. Davies-Colley (1988) provided the mathematical basis for the optical properties of the horizontal black disc and described a sample of observations (N=19) from both lakes and rivers to support the use of the technique.

Since the introduction of the horizontal black disc, few researchers have applied this simple technology. Primary obstacles to wider use of the horizontal black disc may include questions about how horizontal black disc measurements relate to traditional methods of measuring water clarity, as well as concerns about precision, observer bias, and the effects of weather on visibility estimates. In this paper, the effectiveness of the horizontal black disc is examined with respect to these concerns and a slight modification, a horizontal Secchi disc, is introduced. The horizontal Secchi disc is identical to the horizontal black disc except that the disc is painted with alternating black and white quadrants and the periscope in made of white plastic. Like a traditional 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 color. The horizontal Secchi disc allows an assessment of the practical significance of measuring inherent versus apparent optical parameters.

This paper builds on previous work by considering a large data set collected under variable conditions and by comparing several methods at once. These new data describe the correlation between different methods of measuring water clarity and assess the reliability of each. Several observers collected these data over a variety of weather conditions, allowing assessment of the significance of weather and observer bias in data interpretation.

Methods

Study Site

The study site was located on the Skagit River near Mount Vernon, in western Washington State. The mean annual flow of the Skagit River at Mt. Vernon is 475 cm/s (Crumley and Stober 1984), resulting from a combination of managed releases (Ross, Diablo, and Gorge dams) and natural flow, including glacial melt. Data were collected from February to August, 1998. Flow during this period ranged from 270 cm/s to 678 cm/s (USGS). Weather conditions (sun, clouds, or rain) during data collection were recorded each day.

Horizontal discs

The horizontal black disc and the horizontal Secchi disc were used daily from February 24 through August 18, 1998 except for 25 days during which equipment was being repaired or crews were unavailable. The crew consisted of 5 primary individuals on rotating, 3-day schedules. Readings were taken in the 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. For both types of disc, the measure of visibility analyzed here was the average of the distance at which the disc disappeared and reappeared.

For the black disc method, 3 sizes of disc were used, depending on water clarity. This system 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 was necessary because contrast is provided by the black and white paint rather than the edges of the disc.

Vertical Secchi disc

A standard 30 cm plastic Secchi disc was used every morning from May 8 to August 18 except for 5 days when crews were unavailable. The vertical Secchi disc was employed from the shaded side of the drifting boat or the mid-channel fish trap.

Turbidimeter

A portable turbidimeter calibrated with Formazin was used on 11 days during the study period. Each day, 3 independent water grabs were taken with 3 replicate samples each, for a total of 9 turbidity readings. The turbidity measure on any one day was the average of all 9 readings.

Statistical analysis

Three types of computation are included in the data analysis. The unitless correlation coefficient, ρ, is used to describe the intensity of association between each pair of methods for measuring water clarity. A value of ρ 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 sample variability in relation to the sample 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 of the skewness of the data (Zar 1996, p.144).

To detect whether observer pair or weather condition (sun, clouds, rain) had a significant effect on readings taken with the horizontal discs, an analysis of covariance was conducted (Neter *et al.* 1990). Because water clarity is influenced by both daily weather conditions and season, estimation of the effect of these variables on measurements of water clarity must account for the correlation between the in-river conditions being measured and changes in weather and observer pair (some observer pairs were employed more heavily at the beginning of the season and some were employed more heavily toward the end of the season). The analysis of covariance tested whether observer pair or weather condition had a significant effect on the horizontal disc readings given current river condition, as measured with the vertical Secchi disc. In these analyses, the vertical Secchi disc readings were considered the standard and the effects of this assumption are considered.

Results

Comparisons between the four methods of measuring light

The linear relationships between data collected by different methods are described in Figure 2. Correlation is high between all 3 of the visual methods ($0.93 < \rho < 0.98$) but correspondence between methods decreases with increasing water clarity. The relationships between the electronic turbidimeter and the visual methods were consistent but less dramatic ($-0.8601 < \rho < -0.8489$).

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 that describe days when other techniques were also used. Comparisons should be made using the off-diagonal elements which represent identical time periods. For example, when comparing the black disc and the vertical Secchi disc, data from the black disc for days when the vertical Secchi disc was used (CV = 0.4637) should be compared to data from the vertical Secchi disc for days when the black disc was used (CV = 0.5661). The CV for all 3 visual methods are similar. The CV for the electronic turbidimeter is higher in all comparisons.

Weather and observer effect on the accuracy of the horizontal discs

Weather did not have a significant effect on readings made with the horizontal Secchi disc ($p = 0.24$), but it did have an effect on readings made with the horizontal black disc ($p = 0.01$). The differences in horizontal black disc readings resulted from the effects of rain.

Observer pair was significant in explaining the readings made by both the horizontal black disc ($p < 0.01$) and the horizontal Secchi disc ($p < 0.01$).

