The YSI Wiped Turbidity Sensor:
An Overview of Turbidity, Nephelometry and an Advancement in In Situ Measurement of Turbidity

Introduction

Water quality has been of interest since the time of Aristotle – if not earlier – when observations regarding water flow, apparent water quality, and the plants and animals dwelling in various aquatic habitats were first recorded in some scientific fashion. The graphic nature of turbidity facilitates observation and speculation regarding the condition of a water body even by the casual observer. Whether accurate or not, a near universal perception is that clear waters are more desirable or "healthy" than turbid waters, therefore better suited for most uses. Certainly, turbidity can be an indication of ecological degradation; nevertheless, many waters have historically been very turbid and, until this century, very healthy aquatic systems: for example, the Mississippi River. It is apparent that since the presence of water on earth, seasonal fluctuations in turbidity have occurred naturally as rains have washed in detritus and soils, and sunny days have facilitated plankton productivity. This is still true today. In fact, seasonal fluctuations in turbidity can often be indicative of vitality and the manifestation of the cyclical nature of natural processes within an aquatic system. However, few water bodies have been as turbid as present anthropogenic activities have rendered them. Typically, it is an increase of turbidity over "natural" or historic levels that raise concern. However, a decrease in turbidity or the absence of turbidity may also indicate disruption of a natural system: for example, the effects of Asiatic clam (*Corbicula spp.*) infestation (McLarney 1987).

Transparency measurements, as well as early investigators' curiosity regarding the relationship of light penetration to plant and animal distribution and factors affecting light penetration, eventually led to more exacting efforts to discern the nature of substances contributing to opacity. These endeavors ushered in a new aspect of limnological investigation, one that would eventually identify turbidity's role in aquatic ecosystems.

Turbidity and Color

Physical Considerations

Simply stated, substances that contribute to true color absorb light, where factors that contribute to turbidity and apparent color scatter light. Turbidity and color will be discussed together due to the somewhat similar roles these qualities play in producing color and opacity, and consequently their influence on biological processes. These two qualities of water are also discussed together for purposes of differentiating them and making clear what is being discussed on the subject of turbidity. Where water is concerned, color is placed in two categories: true (or specific color) and apparent color. The perceived color – combination of both true color and apparent color – of a water body is the product of the residual radiant energy (light) that originally reached the surface. In other words, the perceived color of water is produced by the reflected, not absorbed, wavelengths of light. What produces residual or reflected wavelengths of light, therefore the perceived color, is a wide variety of physicochemical and biological factors that include, but are not limited to: particulate organic and inorganic matter; plankton density; colloidally suspended substances; substances in true solution; over-shading by vegetation; bottom color; water depth, and wave action. Recall the visible spectrum ranging from red to violet (red, orange, yellow, green, blue, violet), and that wavelength decreases from red to violet. The shorter the wavelength, the farther it will penetrate before being absorbed. If the water observed was absolutely pure, color would be a function of depth alone.

True color results from dissolved substances or from substances held in colloidal suspension. In order to identify the true color of water, a sample must be filtered or centrifuged to remove particulate matter, leaving only water and those dissolved or colloidally suspended substances. The sample is then compared to a series of known and standardized color references. One widely used example of such references is the platinum-cobalt scale, which provides a series of colorimetric references with which to compare the processed water sample and provides a numerical identification for the color in platinum-cobalt units. Much more specific and sophisticated methods exist using optical analyses and comparisons with chromaticity coordinates (Wetzel, 1975). True color is not a source of turbidity, but can affect the measurement of turbidity.

Apparent color is the color of water typically seen and used in a cursory description of a water body's appearance or to estimate perceived changes in characteristics. For example, the "greening" of pond water in the spring and summer is not actually a change in true water color, rather it is a change in apparent color - as well as turbidity - resulting from heightened phytoplankton productivity. Generally speaking, apparent color results from the seston, as well as, bottom color; over-shading (i.e., vegetation); aquatic vascular plants; wave action, and sky color, to name a few. Seston, the particulate mass of various living and nonliving substances in water, is comprised of particulate organic and inorganic matter, plankton and bacteria (Reid and Wood 1976). The seston is also the principal source of turbidity. Sources contributing to the seston are typically placed in two general categories: allochthonous and autochthonous. Humus, silt, organic detritus, colloidal matter, and plants and animals produced outside and brought into the aquatic system are termed allochthonous. Matter produced within the system, such as phytoplankton, zooplankton, bacteria, and plant and animal tissue, are examples of autochthonous substances.

