LIGHT IN NATURAL WATER

A. Physical nature of light

1. Light is a portion of the electromagnetic spectrum.

wavelength in meters
(exponent)

-14	-12	-10	-8	-6	-4	-2	0	+2	+4
γ		X	UV	VIS	IR	Micro	TV	Short	AM
rays		rays		light*		wave	FM	wave	

(*Wavelength is approximately 10^{-6} to 10^{-5} for visible light. Visible light is a very narrow portion of the over-all spectrum of electromagnetic radiation.)

2. Only a portion of the entire spectrum is considered light. The definition of the *visible light spectrum* is based on the sensitivity of the human eye. The human eye is sensitive to only a portion (approximately 400 to 800 nanometers) of the energy of the sun which reaches the earth's surface.

Mnemonic for the spectral colors: ROY G BIV

2. Properties of light

a. Light is transmitted in straight lines, but can be refracted ("bent") or reflected.

b. Light has wavelike properties. In particular, wavelength, speed, and frequency are interrelated:

$$\text{frequency} = \text{speed}/\text{wavelength}$$

(speed = 3×10^{10} cm/sec) (in a vacuum)

Light may be diffracted and may be polarized.

c. Light has particle like properties. In particular, light is absorbed in discrete units, quanta. In photochemical processes such as photosynthesis, quanta must be of sufficient energy for a photochemical reaction to occur. The energy of an individual photon is proportional to its frequency.

3. Light is energy

Light is energy, and should be measured appropriately.

a. Light intensity may be measured in units of watts/cm^2. Light intensity could also be measured in units of ergs/cm^2 sec.

conversion: 1 watt/cm^2 = 10^7 ergs/cm^2 sec

b. Light intensity may also be measured in units of photons. Biologists favor the use of units of photons because photobiochemical processes such as vision and photosynthesis depend on the absorption of discrete photons. The most popular unit of light based on numbers of photons is: microeinsteins/m^2 sec.

One einstein of photons = an Avogadro's number of photons, or specifically:

one einstein of photons = 6 x 10^{23} photons (quanta).

The most commonly used light meters are designed to measure "**PAR**": **Photosynthetically Active Radiation**. That is, the instrument is designed to respond **equally** to the number of photons in the portion of the electromagnetic spectrum which supports photosynthesis (from 400 to 700 nanometers). PAR measured as photons (i.e. not watts) is properly reported as *photon flux density* (PFD), p137 Kalff.

c. Light energy may be converted between units based on quanta and units based on watts if the spectrum of the light is known:

1 einstein/m^2 sec = 12 x 10^{14} ergs/λ cm^2 sec, or

1 einstein/m^2 sec = 12 x 10^7 watts/λ cm^2.

where λ = wavelength in nanometers. Wavelength must be included in the conversion because quanta have more energy when wavelength is short than when wavelength is longer. It follows that a complete characterization of light intensity requires both the total energy, or quanta, and the spectral distribution of the energy.

4. A diatribe on photometric units.

The photometric system of units explicitly includes a consideration of the sensitivity of the human eye. Since this is not the only (nor the most important) biological photochemical process, photometric units such as foot-candles, lux, lumens, etc. are inappropriate for the measurement of light in ecology and should not be used.

5. Annual variation in radiation.

Because of the tilt of the earth's axis, solar radiation arriving at the earth's surface varies substantially by latitude and time of year. Note that in mid-summer, high latitudes receive more dai

