MURKY WATERS:
Gaining Clarity on Water Transparency Measurements

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Does your program measure water transparency? Turbidity? Water clarity? Secchi Disk Depth? Aren't these all the same thing? Why do some groups report turbidity as JTU while some use NTU and others use FTU or even FNU? Is it possible to convert Secchi Disk measurements to turbidity? What about those "turbidity tubes" everyone is using? What do they actually measure? This introduction will provide an overview of the above mentioned methods. It is meant to provide a lead into the two following presentations that will present more specific studies regarding water clarity measurement protocol and the use of "turbidity tubes" in volunteer monitoring programs.

THE SECCHI DISK

Father Peitro Angelo Secchi was a Jesuit astronomer and science advisor to the Pope. The commandant of the Vatican fleet, Commander Cialdi requested that Secchi study the water transparency of the Mediterranean Sea. Aboard the papal steam ship L'Imamacolata Concezione on April 20, 1865 Cialdi recorded the first documented measurements of water transparency made by Secchi. Fr. Secchi lowered a white disk attached to a line down into the water and noted the depth of its disappearance from view. Thus, the "Secchi Disk" was born. Why were sailors interested in ocean water clarity? The clarity of the water could indicate what current the ship was in. For example, the Sargasso Sea in the Atlantic Ocean is extremely clear compared to coastal upwelling currents, which have much higher productivity of plankton and thus less clear waters. So water clarity would help determine which current the ship had encountered, important information for navigation.

Secchi and Cialdi experimented with two types of disks, a 43 cm disk of white clay and a 60 cm diameter disk of sailcloth painted white and stretched over an iron ring. He also experimented with different colors including yellow (the color least absorbed by ocean waters) and brown (red is the color most absorbed but red dyes tend to be unstable). The standard oceanographic Secchi Disk used today is 40-60 cm in diameter dependent on the typical secchi depth measured. It is all white. The standard limnological (lake) disk is smaller, 20 cm (8 inches) with alternating black and white quadrants. This is attributed to Whipple who in 1900 modified the white disk since lakes could have bright or dark bottoms depending upon their depth, geology and bottom cover. Larger black and white disks have been used by scientists measuring transparency in the clearest lake waters like Crater Lake where secchi depth can reach 144 feet (44 meters!).

Secchi Disk Depth is a function of the absorption and scattering of light by particles and dissolved substances in the water (Figure 1). The particles include algae, sediments and detritus (organic particulates). The dissolved substances are the organic acids that result from the breakdown of plants and algae. They may be from the plants and algae of the waters or may originate from the drainage of wetlands or wet humic soils somewhere in the watershed. For more turbid systems the secchi depth is affected more by the particulate components in the water but our research shows that in clearer waters the secchi depth can be greatly influenced by the dissolved components (see further discussion of this below). For all extensive purposes the Secchi Disk acts as a contrast "target" and the Secchi Disk depth is the point where there no longer remains any contrast between the disk and the water background. For this reason, the intensity of the light within a certain range will not necessarily greatly impact the readings obtained.

