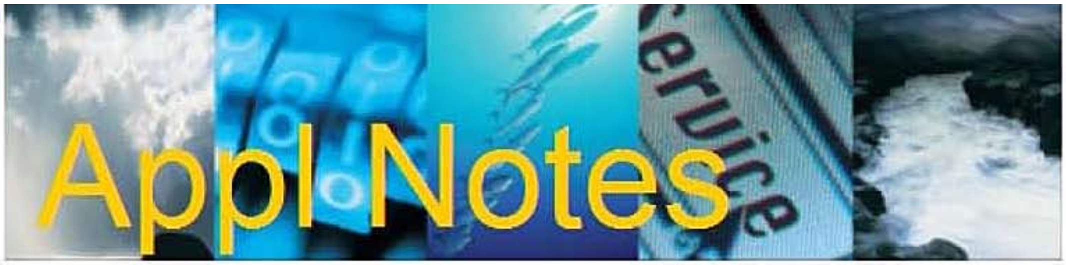

Turbidity Measurement: A Simple, Effective Indicator of Water Quality Change

INSTRUMENTATION AND BEST PRACTICE TECHNIQUES ARE KEY TO EFFECTIVELY MONITOR TURBIDITY IN NATURAL WATER BODIES

by Mike Sadar

THE AMOUNT OF DISPERSED SUSPENDED SOLIDS IN NATURAL water bodies is an important indicator of water quality. These solids that often include silt, clay, algae, organic matter, and other minute particles, obstruct the transmittance of light through the water and impart a qualitative characteristic known as turbidity. Turbidity is often closely correlated to climatological or surface water conditions and changes in turbidity are therefore indicators of changes in environmental conditions.

> "Turbidity data can be used as a surrogate measurement because it is strongly correlated with sediment, nutrients and bacteria, and can be measured in-stream on a continuous basis."

Turbidity can be interpreted as a measure of the relative clarity of water. It is not a direct measure of suspended particles in water but, instead, a measure of the scattering and attenuation effects these particles have on light. The higher the intensity of the scattered or attenuated light, the higher the value of turbidity.

Human activities such as logging, mining, road building, and commercial construction can often lead to chronic levels of suspended solids in lakes, rivers, and streams. High levels of suspended sediment often create negative effects on aquatic life. For example, suspended sediment can interfere with photosynthesis by blocking light from reaching submerged aquatic plants. This not only directly damages vegetation but also results in reduced levels of dissolved oxygen because of the reduced rates of photosynthesis. Moreover, waters with high levels of suspended solids absorb more sunlight and can therefore cause an increase in water temperature that can cause dissolved oxygen levels to drop even further. Low dissolved oxygen then stresses aerobic aquatic organisms and could ultimately lead to fish kills.

Turbidity is a Valuable Surrogate

Section 303(d) of the federal Clean Water Act requires States to establish total maximum daily loads (TMDLs) of various pollutants to help meet water quality goals and to attain designated beneficial uses for each water body.[1] The ability to continuously measure water constituents that are most commonly associated with impairments is often limited by technical and financial constraints. Turbidity, however, can be used effectively as a surrogate measurement because it can be measured in-stream on a continuous basis and it is strongly correlated with sediment, nutrients, and bacteria concentrations.

The United States Geological Survey (USGS) describes a surrogate as "an environmental measurement than can be reliably correlated with an in-stream characteristic, such as concentration or particle-size distribution of fluvial sediment. Surrogate data are typically easier, less expensive, and (or) safer to collect than the target variable, and may enable reliable estimates of uncertainty associated with the measurement." [2]

Turbidity can be used as a surrogate measurement for many environmental influencers, such as for:

- Monitoring the impact of humans on natural water bodies.
- Monitoring pathogens in water, such as E.coli in stormwater runoff from cattle pastures.
- Monitoring sediments to track erosion and landscape change.

- Monitoring natural streams below mining and dredging operations.
- Measuring total phosphorous in water is very difficult, but an increase in phosphate or phosphorous typically correlates to an increase in turbidity levels.

Many parameters influence overall water quality, yet turbidity is especially noteworthy because it is a simple and undeniable indicator of water quality. This allows it to serve as a surrogate for other factors or conditions. For example, high turbidity can mean higher concentrations of bacteria, nutrients, pesticides, or metals. So, a sudden change in turbidity may indicate the presence of a new pollution source (biological, organic or inorganic) in natural waters.

Turbidity Measurement Technologies

It's important to remember that turbidity is not a measure of the quantity of suspended solids in a sample but, instead, an aggregate measure of the combined scattering effect of the water sample's suspended particles on an incident light source. All turbidity measurements detect the amount of light either transmitted through or scattered by the particles in a sample of water.