Ecological Importance

It is beyond the scope of this work to identify and discuss in detail the ecological importance of color and turbidity to aquatic ecosystems. However, a brief discussion highlighting the importance of color and turbidity is necessary for a rounded discussion of these qualities in water, as well as to better understand the need for their study. Addition of substances that cause true color affect the depth of light transmission (extinction), therefore, the depth to which certain wavelengths of light can penetrate and be available to aquatic life. Various phytoplankton species are more or less productive in varying exposures to certain wavelengths of light (Wetzel 1975). The absence of certain wavelengths for significant periods of time can greatly reduce the abundance of certain species or actually eliminate them. By the addition of true color-causing substances, the penetration of necessary wavelengths is altered; consequently the distribution, abundance and population dynamics of the phytoplankton community is altered, often with pernicious effects (Smith 1977). Change in true color also impacts the effectiveness of camouflage. For example, the addition of true color-causing substances can change the contrast relationship between an animal's natural camouflage and its surrounding habitat making the animal more or less visible. Enhanced recognition of prey can result in increased predation and potentially a decrease in, or elimination of, a particular prey population.

Turbidity and apparent color can have similar effects through physical mechanisms. Reduced visibility provides greater cover, and may result in the reduction of predator population, consequent increase in a prey population, and/or a shift to another prey population, perhaps one with less resiliency to predation. Turbidity affects light penetration, consequently affecting plankton primary and secondary productivity and respiration; vascular plant growth; depth of warming and system-wide temperature dynamics; and the ability of aquatic animals to feed and reproduce (Reid and Wood 1976, Lagler et al. 1977, Wetzel 1983, Torrans 1986, Chandler 1987, McLarney 1987).

Economic Importance

It is beyond the scope of this work to identify and discuss in detail the economic importance of color and turbidity where industrial and municipal processes are concerned. Generally speaking, the more turbid the water, the higher the cost to utilize it. Turbidity can be a significant problem for many industries. Many processes require water to be "pure" or "ultra-pure" before use in various production phases. Water free of particulates is necessary to protect the internal workings of pumps, pipes, valves and other moving parts in process systems. In steam electric generation, water free of particulates as well as dissolved substances is necessary to protect boilers and turbines from scale and other deposits (Chandler 1990). To the extent that the initial or "raw water" source – be it a lake, stream or aquifer – has been impacted by anthropogenic activity, treatment costs will, for the industrial user, be concomitantly greater. Suspended matter can harbor pathogens (i.e., bacteria and viruses), as well as increase chlorine demand. Consequently, municipalities must remove particulate matter as a process stage of developing potable water and before disinfecting municipal wastewater (Standard Methods for the Examination of Water and Wastewater 1989). Suffice to say, all suffer as a result of impacted aquatic ecosystems.

Principles, Methods, and Instrumentation

As previously stated, the term turbidity refers to the degree of opaqueness produced in water by suspended particulate matter. The term also describes the measurement of opacity as a function of side scattering and extinction of light by suspended matter. Turbidity in freshwater and brackish water is typically reported in nephelometric turbidity units (NTU). Although observations regarding water quality, including opacity, have undoubtedly been made for centuries, apparently it was not until the introduction of the Secchi disk (ca. 1865) by A. Secchi, that efforts to quantify opacity by *in situ* gauging of light extinction came into practice. Secchi disk transparency measurements, as well as early investigators' curiosity regarding the relationship of light penetration to plant and animal distribution and factors affecting light penetration, would eventually lead to more exacting efforts to discern the nature of substances contributing to opacity. These endeavors ushered in a new aspect of limnological investigation, nephelometry (ca. 1875), one that would eventually identify turbidity's relationship with color, light penetration and aquatic ecology and differentiate it from vertical extinction (Secchi disk transparency).