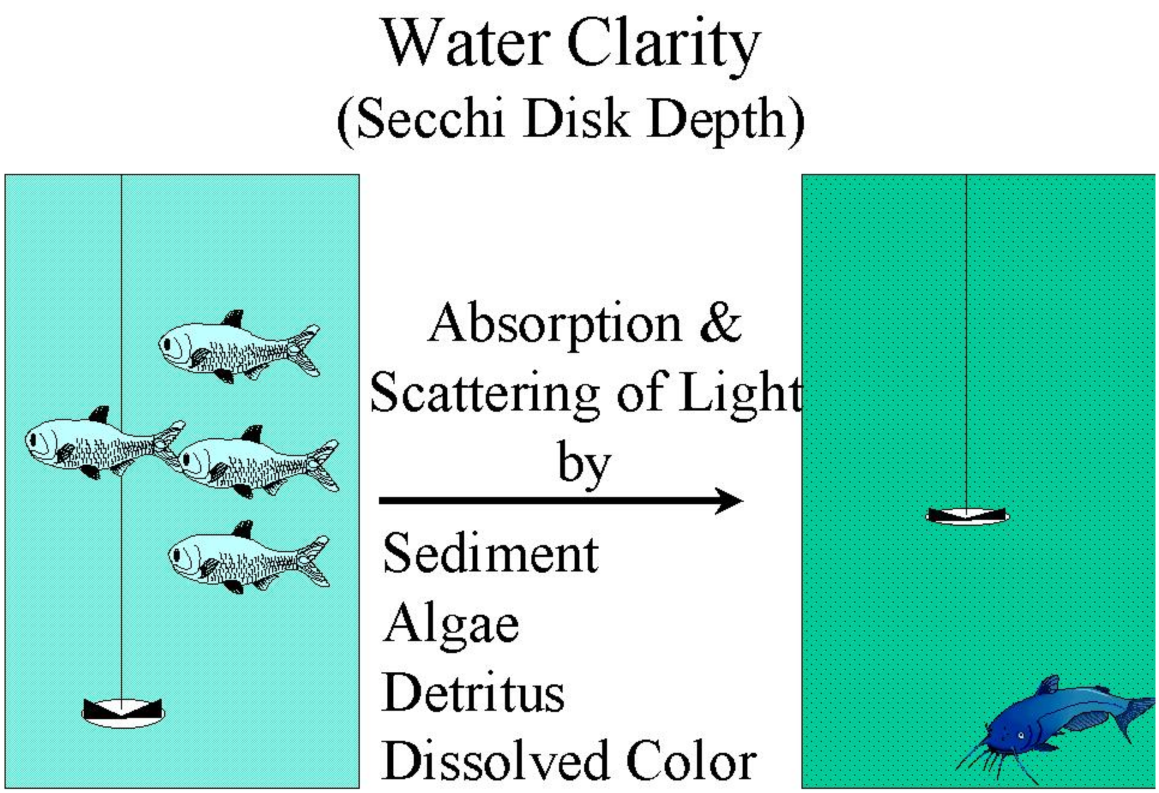

Figure 1

Secchi Disk Methodologies: Things get murky

The Secchi Disk is perhaps the oldest, most durable, the most controversial and potentially indispensable tool of the contemporary limnologist. … If it weren't for volunteer lake monitoring programs, the Secchi Disk might have slowly been lost from the inventory of limnological instruments. Dr. Bob "Secchi Dip-In" Carlson (1995).

Why such a contradicting commentary from the organizer of the Great North American Secchi Dip-In (an event that occurs every year during the first two weeks of July; refer to http://dipin.kent.edu)? It is true that the most common parameter measured by all volunteer lake monitoring programs is Secchi Disk transparency. Also, the concept behind the measurement and the concept of water clarity is very intuitive can be easily explained to the general citizenry. However, his additional comments refer to the inconsistencies in the methodology used and the potential difficulties in the comparison and interpretation of the resulting data produced.

Although Secchi Disk measurements are as old as the science of limnology, there is still no one agreed upon protocol of measurement. First of all, the definition of the secchi depth has varied between practitioners. Some use the depth at which it is “just visible” others have noted the depth of disappearance. Most current limnology field manuals and secchi researchers suggest using the average of the depth of disappearance and the depth of re-appearance when the disk is raised. Even Secchi was well aware of the reasons for variations in transparency depth. During his studies he employed umbrellas and used the shadow of the ship for shading and compared measurements. He concluded that the critical factors in the measurement of the secchi depth were the diameter and spectral reflectance of the disk, a calm or stormy sea, angle and reflections of the sun, reflection of the sky on the water surface, and shadows on the submerged light path. As for sun angle, it is generally agreed that the measurements should be made as closest to true noon as possible. Secondarily, it is important to take measurements before the sun approaches the angle where most of the light reflects off of the water’s surface instead of penetrating the water. This will vary dependent on time of year and season but many programs recommend readings between 10am and 2pm while some allow readings between 9am and 3pm. In the latter case be aware of daylight savings time changes, which may require a shift to true time readings.

The reflectance of the disk is a factor that comes to play during the construction of the disk and it is generally recommended to use a “flat” finish of paint and not a “glossy” one. The former will diffuse the reflection off the disk at all angles while the latter can complicate measurements made when the disk is slightly “off angle “, as it will deflect light unevenly. Theoretically, the reflectance should be standardized but that would be a daunting task. The use of an all black Secchi Disk, promoted by the New Zealand limnologist R. J. Davies-Colley, best tackles this problem, as well as some of the other theoretical optical intricacies involved, although it has not caught on in the research community in other countries let alone volunteer programs. Another construction consideration (and measurement protocol) of the disk involves the use of non-stretching line or fiberglass tape if a marked line is to be used. This can also be avoided if a measuring stick is used to measure the line but that involves taking out yet another piece of equipment for sampling.

