Measuring Water Clarity With a Black Disc

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1 author:

Robert James Davies-Colley
National Institute of Water and A...

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Abstract—Black targets have a major theoretical advantage over reflective targets such as the Secchi disk for assessing the visual clarity of water because their sighting ranges depend only on two optical properties of the water: the beam attenuation coefficient and the diffuse attenuation coefficient. The theory of visibility of black objects applies to observations made with a black disk in 11 rivers and eight lakes ranging 60-fold in water clarity. The horizontal sighting range of the black disk is similar to visual ranges of practical importance in water, for aquatic animals as well as man, and yields an immediate estimate of the beam attenuation coefficient. The black disk is expected to be of particular value for assessing the clarity of river waters that are too shallow for deployment of the Secchi disk.

The Secchi disk has proved itself as an index of visual water clarity over many years in work on lakes and marine waters (Tyler 1968). This device is valued for its robust simplicity and immediate yield of information. Unfortunately, the Secchi disk is often not useful in rivers. In New Zealand, many rivers are fast-flowing, relatively shallow, and generally clear at low flows, presenting severe problems for deployment of the Secchi disk. The disk is often visible on the bottom but even in "optically deep" river waters, it must be heavily weighted to hold the graduated line vertical in the current. Observations can sometimes be made from a boat while drifting in the current, but this may be a hazardous procedure with the potential for fouling a snag.

Some workers have attempted to circumvent the problem of insufficient depth for vertical Secchi observations by viewing the disk horizontally. Unfortunately, the horizontal visual range depends on viewing direction. When viewed toward the sun, the disk is observed in shadow against the water background making it less visible than when it is viewed away from the sun and is brightly lit.

As well as having severe practical limitations for use in rivers with fast currents and shallow water depths, the Secchi disk also has some theoretical limitations. The Secchi depth, while mainly dependent on the composition of a water, is also dependent on the directional structure and spectral quality of the ambient light field. The Secchi depth is therefore an *apparent* optical property in contrast to *inherent* optical properties which depend only on water composition (Preisendorfer 1961).

An ideal measure of visual water clarity would be an inherent optical property permitting direct comparison of water bodies. The appropriate inherent optical property is c, the beam attenuation coefficient. This coefficient quantifies the attenuation of a collimated light beam resulting from the two optical processes of absorption and scattering ($c = a + b$ where a and b are the absorption and scattering coefficients respectively: Jerlov 1976). It likewise quantifies the attenuation of image-forming light rays.

Although the Secchi depth, z_{SD}, is roughly inversely related to c, visibility measurements with the Secchi disk cannot be used to accurately estimate c. Indeed Tyler (1968) and Preisendorfer (1986) have shown that Secchi depth is inversely proportional to, not c, but the sum $c + K$, where K is the attenuation coefficient for diffuse ambient light. Gordon and Wouters (1978) and Hojerslev (1986) showed that c is approximately inversely proportional to z_{SD} (because K covaries with c). The product $z_{SD}c$ varies from <6 to >9, however, depending

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Table 1. List of main symbols, their definitions and units.

Symbol	Explanation	Units
a	Absorption coefficient	m^{-1}
b	Scattering coefficient	m^{-1}
B	Luminance	lumens m^{-2} sr^{-1}
B_b	Background luminance	lumens m^{-2} sr^{-1}
c $(=a + b)$	Beam attenuation coefficient	m^{-1}
C_0	Inherent contrast (range = 0)	dimensionless
C_r	Apparent contrast (range = r)	dimensionless
C_T	Threshold contrast	dimensionless
E	Irradiance	W m^{-2}
I	Illuminance	lumens m^{-2} ≡ lux
K	Illuminance attenuation coefficient	m^{-1}
K_m	Maximal luminous efficiency	683 lumens W^{-1}
Q	River discharge	m^3 s^{-1}
R	Reflectance coefficient	%
r	Range or distance	m
y	Horizontal sighting range of the black disk	m
$\bar{y}$	Phototopic sensitivity function for the "standard" human eye	dimensionless
z	Depth, vertical sighting range of the black disk	m
z_{SD}	Secchi disk sighting range (Secchi depth)	m
Γ	Visual range of the Secchi disk in units of attenuation length, $1/(c + K)$	dimensionless
θ	Vertical angle of the path of sight	degrees, rad.
λ	Wavelength	10^{-9} m = nm
ψ	Visual range of the black disk in units of attenuation length, $1/c$ or $1/(c + K)$	dimensionless

on the ratio of scattering to absorption, on the angular dependence of scattering, and on the ambient light field.

