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TURBIDITY, SUSPENDED SEDIMENT, AND WATER CLARITY: A REVIEW[1]

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ABSTRACT: Suspended sediment causes a range of environmental damage, including benthic smothering, irritation of fish gills, and transport of sorbed contaminants. Much of the impact, while sediment remains suspended, is related to its light attenuation, which reduces visual range in water and light availability for photosynthesis. Thus measurement of the optical attributes of suspended matter in many instances is more relevant than measurement of its mass concentration. Nephelometric turbidity, an index of light scattering by suspended particles, has been widely used as a simple, cheap, instrumental surrogate for suspended sediment, that also relates more directly than mass concentration to optical effects of suspended matter. However, turbidity is only a relative measure of scattering (versus arbitrary standards) that has no intrinsic environmental relevance until calibrated to a 'proper' scientific quantity. Visual clarity (measured as Secchi or black disc visibility) is a preferred optical quantity with immediate environmental relevance to aesthetics, contact recreation, and fish habitat. Contrary to common perception, visual clarity measurement is not particularly subjective and is more precise than turbidity measurement. Black disc visibility is inter-convertible with beam attenuation, a fundamental optical quantity that can be monitored continuously by beam transmissometry. Visual clarity or beam attenuation should supplant nephelometric turbidity in many water quality applications, including environmental standards.
(KEY TERMS: clarity; fish habitat; optical properties of water; recreation; Secchi disc; suspended sediment; turbidity; visibility; water quality.)

INTRODUCTION

Suspended sediment is a ubiquitous water pollutant, causing significant environmental damage and economic costs (Clark *et al.*, 1985). Suspended sediments have a multitude of potential environmental impacts on water bodies, including transport of other pollutants notably sorbed trace elements (Tessier, 1992) and toxic organics. Effects on aquatic organisms are reviewed in Henley *et al.* (2000) and include benthic smothering once sediment settles out of the water column. The effects on the water supply industry may be considerable and involve costly treatment (e.g., AWWA, 1990). However, arguably the most ecologically significant, and certainly the most visually obvious, impact of *suspended* sediment is optical: reduced light transmission through water, or *light attenuation*.

Light attenuation by suspended matter has two main types of biotic effect: reduced penetration into water of light for photosynthesis (Kirk, 1994), and reduced visual range of sighted organisms (e.g., Vogel and Beauchamp, 1999). Reduction of visual range also has considerable effects on human perception of recreational water bodies (e.g., Smith *et al.*, 1995a; 1995b), and their fishability.

Here, our focus is on the phenomenon of light attenuation in water by sediment particles while still suspended. The greater the attenuation of light, the lower the water clarity. There are of course other light-attenuating constituents of water besides suspended particles, most notably the water itself and its content of colored organic matter (humic substances) (Davies-Colley *et al.*, 1993; Kirk, 1994), but typically suspended particles are the dominant influence on light attenuation in natural waters.

The cloudy appearance of water laden with fine suspended sediments is probably familiar to most people. This cloudiness results from the intense scattering of light by the fine particles, a phenomenon referred to as 'turbidity' (Kirk, 1985). Thus waters with high concentrations of fine suspended sediment

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are described as 'turbid,' and inevitably these waters are of low visual clarity. Turbidity is commonly measured in water quality laboratories using a nephelometer, an instrument that detects light scattered by a water sample, usually at 90° to the incident beam. The turbidity measured in nephelometric turbidity units (NTU) is often used as a rough index of the fine suspended sediment content of the water. Turbidity is also commonly, and uncritically, taken as a rough index of water clarity, but published relationships between measures of clarity and turbidity seem rare (Davies-Colley *et al.,* 1993). "Standard Methods" (APHA, 1998) devotes an introductory paragraph in Nephelometric Turbidity Method 2130 to justifying turbidity measurement in terms of water clarity, but no attempt is made to quantitatively *interpret* turbidity in terms of clarity. We stress that turbidity is not the same thing as clarity: these are distinct, although related (inversely – as we show below), optical concepts.

Our experience is that the concepts of turbidity and water clarity, and their relation to suspended sediment concentration (SSC) in water, are poorly understood. In water quality and related fields (e.g., fisheries management), measurements of SSC continue to be made when the main concern is optical (e.g., fish vision) and it would seem more appropriate to make optical measurements, such as turbidity (Lloyd *et al.,* 1987) or water clarity. These optical measurements are also much cheaper than the suspended sediment assay and can be measured on site and continuously if required (see Table 2 below). Furthermore, measurements of turbidity continue to be made in isolation without recognition that this (relative) measure is of little environmental value until cross-calibrated to an absolute quantity such as SSC or clarity, at *each* site of interest.

The purpose of this paper is to review the concepts underlying the three related, but distinct, measurements – turbidity, SSC, and water clarity – in order to reduce some of the conceptual confusion that presently exists in the water quality literature. As part of this review we present empirical relationships between these different measures. We emphasize the effects of suspended sediments on 'optical water quality' (Kirk 1988), particularly visual water clarity, an optical attribute with a direct bearing on aquatic habitat, fishability, and human recreational use of waters. We introduce some fundamental optical properties of waters that link optical quantities like visual clarity to the suspended matter that causes light attenuation. We compare SSC, turbidity, and visual clarity in terms of costs, precision, environmental relevance, and other attributes. We recommend wider adoption of simple, but powerful, methods (including instrumental methods) for measuring visual clarity of waters, because of their distinct advantages over the traditional water quality assays of SSC and turbidity especially where optical effects of SS are of concern.

WATER CLARITY AND WATER OPTICS

The attenuation of sunlight in water is of great ecological importance (Kirk, 1994). Suspended sediments, along with the other main light-attenuating constituents, such as dissolved organic matter and water itself, reduce the amount of light illuminating submerged objects and provide energy for plant photosynthesis. Change in the *light penetration* into water bodies may be expected to have far-reaching ramifications for aquatic ecosystems because of its influence on photosynthetic fixation of energy by aquatic plants (Kirk, 1994).

Light-attenuating materials also powerfully affect natural waters in regard to habitat and recreational amenity by reducing sighting distance in water for animals and humans. Reduced *visual clarity* of waters may greatly affect the behavior of visual predators, notably fish and aquatic birds (Lythgoe, 1979). A minimum visual water clarity seems to be desirable for safe contact recreation, and visual clarity also influences the aesthetic quality of water. Other things being equal, waters of high visual clarity are more aesthetically attractive and more valued for recreation than waters of low visual clarity (Smith *et al.,* 1991; Smith and Davies-Colley, 1992; Smith *et al.,* 1995a; 1995b).

Therefore, there are two main aspects of water clarity that concern water managers: *light penetration* and *visual clarity* (e.g., Davies-Colley and Vant, 1988; Davies-Colley *et al.,* 1993). These two aspects are both strongly affected by suspended matter in water and both are related to the optical properties of water, but in different ways, hence the need to make the distinction. In order to further discuss these two concepts and their relationship to turbidity and to suspended sediment we need to introduce some fundamental optical properties that describe the behavior of light in waters.

Kirk (1994) has comprehensively reviewed the subject of hydrological optics, the scientific study of water as a light-transmitting medium (see also, Davies-Colley *et al.,* 1993). The basic optical processes responsible for attenuation of light in water may be discussed with reference to Figure 1, which indicates the paths of a few representative photons in a light beam passing through a clear container of water. Some of these photons simply disappear within the water volume, their energy having been converted to another form (ultimately heat) by the process of *absorption*. This is quantified by an absorption coefficient (units m^{-1}): the proportion of photons being absorbed per unit (short) length of light path (Kirk, 1994). (The light path must be short so that the absorbed proportion is small.) Other photons are found to change direction abruptly owing to the process of *scattering*, which is similarly quantified by a scattering coefficient: the proportion of photons being scattered per unit (short) length of light path (Kirk, 1994). Most of the scattering is at small angles to the original path, but a very few photons are scattered to the side or backwards. (Typically, about 1.5 percent of scattering in natural waters is at angles greater than 90°.)