Even more controversial than a black vs white vs black and white disk is the effort to deal with the optical state of the water's surface (reflection, glare, glitter). The easiest approach, but one less practical, is to only measure on days of perfect conditions. A more common approach is to employ the recommendation of Father Secchi and take readings off of the shadowed side of the boat. While this often solves the surface interference issues it may actually introduce larger errors especially in cases where the Secchi Disk depth is shallow or ranges through the depths shaded by the boat's shadow. The optical oceanographer J.E. Tyler in his 1968 review of Secchi Disk optics goes into great detail on why taking a reading on the shadow side is problematic and employs a columns full of equations and diagrams. In essence, his conclusion is that due to the optical properties involved, readings become less comparable with each other under changing time, sun angle (and boat type) and even brightness (which typically is not a factor that normally influences proper Secchi Disk measurements). Bob Carlson indicates that this shadow factor can vary Secchi Disk readings by as much as 15%.

To be able to make readings on the sunny side of the boat and deal with the interference from glare, reflection and glitter many groups employ a "view scope". This usually is a 4" or greater diameter tube with or without a lens on its bottom end or a face seal on its upper end. An attached handle facilitates holding the tube just below the surface of the water to view the descent of the disk. To minimize reflection within the tube the interior is painted black. A plexiglass lens on the bottom end will keep water from entering the tube and splashing around. These apparatus can be home-made or obtained from commercial sources. A recent design modification in the commercially made scopes places the lens at an angle to the end of the tube to keep reflection off of the lens to a minimum. A good face seal (neoprene works well) at the top end or shading of the observer's head can also minimize this reflection. Some practitioners have used face masks, view boxes and even children's pool toys (inflatable "fish scopes" and view rafts) but a rigid scope has the most utility for most applications. The length is not a factor for a wide enough tube but care must be taken to only submerge the tube bottom a shallow, set distance. This is often accomplished by marking a line on the outside of the bottom end of the tube or submerging the tube until the end cap that holds on the lens is just under the surface.

European limnologists and pioneer American limnologists employed view-scopes in their secchi measurements but there are many volunteer programs that have not. Theoretically the scope accounts for many of the non-clarity-related interference already discussed above. Independent investigations by volunteer monitoring programs in Minnesota and New Hampshire (See Bob Craycraft's paper below), and most recently, by researchers on reservoirs in New York have demonstrated that higher precision of measurement can be achieved between observers by using a scope. Our results in New Hampshire also indicate that the scope allows for a greater sensitivity in secchi measurements for lakes with deep secchi depths. Does that mean that groups currently not using a scope should start? That all depends on the goals and data objectives of your program. If you have already been taking many measurements and have a long-term program, changing your methodology will complicate multiyear comparisons. You may want to live with a potential loss in the precision of your measurements. If you monitor systems that have very shallow transparencies or are only interested in large water clarity changes, the scope may not make any difference at all in the interpretations of your measurements. If however, you monitor pristine systems or are interested in documenting subtle differences in water clarity or are concerned about precision between observers, you may want to consider using the scope.

Can you convert or compare secchi measurements? Theoretically, on a calm day with little glare or reflection on the water surface the secchi depth measured, with or without a scope, should be comparable. We are currently examining the results of a multi-year comparative effort that involved volunteer monitors and professionals in a wide range of lakes and conditions and have found that the conversion is not just a simple correction factor. Sky, sun, wind, water conditions and time of day all play a part in the difference as would be expected. The important take-home message here is to make sure that no matter what your Secchi Disk protocol of choice is, be sure to document the conditions that occurred and the time of the measurement. This will eventually allow for conversion or comparison using reported factors or your own methodology comparisons.

What Are We Measuring Anyway?

One of the reasons for using a Secchi Disk stated above is that it is an easy to understand measurement. Water clarity by itself can be important: many people will not even think of swimming in a lake, river or ocean if they can't see their toes! Also, a change in transparency over time indicates something is occurring in the water. Thus, Secchi Disk depth variations seasonally or after rain events or heavy recreational use can indicate water quality impacts. Water quality trends over the years can also be documented with a time series of secchi depths. In fact, independent studies done on Vermont and Minnesota volunteer program data disclosed that Secchi Disk depth data was better able to detect long-term trends than either phytoplankton (as measured by chlorophyll) or nutrient (total phosphorous) monitoring.

