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RADIOMETRY
OF
WATER TURBIDITY MEASUREMENTS

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ABSTRACT

An examination of a number of measurements of turbidity reported in the literature reveals considerable variability in the definitions, units, and measurement techniques used. Many of these measurements differ radically in the optical quantity measured. The radiometric basis for each of the most common definitions of turbidity is examined. Several commercially available turbidimeters are described and their principles of operation are evaluated radiometrically. It is recommended that the term turbidity be restricted to measurements based upon the light scattered by the sample with that scattered by standard suspensions of known turbidity. It is also recommended that the measurement procedure be standardized by requiring the use of Formazin as the turbidity standardizing material and that the Formazin Turbidity Unit (FTU) be adopted as the standard unit of turbidity.

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INTRODUCTION

Increasing turbidity and siltation appear to be inevitable consequences of man's activities in and around our coastal waters. Dredging and filling operations, man-made water currents, motorboat propellers in shallow areas, industrial and municipal effluent flows, and dragline fishing operations can contribute heavily to the loss of water clarity and to increasing siltation in estuarine and other coastal areas.

Aside from the aesthetic problems associated with losses in water clarity, organisms such as benthic algae, other bottom vegetation, and some marine animals are sensitive to increases in turbidity.[1] High turbidity blocks out the sun and reduces photosynthesis in bottom vegetation and near-bottom phytoplankton. The siltation which tends to accompany high turbidity can kill living coral and can destroy highly productive grass flats. Large quantities of suspended sediment are detrimental to aquatic life of salmon and trout streams.[2-3]

Filtering and weighing techniques have been developed for determining the amount of suspended materials present in a sample of turbid water.[4] But direct measurement by the conventional methods is difficult and time-consuming. There exist a number of optical measurement techniques which could be performed easily and quickly in situ, if a proper relationship between the optical property being measured and the amount of suspended matter can be found. A few of these techniques give results that are roughly proportional to the amount of suspended material present in the water in certain circumstances.[5-11]

But the optical properties involved in these measurements are in general dependent upon the shape, refractive index, and size distributions of the suspended particles, as well as their absorption spectra. As a result, these optical properties can be proportional to mass or volume concentration only if all the other parameters are held constant. Natural waters tend to exhibit considerable variability in these parameters, making the establishment of the desired relationship difficult.

With reasonable assumptions as to the shapes and indices of refraction of the particles in a given body of water, it is possible to invert the equations describing the optical processes involved, and to obtain rough estimates of the numerical distribution of particle sizes from measurements of the angular dependence

of scattering.[12-16]   However, the large variability in shapes and indices of re-
fraction of the particulates found in natural waters severely restricts the use-
fulness of the technique for routine measurements. Furthermore, the method
involves complex mathematical operations and sophisticated optical instrumenta-
tion which would be quite expensive to build and maintain. It is primarily for
this reason that the easier and simpler-to-measure optical parameters, such as
turbidity and transparency, have found most widespread use.

Turbidity is probably the simplest optical parameter which one can measure
quickly and easily in natural waters. Although turbidity was originally defined
to be an optical measurement of the concentration of suspended solids (having
units of parts per million),[17] it was soon found that the optical measurement
did not always give the same results as other methods and it is now generally
accepted that turbidity is strictly an optical property of the medium. Duchrow
and Everhart attempted to establish a relationship between turbidity and the
concentration of suspended particles which would be valid for the special class
of waters (salmon and trout streams) of interest to them.[1]   But even in this
case, they were forced to conclude that too many factors must remain constant
before a turbidity measurement can be converted to a corresponding suspended
sediment concentration. In spite of these difficulties, optical measurements,
especially turbidity, have been and will continue to be used widely to estimate
the quantity of suspended matter in natural waters.[18-21]

A number of different optical measurements have been labelled turbidity by the
reporting authors or by the manufacturers of the instruments used in the meas-
urement. Many of these measurements differ radically in both the optical
quantity measured and the units in which the measurement of turbidity was re-
ported. This paper is the result of an attempt to examine the radiometric basis
of each of the so-called turbidity measurements and in each case to determine
the relationship of the turbidity measurement to the basic optical quantities
used in hydrologic optics.

The following discussion will begin with the definitions of absorption, scatter-
ing, and extinction parameters and the theoretical basis behind their measure-
ment. Several definitions of turbidity found in the literature will be discussed
as will a number of instruments available for the measurement of turbidity.
The radiometric quantities flux, intensity, irradiance, and radiance, which will
be used in the following discussion, are defined in reference 22.

ABSORPTION, SCATTERING, AND EXTINCTION

If a collimated beam of monochromatic light of wavelength λ and incident irradi-
ance $H_0(\lambda)$ is caused to pass through a macroscopically homogeneous medium,

the irradiance of the beam will tend to decrease with increasing distance through the medium. The loss of energy from the beam as it propagates may be attributed to the fundamental processes of absorption and scattering. That portion of the radiant energy at wavelength λ which is lost due to absorption is totally removed from the system, being transformed into another form of energy altogether. (The transformation of this light into light at a different wavelength will not be considered in this discussion.) That portion of the incident beam which is lost due to scattering is deflected out of the beam by microscopic inhomogeneities in index of refraction within the medium.