The term 'turbidimeter' was first used in the early 1900s (ca. 1914) and since that time a wide variety of devices have been used, with varying degrees of success, to measure turbidity. Early devices such as the Jackson turbidimeter and the Hellige turbidimeter were confined to the laboratory due to sensitive components and power requirements. Perhaps the first widely accepted *in situ* "turbidimeter" was the United States Geological Survey's turbidity rod (Reid and Wood 1976). This device, which actually measured vertical extinction rather than side scattering and reported turbidity in parts per million, represented a transition from Secchi disk transparency measurements as the principal source of *in situ* "turbidity" data to true *in situ* nephelometers.

Before continuing, it is important to mention that turbidity measurements are qualitative and further information is always necessary regarding the nature of suspended matter, opacity, color and light penetration when attempting to understand the importance of turbidity data taken in a given point and time, within a particular aquatic system. It is also important to reiterate that the presence or absence of turbidity does not singularly indicate the condition of an aquatic system. Much care must be taken to incorporate as many observations and as much data from as many facets of the system as possible in order to approach an understanding of that system. Advances over the past four decades have brought nephelometric technology to levels suited for the rigors of *in situ* nephelometry, With these developments, *in situ* turbidity measurement is becoming a commonly requested parameter - particularly in conjunction with dissolved oxygen, temperature, pH, depth and specific conductance - often preferred over lab analysis performed out of context, at some later date. Two methods are standardized and approved by the scientific community for the measurement of turbidity in freshwater and brackish water as it is reported in NTUs. These are: Nephelometric Method 2130 B (*Standard Methods for the Examination of Water and Wastewater 1989*) and ISO 7027 (*International Standard, Second*

Edition 1990 – 04 – 15). These methods differ in several respects; nevertheless both are true nephelometers, measuring the intensity of light scattered at 90^0 to the path of incident light. Though both methods are widely accepted in the scientific community, they perform differently under certain conditions, i.e., varying particle size, water color and level of turbidity. Particle size, shape and distribution can have significant effects on the measurement of turbidity. For example, the total mass of suspended matter in water samples may be identical, however, if particle size, shape or distribution differs; so will the scattering of light from and amongst those particles. Hence, turbidity measurements made by different methods are likely to differ as well (Chandler 1990). Variability in nature is unavoidable, and this fact accentuates the importance of using the same nephelometric method consistently. When collecting turbidity data, it is very important that the investigator use only one of these to avoid introducing additional error through methodology. In some cases, correlations have been made between measurements made with the different methods. However, it is important to note that such correlations require much study and careful scrutiny, and should not be in lieu of standardization to one method.

Having first mentioned methodological concerns inherent to *in situ* nephelometric measurements, our focus should now turn to perhaps the most common problem for *in situ* measurement of any parameter, particularly if the sensor is deployed for extended periods: fouling. Generally speaking, there are two types of fouling, biological or active, and non-biological or passive. The former results from the growth of sessile plants and animals on the optics of the instrument; the latter refers to substances such as silt, clay and organic debris that settle on or adhere to these surfaces. Neither form is found independent of the other; however, in many systems, one form is typically more prevalent. Also, seasonal dominance of one or the other is invariably a factor. Obviously, in the case of nephelometers, the surfaces of greatest concern are the lenses through which light is transmitted and received. In the past, *in situ* nephelometers have been equipped with a variety of features intended to inhibit fouling or compensate for the effects of fouling. Most notable are those using some mechanical means to sweep the sensor surface and those incorporating transmissive correction. Both methods have produced varying degrees of success depending upon length of deployment, water quality, preparation prior to deployment, maintenance intervals and calibration. Though these factors will certainly remain important for any sensing device, recent developments have made a few of these factors, particularly length of deployment, water quality and maintenance interval, somewhat less critical.