Over the past several decades, instrument technology has advanced dramatically and many turbidity measurement techniques have resulted. These new approaches evolved to address interferences or inconveniences associated with earlier turbidity measurement techniques. Different technological approaches (often using different light sources and detector designs) have been used to compensate for or minimize measurement errors attributed to color, bubbles, stray light, absorption, and path length.

Common Turbidimeter Design Criteria

Common turbidimeters involve a light source and one or more detectors with a specific orientation to one another. The vast number of turbidity monitoring technologies can be categorized by three design criteria -- the type of incident light source that is used, the detection angle for the scattered light, and the number of scattered or attenuated light detectors used.

Incident light sources: There are three types of light sources used commonly in turbidimeters: incandescent, LED, and laser.

- **Incandescent light sources** are typically polychromatic with tungsten filaments with a color temperature of 2200 to 3000º Kelvin and emit relatively short wavelengths. These shorter wavelengths will be more effectively scattered by smaller particles. Those methods that are typically compliant to USEPA Method 180.1 or Standard Methods 2130B will utilize an incandescent light source.
- **LED (light emitting diode) light** sources are lower energy emitting light sources when compared to tungsten filament lamps. The most common wavelengths used in turbidity measurements emit 830 – 890nm light that is typically not absorbed by visible color in the sample, thus eliminating a common error source in most turbidity measurements. The International Standardization Organization (ISO) method 7027 requires the use of a light source in this range.
- **Laser-based light sources.** A small portion of turbidity measurement techniques will have laser-based incident light sources that emit energy at a discrete wavelength. Laser-based light **sources** are very sensitive to small changes in turbidity and are often used to monitor filtration performance for clean waters, such industrial processes requiring ultrapure water.

Detection Angle: The detection angle is the angle formed between the centerline of the incident light beam and the centerline of the detector's receive angle. The vertex of the angle is located in the center of the sample view volume and is represented by a red dot depicted in the following figures. The detection angle can have a significant impact on the detection of particles from a size perspective and on the turbidity range of the instrument. Also, the number of the detectors and their relative angle to the incident light beam can help reduce the impact of interferences such as color and subtle changes in the instrument components, such as in the degradation of a light source or fouling of a detector.

- **A 90-degree detection angle** is often referred to as the nephelometric detection angle and is the most common detection angle because of its sensitivity to a broad range of particle sizes (Figure 1). A slight variation of this approach is to utilize a design that does not come into contact with the sample with its measurement optics. This technique measures light scatter below the surface of the water and is commonly referred to as a surface scatter technology.

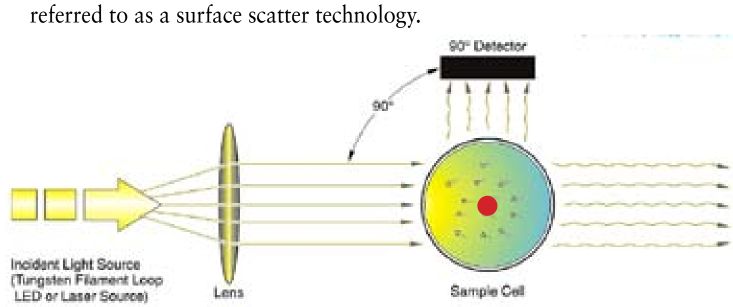

Figure 1. The 90-degree detection angle is the default technology for most regulatory applications. It is very susceptible to color interference and is best used at low turbidity levels.

- **The attenuated detection angle** is geometrically oriented at an angle that is 180-degrees relative to the incident light beam. This detection angle measures the attenuation of the incident light beam due to both light scatter and absorption. This angle has the greatest susceptibility to absorbance and color interferences.

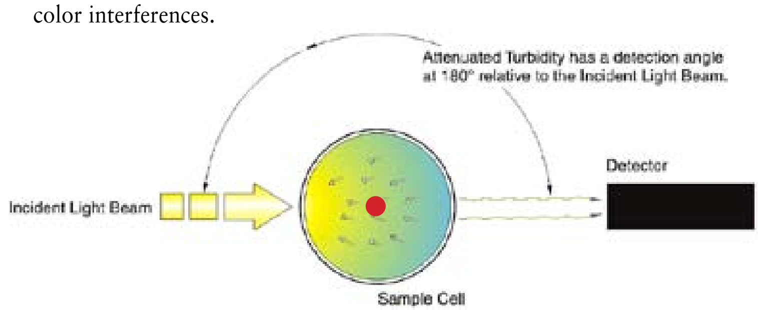

Figure 2. The attenuated detection angle is very susceptible to color as a negative interference and color absorption interference. Measurement sensitivity is highly wavelength dependent.