Consider the infinitesimal distance dx along the path of propagation of the collimated beam. If $H(\lambda)$ is the irradiance of the beam at position x and $dH(\lambda)$ is the portion of the irradiance lost from the beam due to absorption and scattering over the distance dx, then we define the spectral volume extinction coefficient to be

$$c(\lambda) = - \frac{1}{H(\lambda)} \frac{dH(\lambda)}{dx} .$$
(1)

$c(\lambda)$ has the dimension of reciprocal length. If $H_0(\lambda)$ is the irradiance at x = 0 and if $H_c(\lambda, x)$ is the irradiance at some distance x along the beam, then we may integrate equation (1) from zero to x to obtain

$$H_c(\lambda, x) = H_0(\lambda) e^{-c(\lambda) x}$$
(2)

where $c(\lambda)$ is assumed to be constant from 0 to x. Equation (2) is sometimes referred to as "Lambert's Law." Note that in any experiment to determine $c(\lambda)$ by measuring H_0 and H_c over sizeable path lengths, great care must be taken to avoid the detection of multiply scattered light, light which, though being scattered out of the beam, is subsequently scattered back into it.

If $H(\lambda)$ is the irradiance of the collimated beam at position x and if $dH_a(\lambda)$ and $dH_b(\lambda)$ are the elements of irradiance lost from the beam over the distance dx due to absorption only, and scattering only, respectively, then we define the spectral absorption coefficient to be

$$a(\lambda) = - \frac{1}{H(\lambda)} \frac{dH_a(\lambda)}{dx}$$
(3)

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and the spectral (total) scattering coefficient to be

$$b(\lambda) = -\frac{1}{H(\lambda)} \frac{d\,H_b(\lambda)}{dx} \qquad (4)$$

Since $dH(\lambda) = dH_a(\lambda) + dH_b(\lambda)$, clearly $c(\lambda) = a(\lambda) + b(\lambda)$.

If we define $H_k(\lambda,x)$ to be the irradiance of the beam at distance x due to both the direct, unscattered beam, and multiply scattered light (of all orders of multiple scattering), we may write, by analogy with equation (2),

$$H_k(\lambda,x) = H_0(\lambda) e^{-k(\lambda)x} \qquad (5)$$

where $k(\lambda)$ is a (wavelength-dependent) "constant" of the medium which we shall call the spectral diffuse extinction coefficient. It has the dimension of reciprocal length.

The extinction coefficient, $c(\lambda)$, as defined, is an inherent property of the medium and should be independent of the measuring instrument or method. In reality, it is not possible to prevent some (singly and multiply) scattered light from reaching the detector in actual measurements. But there exist techniques for minimizing the amount of scattered light detected and it is therefore possible to come close to a measurement of the true extinction coefficient $c(\lambda)$.

The diffuse extinction coefficient, $k(\lambda)$, on the other hand, depends upon the way in which the measurement is performed, since different instrumental designs may allow more or less scattered light to be detected. To simplify our future considerations and to eliminate this difficulty, let us specify that the detection of light in a collimated beam, after its passage a distance x through the medium, will be a measurement of $c(\lambda)$ if the receiving optics is telescopic with a very narrow angular field of view, an entrance aperture which matches the collimated beam, and if the path length x is not too great. The measurement will be of $k(\lambda)$ if the receiving optics is an irradiance detector whose diameter matches the collimated beam and whose angular response to uniform incident irradiance varies with the cosine of the angle of incidence. The two idealized measurements are illustrated in Figures 1a and 1b. Although $k(\lambda)$ was called a constant of the medium, measurements by Duntley[23] have shown that $k(\lambda)$ exhibits a slight dependence upon the path length x, even for a homogeneous medium.