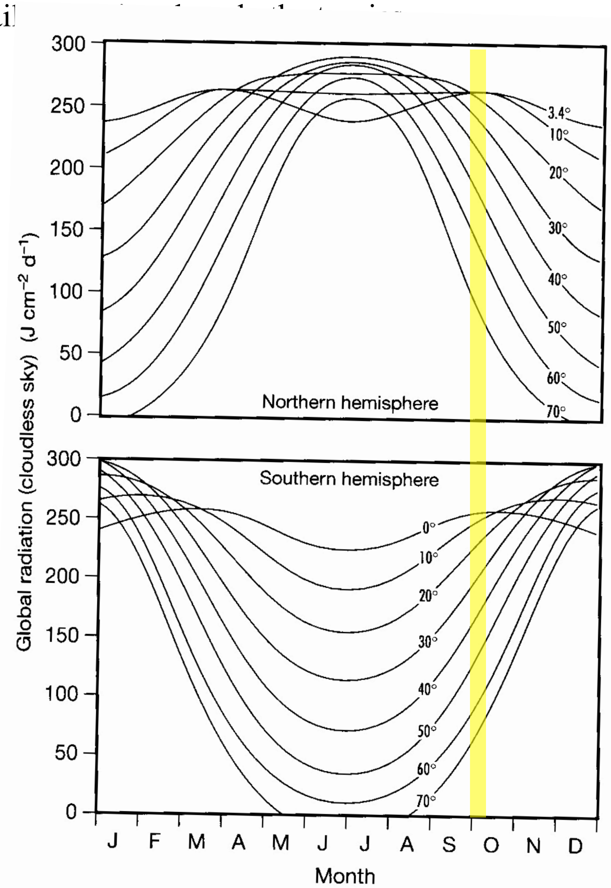


Figure 10–1 Annual variations in radiation reaching the ground on totally clear days. Note the increasing variation with increasing latitude, producing a heating gradient. *(Modified after Straškraba 1980.)*

B. Reflection and refraction

1. Reflection

A portion of the sunlight (whether direct from the sun or scattered by the sky or clouds) is reflected by the water surface. As measured against a line perpendicular to the surface (flat if the surface is calm), the angle of reflection is equal to the angle of incidence. The proportion of the light which is reflected is described by Fresnel's law. Popular opinion to the contrary, only a small fraction of the sunlight striking the surface is reflected, unless the angle of incidence is very close to the horizon.

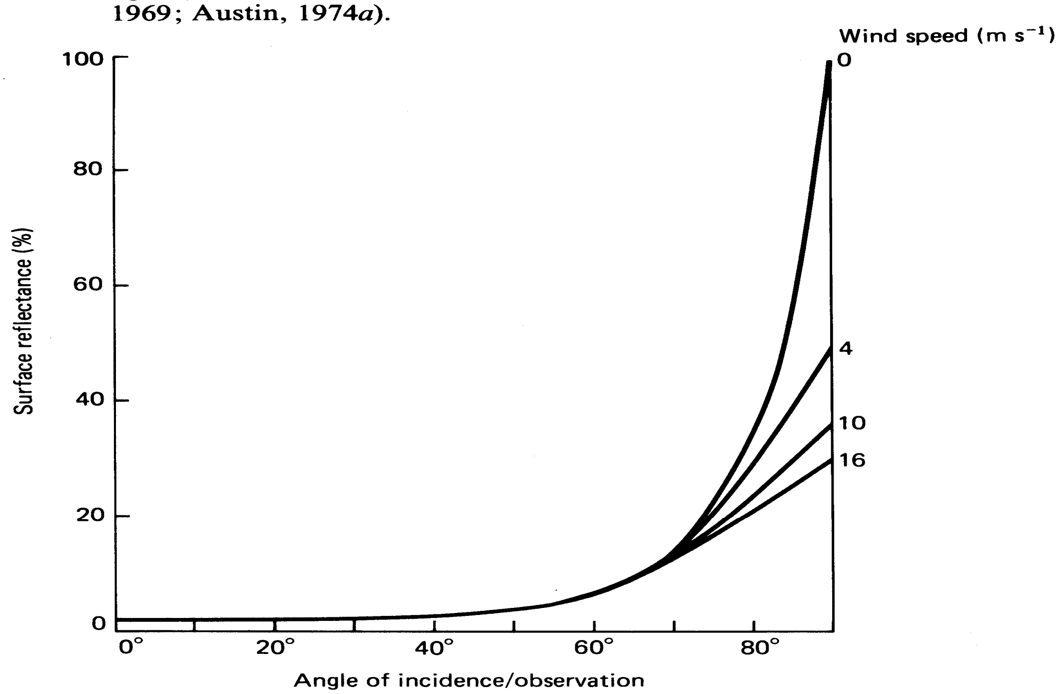
Even when the sun is only 10 degrees above the horizon (80^o zenith angle), 2/3 of the sunlight enters the lake, and only 1/3 is reflected.

