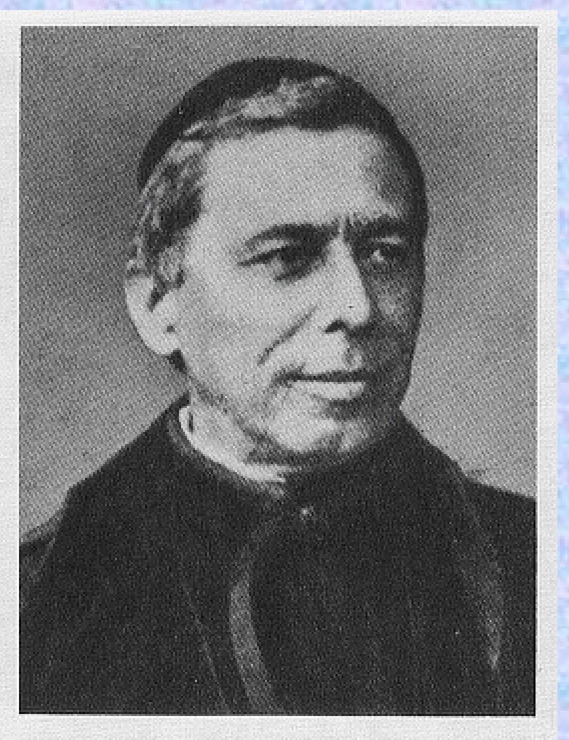
# Radiative transfer of the Secchi/black disk*

- What is the Secchi disk and why is it used?
- What does the Secchi depth depends on?
- How can we improve Secchi depth readings?
- The horizontal and black disk.

Angelo Secchi, 1818-1878

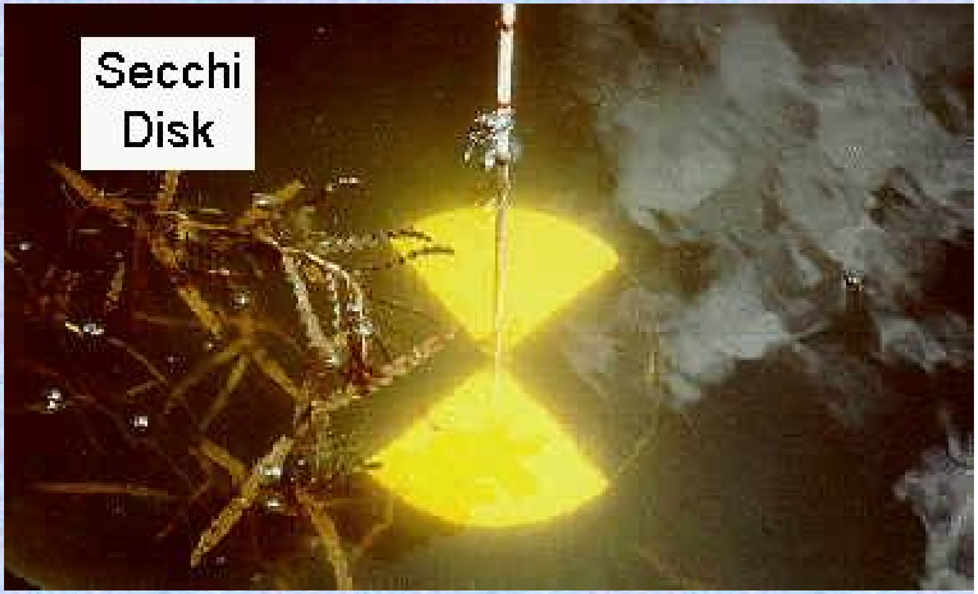


http://www.hao.ucar.edu/public/education/sp/images/secchi.gif

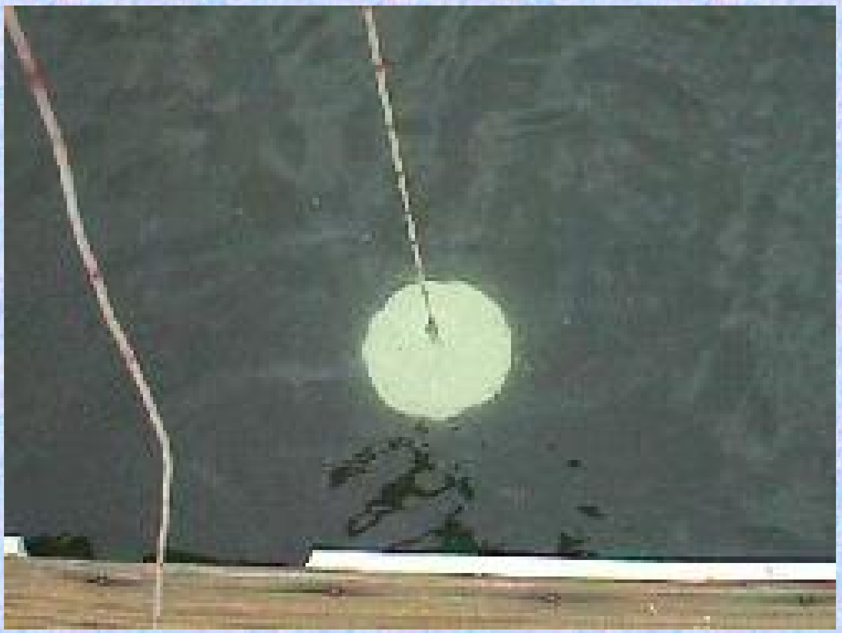
The Secchi disk originated with Fr. Pietro Angelo Secchi, an astrophysicist, who was requested to measure transparency in the Mediterranean Sea by Commander Cialdi, head of the Papal Navy. Secchi was the scientific advisor to the Pope. Secchi used some white disks to measure the clarity of water in the Mediterranean in April of 1865. (http://www.mlswa.org/secchi.htm)