The total scattering coefficient b represents the light lost from the collimated beam by scattering in all directions. The angular distribution of the scattered
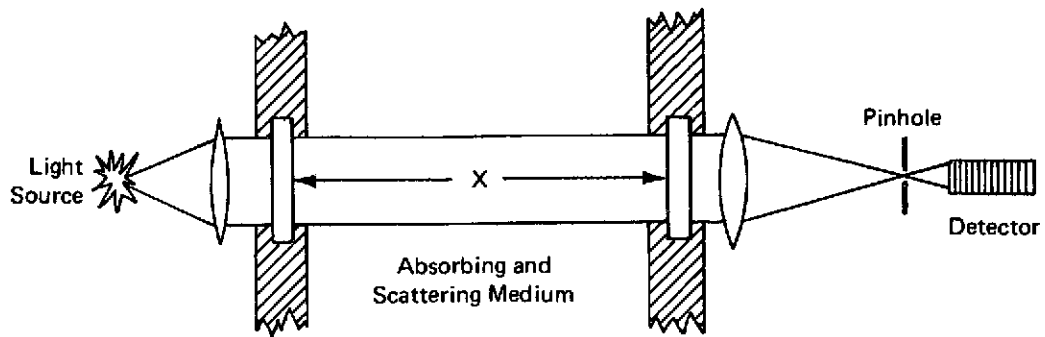
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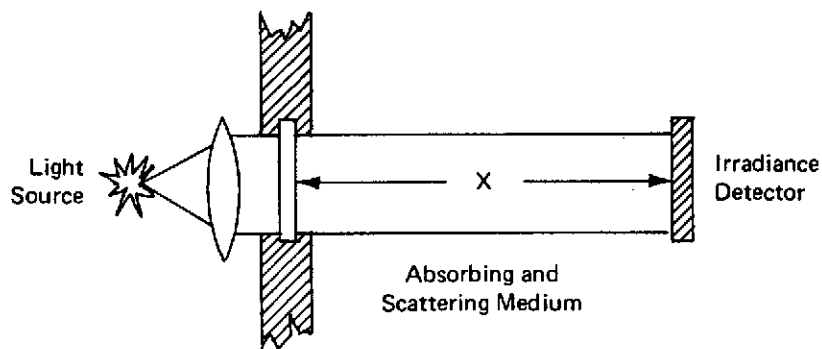Figure 1a. Measurement of Extinction Coefficient $c(\lambda)$.

Figure 1b. Measurement of the Diffuse Extinction Coefficient $k(\lambda)$.
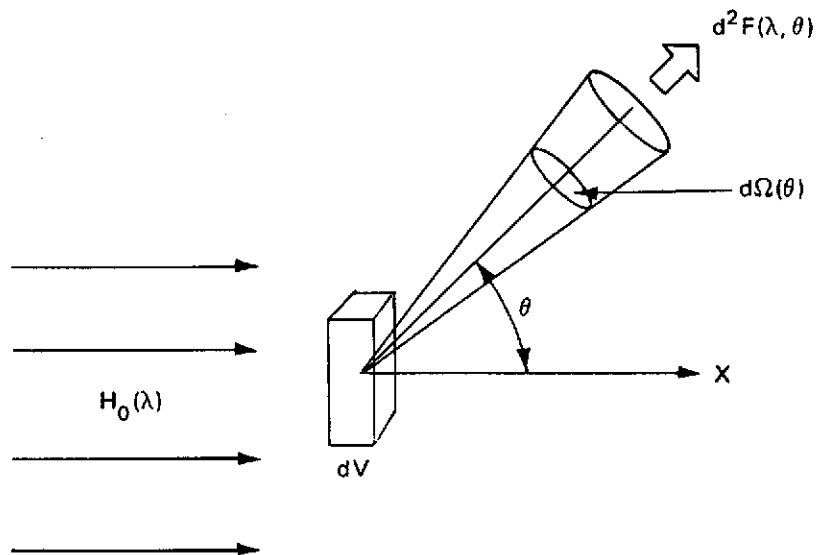

Figure 2. Scattering Geometry

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light is described by the spectral volume scattering function (VSF) which will now be defined.

Consider the small element of volume dV of the scattering medium shown in Figure 2. Let $H_0(\lambda)$ be the incident irradiance. Let $d^2F(\lambda, \theta)$ be the element of flux (power per unit wavelength) scattered into the element of solid angle $d\Omega(\theta)$ in a direction specified by the scattering angle θ. The spectral volume scattering function $\beta(\lambda, \theta)$, assumed constant within dV, is defined by the relation

$$\beta(\lambda, \theta) = \frac{d^2F(\lambda, \theta)}{H_0(\lambda)\, d\Omega(\theta)\, dV} \tag{6}$$

The ratio $d^2F(\lambda, \theta)/d\Omega(\theta)$ is by definition the element of intensity $dJ(\lambda, \theta)$ scattered from the infinitesimal volume dV in the direction specified by the angle θ and may be replaced by it in eq. (6).

The volume scattering function β may be determined using equation (6) by measuring the flux $F(\lambda, \theta)$ scattered into a finite (but small) solid angle Ω, if the incident irradiance $H_0(\lambda)$ is known. In this case the measured flux will be given by a double integral over the scattering volume and the solid angle subtended by the detector:

$$F(\lambda, \theta) = \beta(\lambda, \theta) \int\int H_0(\lambda)\, dV d\Omega(\theta). \tag{7}$$

It is assumed that β is constant over the scattering volume. Once the integrals have been evaluated the resulting expression may be solved for the scattering function.

If the scattering volume and the detector are appreciably large relative to the distance between them, the result obtained will be a weighted average of the scattering function over the range of scattering angles involved. Failure to properly perform the integrals in equation (7) and to keep the range of scattering angles small in a measurement of β can result in serious errors in the measurements.

THE DEFINITION OF TURBIDITY

The literature contains a variety of definitions of turbidity. We shall list each different definition separately and shall number them for later reference.

(1) An early definition is found in Water Supply and Purification by W. A. Hardenbergh,[17] first published in 1938: "The turbidity of a water is expressed by the amount of suspended matter, in parts per million, as ascertained by optical observation." A similar definition is found in ref. 24. The definition derives from the original work of Whipple and Jackson in 1900.[25]

In physical chemistry, a distinction is made between turbidity and nephelometry, and R. B. Fischer, in Standard Methods of Chemical Analysis,[26] describes them as follows: "Turbidity and nephelometry are based on the attenuation due to scattering by particles of different index of refraction."