I wanted to devise a simple technique for field clarity measurement which, unlike the Secchi observation, would be useful in clear, shallow, and fast-flowing rivers and would permit accurate estimation of c. According to Duntley (1962, 1963) an all-black target (black body), viewed horizontally, yields an estimate of the beam attenuation coefficient that is independent of ambient lighting and of the scattering-to-absorption ratio and the angular dependence of scattering in the water. This is essentially an application to water of the Koschmieder (1924, *cited by* Middleton 1952) method for measuring visual range in air with a large black body as the target. Lythgoe (1971) advocated the use of a black target to characterize visual clarity of water and maintained that the black body range is "far superior" to the Secchi depth. Lythgoe (1971) also discussed a method for precise estimation of c from horizontal observations by divers with a device that visually matched the brightness of the target at different ranges to that of the background in a split field, using neutral filters of different optical density.

Precisely because the black body observation must be made in the horizontal direction to yield an estimate of c (as explained below), the measurement does not demand appreciable water depths. (Depths about 50% greater than the visual range are required for vertical observations, e.g. with a Secchi disk.) This characteristic suggests application to shallow and clear water bodies, particularly rivers. The black body range permits estimation of c, however, over a wide range of water clarity.

The general problem of visibility involves attenuation of *contrast* of an image with respect to background. To be seen an object must contrast in color (hue, brightness, or saturation) with its surroundings. Here we are concerned only with brightness contrast defined as

$$C_0 = \frac{B - B_b}{B_b} \qquad (1)$$

where B is luminance (informally the brightness) of the object and B_b is luminance of the background. The definitions and units of the symbols used here are given in Table 1. Luminance (the photometric equivalent of radiance) is the luminous flux ("light" as seen by the human eye, measured in lumens) per square meter of cross-sectional area facing a given direction per unit of solid angle (in steradians) centered on that direction.

Visibility theory, as applied to water by Duntley et al. (e.g. Duntley 1962, 1963), confirmed by many experiments, shows that in deep, optically homogeneous water contrast is attenuated exponentially. At range r the apparent contrast is

$$C_r = C_0 \exp[-(c + K \cos \theta)r] \qquad (2)$$

where θ is the vertical angle of the path of sight.

In Eq. 2, c quantifies the attenuation with distance of luminance reflected from the target. Thus c can be referred to as the *photopic* beam attenuation coefficient (Preisendorfer 1986). The apparent optical property K quantifies the attenuation of diffuse ambient light (illuminance, I) with depth, z, in a water body. By definition

$$K = -\frac{d \ln I}{dz} = -\frac{1}{I}\frac{dI}{dz}. \qquad (3)$$

Equation 2 implies that maximal visual range will occur at the threshold of conscious sighting when C_r is reduced to a low value, C_T. Threshold contrasts as a function of adaptive lighting and angular size have been reported for circular targets by Blackwell (1946). The apparent contrast depends on the inherent contrast of the target, C_0, as well as on water clarity as quantified by $(c + K \cos \theta)$. In the Secchi disk experiment the inherent contrast is maximized because the target is coated with highly reflective white paint and is viewed vertically ($\theta = 0°$, $\cos \theta = 1$) against the relatively dark background water color. By inverting Eq. 2 and setting r equal to the Secchi disk depth, z_{SD} (Preisendorfer 1986), we obtain

$$z_{SD} = \frac{\ln(C_0/C_T)}{c + K} = \frac{\Gamma}{c + K}. \qquad (4)$$

Tyler (1968) estimated that C_0 for the Secchi disk is about 40. However, C_0 varies with background water luminance, which depends mainly on the reflectance coefficient—the ratio of upwelling to downwelling illuminance (Davies-Colley and Vant 1988). Because the inherent contrast of the Secchi disk varies between waters and indeed varies in the same water with different paths of sight, it is not possible to use the Secchi depth in any simple way to precisely estimate the optical properties c or K, or even their sum, $c + K$ (Preisendorfer 1986).