We should expect secchi depth to be related to light extinction through the water column. Our research indicates a very good correlation between secchi depth and sunlight extinction measured using an underwater irradiometer (essentially a waterproof light meter). In fact, some programs use the results of the Secchi Disk depth to determine the extent of the integrated water sample that is to be collected for lab analysis; Since many lake programs are interested in assessing lake productivity (phytoplankton and plant growth) the estimated depth of the photic zone (waters in which photosynthesis takes place) is an important factor.

Limnology texts suggest the Secchi Disk depth represents relative light depths ranging from 1 to 15 percent of the surface light. Our measurements made in a wide range of New Hampshire Lakes with Secchi Disk transparencies ranging from 1.8 to 14 meters disclose the secchi depth occurred at 1.3 to 11 percent of the surface illumination with a mean of 5.5 percent and median of 5.0 percent (n=66). The aforementioned texts report the photic zone to range between 2 to 3 times the Secchi Disk depth. Our results for NH lakes indicate that it is probably closer to (or just less than or greater than) twice the secchi depth for our lakes. Values at that depth range from less than 0.1 percent to 1.3 percent with a mean of 0.4 percent and a median of 0.3 percent.

Secchi disk measurements alone are often made as a surrogate for other more complicated or expensive measurements. Many states have Secchi Disk based criteria or standards. A few use clarity as the primary basis for management decisions. This is fine if you are very sure of how your system works and <u>either</u> phytoplankton (floating algae) or suspended sediment always exclusively dominate as particulates. Or it may be that it is just the clarity of the water you are concerned about. If this is not the case, care must be taken when it comes to interpretation of measurements. It may be a phytoplankton bloom one week, a sediment event the next and an influx of colored water from an adjoining wetland the next. Similarly, relying on a Secchi Disk measurement alone to calculate a trophic state index may be risky. To add to the confusion, certain conditions such as the thin layering out of phytoplankton at the thermocline of a stratified lake (termed metalimnetic layering) can make the disk instantly disappear well before the upper water conditions would dictate. This phenomenon will wreck havoc with modeling, indexes and water quality criteria based on Secchi Disk alone.

To address the “what” is being measured by the Secchi Disk dilemma some groups turn to apparent color measurements. Apparent color is the color of the water due to both particulate and dissolved components. It differs from dissolved “true color” which is measured after filtration so it can not be ascertained in the field. The underlying assumption is that algae tend to impart golden, green, blue-green or reddish brown hues while sediments in water tend to be gray or yellow to light to dark brown in color. The apparent color, as seen by viewing the white quadrant of the disk (sometimes set to one half of the secchi depth) is matched to a color on some sort of color strip or color chart . The Ohio program developed the “Custer Color Strip” (named for its originator Clyde Custer) based on standardized Pantone colors (available at printing centers) that is used by other programs as well. Some groups use the standardized colors found on “Munsel” soil color books while others use a series of paint chip samples. A few field science and educational supply houses sell a standardized color chart devised for stream bottom color description that may also be used for this purpose. By documenting the color at the time of measurement some insight as to what is affecting water clarity may be gained.

Our program has volunteers monitor Secchi Disk depth, along with chlorophyll a (an estimate of algae biomass) and dissolved water color (particles filtered out). Sediment is not directly monitored as it is difficult to get accurate suspended sediment yields in our generally pristine waters unless large volumes of water are filtered. However, by comparing all of our results together we can generally interpret what influence each of these plays on water clarity (while sediment is not measured directly, a decrease in water clarity that does not correspond to an increase in chlorophyll or dissolved color can be attributed to sediment). For New Hampshire lakes we have found for the most part that neither chlorophyll or dissolved color alone explain the variations in Secchi Disk transparency as well as the combination of the two (Table 1). Also, dissolved color tends to gain in influence at levels at or greater than 20 standard color platinate units and at secchi depths greater than 10 meters.

