Proceedings of the Federal Interagency Workshop on Turbidity and other Sediment Surrogates, April 30-May 2, 2002, Reno, Nevada

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Acronyms

List of Acronyms Used in This Report:

Acronym	Name
ABS	Acoustic Backscatter
ASTM	ASTM International (formerly known as the American Society for Testing and Material)
CRADA	Cooperative Research and Development Agreement
EDI	Equal-Discharge Increment
EWI	Equal-Width Increment
GCLAS	Graphical Constituent Loading Analysis System
ISO	International Organization for Standardization
OBS	Optical Backscatter
QA/QC	Quality-Assurance/Quality-Control
SMIARP	Sediment Monitoring Instrument and Analysis Research Program
SSC	Suspended-Sediment Concentration
TMDL	Total Maximum Daily Load
TSS	Total Suspended Solids
U.S.	United States
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Abbreviations for Units of Measure

List of Abbreviations Used in This Report:

Abbreviation	Name
FAU	Formazin Attenuation Unit
FBU	Formazin Backscatter Unit
FNMU	Formazin Nephelometric Multibeam Unit
FNRU	Formazin Nephelometric Ratio Unit
FNU	Formazin Nephelometric Unit
mg/L	milligrams per liter
mm	millimeter
NAU	Nephelometric Attenuation Unit
NBU	Nephelometric Backscatter Unit
NTMU	Nephelometric Turbidity Multibeam Unit
NTRU	Nephelometric Turbidity Ratio Unit
NTU	Nephelometric Turbidity Unit
ºC	degrees Celsius
µm	micrometer

Extended Abstracts (in alphabetical order)

These extended abstracts can be accessed directly at URL: http://water.usgs.gov/osw/techniques/TSS/listofabstracts.htm

PROCEEDINGS OF THE FEDERAL INTERAGENCY WORKSHOP ON TURBIDITY AND OTHER SEDIMENT SURROGATES

April 30-May 2, 2002, Reno, Nevada

John R. Gray and G. Douglas Glysson, Editors
U.S. Geological Survey, Reston, Virginia

EXECUTIVE SUMMARY

The Federal Interagency Subcommittee on Sedimentation sponsored a Workshop on "Turbidity and Other Sediment Surrogates" in Reno, Nevada, on April 30 - May 2, 2002. The Workshop brought together a diverse group from local, State, and Federal agencies, academia, and the private sector with common interests in turbidity and other sediment-surrogate measurements used for estimation of water clarity and (or) selected characteristics of suspended sediment.

This executive summary provides a description of the salient attributes of the workshop and subsequent deliberations; major deliberations and findings; and principal recommendations. The Subcommittee on Sedimentation plans to evaluate the Workshop's findings and recommendations, and develop an action plan to implement those recommendations that the Subcommittee endorses. Hence, this Workshop represents the beginning of a process to provide national standards for measurement and use of turbidity and other sediment-surrogate data.

BACKGROUND

Siltation, also referred to as sedimentation, remains one of the most widespread pollutants affecting assessed rivers and streams. In addition to traditional uses of sediment data, such as for design and management of reservoirs and hydraulic structures, information is needed for contaminated sediment management, dam decommissioning and removal, environmental quality, stream restoration, geomorphic classification and assessments, physical-biotic interactions, the global carbon budget, and regulatory requirements of the Clean Water Act, including the U.S. Environmental Protection Agency's Total Maximum Daily Load (TMDL) Program. Hence, the need for reliable, cost-effective, spatially and temporally consistent data to quantify the clarity and sediment content of our Nation's waters has never been greater.

In spite of the need for more sediment data, there is strong evidence that the amount of nationally consistent daily-sediment data collected in recent years is but about a third of that produced for the Nation in 1980. This is due in part to cost, accuracy, and safety issues.

Although methodologies that normally require collection and analysis of a physical water sample are well established, these traditional methods are increasingly being forsaken in favor of less expensive, potentially safer continuously recording in-situ methods for monitoring water clarity and (or) for obtaining surrogate data for quantification, including analysis of uncertainty, of selected sedimentary characteristics of surface waters. Turbidity measurements are the most common means for obtaining water-clarity data, and for inferring suspended-sediment concentrations. Other sediment-surrogate measurement techniques that include those based on laser-optic, digital-optic, acoustic, and pressure-differential technologies are increasingly being used.

The proliferation of instruments for measuring turbidity and the sedimentary properties of water has occurred despite a lack of nationally accepted standards for collection or use of data derived from these techniques. For example, there currently are many designs of "turbidity" meters that use different approaches and light sources to determine "turbidity" in situ or in a sample. Some methods are based on the International Organization for Standardization (ISO) Standard 7027; some are based on the U.S. Environmental Protection Agency Method 180.1; and some are based on neither, yet all derivative data are reported as "turbidity." This was but one of a number of indicators pointing to a need for better understanding and standardization of data produced by turbidity meters and other sediment-surrogate technologies that led to holding the Workshop on "Turbidity and Other Sediment Surrogates."