Table 2.1. *Reflectance of unpolarized light from a flat water surface. The values of reflectance have been calculated using eqns 2.12 and 2.15, assuming that the water has a refractive index of 1.33*

Zenith angle of incidence, θ_a (degrees)	Reflectance (%)	Zenith angle of incidence, θ_a (degrees)	Reflectance (%)
0.0	2.0	50.0	3.3
5.0	2.0	55.0	4.3
10.0	2.0	60.0	5.9
15.0	2.0	65.0	8.6
20.0	2.0	70.0	13.3
25.0	2.1	75.0	21.1
30.0	2.1	80.0	34.7
35.0	2.2	85.0	58.3
40.0	2.4	87.5	76.1
45.0	2.8	89.0	89.6

Wind and waves influence reflection of light from a lake at high solar angles. High wind = waves = reduced reflectance

Fig. 2.10. Reflectance of water surface as a function of zenith angle of light (incident from above), at different wind speeds (data of Gordon, 1969; Austin, 1974*a*).



2. Refraction

The light which enters the lake is refracted as it enters. That is, the direction of travel of the light is bent toward the vertical. The degree of bending is described by Snell's law:

$$\sin \alpha / \sin \beta = \eta$$

where α = the angle of incident light,

β = the angle of transmitted light, and

η = the refractive index of water (approx. 1.333).

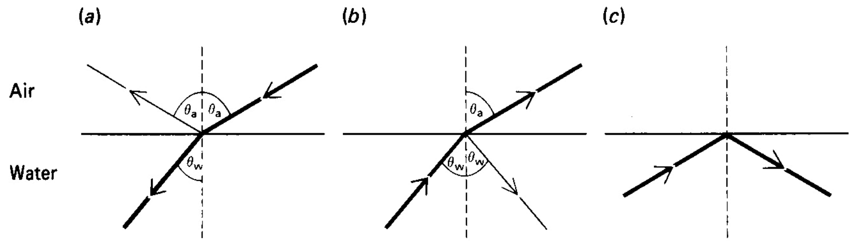
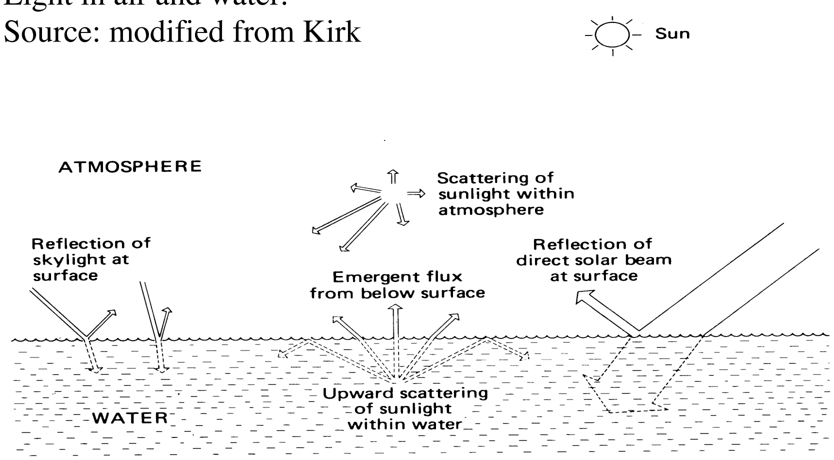


Fig. 2.11. Refraction and reflection of light at air–water boundary. (*a*) A light beam incident from above is refracted downwards within the water: a small part of the beam is reflected upwards at the surface. (*b*) A light beam incident from below at a nadir angle of 40° is refracted away from the vertical as it passes through into the air: a small part of the beam is reflected downwards again at the water–air boundary. (*c*) A light beam incident from below at a nadir angle greater than 49° undergoes complete internal reflection at the water–air boundary.

It is because of refraction that a straight rod stuck in the water appears to bend as it goes through the surface. Kingfishers and other birds compensate for refraction (and without ever studying college physics).