*with some input from a talk by M. Lewis

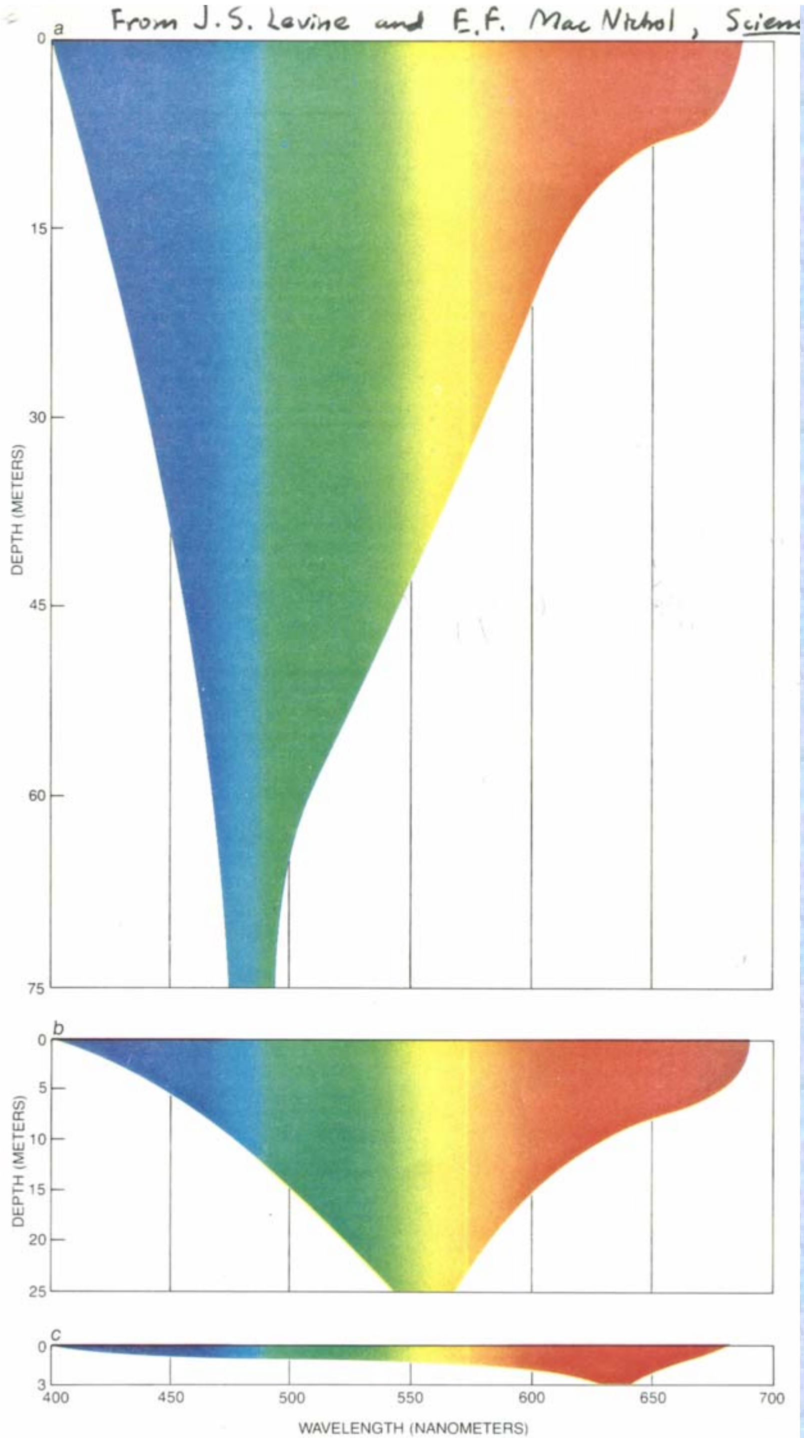
# Secchi disks images from WWW:




http://www.epa.state.il.us/water/conservation-2000/volunteer-lake-monitoring/secchi-disk.jpg



So what is the secchi depth depending on?




# Why does the Secchi disk depth vary?

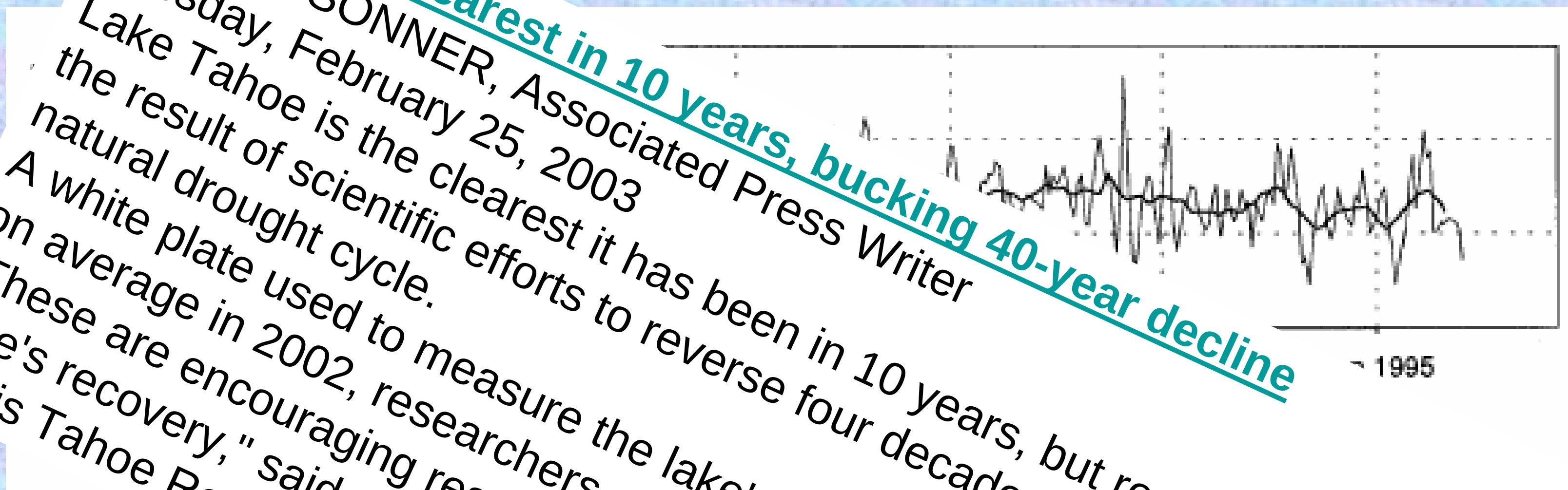
Blue ocean

Coastal ocean

Inland pond

O ervation of Secchi disk detailing long term change:

**Lake t al., 1999):**




## Lake Tahoe clearest in 10 years, bucking 40-year decline

- SCOTT SONNER, Associated Press Writer

Tuesday, February 25, 2003

Lake Tahoe is the clearest it has been in 10 years, but researchers don't know if it's the result of scientific efforts to reverse four decades of declining clarity or part of a natural drought cycle.

A white plate used to measure the lake's clarity could be seen as deep as 78 feet on average in 2002, researchers announced Tuesday.

"These are encouraging results and we hope they indicate the beginning of the lake's recovery," said Charles Goldman, director of the University of California-Davis Tahoe Research Group.