Discussion

Overall, the 3 visual discs performed similarly. All 3 techniques measured the same phenomena and the relative variability of the methods was comparable. Neither measurement orientation nor disc color had a dramatic effect on recorded water clarity and all 3 methods are most accurate at low levels of water clarity. 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 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. The results of this study suggest that variations in the light field may not have a strong influence on measurement of water clarity when such factors as orientation of the device to the sun and time of day are controlled.

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. Turbidity measurements that represent only 1 reading or the average of fewer readings would be expected to have an even higher relative variability. Electronic turbidity readings appear deceptively precise as results are often displayed to the second decimal place but this can be misleading. Turbidity readings are sensitive to imperfections in the glass measuring cell, time since the sample was agitated, polishing of the glass, or other details in the measurement process (see also Telesnicki and Goldberg 1995).

In neither analysis of the effects of weather did the difference between sunny and cloudy skies have a significant effect on the water clarity measurement. Both techniques 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. Rain was a significant factor in interpreting results from the horizontal black disc. While it might be that these results are due to the effect of rain on the vertical Secchi disc readings used as the standard measure for water clarity in these analyses, it does not appear to be the case. Rain increases surface roughness and therefore might have a strong effect on vertical Secchi disc readings which require the observer to gaze through the surface of the water. However, rain had a significant impact on only the readings from the horizontal black disc and not on the readings from the horizontal Secchi disc. The discrepancy between results from the 2 types of horizontal disc indicates that the use of the vertical Secchi disc as a standard was not the cause of the significant pattern. The importance of rain as a factor in interpreting results from the horizontal black disc is unclear but might be related to a differential impact of rain on measures of inherent versus apparent optical properties.

The significance of observer pair in interpreting readings from both the horizontal black disc and the horizontal Secchi disc indicates that ability or visual acuity of the observer influences the measurement of water clarity when using the horizontal discs. The observer effect could be due either to differences in visual acuity or to differences in skill at operating the horizontal discs. The horizontal discs require patience in handling a large buoyant periscope while keeping the target in the line of sight as well as teamwork between the person looking through the periscope and the person holding the target. Higher data variability when further distances between the periscope and the target were required (high water clarity) suggests that operator skill might be particularly important in clear waters. Potential for observer variation to influence results indicates that training and cross-validation may be important components of initiating in-field use of the horizontal discs.

In conclusion, these results recommend the use of horizontal discs for measuring water clarity. Horizontal discs are the best option for many riverine studies due to the impracticality of vertical discs in shallow streams or fast currents, but multiple readings should be considered in clear water where accurate use of the horizontal discs is more difficult. Theoretical arguments suggest that the horizontal black disc may be preferable to the horizontal Secchi disc. Our results conclude that, in the field, such theoretical differences have a minimal effect. The visual discs, though intuitively less precise than an electronic device, provide results that are cheaper and more reliable.