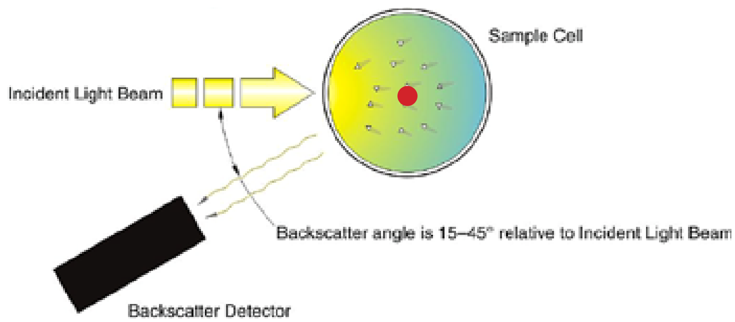

Figure 3. The backscatter angle measures the light that is scattered in the direction of the incident light beam. It is used for high turbidity samples, but is a poor application for monitoring clean waters.

- **The backscatter detection angle** has a detector that is geometrically centered at an angle of between 0 and 45 degrees relative to the directional centerline of the incident light beam. This angle will be sensitive to light scatter that is reflected back in the direction of the incident light source, which is characteristic with extremely high turbidity samples. This is not an appropriate technique for low level turbidity monitoring because it has inherent poor sensitivity at these levels.

Number of Detectors: Some turbidity measurement technology involves the use of signal ratios of two or more detectors to determine the turbidity value. One detector is at 90-degrees from the incident source and the other detector(s) can be at any of several different angles.

- **Multiple Detection Angles.** This ratioing approach will utilize one primary detector, which is typically oriented at a 90-degree angle relative to the incident light beam, and it is often referred to as the primary nephelometric detector. Other detectors will be at various angles including an attenuated, backscatter, and forward scatter angles. A software algorithm is often used to produce the turbidity measurement from the combination of detectors. These detectors can help compensate for color interference and in optical changes such as light source degradation.

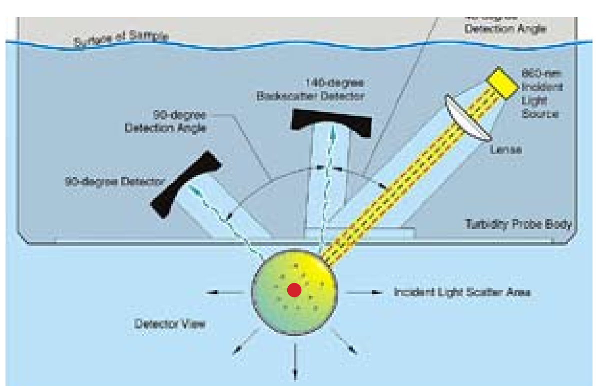

Figure 4. An In-Situ probe turbidimeter with a ratio design. The In-situ designates the measurement to be made in the process (the river, lake, sample transport pipe) itself, Two detectors extend the range of measurement to low turbidity levels and reduce color interference.

- **Dual light source detector.** This unique ratio approach uses a combination of light sources that are geometrically oriented at 90-degree angles to each other. The detectors are also oriented at 90-degrees to each other and at 90 and 180-degrees to each of the light sources. In one phase of measurement, a detector will be the nephelometric (90-degree) detector and the other detector will be at 180-degrees to the light source that is powered. In the second phase of the measurement, the second light source will be powered and the detector positions from phase one are reversed. A software algorithm is then used to generate the turbidity value from different measurement phases.

  The combination of the two phases provides a turbidity measurement that is corrected for color absorption, fouling of the optics, and any optical changes that can occur.

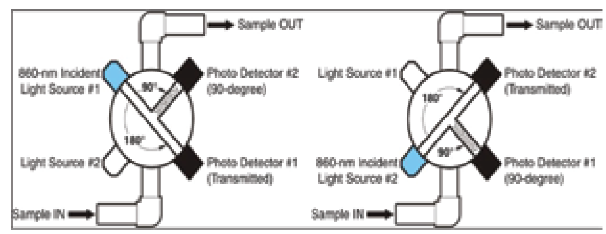

Figure 5. A dual-light source, dual-detector design. Two LED light two detectors combine to perform the turbidity measurement. The measurement consists of two phases. This design eliminates interferences due to color, fouling of optical components, and is very stable over time.

