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*Workshop Proceedings*

ALLIANCE FOR COASTAL TECHNOLOGIES

# MEASURES OF TURBIDITY IN COASTAL WATERS

*Coconut Island, Oahu, Hawaii*

*August 31 - September 2, 2005*

*Funded by NOAA's Coastal Services Center through the Alliance for Coastal Technologies (ACT)*

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**An ACT 2005 Workshop Report**

## A Workshop of Developers, Deliverers, and Users of Technologies for Monitoring Coastal Environments:

# Measures of Turbidity in Coastal Waters

Coconut Island, Oahu, Hawaii

August 31-September 2, 2005

Sponsored by the Alliance for Coastal Technologies (ACT) and NOAA's Center for Coastal Ocean Research in the National Ocean Service.

Hosted by ACT Partner organization the Hawaii Institute of Marine Biology (HIMB), School of Ocean, Earth Science and Technology (SOEST), University of Hawaii.

ACT is committed to develop an active partnership of technology developers, deliverers, and users within regional, state, and federal environmental management communities to establish a testbed for demonstrating, evaluating, and verifying innovative technologies in monitoring sensors, platforms, and software for use in coastal habitats.

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# ACT WORKSHOP: MEASURES OF TUBIDITY IN COASTAL WATERS

## EXECUTIVE SUMMARY

A three day workshop on turbidity measurements was held at the Hawaii Institute of Marine Biology from August 31 to September 2, 2005. The workshop was attended by 30 participants from industry, coastal management agencies, and academic institutions. All groups recognized common issues regarding the definition of turbidity, limitations of consistent calibration, and the large variety of instrumentation that nominally measure "turbidity." The major recommendations, in order of importance for the coastal monitoring community are listed below:

1. The community of users in coastal ecosystems should tighten instrument design configurations to minimize inter-instrument variability, choosing a set of specifications that are best suited for coastal waters. The ISO 7027 design standard is not tight enough. Advice on these design criteria should be solicited through the ASTM as well as Federal and State regulatory agencies representing the majority of turbidity sensor end users. Parties interested in making turbidity measurements in coastal waters should develop design specifications for these water types rather than relying on design standards made for the analysis of drinking water.

2. The coastal observing groups should assemble a community database relating output of specific sensors to different environmental parameters, so that the entire community of users can benefit from shared information. This would include an unbiased, parallel study of different turbidity sensors, employing a variety of designs and configuration in the broadest range of coastal environments.

3. Turbidity should be used as a measure of relative change in water quality rather than an absolute measure of water quality. Thus, this is a recommendation for managers to develop their own local calibrations. *See next recommendation.*

4. If the end user specifically wants to use a turbidity sensor to measure a specific water quality parameter such as suspended particle concentration, then direct measurement of that water quality parameter is necessary to correlate with 'turbidity' for a particular environment. These correlations, however, will be specific to the environment in which they are measured. This works because there are many environments in which water composition is relatively stable but varies in magnitude or concentration.

5. Turbidity is not the best measurement of downwelling irradiance of visible light. Of all turbidity sensors, transmissometers are best suited for measuring light quality; however, the single wavelengths used by most transmissometers will not provide a measure of the

attenuation of all visible light. Sensors that measure turbidity based on light scatter are particularly not well-suited for assessing light quality.

In conclusion, the workshop made specific recommendations for the upcoming ACT test evaluation of turbidity sensors as well as the general recommendations for users in the coastal ecosystems.

## ALLIANCE FOR COASTAL TECHNOLOGIES

There is widespread agreement that an Integrated Ocean Observing System (IOOS) is required to meet a wide range of the Nation's marine product and information service needs. There also is consensus that the successful implementation of the IOOS will require parallel efforts in instrument development and validation and improvements to technology so that promising new technology will be available to make the transition from research/development to operational status when needed. Thus, the Alliance for Coastal Technologies (ACT) was established as a NOAA-funded partnership of research institutions, state and regional resource managers, and private sector companies interested in developing and applying sensor and sensor platform technologies for monitoring and studying coastal systems. ACT has been designed to serve as:

- An unbiased, third-party testbed for evaluating new and developing coastal sensor and sensor platform technologies,
- A comprehensive data and information clearinghouse on coastal technologies, and
- A forum for capacity building through a series of annual workshops and seminars on specific technologies or topics.