Light in air and water.
Source: modified from Kirk



C. Transmission and attenuation of transmitted light

1. Introduction

Light traveling down the water column may be:

absorbed i.e. light energy is converted to heat or to chemical energy by photosynthesis, or

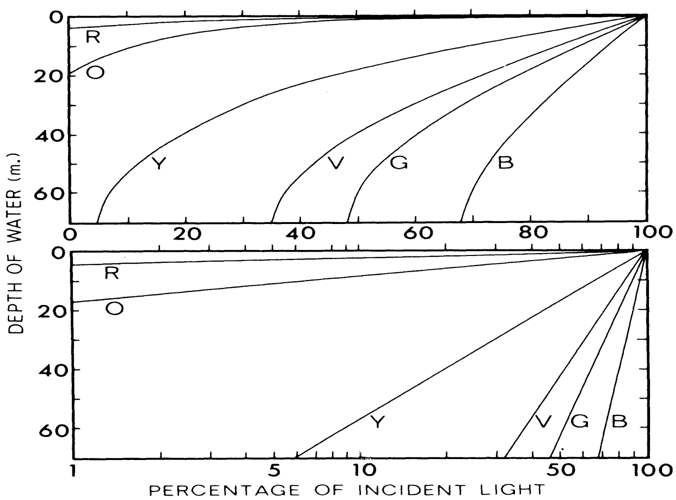
scattered i.e. remains light, but changes direction of travel.

Light may be absorbed or scattered because of its interaction with:

water itself, **particulate matter** suspended in the water, or **dissolved chemicals (photolysis)**, especially dissolved organic matter.

Photolysis is the chemical process by which molecules are broken down into smaller units through absorption of light. Important process for breakdown of herbicides used for control of aquatic weeds.

2. Attenuation with depth



Source:
Wetzel, 1983

Figure 5-7 Transmission of light by distilled water at six wavelengths (*R*-720, *O*-620, *Y*-560, *G*-510, *B*-460, *V*-390 nm). Percentage of incident light that would remain after passing through the indicated depths of water expressed on a linear *(upper)* and a logarithmic *(lower)* scale. (After Clark, 1939.)

Light intensity decreases with depth because of absorption and scatter. The attenuation of light may be described by:

$I_Z = I_0 e^{-k Z}$

where:
I_Z = light intensity at depth Z,

I_0 = light intensity at the surface, and

k = the extinction coefficient of the water.

Or (by taking the natural log or both sides of the equation)

$-(\ln I_o - \ln I_z) = kZ$

$-(\ln I_o - \ln I_z)/Z = k$

(a) Effect of water on light transmission.