Variability Based on Measurement Method

It is normal for different turbidity measurement technologies to deliver different results on the same sample. This is because natural suspended solids - whether algae, silt, organic material, etc. - have wildly different and practically unpredictable optical characteristics, such as the way they absorb and reflect light. From technology to technology, differences in the combination of incident light source, detection angle, and number of detectors, together with the natural variation in sample optical characteristics, lead to different measurement results. Because of this potential for variability, it is important to also provide information on the type of technology used to collect a given set of data.

Nephelometers, or nephelometric turbidimeters, measure the light scattered at an angle of 90° by one detector from the incident light beam generated by an incandescent light bulb. Readings are reported in Nephelometric Turbidity Units, or NTUs. NTU has been the traditional reporting unit for turbidity and is still recognized by some as the "universal" unit of measure, regardless of the technology used.

However, because of the potential to generate data with a high degree of variability when different technologies are used, the American Society for the Testing of Materials (ASTM) has revised its turbidity measurement methods to incorporate a unit reporting protocol that provides traceability to the type of technology used. ASTM D7315[3] was the first turbidity method to incorporate these changes. For examples, when a 90-degree detection angle is used, the letter "N" for "nephelometric" should be used and will be either the first or second letter of the reporting unit. When an attenuated detection angle is utilized, the reporting unit will contain an "A" for "attenuated" and will usually be the second letter of the reporting unit. (See Table 1)

The push by ASTM and other regulatory bodies to have units indicate the type of technology used is a relatively recent development to address reporting discrepancies between different technologies. Stakeholders who are aware of these conventions can now avoid errors such as directly comparing readings measured by a nephelomentric instrument – reported in NTU – with instruments applying absorption or transmission optical designs. This is merely an example of one comparison that can lead to errors but, essentially, any combination of misaligned technologies will lead to the same problem.

Table 1.

Instrument Design	Reporting Unit
Nephelometric non-ratio turbidimeters	(NTU)
Ratio White Light turbidimeters	(NTRU)
Nephelometric, near-IR turbidimeters, non-ratiometric	(FNU)
Nephelometric near-IR turbidimeters, ratio metric	(FNRU)
Surface Scatter turbidimeters	(SSU)
Formazin Back Scatter Unit	(FBU)
Backscatter Unit	(BU)
Formazin attenuation Unit	(FAU)
Light attenuation Unit	(AU)
Nephelometric Turbidity Multibeam Unit	(NTMU)

Additional Sources of Variation

Perhaps the most significant practical consideration in turbidity measurement is the difference in measured values among different instruments that have been calibrated with a natural sample as a standard. Differences in the spectral characteristics of the light source/detector combination are the most important reason for different instruments giving different values for the same sample. This is why it is important to use formazin or at least some other laboratory-made substance that has repeatable spectral characteristics as a primary standard.

"An instrument's capability to measure a wide turbidity range is dependent on three critical design components— light source, detector angle, and sensitivity."

Another variation source is the depth at which the sensor is placed in a water system. For example, if the sensor is placed in a 10-feet-deep river that is flowing at high velocity, the lightest solids will be near the top of the water column and the heavier sand will be at the bottom. The instrument readings will be different depending on where the monitoring instrument is submerged. Ideally, the sensor should be placed where the water is as homogenous as possible, such as over a waterfall or flume.

Best Practices

Best practices are essential for reliable data collection and use. When deciding on which technologies to use for a specific application, it is important to adhere to the following guidelines:

Select the proper monitoring site.

The site should produce a homogenous sample and be readily accessible. Monitoring sites are often put in incredibly remote areas, and if the site goes down for some reason, it may be months before personnel can attend it. The site must be able to be physically accessed during all seasons, or the site should have a wireless system of data transmittal that confirms both successful data acquisition and data quality.

Know the environmental limits of the instrument for the specific sample location.

It's critical to know the environmental limits of the sensor. For example, if it's to be placed in a stream that will freeze solid in wintertime, it's unwise to put in an instrument not specified for that type of condition. Conversely, some instruments will fail readily in a creek bed where it may reach 120 degrees F and water only runs through it once a month. It's important to pay close attention to the manufacturer's specifications – especially operating temperature, sample temperature, and storage temperature.

Select the proper instrument based on light source, detection angle, and sensitivity.

Modern instruments are required to measure very high and low turbidity levels over an extreme range of sample particulate sizes and composition. An instrument's capability to measure a wide turbidity range is dependent on the instrument's design, with the three critical design components being light source, detector angle (or optical geometry), and path length. Differences in these three components affect an instrument's turbidimetric measurement.