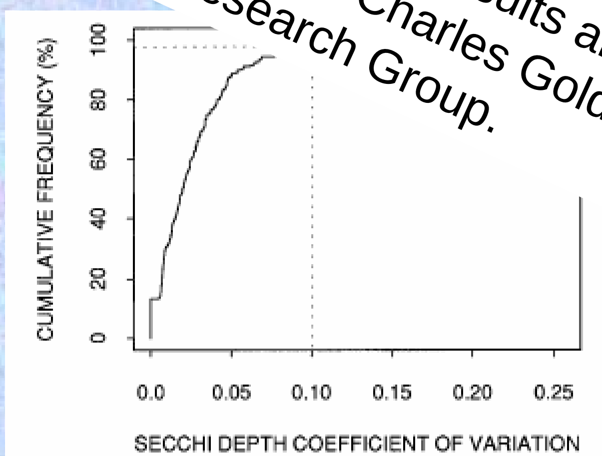
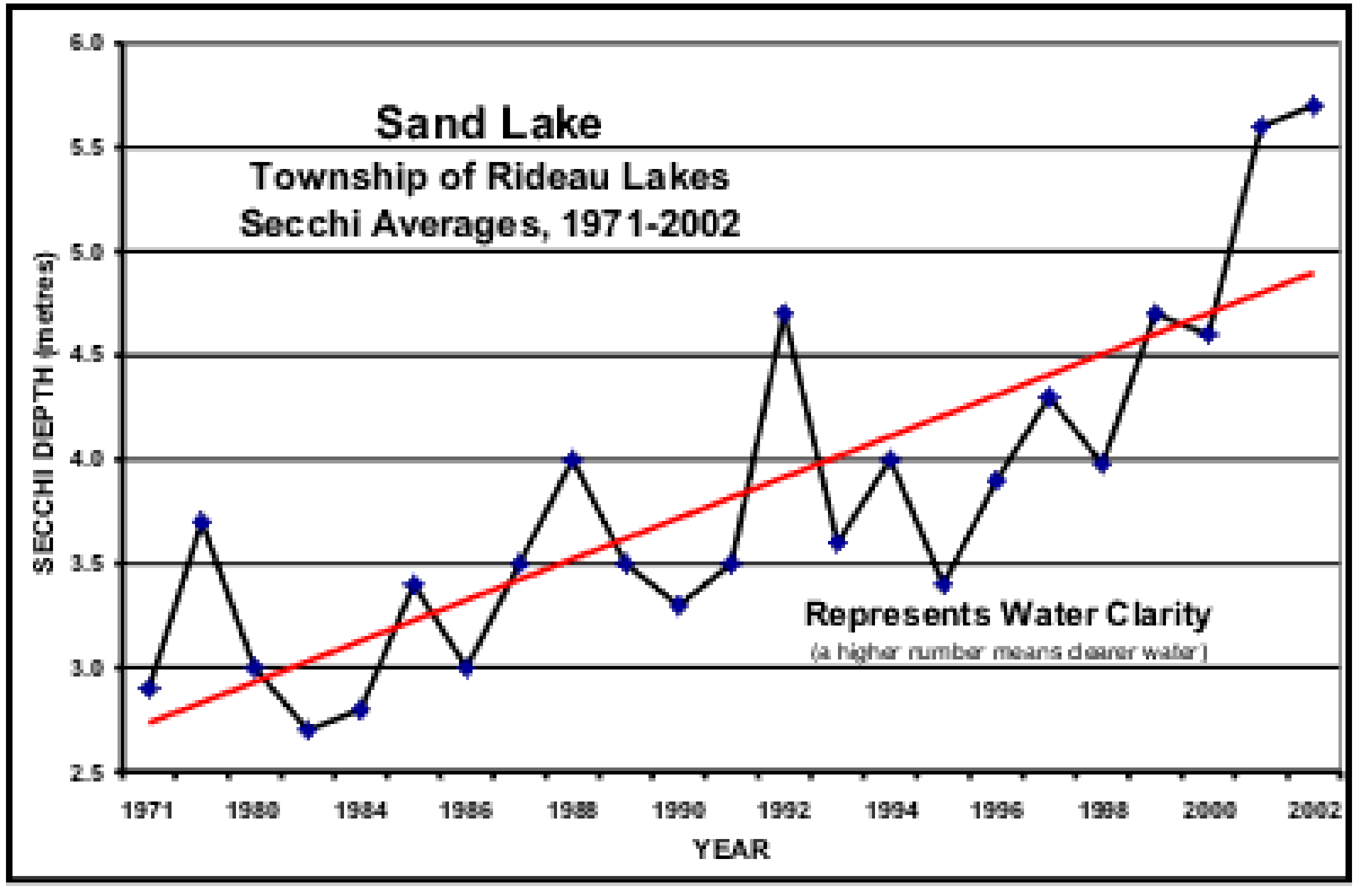


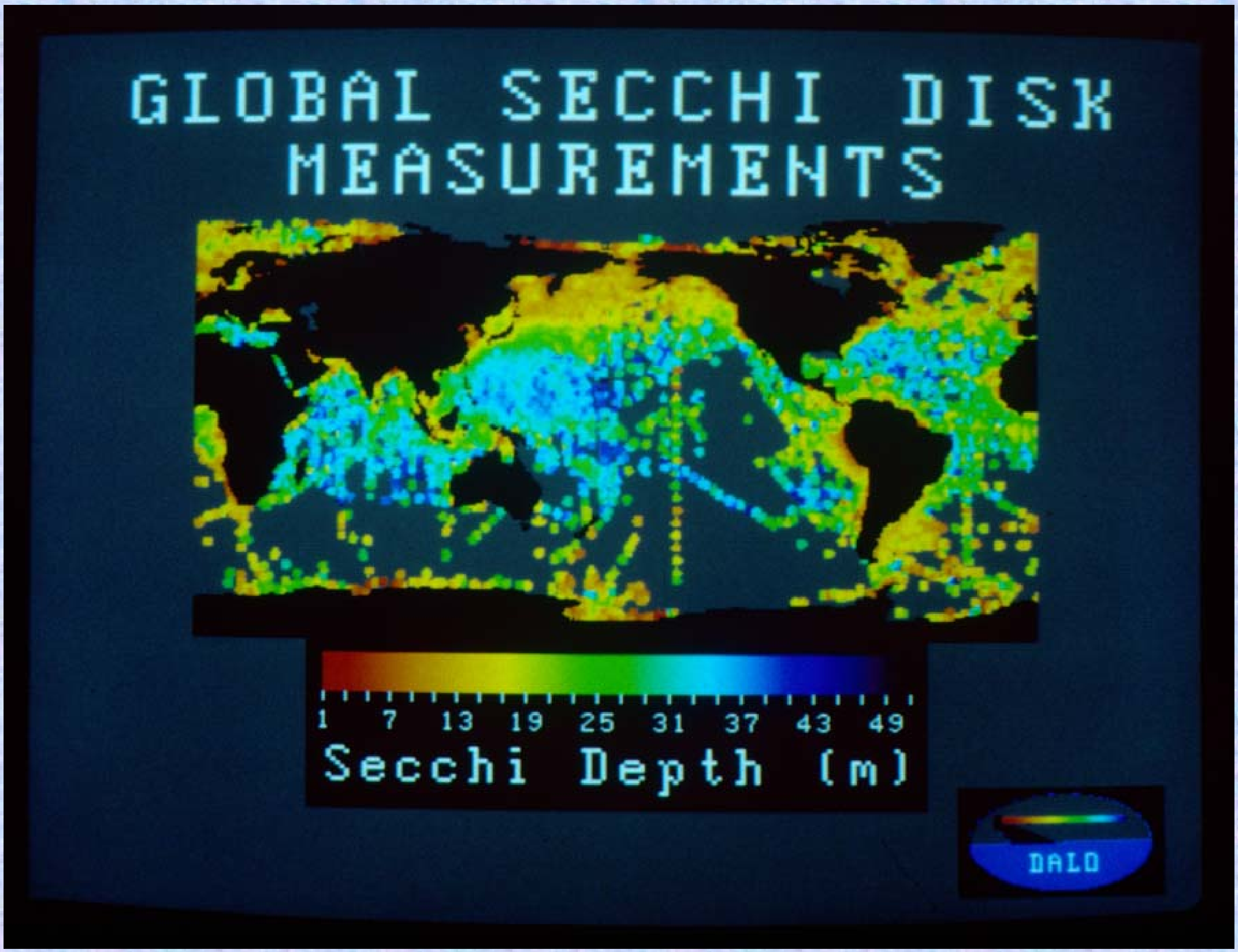

Fig. 2. Cumulative distribution for the precision of Secchi depth based on 217 occasions when two observers made independent measurements.