(2) "In turbidity, measurement is made of the intensity of light transmitted through the medium, i.e., of the unscattered light."

(3) "In nephelometry, the intensity of the scattered light is measured, usually, but not necessarily at right angles to the incident light beam."

(4) Don Eichner, in a pamphlet published by the Hach Chemical Company,[27] states: " . . . in physical chemistry research, turbidity is expressed as a ratio of the intensity of light scattered by a unit volume of the sample to the intensity of the incident light illuminating the sample. This is known as either the Rayleigh Ratio or the Scattering Coefficient and is designated as R_{90} when the light scattered at 90° to the transmitted beam of light is considered."

(5) Several references define turbidity to be an extinction measurement, although it is not always clear whether true extinction or diffuse extinction are involved. The American Public Health Association uses the following definition:[28] "Turbidity should be clearly understood to be an expression of the optical property of a sample which causes light to be scattered and absorbed rather than transmitted in straight lines through the sample." A similar definition is given by Pickard and Giovando:[29] "The optical characteristic of the water which will be used for description here will be the turbidity τ defined by

$$I = I_0 e^{-\tau L}$$

where I_0 and I are the incident and emergent light intensities [sic] of a parallel beam of light passing through a column of water of length L." Piccialli and Piscitelli give an identical definition.[30]

The American Society for the Testing of Materials, in its Manual on Industrial Water and Industrial Waste Water,[31] gives several definitions:

(6) It defines turbidity in general as: "Reduction of transparency of a sample due to the presence of particulate matter." It then goes on to describe three different kinds of turbidity:

(7) "Jackson Candle Turbidity — An empirical measure of turbidity in special apparatus, based on the measurement of the depth of a column of water sample that is just sufficient to extinguish the image of a burning standard candle observed vertically through the sample."

(8) "Nephelometric Turbidity — An empirical measure of turbidity based on a measurement of the light-scattering characteristics (Tyndall effect) of the particulate matter in the sample (Note 1) . . . .
    Note 1. — The measurement of nephelometric turbidity is accomplished by measuring the intensity of scattered light at 90 deg to the incident beam of light."

(9) "Absolute Turbidity — The fractional decrease of incident monochromatic light through the sample, integrating both scattered and transmitted light (Note 2).
    Note 2. — For the small amount of scattering experienced in essentially colorless solutions, absolute turbidity of a 1-cm layer corresponds to the extinction coefficient in the equation expressing Lambert's Law."

Let us examine these definitions, in order to relate them to the fundamental radiometric quantities described earlier. The first definition may be ignored, as it is no longer widely used. The second definition, with its specific exclusion of all scattered light from the measurement, clearly refers to extinction, specified by the extinction coefficient c. Since no mention is made of the wavelength of the measurement, we shall assume that it is made using white light emanating from a tungsten filament incandescent lamp. The result is therefore proportional to the integral of the product of the source radiance spectrum, the sample extinction spectrum, and the spectral response of the detector.

The third, fourth, and eighth definitions clearly refer to the volume scattering function $\beta(\lambda, \theta)$ at a 90° angle of scattering. Definition 3 includes the possibility of measurements at other scattering angles. All three appear to refer to the use of white light in the measurement. The fifth definition specified an extinction measurement but it is not clear whether true extinction or diffuse extinction is involved.

Definition 6 appears to apply to the reduction of transparency due to scattering alone, since the particulates generally contribute very little to the absorption coefficient, except in very turbid suspensions. The reduction of transparency due to scattering is specified by the total scattering coefficient $b(\lambda)$, where, again, we must assume that the measurement is made with white light.

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Definition 7 appears to be related to diffuse extinction, but the presence of a visual observer, the lack of a collimated source beam, and the need to completely extinguish the image of the light source make this an extremely specialized measurement not easily relatable to the fundamental quantities of hydrologic optics.

The nineth definition allows two interpretations. The first is that it is the absorption which is to be determined, since all light is collected which is not absorbed by the sample. When this is divided by the incident irradiance, the transmittance due to absorption only is obtained. This is described by the integral of equation 3.

The second interpretation of definition 9 comes from the technique specified in reference 7 for measuring absolute turbidity using an integrating sphere. The procedure and calculations specified by this reference result in the measurement of a quantity which is proportional to the ratio of the scattered light only to the scattered plus the transmitted light. This ratio is not easily related to the quantities previously defined.

The discussion of absolute turbidity in reference 7 indicates that this measurement is to be made over a relatively narrow range of wavelengths in the visible spectrum, the preferred wavelengths not being specified.