Normally, the longer the path length, the better the detection limit or the instruments ability to see very small changes of turbidity at very low turbidity levels. With a very long pathlength, however, the sacrifice is a wide measurement range. Thus, if one wishes to measure to 10,000 units, a technology will likely have to be selected that does not have a good sensitivity at the very low levels of turbidity (typically below 1 unit).

Calibrate the instrument according to the manufacturer recommendations.

The process of calibrating and verifying calibration of turbidimeters at ultra-low turbidity levels is very sensitive to both user technique and the surrounding environment. As measured turbidity levels drop below 1.0 NTU, the interferences caused by bubbles and particulate contamination (usually only slightly problematic at higher levels), and ambient light can result in a false-positive reading and invalid verification results.

To obtain the most accurate calibration for this linear range, Hydrolab turbidimeters use a 20.0 NTU formazin standard. Formazin is the primary standard for turbidity measurements. This concentration is used because the standard is easy to prepare accurately from a concentrated stock formazin standard, plus the standard remains stable long enough to maintain its accuracy for calibration. In addition, the standard concentration is in the middle of the linear nephelometric range, and contamination and bubble errors have less effect on the calibration accuracy at 20 NTU than they would have on a lower calibration standard.

Formazin is the only true primary standard for turbidity, but an acceptable and approved alternative includes Hach StablCal®. It is the same formazin polymer that has been stabilized with a special matrix. Another marketed standard is a commercially manufactured liquid suspension of Styrene divinylbenzene and referred to as "polymer beads" (SDVB). The optical characteristics of formazin and polymer beads are very different. Polymer bead standards are "rated" based a specific technology type and this varies between different technologies. For example, if a user chooses to use SDVB beads in non-nephelometric technologies, the same concentration of beads may deliver a different value on a different technology. With SDVB materials, the majority of their standards are instrument specific, designed for a specific make and model of turbidimeter and cannot be used anywhere else.

The merits of a calibration standard for turbidity is that it be interference free. Formazin based standards are the only standards that meet this criteria and this allows them to be the universal calibration for ALL technologies.

"Accurately tracing the turbidity measurement of an instrument design technology and adhering to best practices will help effectively ensure the qualification and quantification of turbidity measurements in natural water bodies"

Verify the calibration using same or similar technology.

The key to proper verification is to verify calibration with the same or similar technology. Often, users have an instrument with one technology and will verify it using a totally different measurement technology. For example, an instrument is placed in a stream and it reads 20 units. Then, another sample is measured with another instrument and it reads 40 units. If it is not known that the technologies are different, it will often be assumed that one of the instruments is wrong. If a comparative calibration or comparative verification is performed and read on a different instrument, it is necessary to use a technology that best matches. At the very least, match the most important factor, which would be the light source, and the second most important would be the detection angle. Also, because most turbidity measurement technologies are characterized based on formazin, it is the best choice as a calibration standard for both technologies.

Maintain the instrument.

Maintenance frequency should be based on data value (hourly, daily, weekly, monthly) and monitoring goals. If the monitoring goals are being regulated, for example, those instruments will require much more stringent maintenance and monitoring. Accurately understanding what the needs are of a given site, and how that impacts decisions, oftentimes will dictate maintenance scheduling. Maintenance scheduling can be far more stringent than what the manufacturer suggests, but maintenance activities should never be deferred beyond the manufacturer's recommendations.

Conclusion

Whether profiling ponds, lakes, or reservoirs, or grab sampling in small streams or rivers, monitoring turbidity provides useful information about the relative clarity of water. Turbidity measurement results can, in turn, serve as a valuable surrogate indicator of biological, organic or inorganic pollution. However, it is now general knowledge that different turbidity measuring technologies can deliver very different results. These differences are related to the type of technology used and how this technology is impacted by the different absorptive and attenuation characteristics that are exhibited by the particles in a given sample. The ability of water resource professionals to accurately trace the turbidity measurement to an instrument design technology and adhering to best practices and proper measurement techniques will help effectively ensure the qualification and quantification of turbidity measurements in natural water bodies.

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1. USEPA. 2003a. "Guidance for 2004 Assessment, Listing, and Reporting Requirements Pursuant to Sections 303(d) and 305(b) of the Clean Water Act; TMDL-01-03."

2. Ziegler, Andrew C. "Issues Related To Use Of Turbidity Measurements As A Surrogate For Suspended Sediment" – Proceedings Of The Federal Interagency Workshop On Turbidity And Other Sediment Surrogates, April 30-May 2, 2002, Reno, Nevada.

3. ASTM "D 7315-07a Test Method for Determination of Turbidity Above 1 Turbidity Unit (TU) in Static Mode."