In contrast to the bright Secchi disk, an all-black target (black body) reflects no light and thus is seen as a silhouette. The inherent contrast is -1, irrespective of background luminance. Sighting range depends only on the attenuation coefficients for the water and not on the ambient light field or reflectance coefficient. Equation 2 can be recast to give the maximal visual range for a black body for which $C_0 = -1$. For vertical sighting ($+z$ direction, $\theta = 0°$, $\cos \theta = 1$) we obtain an expression of the same form as Eq. 4:

$$z = \frac{\ln(-1/C_T)}{c + K} = \frac{\Psi}{c + K}. \qquad (5)$$

Ψ, unlike Γ, does not depend on optical properties of the water or on the ambient light field. Indeed, given sufficient light and a sufficiently large target, C_T is nearly constant (Blackwell 1946), and thus Ψ [$=\ln(-1/C_T)$] can be regarded as approximately constant.

For horizontal sighting (y direction, $\theta = 90°$, $\cos \theta = 0$) Eq. 2 yields the following expression for the maximum visual range:

$$y = \frac{\Psi}{c}. \qquad (6)$$

This equation shows that a direct estimate of c can be obtained from a measurement of the horizontal visual range of a large, black target, provided Ψ is known. In principle, if both horizontal and vertical sighting ranges of a large black target are measured, both c and K can be estimated.

The nearest practical approach to an ideal black body is a black cavity. However a more practical (almost-black) target for visibility assessment in water is simply a disk

Table 2. Visibility measurements and optical data for eight lakes and 11 rivers. All black disk observations were made with a 200-mm-diam disk unless otherwise noted. The reflectance coefficient R ($=I_u/I_d$) is for the midpoint of the photic zone.

Site		Time (hours)	z_{SD} (m)	R (%)	K (m^{-1})	c (m^{-1})	y (m)	Ψ_y	z (m)	Ψ_z
Lakes										
Taupo	14 Apr 87	1200	17.7	2.38	0.129	0.286	16.2	4.63	8.05	3.34
Okataina*	13 Nov 86	1330	12.75	2.13	0.140	0.386	9.80	3.78	6.70	3.52
Tikitapu*	14 Nov 86	1200	6.35	3.00	0.248	0.98	5.00	4.92	3.70	4.53
Rotomanuka	19 Nov 86	1230	4.00	0.55	1.01	1.91	2.80	5.35	2.00	5.84
Karapiro†	18 Nov 86	0900	2.60	2.11	0.68	3.28	1.60	5.25	1.30	5.15
Ngaroto†	18 Nov 86	1300	0.65	2.06	3.12	13.50	0.38	5.13	0.31	5.15
Waahi*	15 Apr 87	1130	0.42	12.4	2.98	20.4	0.29‡	5.92	0.24‡	5.61
Hakanoa	15 Apr 87	1320	0.45	5.6	4.28	21.8	0.265‡	5.78	0.23‡	6.00
Rivers										
Waimana	25 Feb 87	1300	—	—	—	0.557	8.4	4.68	—	—
Waioweka	25 Feb 87	1100	—	—	—	0.589	7.5	4.42	—	—
Kauerangat†	7 Jan 87	1200	—	—	—	0.585	7.5	4.39	—	—
Waihou	3 Dec 86	1600	—	—	—	0.615	7.3	4.49	—	—
Waimakariri (NI)	3 Dec 86	1100	—	—	—	0.89	4.70	4.20	—	—
Waipapa	26 Feb 87	1340	—	—	—	1.23	3.50	4.31	—	—
Mangakino	26 Feb 87	1120	—	—	—	1.43	3.25	4.64	—	—
Whakatane	25 Feb 87	0900	—	—	—	1.44	3.20	4.62	—	—
Tahuaatura	26 Feb 87	0900	—	—	—	1.87	2.80	5.25	—	—
Kaniwhaniwha*	14 Jan 87	0950	—	—	—	1.66	2.70	4.49	—	—
Waipa	14 Jan 87	1500	—	—	—	2.15	2.35	5.04	—	—