Observation of Secchi disk detailing long term change:

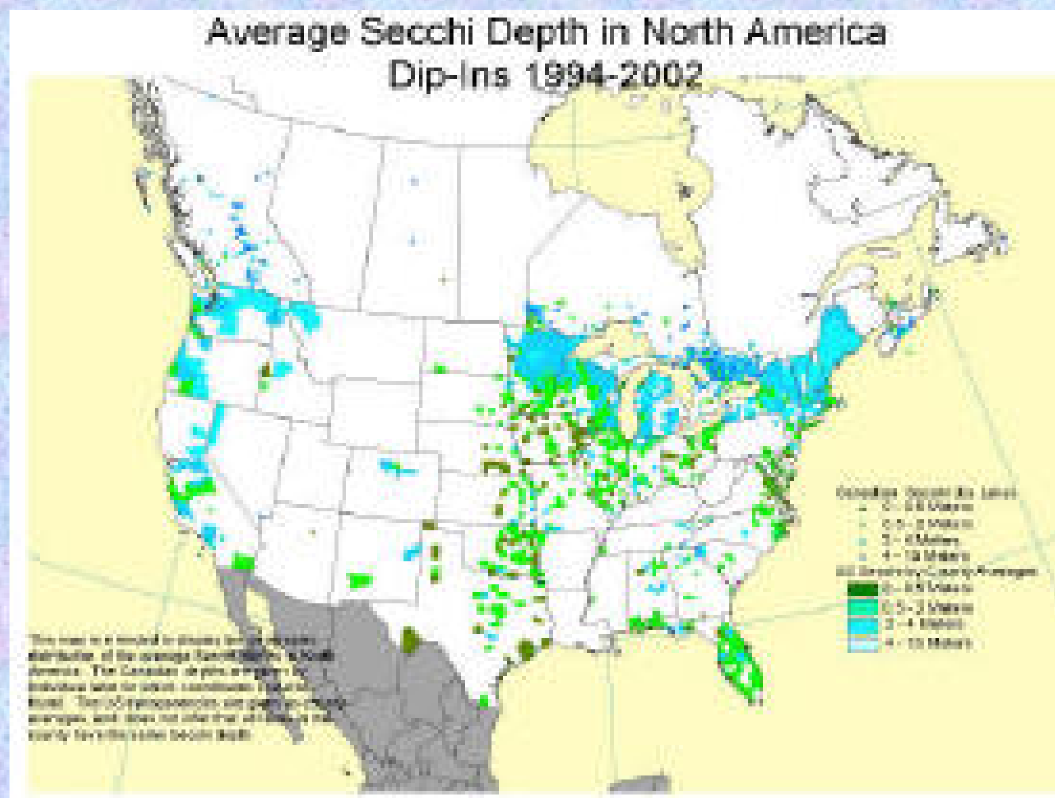
**Canadian lake (Ontario):**



Data banks store Secchi data for future generations:



**Secchi disking provides great data and friends:**




http://dipin.kent.edu/whatis.htm

**Since July, 1994**
**Volunteers have provided**
**30,268 transparency records**
**On 6,626 waterbodies**
**By 9,220 volunteers**
**Belonging to 394 Programs, both volunteer and professional in**
**50 US states,**
**9 Canadian provinces, and**
**6 other countries**

## The equation of radiative transfer applied to the Secchi disk

Zaneveld and Pegau, 2003 (based on the pioneering works of Duntley, Preisendorfer and Jerlov):

$$\cos(\theta)\frac{dL(\theta,\phi,z)}{dz} = -c(z)\,L(\theta,\phi,z) + \int_0^{2\pi}\int_0^{\pi} \beta(\theta,\phi,\theta',\phi',z)L(\theta',\phi',z)\,\sin\theta' d\theta' d\phi' \qquad (1)$$

Separate target radiance ($L_T$) from background radiance ($L_B$)

$$\cos(\theta)\frac{dL_T(\theta,\phi,z)}{dz} = -c\,L_T(\theta,\phi,z) + L^*(\theta,\phi,z). \qquad (3)$$

$$\cos(\theta)\frac{dL_B(\theta,\phi,z)}{dz} = -c\,L_B(\theta,\phi,z) + L^*(\theta,\phi,z). \qquad (4)$$

We take the difference of Eqs. (3) and (4):

$$\cos(\theta)\frac{d[L_T(\theta,\phi,z)-L_B(\theta,\phi,z)]}{dz} = -c\,[\,L_T(\theta,\phi,z) - L_B(\theta,\phi,z)]\,. \qquad (5)$$

Integration of Eq. (5) along a line of sight from r'=0 at the target to r'=r at the observer gives (note that $r = z/\cos\theta$ and that $dr = dz/\cos\theta$):

$$[\,L_{Tr}(\theta,\phi,z) - L_{Br}(\theta,\phi,z)] = [\,L_{T0}(\theta,\phi,z_T) - L_{B0}(\theta,\phi,z_T)]\,\exp(-cr). \qquad (6)$$

Zaneveld and Pegau, 2003 (based on the pioneering works of Duntley, Preisendorfer and Jerlov):

The contrast used by Preisendorfer, Duntley, and Jerlov is the visibility contrast defined by

$$C_v = \frac{L_T(\theta,\phi,z) - L_B(\theta,\phi,z)}{L_B(\theta,\phi,z)} . \qquad (7)$$

A combination of Eqs. (7) and (6) shows that we may write [2,4]:

$$\frac{C_{vr}(\theta,\phi,z)}{C_{v0}(\theta,\phi,z_T)} = \exp(-cr)\ \frac{L_{B0}(\theta,\phi,z_T)}{L_{Br}(\theta,\phi,z)} . \qquad (8)$$

The background radiance has an attenuation coefficient defined by:

$$K_B(\theta,\phi,z) = \frac{-1}{L_B(\theta,\phi,z)} \frac{dL_B(\theta,\phi,z)}{dz} , \qquad (9)$$

so that

$$\frac{L_{B0}(\theta,\phi,z_T)}{L_{Br}(\theta,\phi,z)} = \exp\left[K_B(\theta,\phi,z)z\right] = \exp\left[K_B(\theta,\phi,z)\ r\cos\theta\right], \qquad (10)$$