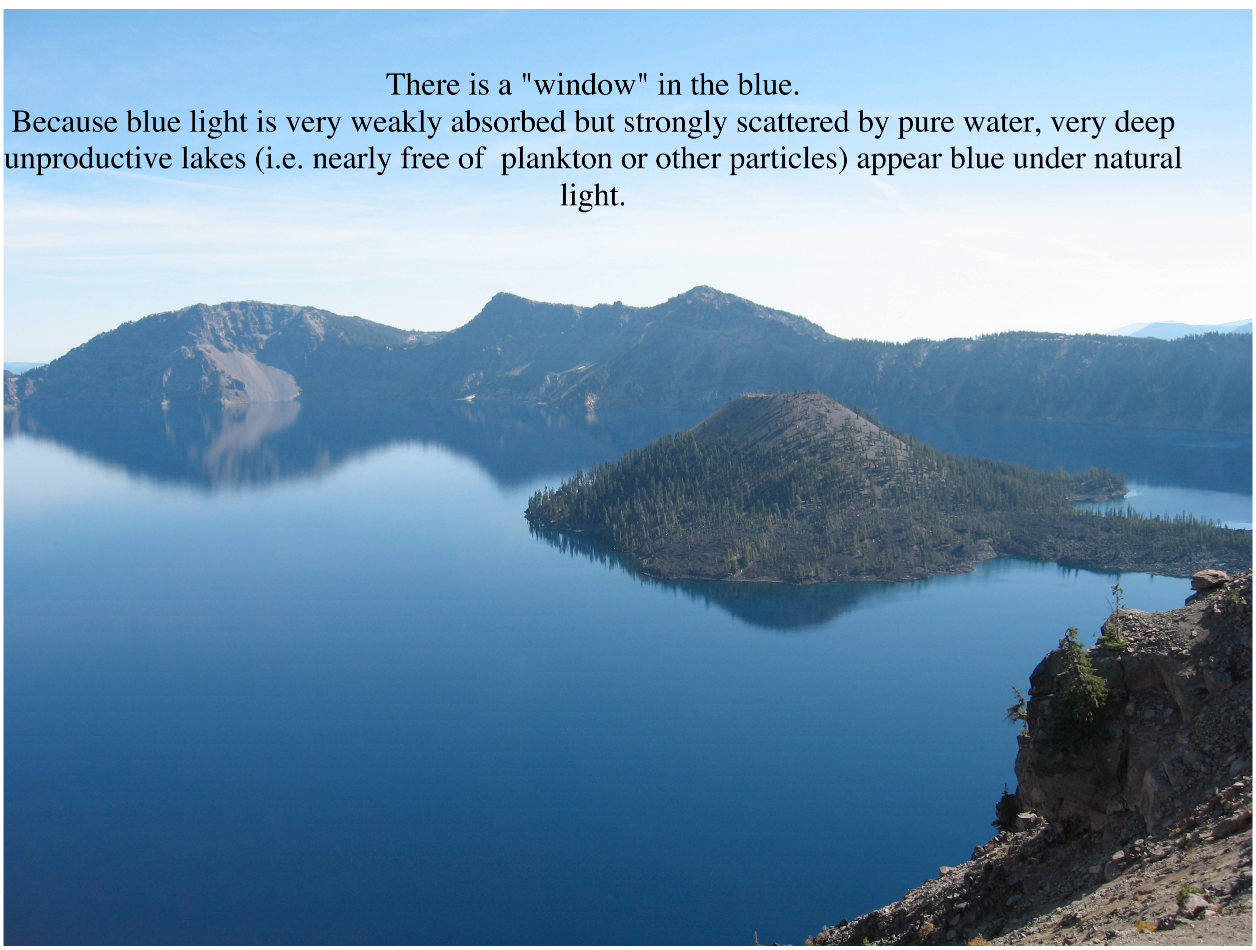
Water *scatters* light proportional to the inverse 4th power of the wavelength.

That is:
scatter $\propto 1/\lambda^4$ where λ is the wavelength. Thus, short wavelength light is much more strongly scattered than long wavelength light. Blue light is strongly scattered by water, but red is only weakly scattered.

Water *absorbs* light, more at some wavelengths than others (long wavelengths are aborbed quickly). Some sample extinction coefficients due to absorption of light by water are: (see Hutchinson, 1957)

wavelength	extinction coefficient (M^{-1})	% absorbed in 1 M
8000 angstroms	2.24	89.4
7000	0.598	45.0
6000	0.210	19.0
5000	0.0075	0.77
4000	0.0134	1.63
4800	0.0050	0.52

Thus, in relative terms, blue light is scattered but not absorbed and red light is absorbed but not scattered



(b) Effect of particles and dissolved colored materials.

Attenuation may be increased in natural water due to the presence of particles and dissolved colored materials.

Particles (plankton, suspended clay, etc.) increase scatter and absorption. Clay and other inorganic particles do not usually affect the light spectrum appreciably. An exception is "glacial flour" which is fine enough to scatter light selectively, and may confer a green color on water similar to the color of chlorophyll. Certain planktonic organisms selectively absorb light and impart a distinct color (commonly green, but sometimes other colors) to the water in which they are suspended.

Dissolved organic matter absorbs light, sometimes preferentially at certain wavelengths. Dissolved organic matter often confers a distinct brownish color (bogs).