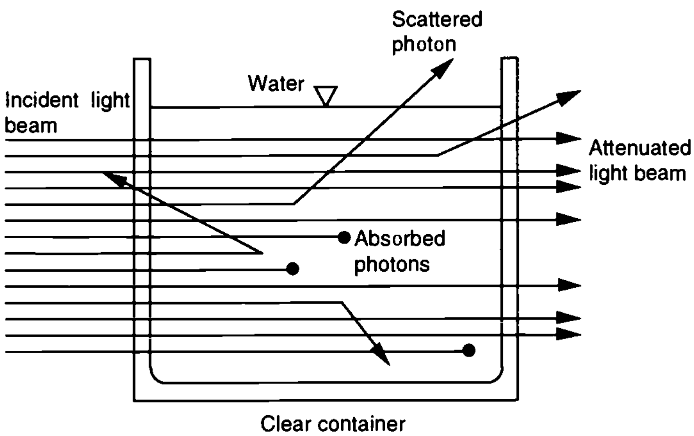

Figure 1. Schematic Diagram Showing the Paths of Representative Photons Interacting With Water by the Processes of Absorption and Scattering (Davies-Colley *et al.*, 1993).

The total light attenuation by both absorption and scattering is quantified by the *beam attenuation coefficient, c* (Kirk, 1994). This is simply the sum of the absorption coefficient, a, and scattering coefficient, b:

$$c = a + b\ . \qquad (1)$$

The beam attenuation coefficient is the most easily measured of the inherent optical properties (Kirk, 1994), and the only one that can be measured routinely. A beam transmissometer of appropriate design can be used to estimate c from measured beam transmittance, T_b, over path length, r:

$$c = \ln(1/T_b)/r\ . \qquad (2)$$

The quantities a, b, and c are known as 'inherent' optical properties because they are properties only of the water itself and do not depend on the incident light field. A very valuable attribute of inherent optical properties is that they are *conservative*. For instance, the total light beam attenuation of a volume of water (= cV, units m^2, where V is volume) is conserved when that water mixes with another water volume of different beam attenuation coefficient. This is the basis of powerful approaches to optical modeling of waters (Davies-Colley *et al.*, 1993). For example, the light beam attenuation (and water clarity) in a river downstream of a tributary or effluent inflow can be estimated from the volume flow of the river and inflow, and their respective beam attenuation coefficients.

LIGHT PENETRATION INTO WATERS

The penetration of (diffuse) light with depth into water bodies is quantified by the diffuse light attenuation coefficient, K: defined as the proportional reduction in diffuse light (= irradiance, E, watts m^{-2}) per unit small depth interval:

$$K = -d(\ln E)/dz\ = -(dE/dz)/E\ . \qquad (3)$$

A useful index of the depth above which lighting is sufficient for plants to grow in water bodies is the euphotic depth, the depth at which photosynthetically available radiation (PAR, ranging from 400-700 nm wavelength, units are moles of photons $m^{-2}\ s^{-1}$) is reduced to 1 percent of its incident value. The euphotic depth is given approximately by:

$$z_{eu} = \ln 100/K(\mathrm{PAR}) = 4.6/K(\mathrm{PAR}) \qquad (4)$$

where K(PAR) is the irradiance attenuation coefficient for the whole PAR waveband.

The two properties quantifying aspects of light attenuation, irradiance attenuation coefficient, K, and beam attenuation coefficient, c, are only weakly related despite their similar names, and should be clearly distinguished.

The diffuse attenuation coefficient, K, is an example of an *apparent* optical property (Kirk, 1994). Apparent optical properties depend mainly on the inherent optical character of the water, but also (weakly) on the incident lighting conditions, notably solar altitude and cloud cover. Another useful apparent optical property of water is the reflectance, R, defined as the ratio of upwards-directed irradiance, E_u, to downwards-directed irradiance, E_d, in water

$$R = E_u/E_d\ . \qquad (5)$$

The irradiance attenuation coefficient, K and reflectance, R can be estimated from measurements of irradiance in water with a submersible light sensor of appropriate spectral and spatial response, such as a PAR sensor (Kirk, 1994). Many investigators lacking a suitable light sensor have attempted to estimate K from visual water clarity measurements with a Secchi disc (see following section), using the simple inverse relationship

$$K = \kappa / z_{SD} \qquad (6)$$

where z_{SD} is the Secchi depth and κ is assumed constant. However, Equation (7) (below) shows that Secchi depth is related inversely not to K, but to $c + K$. Using Equation (6) with empirical literature values for κ, is tantamount to assuming that the PAR reaching the Secchi depth in water is everywhere a constant proportion of surface PAR. But Davies-Colley and Vant (1988) have shown that the product $z_{SD}K$ varies appreciably between waters, mainly with reflectance, R. They caution against attempting to estimate light penetration from Secchi observations because of the possibility of large errors.

Suspended matter in water causes scattering of light, but this, of itself, does not greatly attenuate light except for back-scattering or multiple scattering that results in some photons escaping from the water. However scattering forces photons to take a tortuous path down through the water column, so increasing the probability of light absorption over a given depth interval. This phenomenon is responsible for increase in irradiance attenuation coefficient, K, with increase in SSC, even when the suspended matter does not itself absorb light (Kirk, 1985).

The irradiance attenuation coefficient in waters increases systematically with SSC or nephelometric turbidity as a surrogate. For example, Walmsley *et al.* (1980) reported a linear increase in K(PAR) with turbidity in Rust der Winter Reservoir, South Africa, which contains a high concentration of inorganic suspensoids, and Lloyd *et al.* (1987) found a linear relationship between these variables in Alaskan streams impacted by placer gold-mining. More generally, a non-linear relationship is to be expected between irradiance attenuation and suspended matter concentration or turbidity, depending on the optical character of the suspended particles (Kirk, 1985). For example, Lloyd *et al.* (1987) reported a power law dependence of light penetration measured as K(PAR) on turbidity with an exponent of 0.6 in 14 Alaskan lakes, and Davies-Colley *et al.* (1992) found that K(PAR) increased as the 0.34 power of turbidity in streams impacted by placer gold-mining in Westland, New Zealand.

Optical modeling has shown that K(PAR) increases linearly with absorption and approximately as the square root of scattering (Kirk, 1985). Since suspended particles usually contribute to *both* absorption and scattering, and in different ratio depending on their composition and particle size distribution, the functional dependence of K on SSC is typically a power law with an exponent exceeding 0.5 and sometimes as high as unity (linear relationship). However, there exists no universal relationship of light penetration to SSC or, for that matter, to turbidity or visual clarity. The relationship between light penetration and SSC or its surrogates must be established empirically in a given water body.

The interested reader is referred to Kirk (1985) and Kirk (1994) for more information on the effect of suspended solids on light penetration into waters. The remainder of this paper emphasizes visual water clarity which is probably less well understood than light penetration, despite being of approximately equivalent environmental importance and even more closely related to SSC.

VISUAL WATER CLARITY

Secchi Disc

Historically, water clarity has been measured in standing water bodies using a Secchi disc, a white or black-and-white disc that is lowered into water by a graduated line until the image is judged to disappear from view (e.g., Tyler, 1968). The depth of disappearance, the Secchi depth, is a useful index of *visual* water clarity. Secchi measurement protocols have not been satisfactorily standardized, although recommendations have recently been made (Smith, 2001; Smith and Hoover, 1999). Tyler (1968) and Preisendorfer (1986) have shown that the Secchi depth is inversely proportional to the sum of the two different light attenuation coefficients of water:

$$z_{SD} = G/(c + K) \,. \qquad (7)$$

The coefficient G is usually in the range of 6 to 9 (Tyler, 1968), depending on the reflectance of the white face of the Secchi disc (typically about 75 percent) (author's unpublished data), and on the reflectance of the water, R (Equation 5) which varies appreciably between water bodies. The Secchi depth measurement is therefore itself an apparent optical property that is somewhat dependent on lighting conditions. G also depends on the contrast threshold of the human eye, which is surprisingly near-constant and contributes little to the overall variation among observers with normal vision.

The (weakly related) optical coefficients c and K cannot be separately estimated from Secchi depth using Equation (7) without independent information about the optics of the water body (Preisendorfer, 1986).