ACT Headquarters is located at the UMCES Chesapeake Biological Laboratory and is staffed by a Director, Chief Scientist, and several support personnel. There are currently seven ACT Partner Institutions around the country with sensor technology expertise, and that represent a broad range of environmental conditions for testing. The ACT Stakeholder Council is comprised of resource managers and industry representatives who ensure that ACT focuses on service-oriented activities. Finally, a larger body of Alliance Members has been created to provide advice to ACT and will be kept abreast of ACT activities.

The ACT workshops are designed to aid resource managers, coastal scientists, and private sector companies by identifying and discussing the current status, standardization, potential advancements, and obstacles in the development and use of new sensors and sensor platforms for monitoring, studying, and predicting the state of coastal waters. The workshop goals are to both help build consensus on the steps needed to develop and adopt useful tools while also facilitating the critical communications between the various groups of technology developers, manufacturers, and users.

ACT Workshop Reports are summaries of the discussions that take place between participants during the workshops. The reports also emphasize advantages and limitations of current technologies while making recommendations for both ACT and the broader community on the steps needed for technology advancement in the particular topic area. Workshop organizers draft the individual reports with input from workshop participants.

ACT is committed to exploring the application of new technologies for monitoring coastal ecosystem and studying environmental stressors that are increasingly prevalent worldwide. For more information, please visit http://www.act-us.info/.

## ORGANIZATION OF THE WORKSHOP

The workshop was sponsored by ACT and hosted by the Hawaii Institute of Marine Biology, School of Ocean and Earth Science and Technology, University of Hawaii. The workshop was organized by Drs. Jim Falter and Marlin Atkinson of the Hawaii Institute of Marine Biology, Dr. June Harrigan-Lum, formerly of the State of Hawaii Department of Health, and Dr. Michael Field of the U.S. Geological Survey, Santa Cruz, California. Participants arrived on Wednesday August 31st, 2005 at the Hawaii Institute of Marine Biology on Coconut Island and gathered for a reception and dinner, during which a presentation of the ACT program by Jim Falter was given. Drs. Harrigan-Lum and Field shared their personal experiences making turbidity measurements in coastal environments. Dr. Harrigan-Lum presented work she has done relating turbidity measurements with other fundamental water quality measurements, in streams draining the main Hawaiian Islands. Dr. Field presented his work in the main Hawaiian islands using turbidity measurements to track the transport and fate of land-based sediment in near-shore reef environments and how they may impact coral reef communities.

Workshop discussions commenced on the next day, beginning with an introduction of the workshop goals, followed by an overview of each of the technologies used to measure turbidity based on information given to Dr. Falter by industry representatives attending the workshop. Most of these technologies involved optical measurements of the side or back scatter of single-wavelength light in the near infra-red spectrum.

The morning consisted of two breakout discussion groups and a summary discussion on 1) the needs of researchers and managers and impediments to monitoring coastal water, and 2) the technical abilities and limitations of existing commercially available technologies. The entire workshop was brought together in the afternoon to facilitate discussion between mostly managers and industry representatives on what is needed from turbidity measurements, what such measurements specifically mean from a technical standpoint, and what is technically feasible given the status of current technology.

The following morning, Friday, September 2$^{nd}$, the whole group engaged in a discussion of future technology and recommendations for use by end users, primarily from the public sector, along with suggestions for conducting an objective evaluation of turbidity sensor performance in a variety of coastal environments. A field trip to see some patch reefs within Kaneohe Bay was offered in the afternoon, which was followed by a barbeque in the beach house at Coconut in the evening to promote any further, informal discussion of topics brought up during the workshop. These events were optional, but attended by many. Below is the workshop agenda that was provided to all participants.