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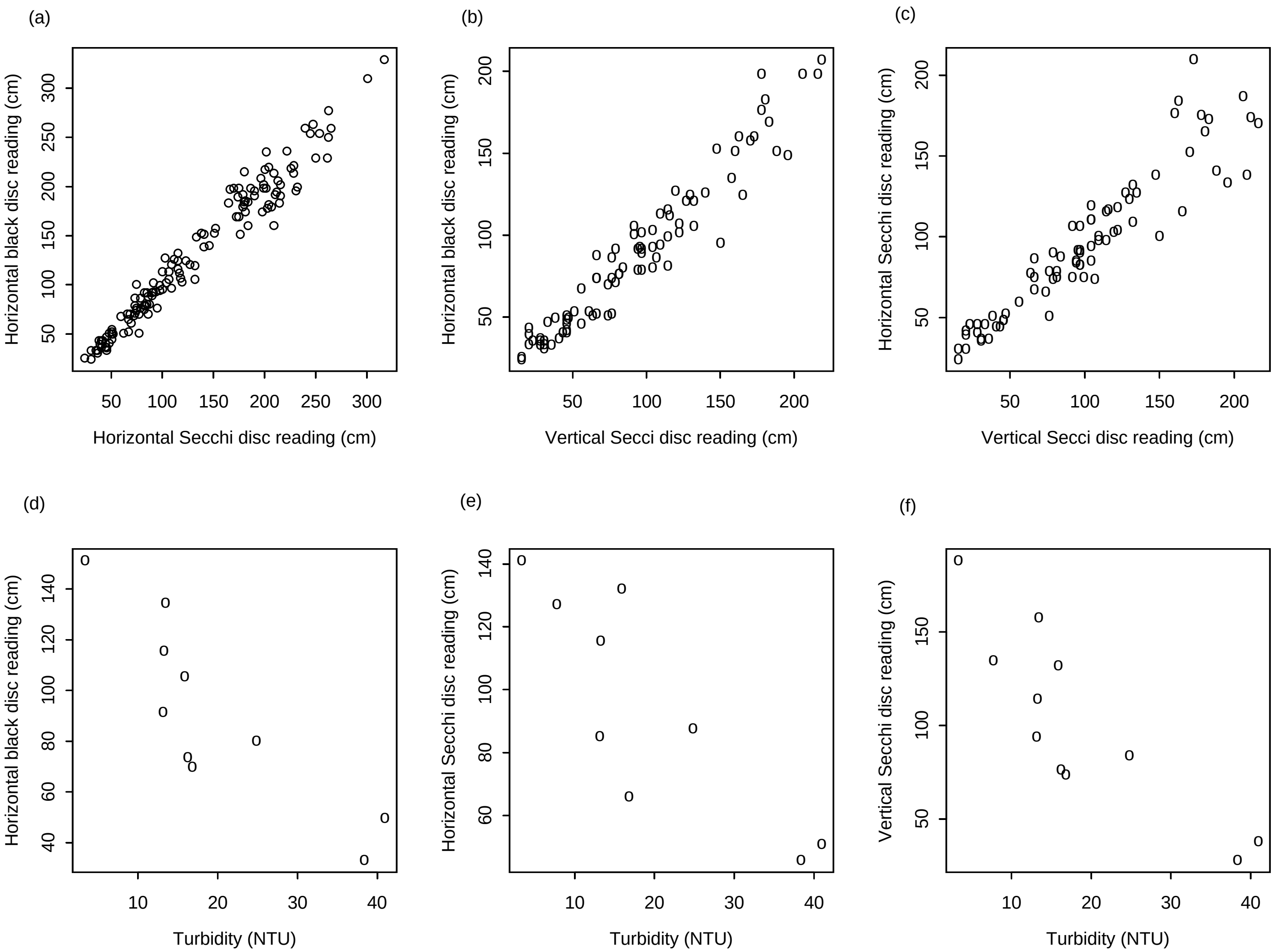
Table 1: Coefficients of variation (CV) describing the relative variability of each method of measuring water clarity over various subsets of the data. Each row includes CV for 1 method of measuring water clarity; columns represent different subsets of days for which the CV is calculated. Diagonal elements of the matrix are the CVs calculated using all available data for that method. Comparisons are most appropriate using the off-diagonal elements in which 2 methods are compared across identical subsets of days.

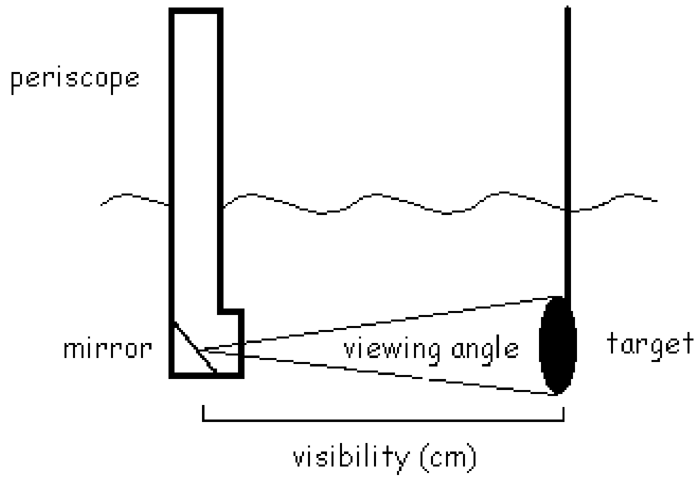
	Data available for horizontal black disc	**Data available for horizontal Secchi disc**	**Data available for vertical Secchi disc**	**Data available for electronic turbidimeter**
Horizontal black disc	0.5610 (N=156)	0.5387 (N=140)	0.4637 (N=86)	0.4084 (N=10)
Horizontal Secchi disc	0.5298 (N=140)	0.5214 (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 turbidimeter	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) (ρ = 0.98) (b) the horizontal black disc distance (cm) and the vertical Secchi disc depth (cm) (ρ = 0.96), (c) the horizontal Secchi disc distance (cm) and the vertical Secchi disc depth (cm)(ρ = 0.93), (d) the horizontal black disc distance (cm) and turbidity in NTU (ρ = -0.86), (e) the horizontal Secchi disc distance (cm) and turbidity in NTU (ρ= -0.85), and (f) the vertical Secchi disc depth (cm) and turbidity in NTU (ρ = -0.86).


(a)
Horizontal black disc reading (cm)
Horizontal Secchi disc reading (cm)
(b)
Horizontal black disc reading (cm)
Vertical Secci disc reading (cm)
(c)
Horizontal Secchi disc reading (cm)
Vertical Secci disc reading (cm)
(d)
Horizontal black disc reading (cm)
Turbidity (NTU)
(e)
Horizontal Secchi disc reading (cm)
Turbidity (NTU)
(f)
Vertical Secchi disc reading (cm)
Turbidity (NTU)


periscope
mirror
viewing angle
target
visibility (cm)