Hydrological Range and Black Disc Visibility

Theoretically, a better measure of visual water clarity is the *hydrological range*, defined as the maximum sighting distance of a perfectly black target, viewed horizontally (Duntley, 1963). The hydrological range depends only on the beam attenuation coefficient, c, and is therefore an inherent optical property that is independent of lighting conditions. Davies-Colley (1988) has shown that c (measured at 550 nm near the peak sensitivity of the human eye) can be estimated with reasonable precision from observations of the hydrological range using a matte black disc, with the empirical equation:

$$y_{BD} = 4.8/c \ . \tag{8}$$

Equation (8) holds over an extremely wide range (from < 0.05 m in very turbid waters (Davies-Colley and Smith, 1992) to 63 m in remarkably clear Waikoropupu Springs, New Zealand (Davies-Colley and Smith, 1995). The empirical coefficient is close to the value expected theoretically from the contrast threshold of the human eye (Davies-Colley, 1988).

The inverse relationship of hydrological range (henceforth 'black disc visibility' or simply 'visibility') and the beam attenuation coefficient (Equation 8) is intuitive. In order to form a recognizable image at the eye, light must travel from object to observer in straight lines (ignoring, for the moment, coherent refraction in a lens system). Thus the attenuation of an *image* carried by light through water is the same as the attenuation of a light *beam*. Equation (8) is extremely useful in practical water quality work because it permits modeling of visual clarity of water, making use of the conservative property of c (Davies-Colley *et al.,* 1993). For example, Equation (8) can be used to predict the visibility in a river after mixing of a turbid water or wastewater inflow.

Although black disc visibility can be observed by a snorkel diver, observations from above water are usually more convenient and may be made using a simple viewer equipped with a 45° mirror (Davies-Colley, 1988) (Figure 2). Furthermore, Davies-Colley and Smith (1992) have reported a method for offsite measurement of black disc visibility of water in a trough constructed of reflective material. This is useful if access to a water body is hazardous as with a river in flood. The lower limit to *in situ* observations is about 50 mm, and in more turbid water, observations made in a trough on a sample diluted volumetrically with clear water of known clarity are to be preferred to direct observations because of practical difficulties with direct measurement of such short visual ranges (Davies-Colley and Smith, 1992).

Black disc visibility has three important advantages over Secchi depth as an index of visual clarity (Davies-Colley *et al.,* 1993). Firstly, because the black target (ideally) reflects no light, the measurement of y_{BD} is independent of ambient lighting, so long as there is sufficient light for normal color vision. The Secchi depth, by contrast, has some 'apparent' optical character and varies weakly with light conditions. Second, y_{BD} yields a valuable, reasonably accurate, estimate of the beam attenuation coefficient, c, (Equation 8). Finally, the black disc is observed horizontally and so is useful in very shallow and clear waters such as rivers (Figure 2) and littoral waters used for bathing. Perhaps the only remaining advantage of the Secchi disc is that valuable historical datasets on the optics of water bodies have been collected with this device.

Duntley (1963) has pointed out that many sighting ranges of practical importance in water approximate the extinction distance of a black body, including the sighting distance at which fish (Lythgoe, 1979) can be seen. Consistent with this, Steel and Neuhausser (in submission) have reported that horizontal sighting ranges of a black-and-white Secchi disc are very similar to black disc visibility in the Skagit River, Washington. Accordingly, we propose that horizontal black body visibility (hydrological range), and, equivalently, the beam attenuation coefficient, be taken as the standard measures of visual water clarity.

Transparency Tubes

A recent development is the use of 'transparency tubes' (e.g., Sovell *et al.,* 2000) for measuring water clarity. Typically these are clear tubes with a small visual target (e.g., 'Secchi disc') painted on the bottom. The viewer pours water into the tube until the image of the target is just extinguished, and the depth of water provides an index of its transparency. These simple devices, albeit restricted to fairly turbid waters, are laudable for raising the general public's awareness of water clarity. But the resulting transparency observations are not usually equivalent to *in situ* visibility because the *in situ* light field in water is not simulated. In New Zealand, an improved transparency tube design comprises a black disc target

Figure 2. Observation of Black Disc Visibility in the Stonehill River, New York, by Staff of the New York City Department of Environmental Protection.

mounted on an aquarium magnet that is moved to the extinction point inside a clear tube while viewing horizontally (Biggs et al., 1998). Measurements with this device (over a restricted range) are equivalent to *in situ* horizontal black disc observations (Cathy Kilroy, NIWA Christchurch, personal communication, Kilroy and Biggs, 2001).

TURBIDITY

Turbidity is a concept associated with the 'cloudiness' of water, which, as we have seen, is caused by the light scattering of suspended particles (Austin, 1973). Therefore, perhaps the most appropriate measure of turbidity is as particle scattering. However, as mentioned above, measurement of scattering *per se* is difficult and currently beyond the scope of routine water quality work. Therefore turbidity is usually measured by nephelometry – the relative measurement of light scattering through a restricted range of angles to the incident light beam. Typically, nephelometers measure side scattering at angles centered on 90°, and indeed APHA (1998) and other water quality manuals stipulate measurement of 90° side scattering.

Because the angular distribution of scattering is rather similar in most natural waters (Kirk, 1994), side scattering is in roughly constant ratio to total scattering. Several studies have reported that nephelometric turbidity correlates fairly closely with the scattering coefficient, b (e.g., Effler, 1988). Indeed, nephelometric turbidity measured (in NTU) on a common instrument, the Hach 2100A nephelometer, is numerically similar to the total scattering coefficient (in m^{-1} units) – and can be used as a rough estimate of the latter (Kirk, 1994)

Turbidity measured by different nephelometers has been reported to produce different numerical NTU values (McGirr, 1974). These differences arise because of differences in optical design of nephelometers (spectral emission of light source, spectral sensitivity of detector, angular range of detector, beam configuration) (McCluney 1975) even when the different instruments are all calibrated to formazin, the intensely scattering suspension used as the (arbitrary) standard in nephelometry (APHA, 1998; Method 2130). For this reason, *the instrument used for turbidity measurements should always be specified* – a subtlety ignored by many water quality professionals who continue to report turbidity data as if it were an absolute scientific quantity.

Figure 3 compares turbidity measurements on the *same* samples from New Zealand river waters on two laboratory nephelometers, the Hach 2100A instrument (vertical light beam) and its modern replacement, a Hach 2100AN (horizontal light beam). There is a close correlation of data from the two instruments over the wide range of water clarity in these rivers. However, the responses differ by 30 percent overall (average ratio is 1.31), and there is appreciable scatter about this ratio (coefficient of variation is 12 percent). Apparently, the scattering by suspended particles within the river waters interacts with different optical designs of the instruments to give different responses. Appreciably greater discrepancy between different makes and models of nephelometer, including field instruments, may sometimes be encountered.

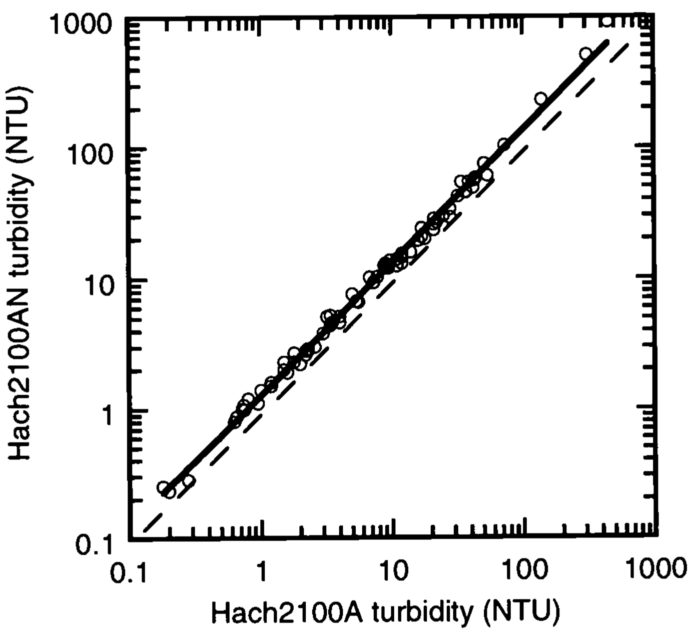

Figure 3. Comparison of Turbidity Measured Simultaneously Using Two Different Nephelometers. A Hach 2100A nephelometer (vertical incident light beam) and its modern replacement, a Hach 2100AN ratio nephelometer (horizontal incident light beam) were used side-by-side on the same batch of 77 New Zealand river water samples. (Average ratio = 1.3, coefficient of variation of the ratio = 12 percent.)