* Partly cloudy.
† Overcast.
‡ Made with a 100-mm disk.

constructed identically to the standard white (or black-and-white) Secchi disk, but painted completely black (e.g. Hojerslev 1986). Black "Secchi" disks of 200- and 100-mm diameter were used in the present study in eight lakes and 11 rivers of diverse optical character (Table 2).

Open-water stations were occupied in the central basins of lakes. Secchi disk observations were made with an underwater viewer on the sunny side of the boat as recommended by Tyler (1968). In the rivers Secchi disk measurements were not possible because of insufficient water depth. Visual ranges of a 200-mm-diameter black disk were observed in the horizontal direction in both rivers and lakes. Vertical ranges of the sighting black disks were also measured in the lakes. Observations of the black disk in lakes were made by snorkeling except in the most light-attenuating waters: Waahi and Hakanoa. In these two lakes and in the rivers, black disks were observed with an underwater viewer I designed. In Waahi and Hakanoa, a 100-mm-diameter black disk was used, rather than the "standard" 200-mm disk, so that the whole area of the target could be seen in the field of view of the underwater viewer.

The underwater viewer was a box made of 3-mm-thick, optically clear, sheet polycarbonate, painted matte black on the inside except for end and side windows (Fig. 1). The side window was used for right-angle viewing (horizontal direction in the water) with a small mirror fitted at 45°. This mirror was easily removed for vertical viewing through the end window. Early observations demonstrated no significant difference between black disk visibility by viewer vs. diver.

The procedure used for vertical observations of the black disk was identical to that for observations of the Secchi disk. Horizontal observations were made with the black disk fixed to a black-painted pole held by the observer's assistant (Fig. 1). Care was taken to ensure that the ambient light field in the water behind the disk, and alongside the path of sight, was not disrupted, e.g. by

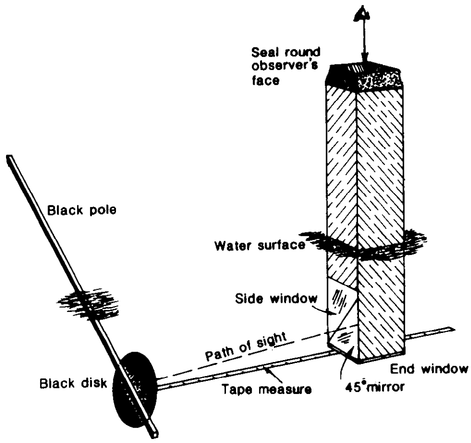

Fig. 1. Underwater viewer fitted with a mirror at 45° for observing the black disk horizontally in water.

the shadow of a boat. Otherwise the horizontal black disk observation was also identical to the Secchi disk observation.

The beam attenuation coefficient for luminance was calculated from the beam transmittance measured with a transmissometer (Martek XMS) fitted with a green filter to approximate photopic response. This instrument measures the transmittance, T, of a light beam over a 0.25-m path in water with reference to calibration in air (Petzold and Austin 1968) and c is calculated as $(1/0.25\ \mathrm{m})\ln(1/T)$.