WORKSHOP GOALS

The principal goals of the Workshop were to:

1. Propose a technically supportable, unambiguous definition of turbidity,
2. Describe the proper use and limitations of instruments to measure the turbidity of a stream and to infer suspended-sediment concentrations from turbidity, and
3. Identify capabilities and limitations of other instruments and (or) techniques that might be used to measure in-situ concentrations and other characteristics of suspended sediment.

WORKSHOP FORMAT

The Workshop consisted of five components: A morning introductory plenary session; two afternoon concurrent sessions; four concurrent breakout sessions; blind sediment sample measurement tests; and the results from a national questionnaire on the collection and use of turbidity data.

The goals of the plenary and two concurrent sessions were to describe the history and status of turbidity and suspended-sediment surrogate sampling; and to serve as a prelude for the four concurrent breakout sessions.

The four concurrent breakout sessions were charged with the responsibility to provide recommendations to the Subcommittee on Sedimentation by the close of the Workshop. Each breakout session had a unique focus as inferred from their titles:

- **Breakout Session 1**: Definition of Optical Methods for Turbidity and Data Reporting.
- **Breakout Session 2**: Use of Optical Properties to Monitor Turbidity and Suspended-Sediment Concentration.
- **Breakout Session 3**: Computing Suspended-Sediment Records Using Surrogate Measurements.
- **Breakout Session 4**: Other Fluvial-Sediment Surrogates.

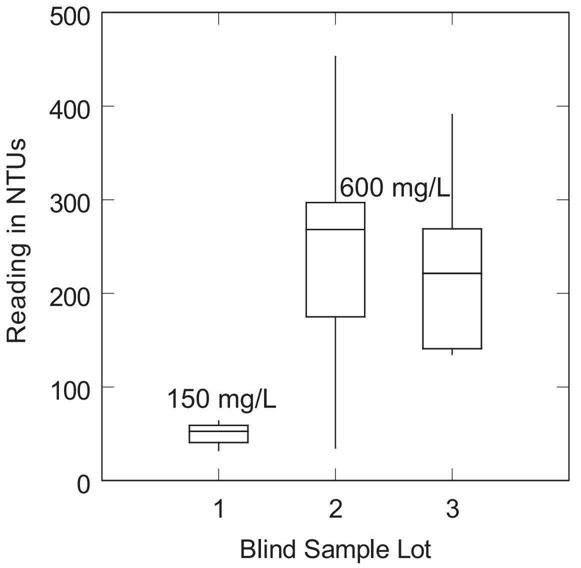
The Workshop also included a blind reference sediment sample measurement session to illustrate the variance in measurements of turbidity for laboratory-prepared blind reference samples. The session involved calibration of instruments and measurement of three lots of blind reference samples representing three sediment-size distributions and two concentrations. Concentrations and material size distributions were not identified on the numbered sample bottles to ensure unbiased measurement. The results of the blind reference sample session were intended to be illustrative rather than quantitative, considering that the Workshop environment was more controlled than that typically experienced in the field, and more controlled than that experienced if each person were in a different field condition.

A questionnaire on the uses of turbidity was distributed to water-quality coordinators for all State and some Tribal agencies prior to the Workshop. The objective of the questionnaire was to address key issues related to turbidity, including water-quality standards, technology, ranges observed, types of water bodies in which turbidity is being measured, seasonal variability, calibration and sampling protocol, and use of other measures of fluvial and suspended sediment. Some results of the questionnaire arrived after the Workshop, and are included in this report.

MAJOR WORKSHOP DELIBERATIONS AND FINDINGS (order does not imply ranking of finding)

A. <u>Nature of Turbidity</u>: Turbidity is a crucial parameter in water-quality regulation, but it is not a well-defined quantity. Different sensors and standards may produce substantially different results from the same sample. This ambiguity complicates the development of turbidity monitoring programs, regulations based on measured turbidity, and the application of estimates of water clarity and sediment concentrations based on those data.

B. <u>Variance in Turbidity Measurements</u>: A review of standard calibration protocols from different manufacturers noted differences of less than 5 percent among the standards. However, the range and standard deviations associated with measurements under the conditions of the Workshop blind sampling session for samples containing sediment concentrations of about 150 and 600 milligrams per liter were comparatively large (see figure). These results indicate that the variability with calibration standards is small compared to other sources of variance—including those associated with the operator, the measurement technology, sub-sampling, and uncontrolled environmental factors—in the turbidity measurement process. The results also provide one means for determining minimum variances associated with field-derived turbidity values.