We emphasize that nephelometric turbidity is merely a *relative* index of side scattering of light referred to side scattering of an *arbitrary* standard (formazin). That is to say, turbidity is not a 'proper' scientific quantity, which may be defined for the present purpose as a quantity whose units are reducible to mass-length-time-charge. Nephelometric turbidity measurements (units, NTU) cannot be converted to scientific units of scattering at 90° (Austin, 1973).

These unsatisfactory aspects of nephelometric turbidity were recognized more than a quarter of a century ago (Austin, 1973; McCarthy *et al.*, 1974; McCluney, 1975). These authors recommended measurement of 'turbidity' with a beam transmissometer of proper optical design. McCluney (1975) advocated replacing the term 'turbidity' by 'side scattering' and reserving the word 'turbid' and its derivatives for descriptive reference to 'cloudiness' of water. Oceanographers have been using beam transmissometers for many decades, but these instruments have not been widely adopted in water quality work on freshwaters. This is unfortunate because beam transmissometers, unlike nephelometers, are capable of absolute calibration (Austin, 1973). If the absorption coefficient, a, is measured as well as the beam attenuation coefficient, c, the scattering coefficient, b, which is more explicitly connected to SSC, can be estimated: $b = c - a$ (Equation 1).

The recommendations of McCluney (1975) and others seem to have been largely ignored, which has undoubtedly delayed progress in the field of 'optical water quality' (Kirk, 1988). However, at least one manufacturer of water quality instruments now provides beam transmissometry as a monitoring option. A beam transmissometer of either 100 or 250 mm path length (C-Star, WET Labs Inc., Philomath, Oregon) can be mated to a multi-parameter water quality probe and logger (Hydrolab, Austin, Texas) (Hydrolab, 1997). This permits integrated monitoring of beam attenuation together with more commonly recorded variables, such as dissolved oxygen, temperature, and water level. Rapid advance in optical characterization as part of water quality survey may be expected once this kind of instrumentation becomes established, and the (exact, inverse) relationship of beam attenuation and visibility is more widely recognized.

OPTICS OF SUSPENDED SEDIMENT

Much has been written on aspects of suspended sediment in waters, and it is not our intention here to review this vast literature. What is important in the present context, is the *optical* character of suspended particles and, to a lesser extent, the settling character of the particles as it may affect their residence time suspended in waters. The (sometimes severe) biological effects of *settled* particulate matter are beyond the scope of this paper.

The physical and chemical, and therefore optical, character of suspended particles can vary widely both between different waters and even in the one (imperfectly mixed) water body at one and the same time. The important attributes of aquatic particles as regards their optical character and other important aspects of environmental behavior, notably settling velocity, are particle *size, shape* and *composition*.

The classic text in the field of particle optics is that of van de Hulst (1957) who gives a thorough discussion of light attenuation by particles of different size, shape, refractive index and absorbing properties. Geometrical optics shows that particles much larger than the wavelength of light (0.4-0.7 µm) attenuate twice the light impinging on their cross-sectional area. This rather unexpected phenomenon is known as the 'extinction paradox' (van de Hulst, 1957). The explanation is simple (Figure 4). The light in a collimated beam actually impinging on the particle is all removed from the beam ('attenuated') by scattering due to the processes of *refraction* and *reflection*, or else is absorbed by pigments associated with the particle. But an equal amount of light is *diffracted* around the particle giving a total *optical* cross-section, exactly twice the *geometrical* cross-section (van de Hulst, 1957).

The light attenuation by a single particle depends most strongly on its size and therefore its projected cross-sectional area. Consequently, light attenuation by a suspension of particles depends mainly on the concentration of particles, expressed, not as SSC, but as geometrical cross-section (projected area) per unit volume. This quantity has the same units as light attenuation ($m^2/m^3 \equiv m^{-1}$). Thus light attenuation by suspended matter depends strongly on the distribution of particle sizes as it controls geometrical cross-section.

Figure 5 shows the attenuation per unit mass concentration (=attenuation 'cross-section,' $m^{-1}/(g\ m^{-3}) \equiv m^2\ g^{-1}$) of suspended spherical particles as a function of their diameter. For 'optically large' particles, the attenuation cross-section varies as the inverse of their diameter, and so declines as particle size increases. For 'optically small' particles, that is particles much smaller than the wavelength of light, attenuation cross-section falls off rapidly with declining size. The most 'optically efficient' particles are therefore particles in an intermediate size range. For quartz-composition particles the attenuation cross-section peaks at 1.2 µm and this peak position is not markedly different for other common minerals found in waters. Organic materials have much lower density as well as much lower refractive index relative to water, with the result that their attenuation cross-section peaks at larger sizes (about 5 µm). This size dependence of light attenuation by organic particles explains why phytoplankton cells contribute appreciably more light attenuation in natural waters than the often more numerous, but much smaller (of order 1 µm), bacterial cells.

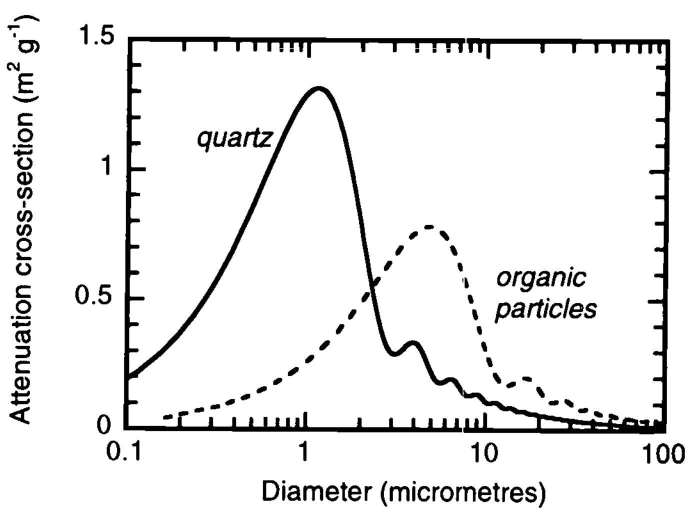

Figure 5. Attenuation Cross-Section (attenuation per unit mass) of a Suspension of Spherical Particles as a Function of Their Diameter (Davies-Colley *et al.*, 1993).

Particle shape has only a second order effect on particle optics. Thus the curves of light attenuation

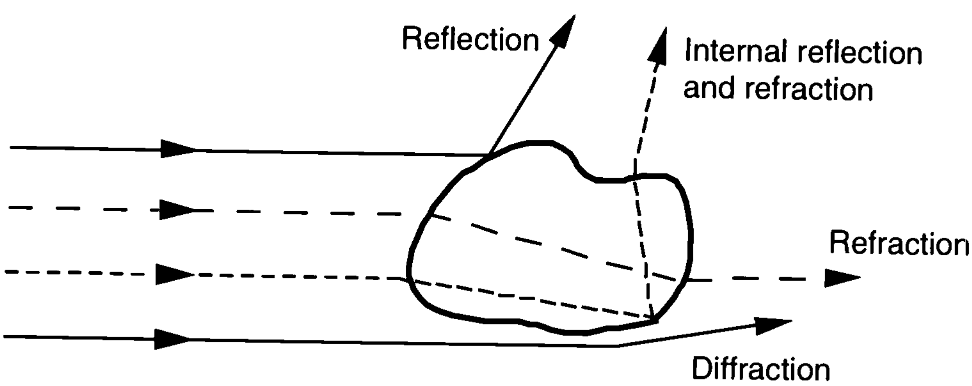

Figure 4. Schematic of the Scattering of Light by a Suspended Sediment Particle Via the Processes of Reflection, Refraction, and Diffraction (Davies-Colley *et al.*, 1993).

cross-section given in Figure 5 apply broadly to non-spherical particles of the same volume (van de Hulst, 1957). However, as could be expected, the scattering by highly aspherical (plate-shaped) two-dimensional crystals of clay minerals (van Olphen, 1977) is appreciably higher than that of spheres of equal volume, particularly at backscattering angles (Gibbs, 1978).

The composition of particles affects light attenuation primarily in that it determines the refractive index, and therefore the refractive power and internal reflection angles (Figure 4) of the particles. However some suspended particles in waters absorb light as well as scattering it owing to pigments within their volumes, or chemically adsorbed on their surfaces. Humic substances, which absorb blue light and thus impart yellow colors to waters, typically comprise the majority of organic matter in waters. Aquatic humus has a strong tendency to complex with iron and aluminum hydrous oxide coatings on aquatic particles (Stumm and Morgan, 1981) and is thought to contribute significantly to absorption of light by particles in natural waters (Kirk, 1985).