To estimate the diffuse attenuation coefficient K, I measured spectral irradiance at several depths with a submersible spectroradiometer (LiCor 1800 U/W). An irradiance scan at a given depth was comprised of measurements of spectral irradiance, $E(\lambda)(\mathrm{W\ m^{-2}\ nm^{-1}})$, at 5-nm intervals over the range of 350–750 nm. Spectral irradiance scans were integrated numerically to obtain estimates of illuminance I:

$$I = K_m \int_0^\infty \bar{y}E(\lambda)\, \mathrm{d}\lambda \qquad (7)$$

where K_m is the maximum luminosity and $\bar{y}$ the photopic sensitivity function for the human eye (Opt. Soc. Am. 1966). The diffuse attenuation coefficient for illuminance, K, was calculated by linear regression of $\ln I$ on z from near-surface to Secchi depths.

The waters sampled are noteworthy in covering a 60-fold range in clarity as measured by horizontal visibility of the black disk, y, from 0.27 m in hypereutrophic Lake Hakanoa to 16.2 m in oligotrophic Lake Taupo (Table 2). Data for both lakes and rivers closely fitted a line of -1 (log-log) slope in accordance with the hyperbolic relationship of Eq. 6 (Fig. 2). Vertical sighting range of the black disk plotted against $c + K$ in Fig. 3 again falls on a (log-log) slope of -1, although there is somewhat more scatter. The theory of visibility of submerged black bodies thus applies to the black disk observed with the procedures reported here. The Secchi depth (Fig. 3) was about twice the vertical sighting range of the black disk.

The lines with -1 slope in Figs. 2 and 3 correspond to the calculated average values of Ψ defined in Eq. 5 and 6. For the nineteen horizontal visibility observations the average value of $\Psi_y = yc = 4.80$ (C.V. = 11.3%). Similarly $\Psi_z = z(c + K)$ averaged 4.89, but the data were more variable (C.V. = 20.7%). These average values of Ψ correspond to threshold contrasts (C_T values) of 0.0082 and 0.0075 respectively. Hojerslev (1986) obtained a very similar average threshold for Secchi disk observations in the Baltic Sea ($C_\mathrm{T} = 0.0070$). Tyler (1968) estimated $C_\mathrm{T} = 0.0066$ for the Secchi observation, based on Blackwell's (1946) tables.

The average value of $\Gamma = z_\mathrm{SD}(c + K)$ for the Secchi disk data in Fig. 3 was 9.52, approximately double Ψ_z. Rather surprisingly the scatter in the Secchi disk data in Fig. 3 (C.V. = 20.9%) is very similar to that for black disk data. Appreciably more scatter in Secchi data than in black disk data was expected because, theoretically, Γ depends on the ratio of scattering to absorption and on ambient lighting (Davies-Colley and Vant 1988). The probable explanation is that, in the lakes studied here, the ratio $b:a$ was not particularly variable. This is indicated by the fact that the reflectance coefficient, R (which is approximately proportional to $b:a$, e.g. Kirk 1981), varied relatively little (R averaged 2.6%, excluding R = 12% in Lake Waahi: Table 2).

The points in Figs. 2 and 3 tend to plot slightly above the average lines at low clarity and slightly below at high clarity in both figures, indicating a trend of Ψ with clarity

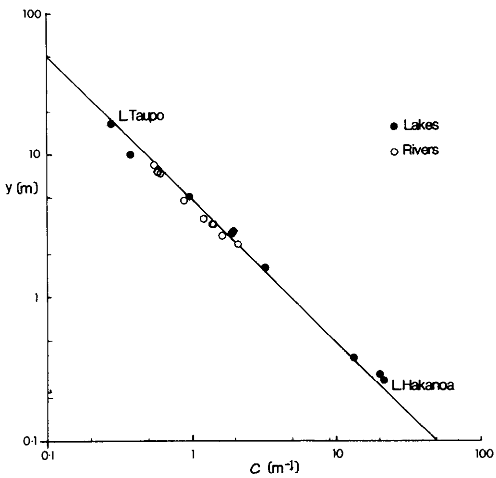

Fig. 2. Horizontal sighting range of the black disk (y), plotted against the beam attenuation coefficient (c). The line corresponds to the average value of $\Psi_y = 4.80$.