YSI has developed nephelometer based on the ISO 7027 methods that employs a wiper that sweeps fouling agents from sensor optical surfaces prior to measurement. Long-term deployments with this nephelometer as part of YSI's submersible, multiparameter water quality monitoring systems have demonstrated constant measurement accuracy and stability. Known advantages to this system in addition to accuracy and stability are: (1) inhibition of both active and passive fouling; (2) nominal power consumption (ideal for extended deployments); (3) removal of bubbles which result from out-gassing of environmental water, and (4) sensor is mounted in the bulkhead of sonde with no interface hardware exposed to the environment.

Conclusion

Turbidity has been of interest to aquatic scientists for centuries. The graphic nature of turbidity facilitates observation and speculation regarding the condition of a water body even by the casual observer. Whether accurate or not, a near universal perception is that clear waters are more desirable or "healthy," than turbid waters, therefore better suited for most uses. The ecological and economic ramifications of chronic increases in turbidity are far-reaching. In recent years, advances have brought nephelometric technology to levels suited for the rigors of *in situ* use. With these developments, *in situ* turbidity measurement is becoming a common request particularly in conjunction with dissolved oxygen, temperature, depth, pH and specific conductance. As a result, turbidity is becoming a common *in situ* parameter, often preferred over lab analysis performed out of context, at some later date. The most common problem for *in situ* measurement of any parameter, particularly if it is deployed for extended periods, is fouling. YSI's wiped nephelometer provides superior protection from fouling, while retaining features necessary for long-term deployments. This advancement facilitates the inclusion of turbidity in water quality field investigations, and permits accurate, long-term monitoring of turbidity.

Key Terms

Allochthonous: component of the seston produced outside and brought into a water body by natural mechanisms.

Autochthonous: component of the seston produced within a water body.

Colloid: a non-settling dispersion of ions or molecules, the size of which ranges between substances in true solution and particles in suspension.

Compensation Point: the depth to which 1% of surface radiant energy penetrates. It signifies the bottom or deepest point of the euphotic zone and is also the point at which production and respiration are at equilibrium.

Euphotic Zone: the lighted zone of a lake or reservoir that extends horizontally from shore to shore and vertically from the surface to the compensation point. Light intensity, throughout the euphotic zone is sufficient to support photosynthesis.

Field parameter: a measurement made *in situ*.

Macrophyte: collective term referring to the whole of macroscopic forms of aquatic vegetation including macroalgae, aquatic ferns and mosses and true angiosperms.

Nephelometer: an instrument used to determine opacity by measuring the intensity of light scattered at 90^0 to the path of incident light.

NTU: acronym for nephelometric turbidity unit, a commonly used unit of measure for opacity, and the standard unit of measure with which to report turbidity data.

Opacity: the relative capacity of water to obstruct the transmission of radiant energy (light).

Phytoplankton: free-swimming or free-floating photosynthetic microorganisms.

Productivity: generally refers to the total of all energy-trapping processes by all organisms in the system. It is measured in a number of ways depending upon the group (i.e., phytoplankton, zooplankton, fish, etc.) for which productivity is being assessed.

Respiration: entails the aerobic processes in cells where energy is used in the production of energy-carrying molecules, as well as the overall exchange of gases between cells, blood and the environment.

Secchi Disk: a widely-used limnological tool consisting of a 20cm-diameter disk with opposite quarters painted black and white. The disk is lowered into the water by a chain or cable, and the depth at which the disk disappears from sight is used as a measure of transparency. The Secchi disk depth, or Secchi disk transparency, is often used to estimate the compensation point.

Seston: the particulate mass of living and nonliving things suspended in water.

Transmissometer: instrument used to determine opacity by measuring the transmission extinction of light through a straight path.

Turbidity: term used to describe the degree of opaqueness produced in water by suspended particulate matter; term also describes the measurement of opacity as a function of side-scattering and extinction of light by suspended matter. Turbidity in freshwater and brackish water is typically reported in nephelometric turbidity units (NTU).

Zooplankton: free-swimming, usually microscopic, animals: many of which prey upon phytoplankton. Zooplankton also feed on suspended organic matter and bacteria.

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