Table 1- Secchi Disk (SD) as Surrogate for Chlorophyll (CHL) and Dissolved Color

Treatment	R-Square
1/Seccchi Disk v ln CHL	0.690
1/Secchi Disk v ln Color	0.545
1/Secchi Disk v ln Color , ln CHL	0.791

N=61; UNH Lake Survey Data 50 Lakes June-August 1999

TURBIDITY

While some programs refer to Secchi Disk transparency as a turbidity measurement this is not correct. The origin of turbidity measurement dates back to about 1900 when Whipple (the same guy who painted the Secchi Disk black and white) and Jackson devised a method that involved holding a flat-bottomed, calibrated glass tube over a special candle and pouring the water sample into the tube until an observer looking from the top of the tube could no longer see the image of the candle flame. Unlike the Secchi Disk measurement where just the distance (depth) was noted these measurements were calibrated to a known standard of suspended material. The tube was calibrated in Jackson Turbidity Units (JTUs) with measured dilutions of a standard solution of silica (diatomaceous earth) in distilled water. The number of JTU's varies inversely and nonlinearily with the height of the sample (e.g., a sample which measures 2.3 cm has a turbidity of 1,000 JTU's whereas a sample measuring 72.9 cm has a turbidity of 25 JTU's; 1 JTU represented 1ppm of silica). This facilitated the measurement of water samples from systems too shallow or with too great a flow to utilize a Secchi Disk. Over the years other materials were calibrated to JTU's (clay, Fuller's Earth, acid washed stream bed sediments) and the system was modernized by replacing the candle with a light bulb and increasing sensitivity using a series of neutral density filters. The major limitations that lingered, however, was that the minimum detectable limit remained at about 25 JTUs and there was not an acceptable primary standard that insured comparability of measurements.

By the early 1970s Formazin, a chemically created polymer, was established as the new primary standard for turbidity. A certain design of Turbidity Meter, the Nephelometer, became the preferred instrument of turbidity measurement. It offers much greater sensitivity and minimizes differences between observers as it measures turbidity photometrically. The basic design requires that the instrument measure the amount of light scattered at 90 degrees when a beam of light is transmitted through the sample. Most current nephelometers employ two light detectors (Figure 2) one at 90 degrees to the incident light, and one directly in the beam's path to measure transmitted and forward scattered light. The second detector is used to minimize the inferences of color and larger particles. This instrument employs the ratio between the two detectors to calculate the sample turbidity. Units are reported as Nephelometric Turbidity Units (NTU; the most popular), Formazin Turbidity Units (FTU) or Formazin Nephelometic Units (FNU) which are all equivalent. Due to Formazin's short term stability and toxic nature, secondary standards that have been formulated in comparison to the primary standard are in more common use. These substances offer many times the shelf life and less danger of poisoning.