UNITS OF TURBIDITY MEASUREMENT

The units of turbidity measurement are nearly as varied as the definitions of turbidity. The statement of turbidity in ppm of suspended solids has been largely discontinued, due to the difficulties described earlier, and will not be further considered. The remaining units of turbidity are described as follows:

(1) Jackson Turbidity Unit (JTU). The JTU scale ranges from 0 to 1000 and is based upon the depth of a sample in the Jackson Candle Turbidimeter that is just sufficient to extinguish the image of a burning standard candle observed vertically through the sample. The correspondence between numbers on the JTU scale and depths of the sample was evidently chosen originally so that the JTU scale would give the approximate concentration, in parts per million, of Fuller's or diatomaceous earth suspensions in clear water. With the discontinuation of the ppm designation, the correspondence between the JTU scale and observed sample depths must now be considered purely arbitrary. The correspondence is tabulated in reference (7).

(2) Formazin Turbidity Unit. For many years and until very recently, the Jackson candle turbidimeter has been the accepted instrument for measuring turbidity. Many state pollution statutes still specify permissible turbidity levels in Jackson Turbidity Units.[32] The cumbersomeness and innaccuracies of the Jackson Candle Turbidimeter, in this age of sophisticated technology, has resulted in the use of more modern electro-optical instruments for the measurement of turbidity. Many of these are calibrated in Jackson Turbidity Units even though the principle of the measurement is wholly different from that of the Jackson candle turbidimeter. In any event, the results obtained with the new instruments will be comparable to those obtained using a Jackson Candle turbidimeter only if the calibration is based upon the use of a set of standard suspensions in both instruments. In the past the materials used in preparing such standards were those found prevalent in nature. As a result, the material used varied from time to time.

In 1926 Kingsbury and Clark developed an excellent turbidity standardizing material, called Formazin.[33] It is prepared by accurately weighing and dissolving hydrazine sulfate ($N_2H_4 \cdot H_2SO_4$) and hexamethylenetetramine in distilled water. The solution is allowed to stand for 48 hours during which time it develops a white turbidity. The mixture can then be diluted to obtain standards of any concentration, with a reported repeatability accuracy of ±1 percent.[34] As a result, an attempt is now being made to establish a turbidity unit, called the Formazin Turbidity Unit (FTU), which is based directly upon the optical properties of Formazin, independent of the candle turbidimeter and its peculiar units. According to the proposed new standard, a Formazin suspension of 5g of $N_2H_4 \cdot H_2SO_4$ and 50g of hexamethylenetetramine in 1 liter of distilled water is defined to have a turbidity of 4000 FTU.[34]

(3) Nephelos Units. In some investigations in physical chemistry, the rate of precipitation of a given substance during a chemical reaction is studied by measuring the turbidity increase as the precipitate is formed. In such studies, the nephelometric turbidity method is used and only the relative turbidity levels during the reaction are of interest. In investigations of this sort, the researcher typically prepares his own turbidity reference suspensions, for comparison with the sample under study. The Coleman Instruments Division of the Perkin-Elmer Corporation markets a Nepho-Colorimeter which can be used to measure nephelometric turbidity. The company markets a set of specially prepared turbidity standards composed of titanium oxide dust suspended in a resin dilutant.[35] A purely arbitrary scale of units, called "Coleman Nephelos Units," is assigned to these standards. The company maintains a set of primary standards having turbidities of 5, 10, 20, 40, and 80 Coleman Nephelos Units. According to the company, one Coleman Nephelos Unit is roughly equivalent to 3.1 Formazin Turbidity Units.[35]

(4) Percent Transmittance. In extinction type turbidity meters, the turbidity is often expressed as the percent transmittance of a collimated light beam per unit length of propagation through the sample. Usually with instruments employing this technique some combination of true extinction (unscattered light) and diffuse extinction (scattered and unscattered light) is what is measured. The results are therefore likely to depend upon the length of the collimated beam through the sample. As a consequence, the turbidity is sometimes expressed as the percent transmittance through the length of the sample actually used.

(5) Reciprocal Length Units. In extinction type turbidity measurements, the turbidity is also expressed as an "effective" extinction coefficient $c*$ defined by the relation

$$c^* = -\frac{1}{L} \ln \left(\frac{H}{H_0} \right) \tag{8}$$

where H is the irradiance received by the detector in a collimated beam after passage a distance L through the medium from the source of irradiance H_0. As before, the $c*$ which is measured may be neither the "pure" extinction coefficient c nor the diffuse extinction coefficient, as defined earlier, but some unknown combination of the two. According to the above equation, the units of $c*$ should be those of $1/L$, namely reciprocal length. Although the natural logarithm is a pure number, and is therefore dimensionless, Duntley suggests that the units of $c*$ should be ln per unit length.

TURBIDITY METERS

There is a large number of instruments available for the measurement of turbidity. Several of the most prevalent ones will now be described. In the next section we will examine the measurement principles behind these instruments, as they relate to the fundamental quantities of hydrological optics defined earlier.