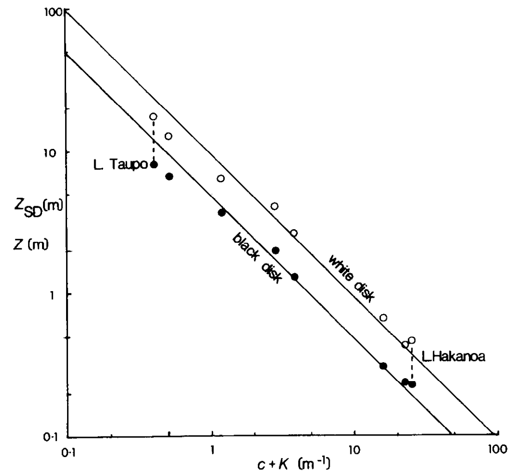

Fig. 3. Vertical sighting ranges of the black disk and Secchi disk plotted against the sum of attenuation coefficients ($c + K$). The lines correspond to the average values of Ψ_z (=4.89) and Γ (=9.52). Data for lakes only (vertical observations were not made in rivers).

($P < 0.05$). As the angle subtended by the target at the eye decreased with increased visual range, Ψ apparently also decreased. The trend in Γ with clarity is approximately log-linear and the following regression equations were fitted:

$$\Psi_y = 5.207 - 0.368 \ln y \quad (n = 19,\ r^2 = 0.62);$$

$$\Psi_z = 5.048 - 0.562 \ln z \quad (n = 8,\ r^2 = 0.67).$$

On the basis of Blackwell's (1946) experiments, we would expect a decrease in ψ corresponding to an increase in threshold contrast with decrease in angular size of the target. It is difficult, however, to explain the magnitude of the observed change in view of the angular size of the black disk and the lighting conditions encountered in this study. Even in very clear Lake Taupo the angular size of the disk at extinction, taking into account the magnifying effect of refraction at the diver's faceplate, was 0.9°, sufficiently large to be regarded as a "large" target according to Blackwell's (1946) tables.

Blackwell's data do show that, at low lighting levels, threshold contrast changes rapidly with angular size, even for large targets. In the present study, however, the lighting should have been adequate (i.e. $\gtrsim 10$ lumen $m^{-2}\ sr^{-1}$) even with vertical viewing in the darkest waters. Over the experimental angular size range and lighting levels from Blackwell's (1946) tables, we would expect C_T to vary in the range 0.005–0.010, corresponding to a 14% variation in Ψ. The measured values of Ψ_y changed by about 40%, and Ψ_z by nearly a factor of two, for reasons that are obscure but may relate to uncontrolled "field factors" influencing visual tasks (Taylor 1964).

Except for the change in Ψ over the very wide range of clarity investigated, the conformity to theory of the data for horizontal viewing justifies use of Eq. 7 to estimate the beam attenuation coefficient, c, from the horizontal sighting range, y. With an allowance made for trend in Ψ_y with y (using the regression equations given above), the standard error of the estimate of c is about 7%, which represents remarkably good precision.

An alternative (and perhaps preferable) procedure to correcting for trend in Ψ would be to use different-sized disks in waters of different clarity, in order to keep angular size nearly constant, say in the range 2–10° of arc. The "standard" 200-mm-diameter black disk would be suitable for waters of moderate clarity ($1.5 < y < 5$ m). For clear waters ($5 < y < 15$ m) a disk of 600-mm diameter would be used. For very clear

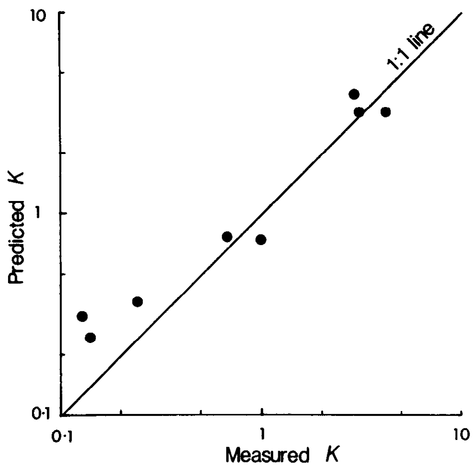

Fig. 4. Comparison of measured values of the illuminance attenuation coefficient (K) with values calculated from sighting ranges of vertical and horizontal black disks.

waters ($y > 15$ m, e.g. Lake Taupo) targets of 1 m or greater in size should be used but would be awkward for routine work. At the other extreme, in turbid waters ($0.5 < y < 1.5$ m) a black disk of 60-mm diameter would be appropriate, and for very turbid waters ($y < 0.5$ m, e.g. Lake Hakanoa) a 20-mm-diameter disk would be used.