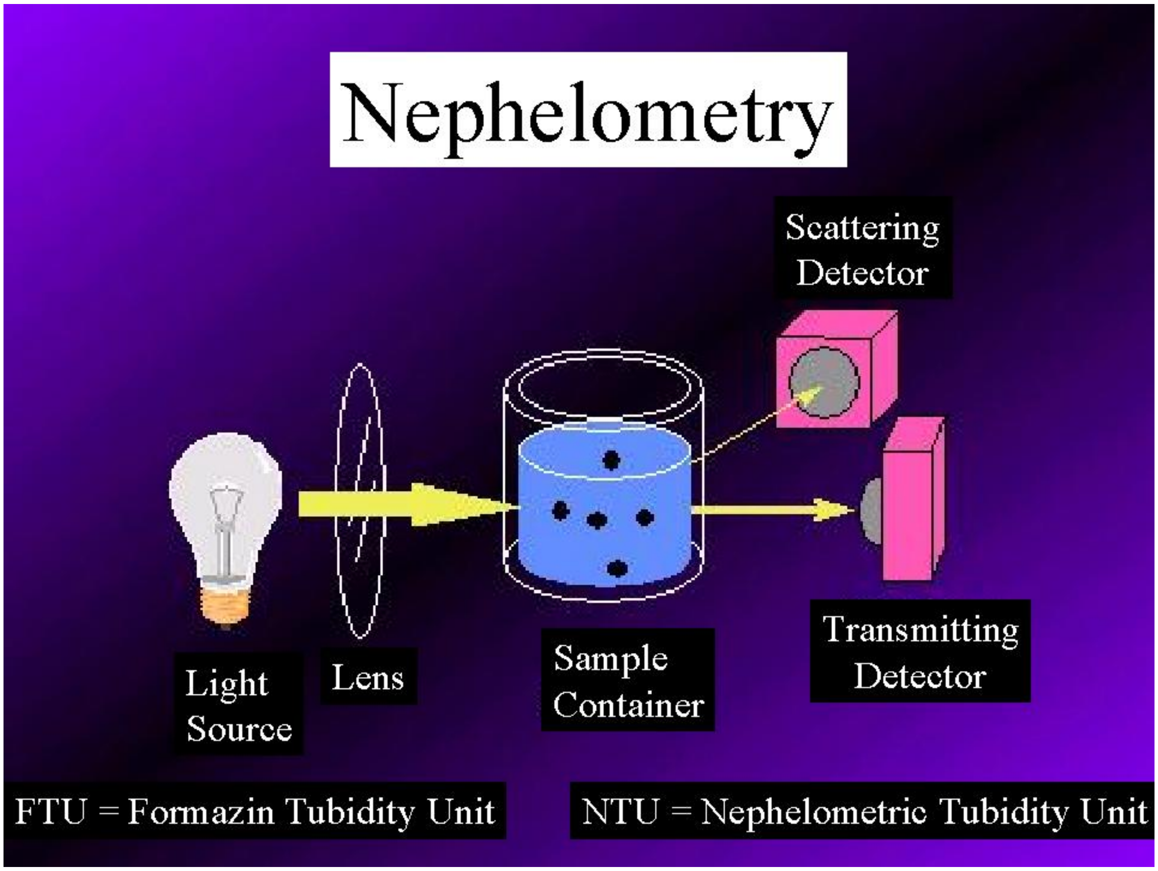

FIGURE 2

For those groups that have data quality objectives that require EPA or state acceptance, there are set design standards that a nephelometer must have. They include the following:

- The detector should be centered at 90 degrees +/- 3 degrees to the incident light path.
- The maximum distance traversed by the incident and scattered light within the sample tube is 10 cm.
- Instrument sensitivity should permit detection at a turbidity difference of 0.02 NTU or less in water less than 1 NTU.
- The detector and any filter system are to have a spectral peak response between 400 and 600nm.
- The light source should be a tungsten lamp operated at a color temperature of 2,200 to 3,000 Kelvin

Some recent Nephelometers, Turbidometers and in-situ Turbidity probes, even some with higher precision and sensitivity than EPA approved units do not meet the above requirement of a tungsten lamp as they employ a more monochromatic LED light source (generally in the red or near infra-red wavelengths). These may be acceptable under the international ISO standard for turbidity, ISO 7027. However, unless there is a move to performance based standards or you can demonstrate inter-calibration between these and an approved unit, your data may be considered “qualified”. We have actually compared these LED units to tungsten lamp units and found the LED based units have a greater accuracy as they tend be less affected by high levels of dissolved color which causes more interference at the blue end if the spectrum than at the red end.

As expected, due to the optical principles employed, the turbidity of a water sample will generally correlate very well with suspended sediment content. Many states have existing standards or criteria for turbidity that may cover, contact recreation, drinking water, aquatic habit or general surface water quality. Some lake, river and coastal groups use nephelometers in their monitoring programs but typically these units are cost limiting, generally running between $500 and $1,000 for accurate meters.

TURBIDITY TUBES

A relatively new apparatus on the scene, the “turbidity tube” is gaining in popularity in its use by volunteer stream monitoring groups and teachers and students involved in Project GLOBE. It consists of a transparent plastic or glass tube (usually between 1 and 2 inches diameter) that has some sort of visibility target (often a “mini” Secchi Disk) at its bottom end that is open at its top. The observer pours water into the tube until the target can no longer be seen. This is sort of a hybrid process that combines the Secchi Disk and Jackson Turbidometer approaches. The height of the water level is documented using some sort of scale that is marked or etched on the side of the tube. Some tubes are fitted with a drain hole located at or near the bottom while others add a short length of tubing and a hose clamp or even a large syringe to more accurately control the water level during measurement.

The first documented use of a turbidity tube has been attributed to Noel Morgan who in 1991 employed a 2 liter plastic soda bottle marked and calibrated in NTUs to estimate turbidity in the storm runoff of Australian farms. Cost effectiveness was the major underlying factor in his design and these were typically very turbid systems being monitored. Sometime around the same time or slightly after, an article in the GREEN Program Newsletter documented the use of a long glass tube fitted with a syringe level control to measure river water turbidity in Africa. This unit was calibrated in centimeters above the visibility target. By 1994 the “Aussies” had developed a mass production model of the turbidity tube at a cost slightly over $10 a piece. This unit was a comparatively sleek model, two feet of polycarbonate tubing about 1 ½ inched diameter with a black painted target (wavy lines) on a white background. The units were calibrated in NTUs. The Australian Waterwatch Program conducted a nation-wide turbidity monitoring event during national Water Week employing over 700 tubes.