(1) The Jackson Candle Turbidimeter.[36] To a present-day researcher, using modern sophisticated instrumentation, the Jackson Candle turbidimeter may seem to be incredibly archaic and inaccurate. On the other hand, it has only one moving part (the candle), it uses no electricity (and is therefore free of electronic component failures), it requires relatively minor adjustments, and is inexpensive. In this era of chronic fossil fuel shortages, its extremely low consumption of (renewable) resources is an added benefit of no small significance. A drawing of the Jackson candle turbidimeter is shown in Figure 3. It consists of a metal stand a, a metal container b for the glass tube c, and a

standard candle <u>d</u> that is set beneath the glass tube <u>c</u>. <u>The Manual on Industrial</u> <u>Water</u> of the ASTM[7] describes the turbidimeter as follows:

The glass tube and the candle shall be supported in a vertical position so that the center line of the tube passes through the center line of the candle, the top of the support for the candle being 7.6 cm (3 in.) below the bottom of the tube. The glass tube shall be graduated either in turbidity or in centimeters . . . . . The glass tube shall have a flat, polished glass bottom. The candle shall be made of beeswax and spermaceti, gaged to burn within the limits of 114 to 126 grains per hr. The candle support shall have a spring or other device to keep the top of the candle pressed against the top of the support. . . . . Take care to keep the glass tube clean, both inside and outside. Accumulations of dirt inside and soot and moisture outside will seriously interfere with the reliability of the results. In order to obtain reasonably consistent results, the candle flame must be kept to as nearly standard size and spacing as possible. This requires frequent triming and adjusting. Do not keep the candle lighted for more than a few minutes at a time or flame size will increase.

In operation, the depth of sample liquid in the glass tube is increased until the image of the candle flame just disappears from view, and the turbidity is determined from the graduations on the side of the glass tube.
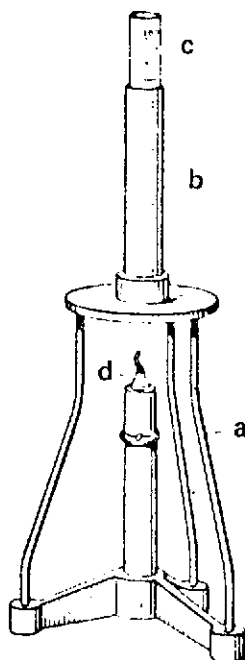

Figure 3. The Jackson Candle Turbidimeter: a — stand; b — metal container for the glass tube; c — glass tube; d — standard candle

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(2) The Hellige Turbidimeter.[36] The Hellige turbidimeter consists of a light source, reflector, adjustable slit, a platform supporting a special apertured mirror, a specimen tube, and an eyepiece contained in a box-like apparatus with a knob on the side for adjusting the slit opening. An optically clear plunger is inserted in the top of the sample tube to insure that the liquid depth is as required.

The instrument allows the operator to visually compare the brightnesses of two superimposed beams of light from an opal glass lamp bulb. The brightness of the transmitted beam is compared to that produced by scattering at 90 degrees. Through the use of neutral density filters and the knob which controls slit width, the visual brightness of the transmitted beam is reduced by a known amount until it matches that of the scattered light. If in the center of the field of observation through the eyepiece there is a small circular spot that is either lighter or darker than the general shade of the surrounding field, the operator turns the control knob until the spot disappears and the entire field is of uniform brightness. A set of calibration charts is then used to determine the turbidity in ppm silica from the scale reading on the control dial.

(3) The Coleman Nepho-Colorimeter.[36] Two different turbidity measurements are possible with this instrument. Nephelometric turbidity is measured as follows: A beam of white light is projected through the suspension and the scattered light is measured by two photocells at right angles to the incident beam. Readings are taken of the sample turbidity and of a turbidity standard supplied by the manufacturer. A ratio of the two readings, multiplied by a scale factor, gives the turbidity in Coleman Nephelos Units.

Extinction turbidity is measured either with or without spectral filtering of the light. Results are expressed in terms of percent transmittance, and may be converted to other units by comparison with standards of known concentrations.

(4) Ecolab Portable and Laboratory Turbidimeter.[37] A cell containing the sample is inserted into the instrument and the white light from an incandescent lamp which is scattered at approximately 90° is measured. Standardization is accomplished with the use of reference standards provided with each instrument, and readings are in Formazin Turbidity Units.

(5) Hach Turbidimeters.[38] The Hach Chemical Company markets a number of different turbidimeters based on the scattering of white light at right angles to the incident beam, all giving readings in Formazin Turbidity Units. Their model 2100A laboratory turbidimeter gives readings over five ranges from zero to 1000 FTU's, by comparison with a set of permanent turbidity standards which simulate the Formazin suspensions.

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(6) <u>Monitek Turbidimeters</u>.[39] Monitor Technology markets several different turbidimeters. Their Model 150 laboratory turbidimeter measures the ratio of light scattered at small angles to that in the direct, transmitted beam, and expresses the result in Jackson Turbidity Units. The Monitek model 250 laboratory turbidimeter is based on the same forward-scattering principle as the model 150, but gives results in ppm silica scale. The Monitek model 350 submersible turbidimeter is also based upon the ratio of forward scattered light to unscattered light but it employes a special optical system incorporating two light sources, two detectors, and a baffle, to minimize the effects of ambient light, liquid color, and absorption and scattering at the sensor windows. Results are obtained in JTU's. The model CR-450 transmittance monitor is designed to measure the transmittance of the liquid in percent over each of two wavelength bands defined by a pair of optical filters used in the instrument.