Particles that persist suspended in natural waters, and therefore contribute to light attenuation, must, of necessity, be fairly slowly settling. This means, in practice, that suspended matter in natural waters is mostly very fine-grained, or of low density relative to water, such that its Stokes' law settling velocity (e.g., Lerman, 1979) is very low. This is where the composition of particles again becomes important – particularly in regard to the great density difference between organic and mineral materials. Dense mineral particles (e.g., quartz, relative density = 2.65) generally only remain suspended if particle diameters are smaller than the sand/silt boundary at 63 µm (with corresponding settling velocities < 2 mm s^{-1}). Disc-shaped clay particles settle at only half the speed of spheres of the same volume (and only 1/10 the speed of spheres of the same diameter) (Lerman, 1979), which contributes to the persistence of clay minerals in natural waters. Organic particles, or flocculated aggregates of organic and mineral particles containing trapped water, typically have low relative densities and correspondingly low settling velocities. Such low-density particles are commonly found suspended in natural waters even at macroscopic sizes (> 1 mm diameter).

The combination of increasing settling velocity, and decreasing attenuation cross-section, as particle size increases, means that particles greater than silt size are seldom important contributors to overall light attenuation in natural waters. Particles in the sand size range are sometimes temporarily suspended in rivers, notably during floods, but sand particles seldom contribute significantly to light attenuation simply because their projected areas, and therefore their attenuation cross-sections, per unit mass, are low. Conversely, colloidal particles that are much smaller than the wavelength of light remain suspended almost indefinitely, but their attenuation cross-sections are low (Figure 5) so that they too contribute little to overall light attenuation in natural waters. The net result is that particles in the size range 0.2 to 5 µm for minerals, and a little larger (1 to 20 µm) for organic particles, dominate light attenuation in natural waters (Davies-Colley *et al.,* 1993; Kirk, 1988). Consequently, clay minerals (typically of order 1 µm), and certain small organic particles notably phytoplankton cells (typically of order 5 µm), dominate the light attenuation in most natural waters. Moreover, the beam attenuation cross-section of river or lake water, obtained by dividing c by the SSC, is typically in the 0.1 to 1 m^2 g^{-1} range that is characteristic of these 'optically efficient' particles.

INTER-RELATIONSHIPS BETWEEN TURBIDITY, SSC, AND VISUAL CLARITY

Implicit in this review is that there exist broad correlations between the three variables turbidity, SSC, and visual clarity. By way of example, Figure 6 shows the inter-relationships between these variables in a wide range of New Zealand rivers at baseflow (Davies-Colley and Close, 1990). All three variables are reasonably closely correlated, although the two optical variables are more closely related to each other (Figure 6B) than either is to SSC (Figure 6A and 6C).

The weakness of the correlations of the two optical variables with SSC may be attributed to the wide range of optical character of suspended matter in New Zealand rivers. Davies-Colley and Close (1990) showed that the particle attenuation cross- section ranged from 0.2 to 2.9 m^2 g^{-1}, with a median of 0.84 m^2 g^{-1}. The high extreme is rather higher than the 1.3 m^2 g^{-1} peak for quartz spheres (Figure 5), although plausible for a suspension of clay particles. The median is consistent with dominance by mineral rather than organic particles of order 1 µm diameter. Davies-Colley and Close's (1990) interpretation was that clay mineral particles dominate light attenuation in rivers at baseflow, however organic particles or non-clay minerals that are more weakly light-attenuating, but sometimes numerically dominating, also contribute appreciably.

In waters with a limited range of particle characteristics, the mutual correlation of visual clarity, turbidity, and suspended sediment may be appreciably closer than illustrated in Figure 6. SSC may then be predictable from the optical variables with reasonable

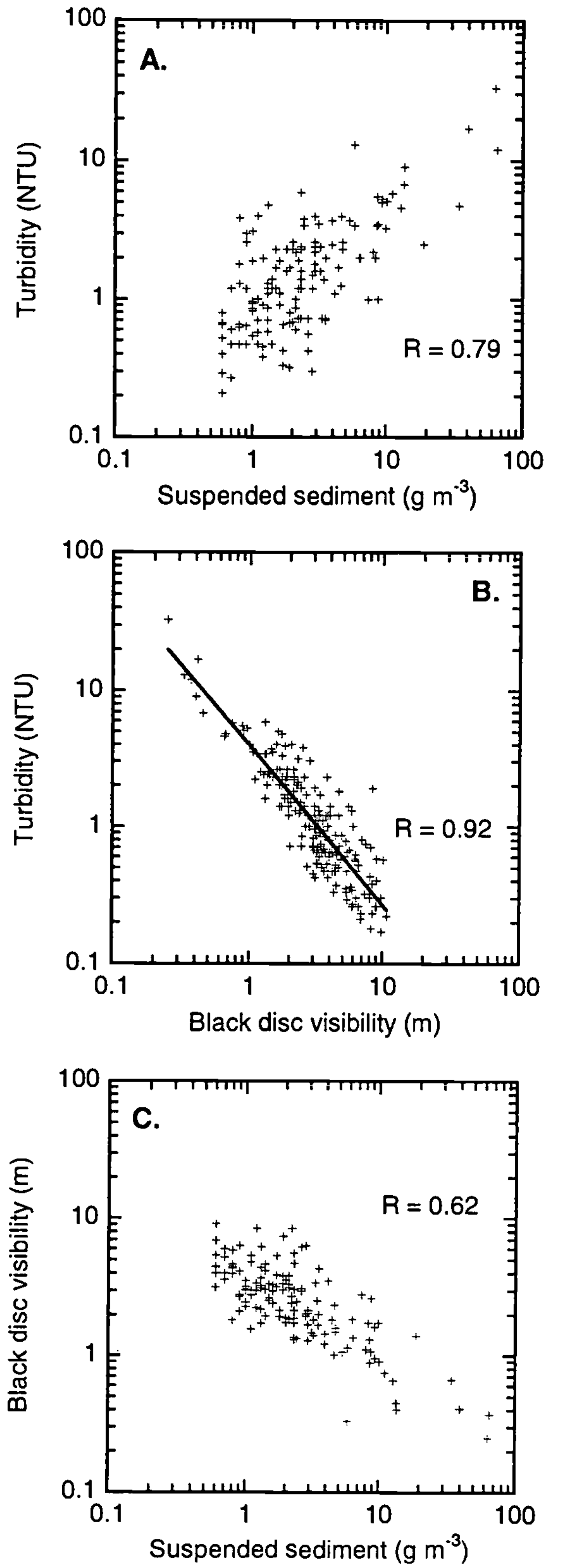

Figure 6. Mutual Relationships of Visual Clarity, Turbidity (Hach 2100A) and Suspended Sediment Concentration in 97 New Zealand Rivers (each river site sampled up to three times-n = 274 in total). Panel A. Turbidity Versus Suspended Sediment, B. Turbidity Versus Black Disc Visibility, and C. Black Disc Visibility Versus SSC. (Davies-Colley and Close, 1990).

precision. For example, Lloyd *et al.* (1987) found a close correlation (r = 0.96) between turbidity and SSC in five streams in Alaska suffering turbidity from placer mining, but weaker correlation (r = 0.91) and considerable scatter for 235 samples obtained by the U.S. Geological Survey from 34 Alaskan rivers. Where SSC really is the concern, for example where estimates of suspended matter yield are required, then such correlations may be very useful. But if *optical effect* of suspended sediment is the concern then there seems little point in attempting to estimate SSC from optical measurements.

The question arises, can historical turbidity data be converted to visual clarity (or, equivalently, beam attenuation) and vice versa? Such inter-conversions are inevitably rough, being dependent on the optical character of the particles in the waters of interest as well as the particular nephelometer used. For example, Smith *et al.* (1997) reported paired turbidity-visibility data for 77 New Zealand river sites from New Zealand's National Rivers Water Quality Network (NRWQN) (Figure 7). The regression line in Figure 7 is a power law which may be used for prediction of black disc visibility, y_{BD} from turbidity, T (measured on a particular instrument, the Hach 2100A nephelometer):

$$y_{BD} = 2.63T^{-0.807} \tag{9}$$

The relationship is fairly close (r = 0.94) reflecting the wide data range, although there is appreciable scatter about the regression line (which, incidentally, is very similar to that for individual data-points in Figure 6B). Furthermore, although the relationship between black disc visibility and turbidity is roughly inverse, it is not *exactly* inverse (implying power law exponent = -1).