## MOTIVATION OF WORKSHOP

Turbidity is a property commonly used to describe water quality in both marine and freshwater environments, providing a gross assessment of light attenuation and suspended material. Turbidity is often not a direct measure of the quantity of interest, such as suspended sediment, living particles, and non-living organic matter, but rather a measure of the effect of the desired quantity on the optical properties of the water. At present, there are numerous methods for quantifying turbidity (e.g., light attenuation, surface scatter, side scatter, laser diffraction, acoustic back-scatter, etc.). Differences in methods of measurement and their individual responses to varying types of suspended material have made the measurement of turbidity difficult to perform in a consistent and standardized way. This has necessitated many public-service agencies (e.g., USGS, US EPA, ISO, ASTM, etc.) to define turbidity in very specific terms based on optically-based methods of measurement since optically-based methods have been the most conventionally used. Although such standards and definitions were created to be both technically and legally specific, thereby minimizing the ambiguity in interpreting what turbidity is and how its measured, they still suffer from fundamental deficiencies in their ability create an absolute standard between different natural water types and even different instruments designs employing the exact same principles of measurement. Despite years, and even decades, of attention to this problem, the questions of what turbidity is, how it is measured, and what measures of turbidity tell us have still not yet been resolved. If turbidity continues to be used by scientists and government agencies as a primary variable for characterizing water quality, then an unbiased comparison and evaluation of existing turbidity measurement methods is needed.

## TECHNICAL OVERVIEW: ABILITIES AND LIMITATIONS OF TURBIDITY MEASUREMENT
(BASED ON BREAKOUT SESSION #1)

### *Definitions of turbidity -- descriptive and technical*

#### *USGS*

*'An expression of the optical properties of a sample that causes light rays to be scattered and absorbed rather than transmitted in straight lines through a sample; and is caused by the presence of suspended and dissolved matter such as clay, silt, finely divided organic matter, plankton, other microscopic organisms, organic acids, and dyes'.*

#### *US EPA - 180.1*

This has been the most common definition of turbidity for use in the determination of water quality. There are two standard definitions of measuring turbidity based on the scattering of white light from a tungsten source operating at a color temperature of 2200-3000 °K. Total pathlength traveled by light in any direction is not to exceed 10 cm from the light source.

1. *Ratiometric* - the ratio of light intensity measured at a 90° angle from the direction of the emitted light to the intensity measured in the same direction as the emitted light.

2. *Non-ratiometric* - the intensity of light measured at a 90° angle from the direction of the emitted light.

A detailed copy of the US EPA 180.1 protocols can be downloaded from the US EPA web site: www.epa.gov.

#### *ISO 7027*

*'Reduction of transparency of a liquid caused by the presence of undissolved matter'.* This is an international standard developed for the testing of drinking water. ISO 7027 proposes different criteria for turbidity measurement depending on the method of measurement. A detailed copy of the ISO 7027 standards and protocols can be purchased from the International Standards Organization web site: www.iso.org.

### *Other Standards*

While the above three are the most common standards for defining and/or measuring turbidity, other standards have been proposed such as Great Lakes Instruments II (GLI-II or EPA 180.2) which uses two light sources and two detectors at 90 degrees such that there is a reference detector as well as a scatter detector for each lamp. Additional standards have been proposed by the ASTM and other private organizations.

## ***The physics of light in natural waters: a primer***

Most measurements of turbidity rely on optical methods; therefore, it is necessary to understand the fundamental behavior of light in natural waters in order to follow discussions of the strengths and limitations of optical measurements of turbidity made during the workshop. See article by R.W Austin EPA Seminar Oct 17-18, 1973 on this web site and Casey Moore, 2004, *Transmissometry and Nephelometry*.

### *Absorption*

Light absorption occurs when photons of a given wavelength are intercepted by water, dissolved in particulate compounds in the water, and transferred into a non-radiant form of energy such as heat. Thus, absorption is the process by which radiant light energy is physically removed in the water.

### *Scattering*

Scattering occurs when photons of light interact with water and dissolved and particulate compounds in the water, resulting in an alteration in the direction of light propagation due to reflection, refraction, and/or diffraction. Light in a vacuum travels continuously in the same direction. However, light in natural waters has a tendency to disperse or spread out depending on the degree of scattering. Scattering of light can occur in all directions, although it is strongest in the forward direction (i.e., closer to the original direction of light propagation). In general for coastal systems, suspended particulate matter affects the scattering properties of natural waters much more than dissolved compounds or the water itself.