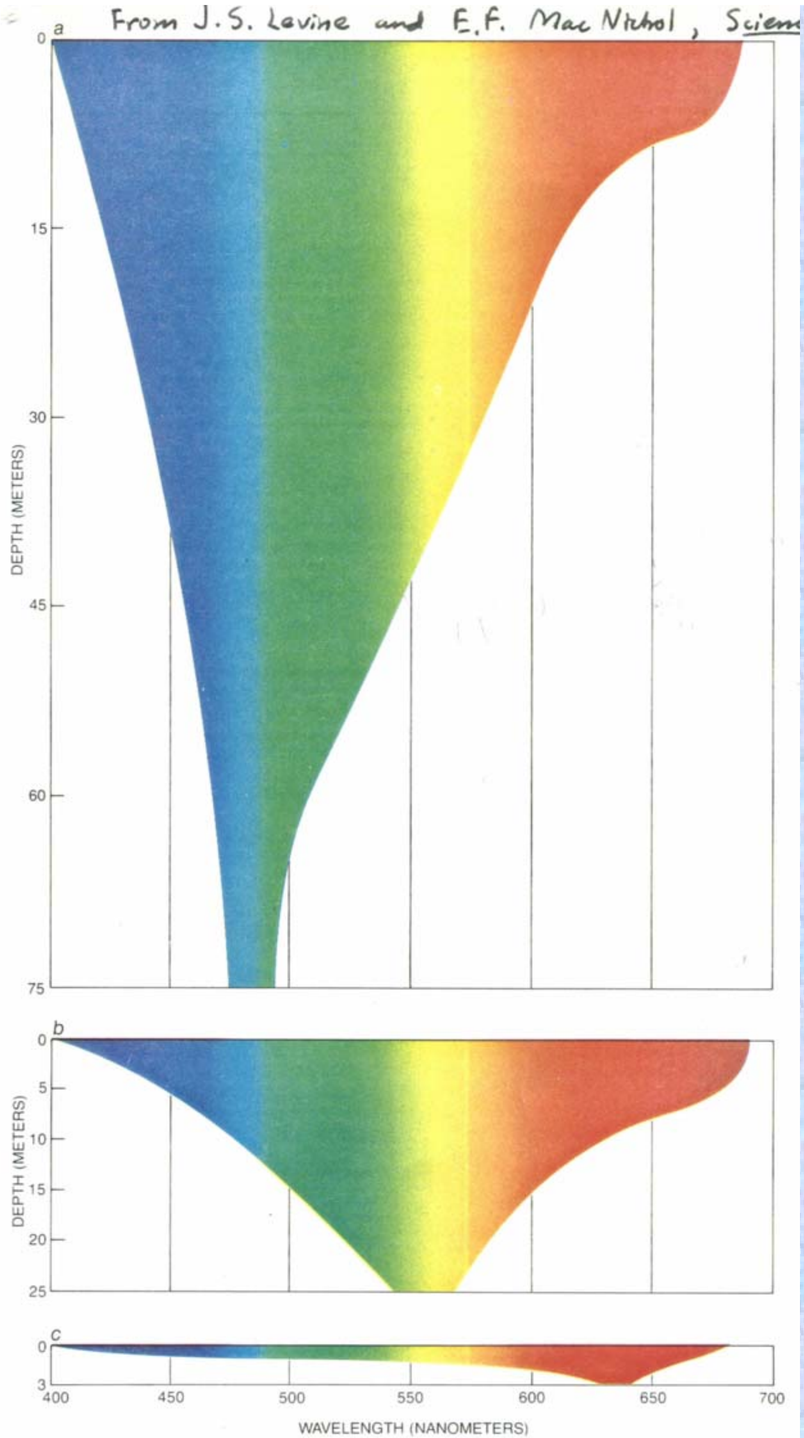
and

$$\frac{C_{vr}(\theta,\phi,z)}{C_{v0}(\theta,\phi,z_T)} = \exp\left[-cr + K_B(\theta,\phi,z)\ r\cos\theta\right] \qquad (11)$$

Duntley [3] sums up decades of underwater visibility experiments by stating:

" Along an underwater path of sight a remarkable proportion of the objects ordinarily encountered can be seen at limiting ranges between 4 and 5 times the distance 1/[ c-K(θ,φ,z) cosθ], regardless of their size or the background against which they appear, providing ample daylight prevails."

What happens when $\theta=\pi/2$?




What wavelengths are the Secchi reading indicative of?

Blue ocean

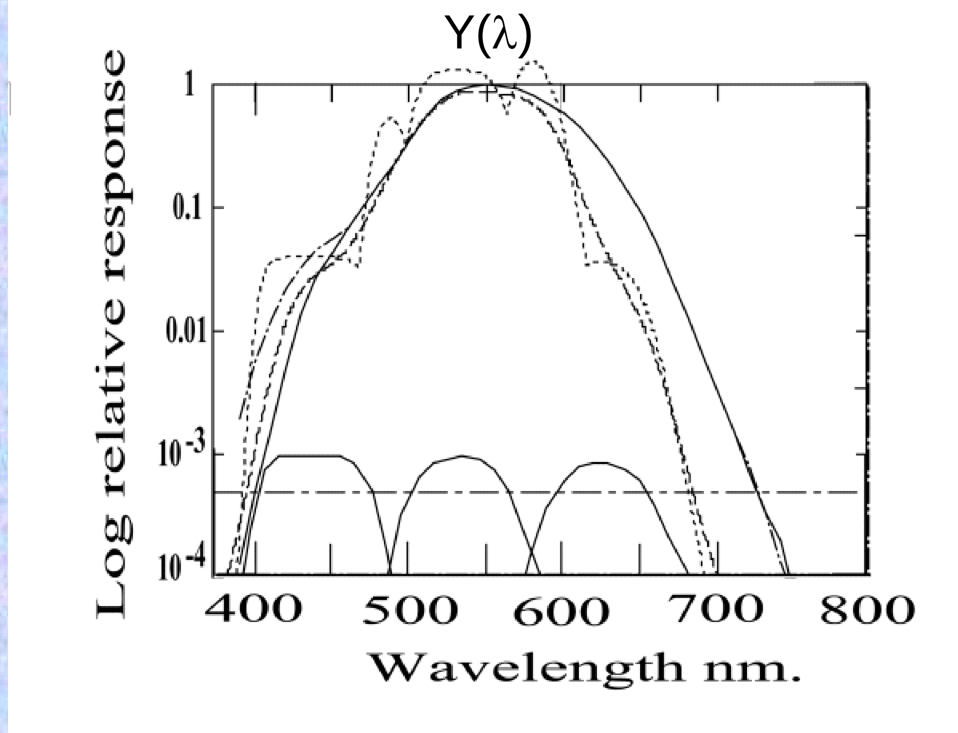
Coastal ocean

Inland pond

## So far we worked with monochromatic light. But what is the light our eye perceive from the disk?

The eye perceives photopic parameters, that is, it observes light spectra convolved with the spectral sensitivity of the human eye.

THE PHOTOPIC LUMINOUS EFFICIENCY FUNCTION




**Photopic attenuation:**

$$\alpha_U = -(1/r)\ln\left\{ \int_{400}^{700} Y(\lambda)\,[-\exp(-c(\lambda)r)]\,d\lambda \; \left[ \int_{400}^{700} Y(\lambda)\,d\lambda \right]^{-1} \right\}$$

http://www.4colorvision.com /files/photopiceffic.htm

If we view the disk vertically (r=z) it follows that:

Preisendorfer 1986, L&O "Secchi disk science: Visual optics of natural waters":

Sea surface effects

$$[\text{binocle}] \quad (\alpha + K)z = \ln[\,\mathscr{T}C_0/C_z]$$

$$[\text{direct ocle}] \quad z_{SD} = \frac{\ln[\,\mathscr{T}C_0/C_T]}{\alpha + K} = \frac{\Gamma}{\alpha + K} \quad (\text{m}).$$

$$[\text{inverse ocle}] \quad \alpha + K = \frac{\ln[\,\mathscr{T}C_0/C_T]}{z_{SD}} = \frac{\Gamma}{z_{SD}} \quad (\text{m}^{-1}).$$

Rules of thumb: $\Gamma \sim 8\text{-}9$ and $K/\alpha \sim 0.4$

All of the things that one might think would interfere – the illumination conditions, sea-state, the nature of the disk, and human-to-human variability – actually have little effect since they are all contained inside the logarithm. The primary source of variability in the Secchi disk depth is the optical properties of the sea, specifically the attenuation of light.