(7) <u>Anacon Turbidimeter</u>.[40] The Anacon model 303 (submersible) suspended solids monitor projects a white-light beam through a window into the sample medium. Light backscattered by the medium returns through the window to a photoresistive detector element. The output of this detector is compared with that of another detector monitoring the output of the light source. The resulting output signal is given in millivolts.

(8) <u>Martek Transmissometer</u>.[41] The martek model XMS <u>In Situ</u> Transmissometer projects a cylindrically limited beam through a path length of 1 meter to a detector with a narrow angular field of view (in order to minimize the amount of small-angle singly scattered and multiply scattered light involved in the measurement). It employs an internal reference light path to allow a check on the stability of the calibration while the unit is submerged. A broad-band optical filter is included in the light path to restrict the wavelength range over which the measurement is obtained. Readout is in percent transmittance.

(9) <u>Hydro Products Transmissometer</u>.[42] The Hydro Products Model 612S Transmissometer projects a collimated beam of light through a path length of 10 cm. (which may be extended to 1 meter by the use of an extension tube) to a detector with a narrow angular field of view. The 10 cm path length is useful for areas of high turbidity where multiple scattering and small signals restrict the accuracy of measurements when a one meter path is used. A broad-band optical filter is included in the light path to restrict the wavelength range of the measurement. Readout is in percent transmittance.

(10) <u>Bendix Transmissometer</u>.[43] The Bendix Model C2 transmissometer projects a collimated beam through a one meter path to a detector having a narrow angular field of view. One detector monitors the light source directly and another monitors the transmitted beam. The ratio is proportional to the transmittance.

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An optical filter can be placed in the light path to restrict the spectral range of the measurement. The Model S-4 readout unit converts the detector signals into a percent transmittance reading.

(11) Secchi Disk. A white circular disk, called a Secchi disk, lowered into a natural body of water until it just disappears from view, yields approximate information about water clarity. Although the measurement of Secchi depth is not strictly a turbidity measurement it is included here for completeness, and because it is widely used to estimate the transparency of natural waters. The hydrological optical parameter with which it is most closely associated is the contrast transmittance, defined in reference 23. The eye can just barely distinguish a contrast of about 0.002. By substituting this value into the equation[44] defining the decrease of contrast transmittance with depth, one can obtain an approximate analytical expression relating the depth at which the image of an object in the sea just disappears (Secchi depth) to the extinction coefficient of the water. The measurement of Secchi depth is subject to a number of extraneous influences, most notably the disruption of the image due to surface waves, the extent of obscuration of the sun due to atmospheric haze, clouds, or overcast, and variations in the visual acuity of individual observers. As a result, the Secchi depth measurement is extremely subjective and inaccurate, and can be regarded as little more than a qualitative estimate of water clarity.

DISCUSSION

It is difficult to establish the radiometric basis of the Jackson candle turbidity measurement. A detailed radiometric treatment of the problem is beyond the scope of this paper. The obsolescence of the measurement has resulted in its growing abandonment in favor of more accurate and reliable methods.

The Hellige turbidimeter produces a result which is related to the ratio of 90° scattered light to attenuated light. For samples having low turbidity, this ratio is proportional to the volume scattering function at 90°. As the turbidity increases, multiple scattering in the cell and attenuation of the transmitted beam influence the measurement markedly and the result can no longer be easily related to the fundamental quantities defined earlier. The presence of a visual observer in this measurement does not reduce its reliability and accuracy, since the observer is merely nullifying the difference between two adjacent light levels, and the eye is capable of detecting very small differences in brightness.

The nephelometric turbidity measurement using the Coleman Nepho-Colorimeter compares the VSF at 90° of the sample with that of a set of standard suspensions.

The final turbidity of the sample is the result of a linear interpolation between standard readings, based upon the measured scattered irradiance. This instrument can also be used to measure the transmittance of the sample, over a narrow range of wavelengths by inserting a filter into the beam. The measured turbidity (in percent transmittance) can be converted into an extinction coefficient c*, through the use of the formula

$$c^* = -\frac{1}{L} \ln T \qquad (9)$$

where T is the transmittance and L is the length of the light path through the cell.

The Ecolab and Hach turbidimeters are based upon the comparison of the 90° scattered light from the sample with that scattered by a turbidity standard. White light is used in both instruments, so that the signal is proportional to the integral over wavelength of the source spectral radiance, the transmittance of the sample (and the optical components of the instrument), and the spectral response of the detector. In both instruments the readout is in FTU's directly. Comparison with the turbidity standard is automatically accomplished when first setting up the instrument for operation. This is done by adjusting the sensitivity to give the correct reading when the turbidity standard is inserted into the sample volume.

The Coleman, Ecolab, and Hach nephelometric turbidimeters are all sensitive to variations in light source brightness and detector response and their calibrations must be checked frequently. The presence of dirt and bubbles on the walls or windows of the sample cells can produce significant amounts of unwanted scattered light which can result in erroneously high readings, especially in the lower measurement ranges.