### *Attenuation*

Attenuation is the total reduction in radiant light energy that occurs when a ray of light travels through a given distance (or path length) of water. While absorption is the phenomena by which light is removed from water, scattering also increases light attenuation by increasing the convoluted path length a given ray of light must traverse to cross a given straight-line distance through the water, thereby increasing the amount of absorption occurring over that straight-line distance. It is the diminishing effects of both absorption and scattering which determine the attenuation of light over a given distance through a column of water. For homogeneous bodies of water, the attenuation of light can be modeled as the sum of both absorption and scattering effects:

$$I(z) = I_o e^{-k_d z}$$

$$k_d = k_a + k_s$$

where $I(z)$ is the intensity of incident light measured a straight-line distance z from a given point of light intensity $I_o$. $k_d$ is the attenuation coefficient, $k_a$ is the absorption coefficient, and $k_b$ is the scattering coefficient. It is important to note that both absorption and scattering occur in all waters, pure or natural, to greater or lesser degrees. $k_d$, $k_a$, and $k_b$ all have units of $m^{-1}$ whereas turbidity is generally measured in NTUs or Nephelometric Turbidity Units. In general, these metrics can be roughly converted between one another given an approximation that 1 $m^{-1} \approx 1$ NTU.

## Methods of measuring turbidity

### *Sensors based on light scattering*

### *Side-scattering turbidity sensors ($\theta \approx 90°$ with respect to the direction of light propagation)*

Side-scattering turbidity sensors measure the light scattered by a volume of water at a 90° relative to the path of emitted light. Most side-scattering turbidity sensors use a single wavelength in the near infra-red range (NIR: $\lambda$ >760 nm) and most calibrate the intensity of the side-scattered light to a direct measurement of the emitted light intensity to remove uncertainties due to temporal variation in the source strength, electronics, and other miscellaneous effects. Side-scattering turbidity sensors are best suited for less turbid waters (<1000 NTU) and benefit from a more well-defined measurement volume than sensors measuring the light scatter at more obtuse angles. ISO 7027 requires that side-scattering turbidity sensors use a scattering angle of 90° ±2.5°, a wavelength of 860 nm with a spectral bandwidth of no greater than 60 nm, and be calibrated against a specifically prepared Formazin solution.

### *Back-scattering turbidity sensors ($\theta$ > 160°)*

Back-scattering turbidity sensors measure the amount of light scattered backwards off a given volume of water; generally employing a single waveband ~80 nm wide in the NIR range. Back-scattering turbidity sensors are best suited for very turbid waters (up to 30,000 NTU) and not well suited for low turbidity waters (<10 NTU). They also have a much less well-defined sampling volume than do side-scattering turbidity sensors which will change with the level of turbidity.

### *Turbidity sensors using non-standard scattering angles (100° < $\theta$ < 160°)*

One manufacturer builds a turbidity sensor which specifically measures the scattering of a narrow waveband chosen by the end user in the visible and NIR range at a detection angle 117°. The manufacturer chose this wavelength to minimize the sensitivity of the measurement to the type and size distribution of particles in the water, resulting in a ess bias and more robust measurement of the concentration of mass suspended in the turbid water. The transmissometer is not sensitive to the index of refraction of suspended particles.

### *Transmissometers ( $\theta$ = 0°)*

Transmissometers effectively measure beam attenuation, or the reduction in intensity of a column of light as it crosses a given straight-line path length of water. As such, its measurement is affected by both scattering and absorption. Representatives from industries manufacturing transmissometers were not represented at the workshop, however, many of the industry representatives attending the workshop were sufficiently familiar with the technology of transmissometers to discuss their important attributes. It was suggested that greater than half of end users measuring turbidity use transmissometers. Transmissometers vary in the wavelength they employ with most measuring light attenuation in the NIR. The amount of attenuation measured will be highly dependent on the wavelength chosen. Transmissometers are more sensitive to the absorption of light by water and dissolved compounds than scatterometers. Multi-spectral transmissometers could be used to estimate particle size distributions based on the slope of attenuation versus wavelength. The upper measurement limit for most transmissometers assuming a 25-cm path length is ~20 NTU. ISO 7027 requires that transmissometers use a measurement angle of 0° ±2.5°, a wavelength of 860 nm with a spectral bandwidth of no greater than 60 nm, and be calibrated against a specifically prepared formazin solution.