Example for an empirical relationship (field cals) from Tangier Sound

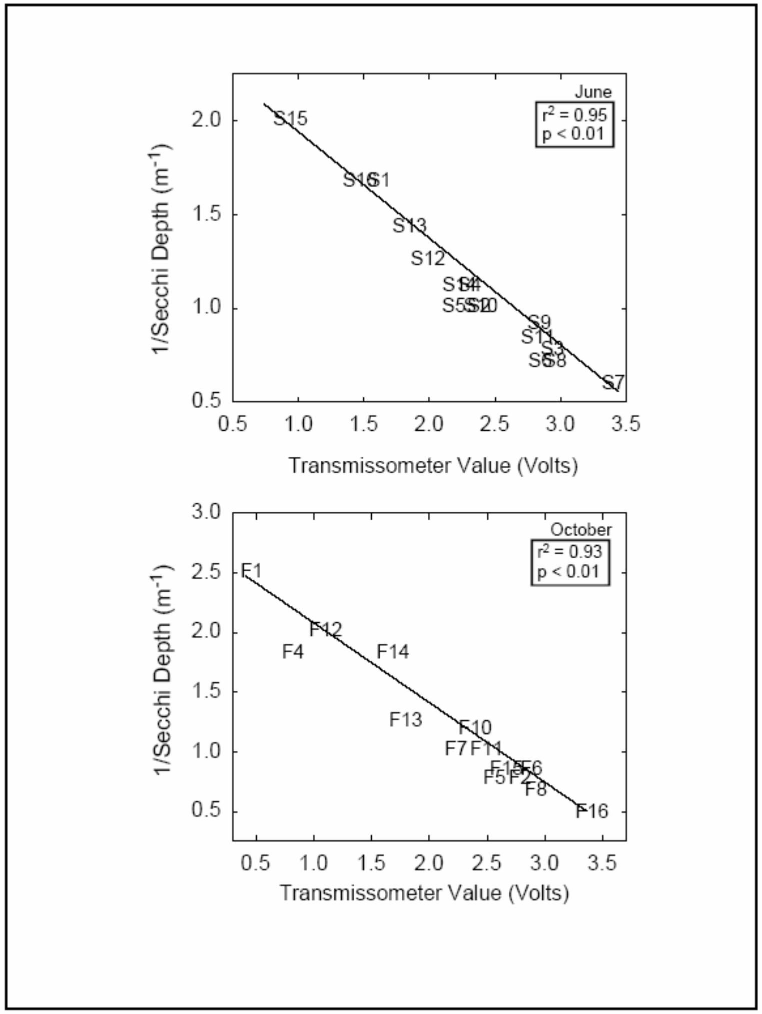



Figure 5-3. Field calibrations of inverse secchi depth vs. transmissiometer value in June (upper) and October (lower). Observation labels correspond to station locations in Figure 5-1.

http://cblcbos1.cbl.umces.edu/sone/IR17_Chapter5.pdf

# Dealing with issues associated with the surface:

"Even Secchi (1866) and his helpers instinctively used hats and umbrellas to make $\tau$= 1."

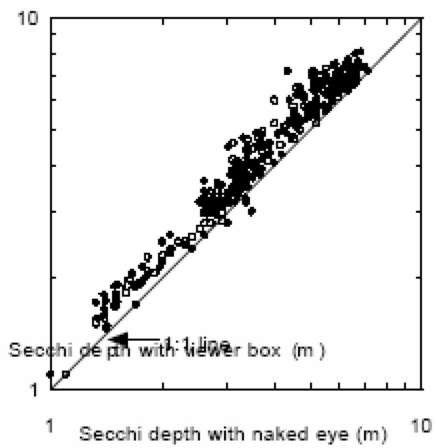



Figure 1. Relationship between Secchi depth measurements made with the aid of a viewer box and the naked eye. The open and closed symbols refer to measurements made on the sunny and shady side of the boat, respectively.

Smith, 2000

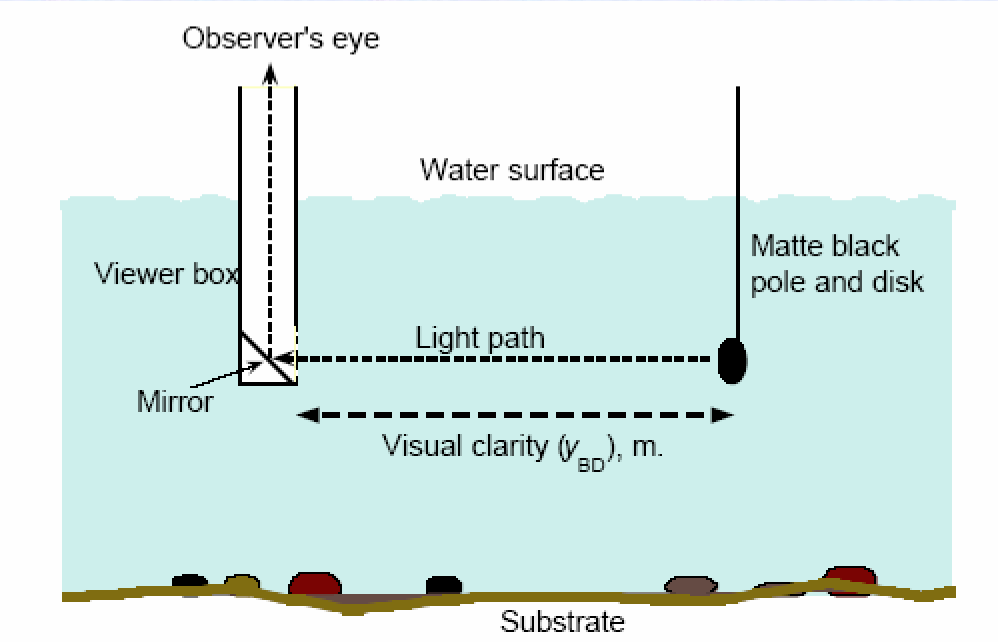
Preisendorfer concludes:

•(i) the Secchi disk reading yields a quantitative estimate of the apparent optical property $\alpha$ + K of a medium.

•(ii) The primary function of a Secchi disk is to provide a simple visual index of water clarity via $z_{so}$ or $\alpha$ + K.

•(iii) To extend the use of the disk with auxiliary objective measurements (of $\alpha$ or K, or both) is to risk obviating or abusing this primary function.

# Another approach: the horizontal black disk:




Measurement of visual clarity, as a schematic and photograph

For horizontal contrast reduction cosθ=0 in Eq. 11, so that

$$\frac{C_{vr}(\pi/2,\phi,z_T)}{C_{v0}(\pi/2,\phi,z_T)} = \exp[-cr]$$

Zaneveld and Pegau, 2003

Davies-Colley (1988): A black disk is superior to the white disk Contrast=-1.