A close relationship is sometimes found between turbidity and visual clarity in *particular waters* with light attenuation dominated by particles of similar optical character. By way of example, Figure 8 shows data for turbidity and black disc visibility in the Esopus and Schoharie watersheds in New York in which turbidity is caused by widespread clay-rich glacial deposits. The data is plotted on both linear and logarithmic grids to emphasize the inverse relationship between the two optical variables. Again we have an imperfect inverse relationship between visibility and turbidity, despite very good overall correlation.

SSC and optical character of rivers are known to vary appreciably with time, mainly with state of flow (Smith *et al.,* 1997). Consequently, mutual relationships between optical variables and SSC at the one river site sampled at different states of flow are similar to those for rivers generally. Figure 9 shows that black disc visibility, SSC and turbidity are all strong functions of flow in the Grey River at Stillwater, New Zealand. Turbidity is a less rapidly increasing power law function of flow than SSC in the Grey River (Figure 9B) because as flow increases, coarser particles, with lower attenuation cross-sections (and lower side scattering per unit mass concentration) are thrown into suspension. For related reasons the power law function defining the visibility-flow relationship for the Grey River (Figure 9A) has a smaller (negative) exponent than SSC versus flow.

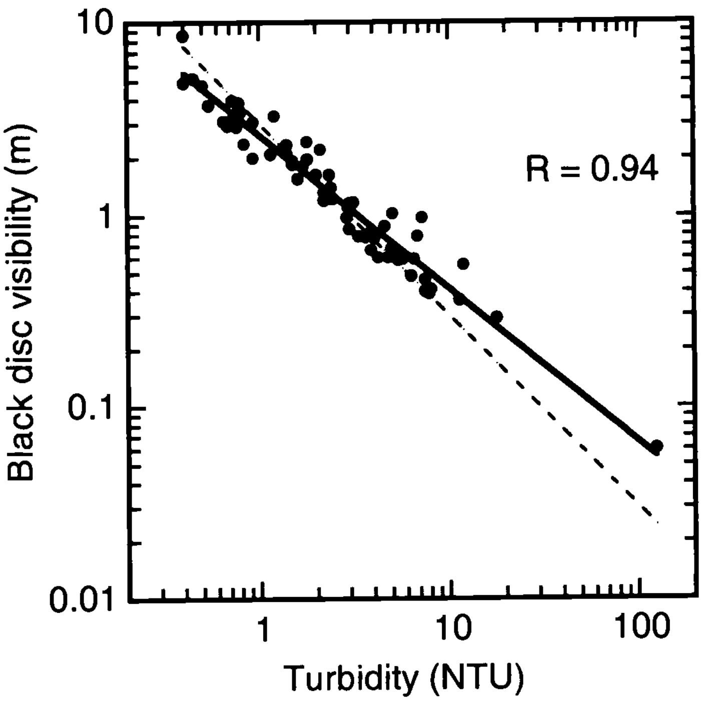

Figure 7. Black Disc Visibility and Nephelometric Turbidity (Hach 2100A) at 64 River Sites in New Zealand. Data are medians for sites in New Zealand's National Rivers Water Quality Network (Smith *et al.*, 1997). Each site is sampled monthly, and six years of data were used for the analysis, that is, each point represents the median of 72 samples. Both the power law fit to the data (solid line) and a simple inverse (y_{BD} = 3.02/T) (dashed line) are shown.

Table 1 gives the correlation matrix for the four variables flow, black disc visibility, SSC, and turbidity for the Grey River at Stillwater. This shows that the optical variables visibility and turbidity are closely related to each other and to SSC, reflecting the underlying relationship of each of these variables to flow in this river.

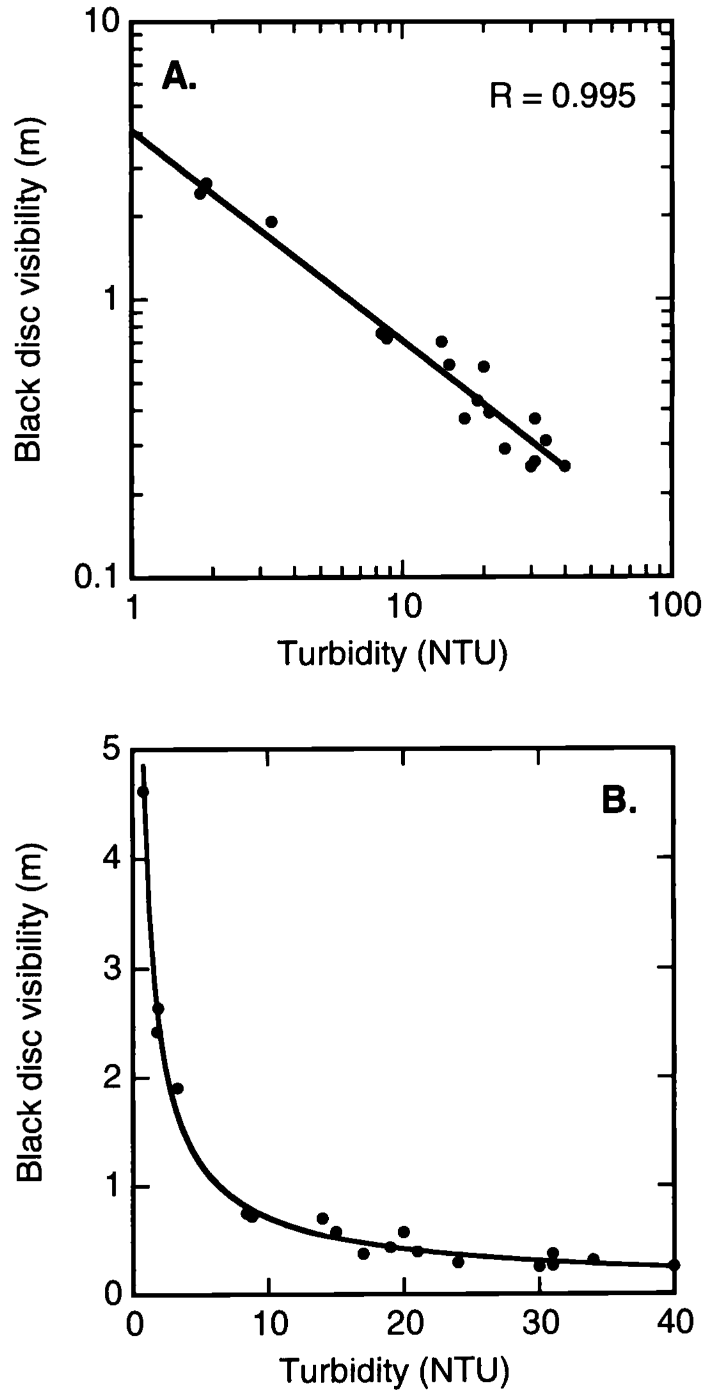

Figure 8. Black Disc Visibility Versus Turbidity (Hach 2100AN nephelometer) for 16 Sites in the Esopus and Schoharie Catchments, in the Catskill Region of New York (New York City Department of Environmental Protection, unpublished data). A. Logarithmic Scales, B. *Same* Data on Linear Scales. The data is well fitted (r = 0.995) by a power law: $y_{BD} = 4.09T^{-0.76}$.