## General attributes of turbidity sensors

1. Most turbidity sensors employ very good means for temperature compensation and offer a sensor response which is nearly independent of temperature. The operating range for most sensors is between 0 and 40°C which covers most coastal environments.

2. Most sensors give a very linear response over the operating range of turbidities that they were designed to measure. Accuracy and precision of each turbidity sensor depends on the range of turbidities for which they were designed to measure. Resolutions of most turbidity sensors claim to be on the order of 0.01 to 0.1 NTU, while the accuracies were typically on the order of 1 to 10 NTU. There were some questions raised, however, of whether a resolution of 0.01 NTU could be verified against known turbidity standards.

3. The depths of operation for which turbidity sensors have already been designed range anywhere from hand-held models for direct measurement in surface waters to self-contained, logging units which can operate at depths of up to 6000 m.

4. Only a few sensors offer some form of anti-fouling measures.

5. Most sensors are built to be compliant with the ISO 7027 standard of turbidity measurement.

6. The two most important variables affecting variation in the measurement of turbidity by light scatter over the full range of natural waters are particle concentration and particle size distribution. The spectral reflectivity of suspended particulate matter, dissolved matter, and water, as well as the index of refraction of the suspended particles, are less important to scattering-based turbidity sensors. This is certainly the case with very turbid land-based water sources such as rivers and streams. However, this may not be the case when considering waters within the coastal zone. Because the turbidity of coastal waters is generally 'low' (<10 NTU), the ratio of light attenuation due to scattering resulting from absorption may be much less than in rivers and streams carrying heavy sediment loads. This will require further review of the literature and/or additional field studies.

7. In addition to particle size affecting turbidity measurement through differential effects on absorption and scattering, there is a fundamental difference between particles larger and smaller than the wavelengths of visible and NIR light used to measure turbidity. The optical properties of particles < ~400 nm will appear to turbidity sensors as distributed over a continuum while particles > ~ 400 nm will appear as discrete events leading to substantial temporal variation in the sensor signal. Such variation may require additional filtering and/or averaging before a stable measurement can be made. However, the effects of such filtering processes on the fundamental turbidity measurements have not been fully evaluated.

## Calibration standards

Because of the problems stated earlier, the choice of a turbidity 'standard' is not an easy decision to make. The traditional turbidity standard was a suspended formazin polymer, however, the compounds needed to synthesize this polymer are carcinogenic. Alternative non-toxic synthetic polymer particle suspensions are being made available by one manufacturer which, unlike formazin, will not settle out of suspension for years without inversion, and eliminates the need for hazardous waste handling and disposal. Gel and even dry reference materials may be useful for quick evaluation of sensor performance. However, their use as a turbidity standard has not been proven. Some protocols for the calibration of turbidity sensors rely on calibrating the actual turbidity sensor in the field with secondary 'standards' made from sequential dilutions of the water to be measured. These secondary standards are then brought back to the lab and measured with a bench-top instrument that has been calibrated with a primary standard made from synthetic polymers. During transport, the water motions controlling settling and re-suspension of turbidity-causing particles in situ are no longer present, thus rendering the use of secondary standards made in the field suspect.

## MANAGERS USE AND NEEDS OF TURBIDITY MEASUREMENTS.
### (BASED ON BREAKOUT SESSION #2 WITH MANAGERS AND SCIENTIST)

Managers Use and Needs of Turbidity Measurements. (Based on Breakout Session #2 with Managers and Scientists)

Managers and scientists discussed their needs and uses of turbidity measurements so that a consensus on these issues could be considered in the wider discussion with industry. Turbidity is widely used to monitor the environment in several ways. Turbidity is used to determine the depth of light penetration for both benthic and pelagic environments. Clear water provides a better light environment for benthic plants. Clear water often indicates less eutrophic conditions for plankton. Even though light quality is also considered important, it is difficult to make these measurements with relatively inexpensive equipment. Turbidity is also used as a proxy for total suspended solids and phytoplankton. In many applications, managers use turbidity measurements and fluorometery in tandem to get total suspended solids from turbidity and phytoplankton biomass from fluorescence.