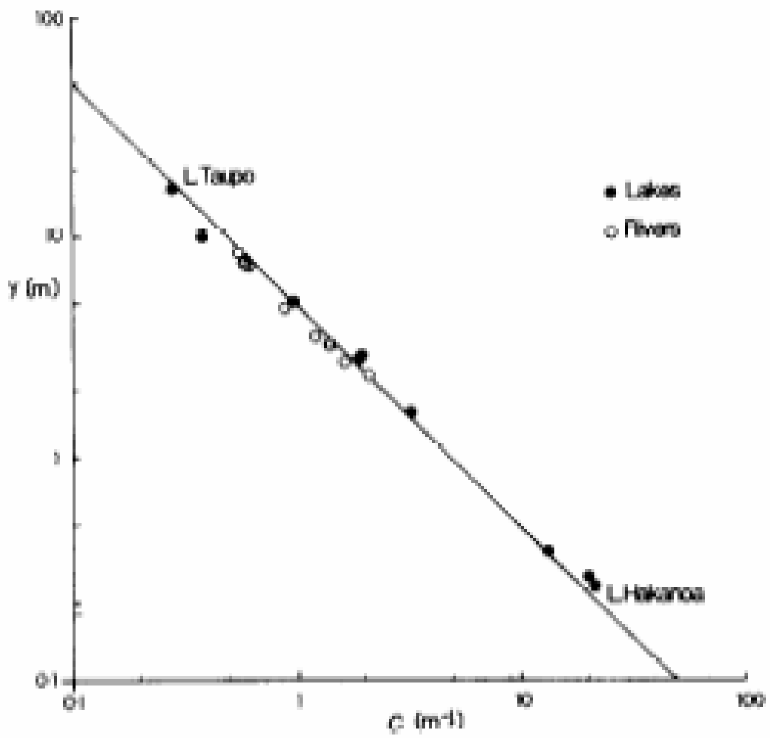



Fig. 2. Horizontal sighting range of the black disk ($y$), plotted against the beam attenuation coefficient ($c$). The line corresponds to the average value of $\Psi_y = 4.80$.

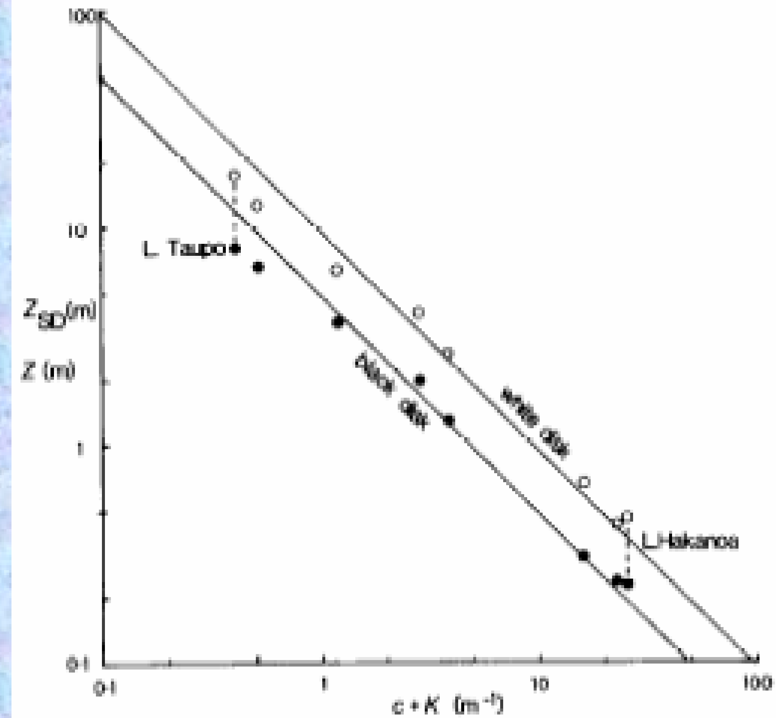



Fig. 3. Vertical sighting ranges of the black disk and Secchi disk plotted against the sum of attenuation coefficients ($c + K$). The lines correspond to the average values of $\Psi_z$ (=4.89) and $\Gamma$ (=9.52). Data for lakes only (vertical observations were not made in rivers).

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

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

Relationship with turbidity:

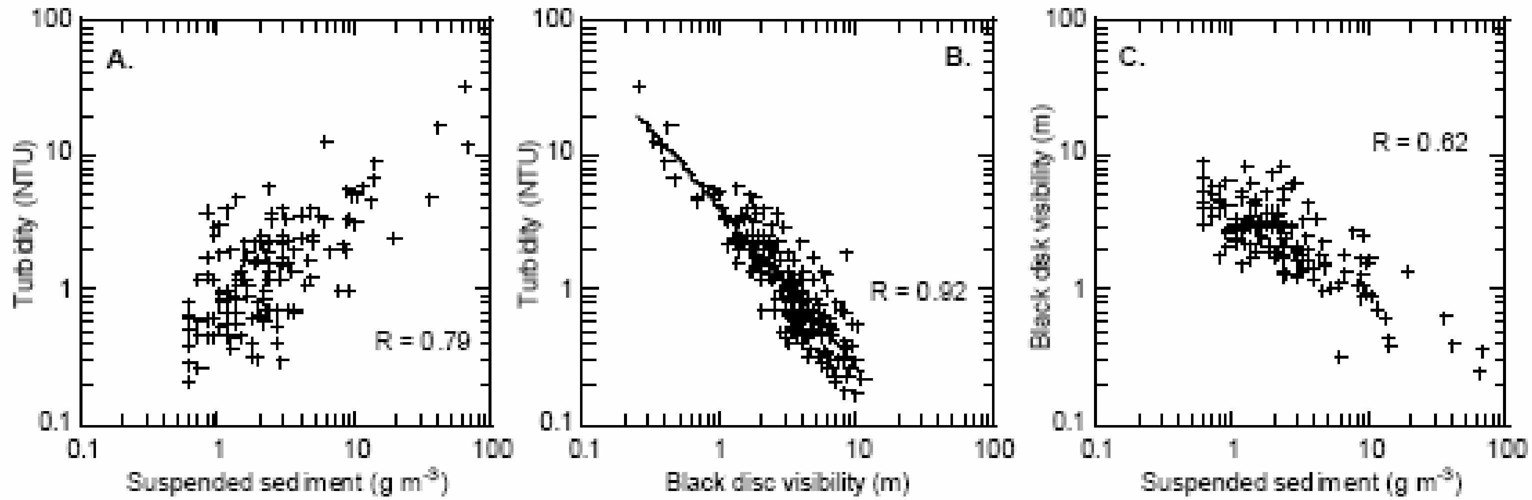



Figure 2. Mutual relationships of visual clarity, turbidity (Hach 2100A) and suspended sediment concentration in 97 New Zealand rivers (each river site sampled up to three times—$n$ = 274 in total). Panel A. turbidity versus suspended sediment, B. turbidity versus black disc visibility, C. black disc visibility versus SSC. (Figure 3 of Davies-Colley and Close, 1990—used with permission)

Smith and Davies-Colley, 2000

A robust visibility parameter: relationship of a beam-c @532 and the visibility range.