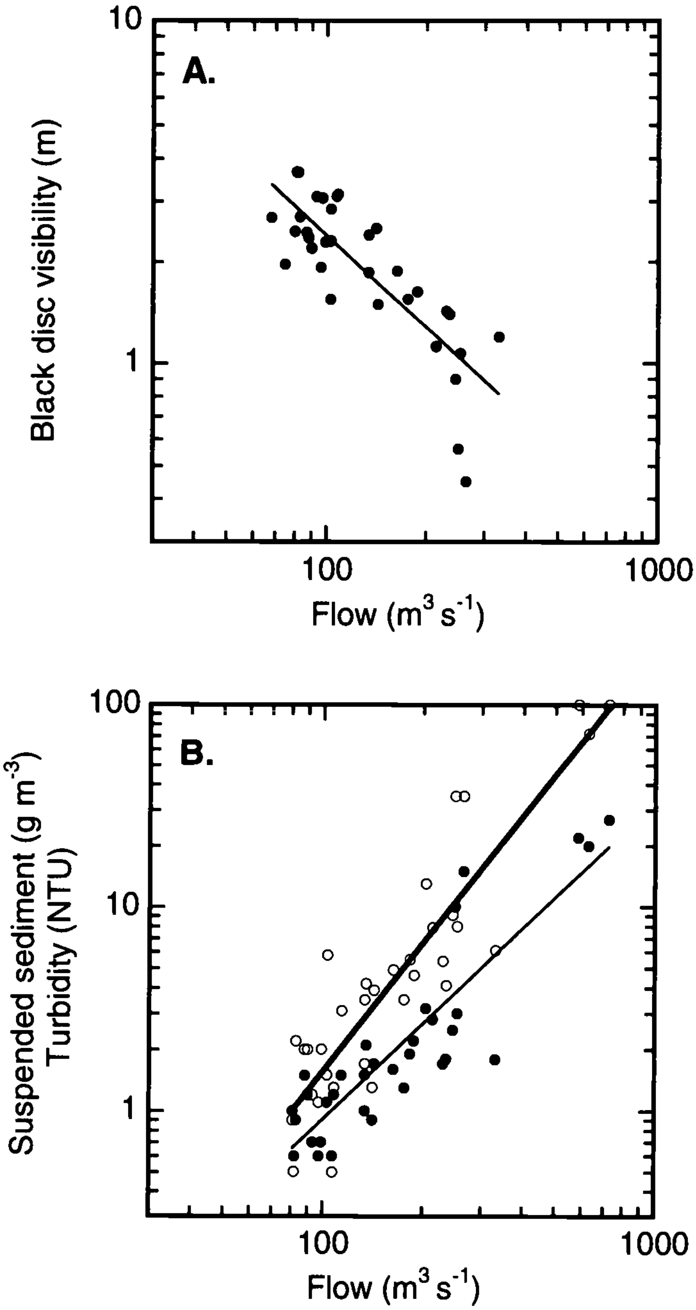

Figure 9. Visual Clarity, Turbidity (Hach 2100A), and Suspended Sediment, Versus Flow in the Grey River, New Zealand. A. Black Disc Visibility Versus Flow. B. Turbidity (solid points) and SSC (open points) Versus Flow. Low visibilities were not measured at high, and hazardous, flows (> 400 m^3 s^{-1}). Author's unpublished data from 1987 – prior to development of offsite measurement protocols suitable for flood waters (Smith and Davies-Colley, 1992).

SSC AND TURBIDITY COMPARED WITH VISUAL CLARITY

Table 2 compares and contrasts the traditional water quality measures, SSC and nephelometric turbidity, with visual water clarity. The principle and procedure of each measurement is summarized, and necessary equipment and calibration are indicated. We reiterate in Table 2 that turbidity is not really a scientific measurement being merely a relative index of scattering with reference to an arbitrary standard scattering material (formazin).

TABLE 1. Correlation Matrix for Flow, Black Disc Visibility (y_{BD}), Suspended Sediment, and Turbidity (Hach 2100A nephelometer) in the Grey River at Stillwater (Pearson correlation coefficients for log-transformed variables) (author's unpublished data).

	Flow	Visibility y_{BD}	Suspended Sediment	Turbidity
Flow	1.000			
Visibility, y_{BD}	-0.815	1.000		
Susp. Sediment	0.896	-0.929	1.000	
Turbidity	0.891	-0.924	0.952	1.000

Cost

In principle, SSC is a simple laboratory analysis, but the procedure is involved and time-consuming in practice, thus SSC is considerably more expensive than optical measurements (Table 2). Turbidity measurement is fairly simple and cheap if a suitable nephelometer and standards are available. Depreciation of the nephelometer may be a significant proportion of the analytical cost even where sample throughput is high. Charges quoted by a commercial U.S. laboratory with high throughput of both SSC and turbidity analyses ($23 and $5 respectively) are given in Table 2.

Field equipment for black disc visibility observations is comparatively cheap (about US$400 for a full set of equipment, including three sizes of black disc, the viewer and mirror, and accessories). A visit to the field site is normally made for water quality sampling, so it is the *extra* field time that contributes to the cost of visibility observations. We allowed a generous ten minutes extra field time at $20/hr ($3.33/observation), and $0.6 depreciation/observation, for the purpose of estimating an indicative cost of $4/observation in Table 2. We note that both the numerical values, and overall pattern, of costs in New Zealand is very similar to those in the USA (Table 2).

TABLE 2. Comparison of Suspended Sediment Concentration, Nephelometric Turbidity, and Visual Clarity Measurement for Water Quality Assessment.

Attribute	Suspended Sediment Concentration (SSC) (nonfilterable residue – NFR)	Turbidity	Visual Clarity (or alternatively, beam attenuation coefficient)
Principle and Procedure	Weight of particulates captured on a glass fibre filter through which a known volume of water sample has been filtered.	Side scattering of light by nephelometry (relative scale).	Sighting range of a black disc viewed horizontally through water (or Secchi depth) (alternatively, beam transmittance measurement).
Equipment	Filter assembly with vacuum pump, oven, weigh balance, desiccator, glass fibre filters.	Nephelometer and standards.	Underwater viewer and visual target, tape measure (beam transmissometer).
Calibration?	None.	Arbitrary calibration to formazin.	None
Scientific Measurement? (units)	Yes (g m^{-3}).	No, arbitrary, relative measurement (in NTU).	Yes (m) (beam attenuation coefficient, m^{-1})
Cost (and difficulty)	Simple, but involved and consumptive of technician time – hence expensive. **\$23/sample** (NZ\$18/sample)	Fairly simple (standards required for calibration). **\$5/sample** (NZ\$6/sample)	Simple, but does require access to water body. **\$4/observation**[1] (NZ\$4/observation)
Precision (typical standard error)	10 percent[2]	10 percent[3]	4 percent[4,5]
Sample Size	Depends on sediment concentration. For best precision, 100 mg is required (i.e., 10L volume at 10 g m^{-3}).	100 mL or less for a laboratory measurement.	Not applicable (usually done *in situ*).
Stability of Samples (and storage)	Stable for several days (store chilled, dark).	Unstable (store chilled, dark, and measure within 24-hours of collection).	Not applicable (usually done *in situ*).
On Site or *In Situ* Measurement?	No (must be done in a laboratory).	Yes (portable models).	Yes (usual procedure).
Continuous Monitoring?	No.	Yes (*in situ* turbidity monitors).	Yes, as beam transmittance (from which visibility may be calculated).
Environmental Relevance	Relevant to **sediment yields** (in geomorphology, agronomy), and **benthic effects** of sedimentation. Less relevant to optical effects.	*Indirectly* relevant – because the measurement is *relative* to *arbitrary* standards. Requires calibration (e.g., to suspended solids or visual clarity).	Relevant to **aesthetic quality** of water and **habitat** for sighted aquatic animals. Less relevant to sediment mass-related impacts.

[1]Assuming ten minutes *extra* on site per observation (at US\$20/hr), and allowing \$0.60/observation for equipment depreciation.
[2]McGirr (1974), APHA (1998).
[3]McGirr (1974), ASTM (1996), U.S. EPA (1999).
[4]Davies-Colley and Close (1990).
[5]Smith and Hoover (1999).

Precision

Precision of SSC measurements is limited mainly by the amount of filterable residue collected, and therefore the volume of sample that is filtered (see below). An indicative standard error of 10 percent (APHA, 1998) is quoted in Table 2. Turbidity measurement typically has a standard error of around 10 percent at around 1 NTU (e.g., coefficient of variation is 10 percent for turbidities of about 1 NTU, ASTM, 1996). APHA(1998) gives a table of recommended reading precision for nephelometers consistent with an underlying standard error of order 10 percent.