Where both horizontal and vertical black disk observations have been made it should be possible to estimate the diffuse attenuation coefficient, K, as

$$\hat{K} = (c + \hat{K}) - \hat{c} = \frac{\bar{\Psi}_z}{z} - \frac{\bar{\Psi}_y}{y} \quad (8)$$

in which the caret denotes an estimated, rather than a directly measured quantity. There is overall agreement of measured and calculated K values but with considerable scatter (Fig. 4). K was in error by a factor >2 in Lake Taupo, but agreement was better in the more turbid lakes. Most of the error in $\hat{K}$ derives from taking the difference between $(c + \hat{K})$ and $\hat{c}$ which are typically nearly equal numbers because $c \gg K$. The standard error in $\hat{K}$ is about 50% in Fig. 4, although it improves to about 35% when a correction is made for trend in Ψ with angular size of the disk. Thus, the precision with which K can be estimated is rather low. The black disk may not live up to its promise of providing an accurate estimate of K as well as c, but then neither can the Secchi disk be used to estimate K accurately (Davies-Colley and Vant 1988).

Besides the already noted theoretical and practical advantages of the black disk over the Secchi disk, there is a further advantage. The visual range of the black disk is more similar to sighting ranges of practical importance underwater than is visual range of a high-contrast target like the Secchi disk. Duntley (1963) reported that the sighting range of a great variety of commonly encountered submerged objects is about 4–5 attenuation lengths [i.e. 4–5 times $1/(c + K \cos \theta]$, similar to the black disk range at about 4.8 attenuation lengths. This correspondence suggests that the inherent contrast of many objects underwater is not very different from an absolute value of unity. For example the sighting range of fish, being large, low-contrast (often counter-shaded) targets (Lythgoe 1979), is likely to be similar to the black disk range. The possibility of obtaining fairly accurate estimates of c from measurement of the black disk range may prove to be of practical value in studies of the visual behavior of aquatic animals. It is the beam attenuation coefficient, more than any other factor, which controls visual ranges underwater, for animals as well as for man (Lythgoe 1979).

The black disk is evidently a better tool than the white disk for assessing river water clarity. The white disk can seldom be viewed vertically in rivers, and horizontal measurements are significantly dependent on viewing direction, whereas the black disk can be viewed horizontally to provide a measure of visual water clarity (y) and, in turn, an estimate of the beam attenuation coefficient, c. Because c, being an inherent optical property, is rigorously additive, we can write an "attenuation balance" for a reach of river in which a tributary or effluent inflow occurs: $c_d Q_d = c_u Q_u + c_{in} Q_{in}$, in which Q is discharge and the subscripts denote the inflow and river sites upstream and downstream of the inflow. Thus the black disk provides a simple means for predicting the effect on visual water clarity of a turbid inflow to a river.

In conclusion, the black disk method for assessing visual water clarity conforms to the theory of visibility for large, dark objects. The black disk seems unlikely to supplant the Secchi disk for assessing clarity of lake waters, if only because of the need for continuity of existing data sets (e.g. Davies-Colley 1987). The black disk has significant practical as well as theoretical advantages for measuring visual water clarity, however, particularly in rivers where deployment of the Secchi disk is difficult.

Robert J. Davies-Colley

Water Quality Centre
Ministry of Works and Development[1]
Private Bag
Hamilton, New Zealand

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[1] The Water Quality Centre is now part of the Department of Scientific and Industrial Research, Box 11-115, Hamilton, New Zealand.

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