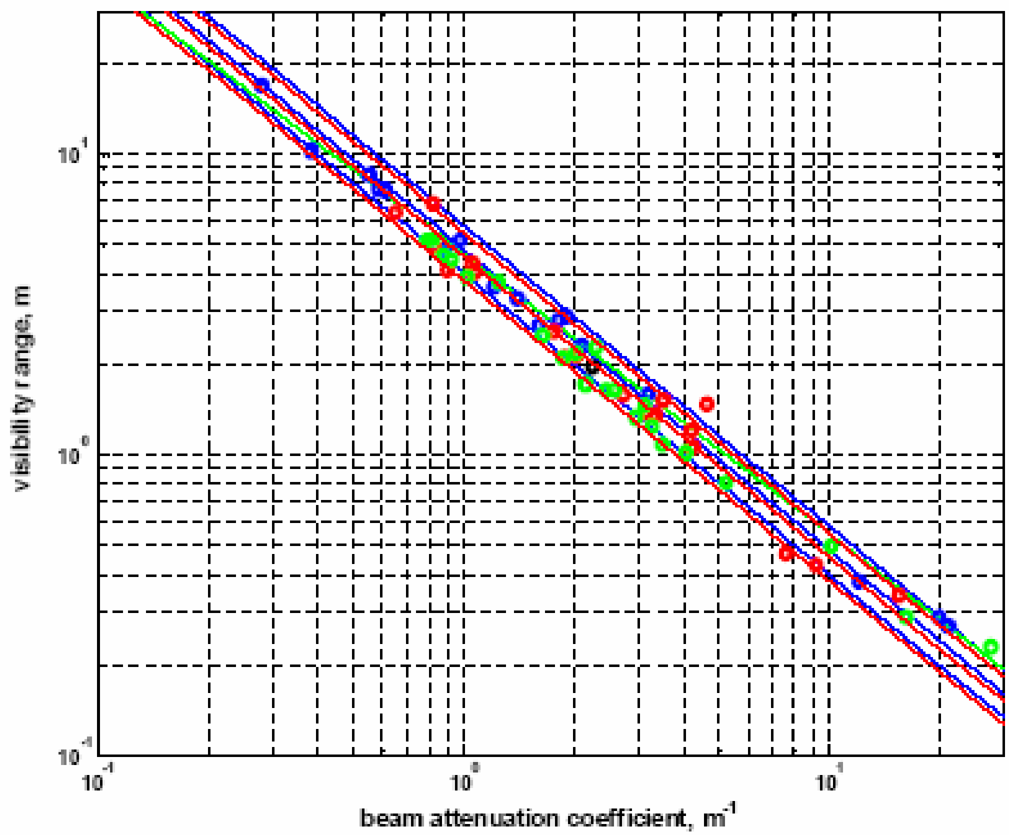



Fig. 3. Horizontal visibility of a 200 mm diameter black target. Blue points, Davies-Colley, "green" c-meter; red points, Zaneveld, c(532)*0.9+0.081; black point, Twardowski $c_{pg}(532)$*0.9+0.081; green points, Pegau, $c_{pg}(532)$*0.9+0.081;
blue lines vis. range = $y = 4.8/\alpha$ and +/- 20% lines;
green line vis. range= $y = (5.207 - 0.368 \ln y)/\alpha$ ;
red lines vis. range = $y = 4.55/\alpha$ and +/- 20% lines; $r^2 = 0.985$.

Zaneveld and Pegau, 2003

# Conclusion: How to build a horizontal black disk (http://depts.washington.edu/cwws/Outreach/FactSheets/secchi%20rev.pdf).

Viewing disc
- 4-5' thin copper pipe
- 5 gallon paint bucket lid or 2'x2' sheet of stiff black plastic
- 2 copper pipe ends
- 2 pipe brackets
- 4 small nuts and bolts
- black spray paint (matte)

## Instructions

Step 1. Cut the corner off the periscope elbow at a 45 degree angle (retain cut-off corner). Trace around cut-out onto mirror with grease pen. Cut out oval-shaped mirror using glass-cutter and pliers.

Step 2. Trace original round end of elbow onto Plexiglas. Cut out circle of Plexiglas.

Step 3. Clean mirror and Plexiglas.

Step 4. Attach elbow to long pipe with ABS glue.

Step 5. Attach mirror to back of elbow with silicone glue. Let dry.

Step 6. Attach Plexiglas to outside of viewing window and the cut-off corner of elbow to the back of mirror with silicone. Be careful to make a complete seal between the Plexiglas and the elbow but try to keep the Plexiglas window free of silicone.

Step 7. Cut the rubber tubing down the center and fit over the top end of the periscope (or use foam padding). Fix the tubing or padding in place with duct tape. This padding provides protection for your face as you peer through the periscope. The padding should not obscure the view.

Step 8. Drill holes in sides of periscope toward the top (for most comfortable use, one hole should be facing toward the viewing window and the other hole should be directly opposite). Thread the webbing through each hole and knot in place. Knots should be small so as not to obscure the view. Do not thread webbing through both holes so that the webbing passes through the center of the pipe (or attach handles to sides of pipe).

Step 9. For horizontal viewing disc, paint the bucket lid with alternating black quadrants (scuffing the surface with 100 grit sandpaper first will help paint to adhere). For horizontal black disc, cut out four sizes of black circles (20 mm for very turbid waters, less than 0.5 m visibility; 60 mm – 0.5 to 1.5 m visibility; 200 mm – 1.5 to 5 m visibility; and 600 mm – 5 to 15 m visibility).

Step 10. Attach target to copper pipe using pipe brackets, nuts, and bolts. For the horizontal black disc, you may simply want to silicone the small disc to the top end of the copper pipe then spray with black matte paint. Attach pipe ends.

## Building materials

Equipment jigsaw, drill, caulking gun, glass-cutter, and glass pliers

Materials These materials will make one complete horizontal viewing disc (either black or secchi). Other materials can often be substituted. A 2-3 m measuring device is also necessary. If the disc will be used from a boat, a cloth tape measure can be taped to the side of the boat. If the disc will be used at the edge of a river a length of PVC pipe marked in 10 cm intervals works well.

Periscope
- 4-5' of 4" diameter PVC or ABS pipe
- 90 degree 4" diameter PVC or ABS elbow
- small sheet Plexiglas (at least 4" square)
- mirror (at least 6" square)
- grease pen, silicone glue, and ABS glue
- rubber tubing or foam padding (about 12")
- duct tape
- several feet of webbing or other material for a strap/handles

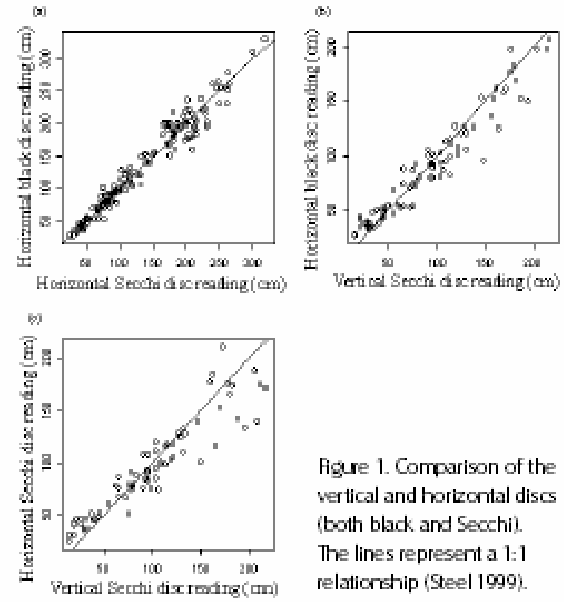
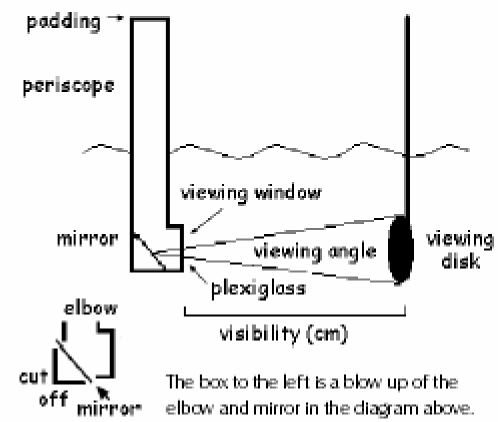



Figure 1. Comparison of the vertical and horizontal discs (both black and Secchi). The lines represent a 1:1 relationship (Steel 1999).




The box to the left is a blow up of the elbow and mirror in the diagram above.

Schematic of a horizontal viewing disc

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