In 1996 an Australian delegation from Waterwatch attended and presented at the 5th National Volunteer Monitoring Conference in Madison Wisconsin. In addition to teaching us all of the verses of “Waltzing Matilda” (and explaining the majority of the words!) they left some of their turbidity tubes in their wake. Interest in the use of these tubes peaked and programs in this country started experimenting with these tubes. Currently, stream volunteer groups and GLOBE participants use a tube calibrated in centimeters. This is the general preference as this type of linear scale offers a greater ease of taking a reading and a higher precision of measurement. The NTU scale is a non-linear, logarithmic one that has different distances between major markings and therefore makes interpolation between the calibrated marks difficult. It is much easier to develop a conversion equation for obtaining estimations of turbidity from the centimeter scale. While this should be done for your own specific waters, there are general conversion graphs for GLOBE participants by scientist advisors at the University of Arizona that have been made available. These conversion factors generally work best in the higher range of turbidity encountered (10 to 400 NTU in this case).

In effect, the “turbidity tube” is actually more a “transparency tube” in terms of the underlying optics of the measurements, especially since these days turbidity is synonymous with nephelometry. However, tube readings do generally correlate very well to turbidity and suspended sediment for within system measurement and for low color waters as indicated by reports from the Minnesota monitoring program (also see Jennifer Klang’s paper below). This is most likely due to the fact that sediment tends to be the predominate particulate in the rivers and streams monitored.

As with Secchi Disk measurements, care needs to be taken in standardizing your protocols. Consideration should be given to:

1. Whether the readings are taken in the shade or sun
2. The position of the observer in relation to the sun.
3. Appropriate target design and length of tube to cover the range of clarity.
4. Whether a standard diameter of tube should be used.

While there have been no recommendations on the best way to approach measurements, preliminary research by our program suggest that considerations 1 through 4 are important considerations. Readings in a bright environment can be significantly different than the same sample viewed under more subdued light. This may be a function of the observer’s acclimation to bright light or due to stray light from the side of the tube causing interference. Using the head of the observer to shade out the sun above was important in minimizing glare during measurements. Only at high dissolved color levels or for clearer water conditions that necessitate the almost filling of the tube did the “mini-secchi” target make measurements easier to determine compared to the wavy line target of the Australian tube since. The small distance between the lines on the latter target was problematic for determining the reading in those measurements. No significant difference was found when using tubes of different diameter (1.5 and 2 inches) over a range of different turbidity and color levels.

Dissolved color greater than about 15 platinate units started to influence the comparability of “transparency tube” measurements and turbidity values. The minimum detection level for the manufactured tubes used in our studies was about 10 NTU. This may be improved through the use of a longer tube. However, the longer the tube, the more cumbersome the measurement may be. Perhaps an improvement in design that employs a mirror and prism set that can be economically designed to measure more pristine waters without necessitating an oversized tube can be made.

With the “transparency tube” river and stream and river monitors now have a low cost water clarity device akin to the Secchi Disk of lake and coastal monitors. But just as with Secchi measurements, care needs to be taken in standardizing the monitoring protocol and in interpreting the results.

Last Words

So, are things becoming clearer? Or are they just more transparent? Just remember, even with the simplest of measurements complications can ensue. Thus, standardization and supplemental observations will remain the key in understanding the optical dynamics of your waters and the interpretation of changes measured. Be sure never to call a Secchi Disk measurement turbidity if I am around- there are many other proper options like clarity or transparency. Theoretically the proper way to measure Secchi Disk depth is by using the average of the depths of disappearance and reappearance of a flat painted, standard sized disk off of the sunny side of the boat with the sun overhead and a viewscope in hand (Phew!). But then again, you need to consider the impact to your already existing program of a change in protocol. You <u>can</u> interchange NTU, FTU and FNU at will but JTU implies a lack of a specific primary standard referenced. More expensive Nephelometers will be required to measure very low turbidity levels. However, the “<u>TRANSPARENCY</u> Tube” (take note of this important name change) may make a fine addition to your monitoring program.