Major questions for managers is whether light quality is varying from the resuspension of bottom material, variable total suspended solids, or whether light quality is from changing biomass of phytoplankton. Hence, the management issues are related to managing land-based sediment loading and transport or nutrient inputs and stratification. Apparently, sorting this out is difficult with high temporal and spatial variability in the natural environment. Calibrating the instruments consistently is also problematic. There was much discussion regarding the calibration in the field versus laboratory, long-term stability and variability of these numbers, implying that local managers require extensive calibration data sets to "make sense of their numbers". It is difficult to have long time series of environmental data when the instruments keep changing; there are upwards of 25 different models, representing several "standard" and "non-standard" designs and methods.

Turbidity in units of NTU is also used for regulatory purposes. Mangers discussed the problem that field calibrations of transmissometers were not consistent with lab calibrations, making it difficult to verify their measurements. There was some consideration that the ISO 7027 standard be tightened. Again, the high spatial and temporal variability makes regulatory procedure difficult. It is impossible in these situations to interpret extreme values, especially for regulatory procedures. In view of the spatial and temporal variability and the issues with documenting and maintaining QA and QC procedures, it is nearly impossible to interpret abnormal data. Thus these instruments create a level of frustration for the manager trying to interpret long term trends with fairly frequent outlying data.

The managers felt that there needs to be better standards or at least better protocols for calibrating. The major issues are differences within the same instrument and differences between instruments. Typically a primary standard is used on the bench (e.g., formazine) and a secondary standard in the field, thus resulting in problems with QC, QA and regulation. Consequently, many managers have become increasingly reliant on site-specific or local calibrations.

Biofouling is a common problem with turbidity sensors as it is with nearly all coastal instruments. Most turbidity sensors will last only 1-2 weeks. Particle settlement is also a problem depending the configuration of lenses and optics. The sensor may read 0.1 NTU but the accuracy is still only NTU of ~1.

Turbidity is now being used as a "trigger" during sporadic events to initiate other types of sampling, including manual water sampling and other sensor arrays. This may be a more common use of turbidity measurements in the future.

## General Assessment and Summary
(Based on 2 Day Discussion)

Existing definitions of turbidity and standards of turbidity measurement by optical methods are still deficient because these measurements are simultaneously affected by multiple optical phenomena. How each instrument responds to a given sample of water depends upon the exact geometric configuration of the sensor's optics, and its particular, sensitivity on the scattering and absorption characteristics of the water. How each sensor processes the signal it generates (e.g., amplification, filtering, optical feedback, T-compensation) is also a source of inter-sensor variability. Because of these differences, different sensors can give very different readings of 'turbidity' in the same exact water sample. The best estimate of between-sensor error presented at the workshop was a factor of 2-4. Some attempts have been made to redress these inherent discrepancies in instrument function by creating different units of turbidity measurement (e.g., NTU, FTU, FNU, NTRU, etc.). In addition, certain standards of turbidity measurement have relied on specific constraints on sensor configuration (e.g., US EPA 180.1). However, these requirements are still regarded by most manufacturers and end users as not stringent enough. Furthermore, because of inter-sensor differences, a universal turbidity standard for all natural water bodies may be impossible. Turbidity sensors can be tuned or calibrated to have a linear and accurate response to concentrations of an industry-accepted synthetic polymer standard, however, this does not mean that the response of a turbidity sensor to a natural water sample will be either linear or standardized. In this sense, turbidity sensors are simply generating non-dimensional measurements of water opacity specific to their particular design configuration. Synthetic standards may still have some utility in monitoring sensor performance by checking the stability and reliability of each sensor's optics and signal processing.