The effects of particles and dissolved chemicals may be formally incorporated in the expression for attenuation with depth according to:

$$I_Z = I_0 \, e^{-(kw+kp+kd) Z}$$ where:

k_w= extinction due to scatter and absorption due to water,
k_p= extinction due to scatter and absorption due to particles, and
k_d= extinction due to scatter and absorption due to dissolved color. Total extinction is due to the sum of the three.
Z = depth (from surface)
I_Z = light intensity at depth Z
I_0 = light intensity at the surface

Note: symbol used to designate the extinction coefficient varies with author. The current convention is to use k. In any case, the units are m^{-1}.

In practice, <u>all 3 processes are lumped together and measured by a single light attenuation coefficient</u>. The extinction coefficient characteristic of a lake may be estimated by measuring light intensity at successive depths with an underwater light meter during more or less constant light conditions. (If surface light is changing rapidly due to passing clouds, it is difficult to obtain meaningful results. Clear sky or heavy overcast allow the collection of the appropriate data.) The extinction coefficient is then the slope of the log of light intensity vs. depth.

It should also be apparent why k is an approximate measure of biological activity, particularly if there is not much inorganic particulate material present. An increase in the amount of plankton will cause an increase in light scatter and absorption, and a corresponding decrease in light intensity at depth.

(c) Effect of ice and snow. See figure 10-4, p140. A surface covered by ice or snow can greatly attenuate the light entering the lake, depending on the type of ice or snow and the thickness of the covering.

3. Instruments to measure underwater light

a. Irradiance meters

Several companies manufacture suitable underwater light meters, or *irradiance* meters (e.g. Licor). Most chose units of quanta (not watts) with a flat response between 400 and 700 nm. Such meters are described as "PAR" meters, for Photosynthetically Active Radiation, and measure light as PFD (photon flux density).

The shape of the photocollector dictates the geometry of the light field that is measured. The two choices are:

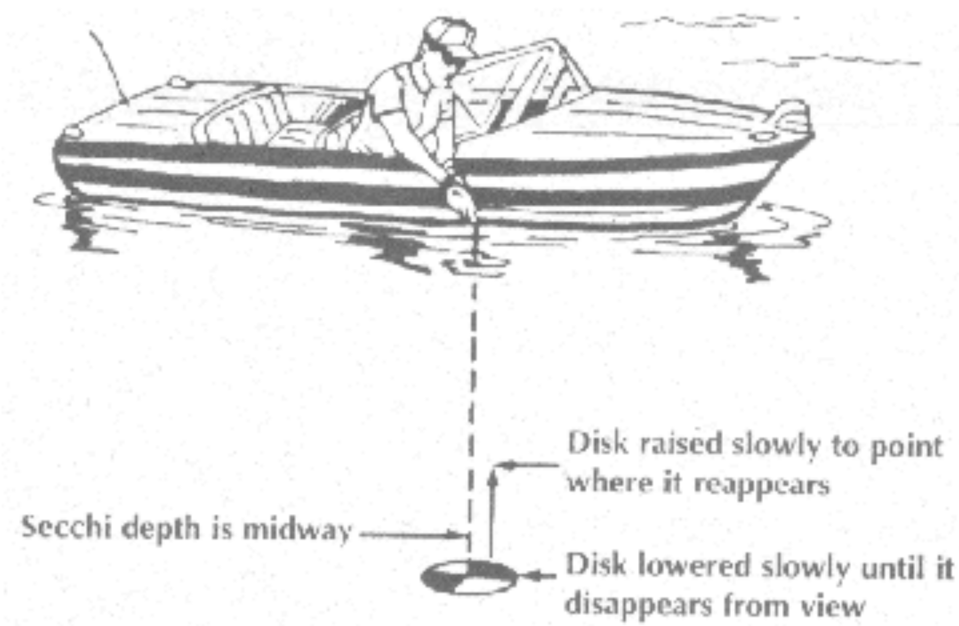
(1) A flat diffusing collector to measure *irradiance* (radiant flux per unit area of the surface). Such instruments measure *irradiance*, E. The collector may be oriented upward to measure downward irradiance, E_d, or oriented downward to measure upward irradiance, E_u

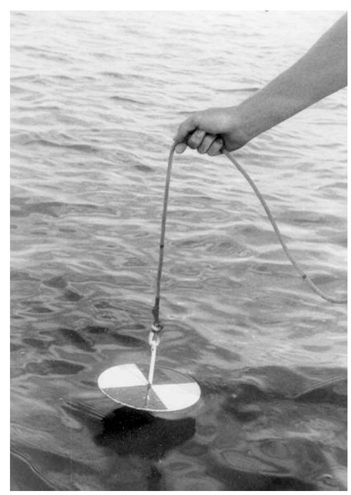
(2) A spherical collector to measure *scalar irradiance* ((total light from all directions).