The Monitek turbidimeters measure the ratio of small-angle scattered light to transmitted light, giving results which are roughly proportional to the integral of the volume scattering function over the range of angles involved. This proportionality is approximately linear when the water is moderately clear, since the transmitted beam is to a good approximation equal to the incident beam. As the turbidity increases, the transmittance increases and the relationship between measured turbidity and the scattering function becomes nonlinear. The presence of multiple scattering in the higher turbidity ranges further restricts the linearity of the relationship. Standard turbidity samples should be used to insure calibration of these instruments in the higher measurement ranges.

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The Anacon turbidimeter measures the light backscattered by the sample medium and is sensitive to variations in lamp brightness and detector sensitivity. Although it is intended only for relative turbidity measurements, the use of standard turbidity samples should make absolute turbidity measurements possible with this instrument.

The Martek, Hydro Products, and Bendix transmissometers are true extinction meters and give transmittances over fixed path lengths which are easily converted into extinction coefficients using equation (9). The unavoidable detection of multiply scattered and small-angle forward scattered light will produce transmittance readings which are slightly higher than they should be. This error will increase with increasing turbidity for fixed path lengths.

CONCLUSIONS

The variety of significantly different turbidity definitions and measurement techniques has likely arisen out of the differing needs of investigators in different disciplines and of the convenience of the word turbidity as a catchall term for all water clarity measurements. The disparity in the needs of different disciplines is likely to continue this situation.

Economics offers another possible explanation of the lack of uniformity. The ideal turbidimeter would likely cost much more than a simpler, less accurate, but cheaper instrument. The cheaper unit, if adequate to the tasks for which it is intended, is likely to have much wider acceptance and more frequent use. Thus, we can expect the present variability in turbidity measurements to continue for some time.

Looking at the turbidity definitions and measurement techniques described earlier suggests two predominant (though not inclusive) classifications: those which are based upon a comparison with standard suspensions of known turbidities and those which are based upon the absolute measurement of some optical quantity. In the first category are the Hellige, Coleman, Ecolab, and Hach nephelometric turbidimeters. In the second category are the Coleman (extinction mode), Monitek, Martek, Hydro Products, and Bendix instruments.

However, almost any measurement of the transmittance or scattering properties of a suspension can be converted into a turbidity measurement of the first class simply by replacing the sample with one or more standard Formazin suspensions and comparing the sample readings with the standard readings. Ideally the turbidities of the Formazin standards should be chosen so as to bracket the turbidity of the sample and should not be too different from the sample turbidity. The

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results obtained when using this method may not always agree with those using the 90° scattering, or nephelometric, method, due to differences in the absorption and scattering properties of the sample from those of Formazin. But for some applications, the lack of agreement may not be excessively large and the technique can then be used.

Used properly, the in situ transmissometers can be expected to give the most accurate, reliable, and reproducible results in measurements of the clarity of natural waters.

The 90° scattering, or nephelometric, type of turbidimeters are theoretically capable of the same accuracy and reproducibility. Variations in detector acceptance angle, shape of the scattering cell, and overall spectral response from instrument-to-instrument, however, decrease the value of this type of instrument for water clarity measurements. Furthermore, most of the nephelometric turbidimeters are laboratory instruments and as such are sensitive to changes which take place in the sample from the time it is collected to the time it is measured. These changes can be substantial. Most of the transmittance meters are in situ devices and do not suffer from this problem, and are therefore the preferred type of instrument for water clarity measurements in natural waters.

If, on the other hand, one is looking for a turbidity measurement which comes closest to being proportional to the concentration of suspended solids, then a scattering type of instrument would appear to be the best choice. The ideal scattering turbidimeter would measure the volume scattering function at one or more angles, and at a given wavelength, chosen to minimize variations in the scattering function when going from one type of particle to another at the same concentration. The selection of the best scattering angles and wavelengths to use in such an instrument would be a worthwhile research topic.

The term "turbidity" has been used throughout this paper to include a great variety of measurements of water clarity. The basic question is: Does the term really need to be so broadly defined? This author does not think so. Transmittance measurements, as described earlier in this paper, are well-defined, the terminology is well-accepted, and there is no real need to call them turbidity measurements. Measurements of the volume scattering function are similarly well-defined and the terminology is widely accepted. It would therefore seem reasonable to exclude these measurements from the definition of turbidity.

It is proposed that the term turbidity be restricted to the nephelometric type of measurement involving a comparison of the sample with standard suspensions, where the results are given in Nephelos, Jackson, or Formazin turbidity units.

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It is furthermore proposed that the use of Nephelos and Jackson turbidity units be discouraged, with Formazin being accepted as the universal standardizing material, due to its relative ease of preparation and use and its high temporal stability.

As a generic term, turbidity would still refer to the visual cloudiness characteristic of liquids having a large amount of particulates in suspension. But as a physical quantity, turbidity should refer only to a limited class of measurements the results of which are given in Formazin Turbidity Units.

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