Most manufacturers and many end users understand the limitations in using turbidity sensors but still find them of great utility in a number of different ways. They can be used simply as inexpensive monitors for signaling drastic changes in water quality resulting from large run-off or particle suspension events, or even blooms from toxic algae. If users are interested in large changes in turbidity, then the numerous uncertainties in attaching the output of a given sensor to a standardized, quantitative measurement of turbidity may not even be important. Because of their relative ease in making a measurement, they can facilitate greater temporal and spatial resolution of gradients in water quality. This use of turbidity sensors is particularly effective when sensor measurements are made in conjunction with more rigorous methods for measuring the composition of a few end-member water types and the sensor output is correlated with different combinations of these end-member types. Most researchers and managers who are serious about rigorously measuring water quality use turbidity sensors in this way and find them a more cost-effective alternative to more sophisticated instruments designed to specifically measure the abundance and size distribution of suspended particles or the apparent and inherent optical properties of natural waters. What would best serve these researchers and managers would be to perform an unbiased evaluation of a number of different sensor designs across a large geographic and compositional range of natural water types. The multi-variate database which would result from such an expansive evaluation would provide a very useful tool for researchers and managers to relate the output of a given model and sensor design to the water quality parameter of interest. It would also allow potential end users to choose the model and design of turbidity sensor which is best fit for their particular environment and water quality parameter of interest. Furthermore, such a database could be amended with additional data from end users to increase the sophistication and statistical rigor of the quantitative relationships derived between sensor output and water qualities of varying composition. The following recommendations were made for the upcoming ACT Technology Evaluation of Turbidity sensors. The recommendations are listed in the order of importance as determined by the entire group:

1. ACT evaluation should get a complete data set of the following water quality parameters at each national test site: total suspended solids (wet and dry), particle size distribution, temperature and salinity, chlorophyll concentrations; particulate organic matter, downwelling surface PAR irradiance, multi-spectral volume scattering function, and multi-spectral absorption.

2. ACT should provide informative documentation to explain the principles of hydrological optics so end users can better understand what turbidity sensors actually measure as compared to what users think they measure.

3. Sensors should be calibrated on the bench-top only (not in the field) using only manufacturer-supplied calibration standards and following detailed protocols also provided by the manufacturer.

The above recommendations were made for the ACT Performance Verification of turbidity sensors. The group also made some general recommendations for the parties using turbidity sensors in coastal environments. The five most important recommendations are listed in the Executive Summary. Here we list all of those discussed, in order of importance.

## GENERAL RECOMMENDATIONS

1. To minimize inter-sensor variability, the coastal community including IOOS, should tighten instrument design configurations, choosing a set of specifications that are best suited for coastal waters. ISO7027 is not tight enough. Advice on these design criteria should be solicited through ASTM, Federal, and State regulatory agencies representing the majority of turbidity sensor end users. Parties interested in making turbidity measurements in coastal waters should develop design specifications for these water types rather than relying on design standards made for the analysis of drinking water.

2. Coastal observing groups should assemble a community database relating output of specific sensors to different environmental parameters, so that the entire community of users can benefit from shared information. This would include an unbiased, parallel study of different turbidity sensors, employing a variety of designs and configuration in the broadest range of coastal environments. This effort should be spear-headed with an unbiased evaluation of a number of different sensor designs across a large geographic and compositional range of natural water types by an organization such as ACT.

3. Turbidity should be used as measure of relative change in water quality rather than absolute measure of water quality. Thus this is a recommendation to managers to develop their own local calibration approach.

4. If the end user specifically wants to use a turbidity sensor to measure a specific water quality parameter such as suspended particle concentration, then direct measurement of that water quality parameter can be correlated with 'turbidity' for a particular environment. However, these correlations will be specific to the environment in which they are measured. This works because there are many environments in which water composition is relatively stable, but varies in magnitude or concentration.

5. Turbidity is *not* the best measurement of downwelling irradiance of visible light. Of all turbidity sensors, transmissometers are best suited for measuring light quality. However, the single wavelengths used by most transmissometers will not provide a measure of the attenuation of all visible light. Sensors that measure turbidity based on light scatter are particularly not well-suited for assessing light quality.

6. Create new turbidity standards that are appropriate for coastal waters, and other waters which are generally much lower in their turbidities than rivers and streams. For example, synthetic beads are already being used as standards for measuring optical properties of coastal waters. They could be used for turbidity standards as well.

7. The practice of using secondary standards to calibrate field sensors in the field and relating those calibration curves to primary standards measured on bench-top turbidity sensors using accepted synthetic solutions should *not* be followed. Turbidity sensors used

in the field should be calibrated only in the lab using primary, industry-standard solutions before and after use in the field.

8. Transmissometers should be used in place of turbidity sensors when the end user is unsure of which property of water is causing it to be turbid. This is because measurements made with a transmissometer are easier to interpret and less ambiguous than measurements made with scattering-based sensors.

9. Definitions of turbidity should be based on what is actually measured rather than environmental parameters which affect turbidity.

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