[Kirk (1992) discusses the merits of the two possible choices, and much more.]

(b) Secchi disk

The Secchi disk is a venerable and useful instrument for measuring the optical properties of natural water. As an index of the *aesthetic* characteristics of light in lakes it is perhaps th e most suitable instrument. As discussed in Kalff (p148 ff), the Secchi disk has many advantages (simplicity, economy) but also some disadvantages. In particular, Secchi disk visibility is *less* affected by dissolved color and *more* affected by turbidity, so that no direct comparison with k_d can be assumed. Kalff discusses some of the approximations (and their limitations) used for estimating k_d from Secchi data.





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 l865. Various sizes of disks have been used since that time, but the most frequently used disk is an 8-inch diameter disk painted in alternate black and white. All white disks are often used in oceanography, and larger disks are often used in extremely transparent waters.

D. Ecological significance of light.

Photosynthesis is usually proportional to light intensity (more on this later). As a rough "rule of thumb", photosynthesis is not possible at depths below the 1% light intensity level. As will be discussed under the measurement of primary productivity, an accurate characterization of the light intensity throughout the water column is needed to measure primary productivity. Since primary productivity is the basis of all food chains, it should be obvious why an accurate measure of light attenuation in the water column is useful. The importance of light to primary productivity has given rise to an extensive vocabulary (**trophogenic zone, photic zone, euphotic zone, compensation depth, critical depth**, etc.). See Kalff, p145. (More on this with the discussion of primary production later in the course.)

Light is also important for many visual feeders, including many fish. The vertical migration of the zooplankton, an important process, is (mostly) related to the daily change in light intensity in the water column.

E. Color

There have been various attempts to develop color scales to describe the visual appearance of lakes or the water in them. The two most widely used indices have been the Forel-Ule scale for lake color, and the platinum scale for water color.

The Forel-Ule scale uses a variety of different inorganic salts to develop color standards which may be compared to lakes. The result is a "color index" for the lake. This scale has fallen into disuse. The platinum scale is also based on a selection of inorganic salts, but differs from the Forel-Ule scale in that it is based on a single mixture, with higher concentrations corresponding to more colored water and more dilute concentrations of the salts corresponding to less colored water. The "Platinum color" of a water may be measured with a spectrophotometer and is accordingly somewhat less subjective.

Some homework

The following sample problems are based on:

$I_Z = I_0 e^{-k Z}$

where: I_Z = the light intensity at depth Z, in meters,

I_0 = the light intensity at the surface,

e = the base of the natural logs,

k = the extinction coefficient, in M^{-1}, and

Z = depth in meters.

Problem #1

Light intensity just below the surface of Blue Lake was observed to be 1850 μEinsteins/M^2 sec, and at a depth of 5 meters, 950 μEinsteins/M^2 sec. What is the extinction coefficient for these data?

Problem #2

If the extinction coefficient equals 0.15 M^{-1}, what fraction of surface light reaches 10 meters?

Problem #3

If the extinction coefficient is 2.5 M^{-1}, at what depth does the light intensity equal 1 % of surface light? (or, how deep is the photic zone).

Some additional reading on light:

Kirk, JTO. 1994. Light and Photosynthesis in Natural Waters. Cambridge Press.

Kirk, J.T.O. 1992 "The nature and measurement of the light environment in the ocean". Pages 9-29 in, Primary Productivity and Biogeochemical Cycles in the Sea, (Falkowski and Woodland, Eds.) Plenum Press This is an excellent reference to develop a basic understanding of light in natural water. In spite of the title, it applies equally well to lakes.