The coefficient of variation for replicate visual clarity observations, by black disc or Secchi disc, is about 4 percent (Davies-Colley and Close, 1990; Smith and Hoover, 1999), implying appreciably better precision than for SSC or turbidity (Table 2). This comparison, favoring visual observations, will surprise many people. The prevailing perception is that a method involving the human eye and brain must be subjective (i.e., subject to bias) and therefore inaccurate by comparison with 'objective' laboratory or instrumental measures. For example, in his otherwise excellent paper advocating replacement of turbidity by beam transmissometry, McCluney (1975) dismisses Secchi disc measurements as "extremely subjective and inaccurate." Actually, the subjectivity of visual clarity measurement is a minor source of error, because the contrast sensitivity of the human eye is very nearly constant for individuals with normal eyesight (Tyler, 1968). The absence of any calibration step in visual clarity measurement also contributes to good overall precision.

Sample Size

A comparatively large sample is required for SSC measurement – ideally sufficient volume to yield around 100 mg of non-filterable residue (i.e., 1 liter at SSC =100 g m^{-3}, 10 liters at 10 g m^{-3}). A maximum of 200 mg of residue should be collected on glass fibre filters so as to avoid forming a water-occluding crust (APHA, 1998). Collecting sufficiently large volumes to yield 100 mg of filter residue may only be practical for relatively turbid waters (say > 10 g m^{-3}). Even when excess sample volume is available, precision of SSC measurement might be constrained by filter-clogging colloids limiting the volume that can be filtered.

An important advantage of turbidity measurement is that only 100 milliliters or less is required for laboratory analysis (Table 2). Turbidity may also be measured *in situ*, so obviating the need for any sample. Visual clarity measurement is usually done in the water body and does not require a sample. If the visual clarity observation can not be done *in situ*, for example because the visibility is too low for direct measurement (say < 50 mm) or because conditions in the water are hazardous (e.g., during flood flow in a river), measurements can be made on the bank of the water body using a trough of about 10 L volume (Davies-Colley and Smith, 1992), so there is seldom any need to return inconveniently large samples to the laboratory.

Stability of Samples and On-site Measurement

Suspensions of aquatic particulates will often undergo slow agglomeration on standing (Phillips and Walling, 1995). Microbial growth seems to be the main cause of such changes – probably as a result of bio-flocculation by bacterial extra-cellular polymers (Phillips and Walling, 1995). Usually turbidity declines with particle aggregation, therefore samples for turbidity measurement are unstable (Table 2) and should be analyzed as soon as possible after collection, ideally within 24 hours. Changes on standing affect suspended solids mass concentration less than the optical character of the suspended particulates, so samples for measurement of SSC may be stored for longer than turbidity samples (Table 2). Samples for both turbidity and SSC measurement should be stored chilled (not frozen) and dark (APHA, 1998).

In-situ optical measurements are generally to be preferred to laboratory measurements because of the immediate yield of useful information. Visual clarity measurement has the very great advantage that it is (usually) an *in situ* measurement that is immediately meaningful without interpretation or calculation, and can guide the field worker on-site regarding further investigations or the taking of water samples.

Continuous Monitoring

A major advantage of optical measurements over necessarily laboratory-based measurement of SSC is the potential for continuous monitoring (Table 2). A number of turbidity monitors are commercially available and have proven very useful for tasks such as refining sediment yield measurement in rivers and for capturing pollution 'events.' Unattended monitoring with these instruments is limited mainly by the tendency for obscuration of optical windows by microbial growths. Double beam instruments, that factor out the decline in window transmission over time, represent one approach to address this problem. Visual clarity, as such, cannot be measured continuously, but a beam transmissometer can be operated as a de facto water clarity monitor using the exact, inverse, relationship between c and black disc visibility (Equation 8).

Environmental Relevance

Perhaps most important of the attributes considered in Table 2 is the *environmental relevance* of the different measures. Suspended mass concentration, and thus mass load (concentration X flow), is highly relevant to studies of sediment yield in geomorphology and related fields, and to concerns with effects of sediment once settled. But while sediment remains suspended optical measures are often more environmentally relevant than SSC. Turbidity, although an optical measurement, is not immediately relevant to environmental problems because it is a relative and arbitrary measurement – even though turbidity is often treated as though it were an absolute scientific quantity (McCarthy *et al.*, 1974). To be really useful, turbidity measurements must be *calibrated* (e.g., to SSC or to visual clarity) depending on whether the main concern is mass concentration of suspended sediment or its optical effect. For example, a relationship between visual clarity and turbidity (e.g., Figures 7 and 8) may be used for approximate inter-conversion of these quantities in a particular water and with a particular nephelometer.

Visual clarity is more environmentally relevant than turbidity because it is a *direct* measure of an optical attribute of water that strongly affects aquatic habitat and human use of waters. For instance, a number of studies of reactive distance of predator fish have characterized the test water in terms of turbidity (Abrahams and Kattenfeld, 1997). But turbidity has no immediate physiological meaning, unlike visual range, which is an upper bound to, and ultimately controls, reactive distance.

Arguably, optical measures are also more relevant than SSC to adsorption of contaminants onto suspended sediment because light attenuation is proportional to the concentration of chemically-adsorbing surface area of particles. We are not aware of previous work recognizing this conceptual link between optical and contaminant-adsorbing properties of suspended sediment.

Considerations of environmental relevance, together with the great differences in analytical cost, are the main reasons why visual clarity (as black disc visibility), but not SSC, is measured in New Zealand's National Rivers Water Quality Network (Smith and McBride, 1990). Turbidity is also measured in the NRWQN, but merely as a quality control check.

Environmental Standards

We consider that nephelometric turbidity is unsuitable for environmental standards because it is not an absolute, scientific measurement (Austin, 1973; McCarthy *et al.*, 1974; Telesnicki and Goldberg, 1995) and is imperfectly related to the attribute of water that it purports to indicate, namely visual clarity (APHA, 1998). Nor is SSC a suitable measure for standards where the environmental effects of suspended matter are related to its light attenuation rather than to its mass concentration. The main environmental protection statute in New Zealand, the Resource Management Act of 1991, imposes standards in terms of water clarity, but not turbidity or SSC. The visual clarity standards are supported by guidelines (MFE, 1994) recommending a minimum black disc visibility of 1.6 m for contact recreation, and a maximum proportional reduction in visual clarity between 20 percent and 50 percent depending on water classification and intended water use. Furthermore, to protect light penetration into waters, a maximum 10 percent reduction in euphotic depth is recommended. The wide adoption by resource managers of practical means for measuring water clarity, notably black disc visibility, and the incorporation of the MFE (1994) guidelines in regulations, is improving the protection of optical attributes of New Zealand's natural waters.

CONCLUSIONS

This paper has compared and contrasted SSC with measures of the optical effects of suspended sediment – cloudiness of water (measured as nephelometric turbidity) and visual clarity (measured as black disc visibility or Secchi depth). SSC continues to be measured in water quality and related fields (e.g., fisheries management) when much of the environmental impact of *suspended* sediment is optical – which calls for an optical measurement. Even where sediment mass concentration really is the main feature of interest, *in situ* monitoring with optical sensors may permit greatly refined estimates of sediment yield. When it is the optical effect of the suspended sediment that is of primary concern to water resource and fishery managers, light penetration or visual clarity are usually the most appropriate measures. Visual clarity is a true scientific measurement that is not particularly subjective and can be measured with appreciably better precision than either turbidity or SSC (Table 2).

We recommend that water quality scientists and managers carefully consider their objectives in measuring SSC in waters. In many situations optical measurements might be more relevant. In any case, far more measurements (or continuous measurements) may be made, or the same number of measurements may be made far more cheaply, with SSC replaced by an optical measurement. Turbidity measurement may be appropriate where a relative index of water cloudiness is sufficient, or if there is some inherent advantage of a laboratory assay. However, we believe that, to be meaningful, turbidity needs to be calibrated to a proper scientific quantity. Visual clarity measurement has most of the advantages of turbidity, but is a preferred optical measurement, being a true scientific quantity that can be measured with better precision and even more cheaply, and has immediate environmental relevance. Visual water clarity measurement deserves to become more widely adopted in water quality and related fields – preferably measured as hydrological range (black body visibility). Visual clarity is usefully supported by continuous measurement, not of arbitrary nephelometric turbidity, but of beam attenuation, an inherent optical property of water.

Generally SSC is not an appropriate measure for environmental standards where the environmental effects of suspended matter are related to its light attenuation rather than to its mass concentration. Nephelometric turbidity, which is not a proper scientific measurement, is not entirely suitable either. We recommend formulation of environmental water quality standards in terms of visual water clarity, recognizing its environmental relevance and significant practical advantages over both SSC and turbidity.

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