C. Turbidity Metrics: All but 5 of the 40 agencies that responded to the questionnaire indicated that narrative or numeric standards (metrics) for turbidity have been established in their jurisdictions. In addition to water-quality standards, several agencies are using either turbidity or total suspended solids (TSS) data to identify sediment-impaired streams or stream reaches to develop TMDL's for sediment.

D. Turbidity as a Surrogate Measurement: Agencies responding to the questionnaire identified water clarity as the parameter of primary interest when measuring turbidity. Several agencies have correlated either turbidity or TSS with habitat or aquatic life. Reported ranges in turbidity vary widely among reporting agencies, ranging from below detection limits to over 10,000 nephelometric turbidity units (NTU). The majority of agencies are using instruments operating on the bulk optical properties of the water-sediment mixture, including turbidimeters, optical backscatter meters (OBS), and optical transmissometers to infer turbidity, and analyses of grab samples to provide the comparative suspended-sediment concentration or TSS data.

E. Turbidity Calibration Standard and Method: The majority of States and Tribes who responded to the questionnaire and that measure turbidity use formazin as a calibration standard and U.S. Environmental Protection Agency Method 180.1 for analysis.

F. Turbidity Data Storage: The majority of States and Tribes responding to the questionnaire use Oracle, STORET, or a local database or spreadsheet for data storage and analysis. Data currently are stored under a parameter code designated as "turbidity" and no distinction is made between data collected using different equipment technologies or collection procedures. As illustrated by the blind sample test, considerable variance among measurements of the same sample can exist. Because of this, the existing data will probably not be comparable with data in other data sets and possibly not compatible within a give data set.

G. Proliferation of Other Sediment-Surrogate Technologies: A number of surrogate technologies other than turbidity are being used to infer suspended-sediment concentrations and other characteristics of fluvial sediment. Derivations of these data suffer from many of the drawbacks affecting turbidity, including the lack of reliable standards for in-situ calibration.

PRINCIPAL WORKSHOP RECOMMENDATIONS (order does not imply ranking of the recommendations)

1. Turbidity Definition: Adopt the current definition of turbidity for natural water and wastewater, contained in ASTM Standard Test Method for Turbidity in Water, D 1889-00, to wit: *Turbidity—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. (Turbidity of water 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.).*
2. New Turbidity Standard Method: Adopt a new standard method for measurement of the optical properties of natural water and wastewater. The method should include a hierarchical decision tree

for selection of an instrument for a specific application. The standard method should specify that the different instrument types and models will yield different turbidity results and generally should not be expected to be equivalent. Existing water-quality monitoring guidelines, with consideration for instrument manufacturer protocols, should be updated to reflect the new standard method.

3. Storage of Turbidity Data: Until a uniform industry standard is developed for the measurement and storage of the optical properties of water, consider storing the derivative data on the basis of instrument manufacturer, an instrument identifier, and sensor mode, or otherwise use another method that captures most or all of the specific information that may enable eventual adjustment of these data. Data descriptors for internal and external use with a detailed description of the turbidity methodology should be included in the database. A set of proposed turbidity reporting units to differentiate between various instruments and methodologies should be developed (data reporting should consider and include incident light wavelength, orientation and number of detectors, instrument manufacturer, model number, calibration measurement documentation, reporting of variability, and other relevant factors.)
4. Retrospective Turbidity Comparisons: Quantify instrument differences to enable valid comparisons that may be required for retrospective data mining for comparison of data collected by new and historical techniques. Document the percentage difference in data derived by historical and newer methods, and include references for published reports that compare turbidity data collected with different instruments and (or) methods.
5. Technology Transfer and Communication: Increase technology transfer between groups and individuals with interests in turbidity and other sediment-surrogate technologies. A steering committee should be formed that includes a coordinator and topical expert advisers on turbidity and on other sediment-surrogate technologies. Resources associated with the steering committee may include publication of a newsletter, creating and maintaining a web-based compilation of information, supporting user groups and on-line help, documenting methods, transferring industrial technology to the environmental field, and otherwise providing guidance to the Subcommittee on Sedimentation.
6. Stakeholder and Peer Review: Keep the public and users of turbidity and other sediment-surrogate data informed of the issues involved in producing these data, including assumptions, limitations, methods, and applicability.
7. Testing and Development Program for Instruments and Methods: Develop a program to foster research, testing, and evaluation of instruments and methods for measuring, monitoring, and analyzing water clarity and selected characteristics of fluvial sediment by cost-effective, safe, and quantifiably accurate means. Technically supportable and widely available standard guidelines for sensor deployment, calibration, and data processing, including real-time data are needed. Acceptance criteria for data from a given parameter, such as suspended-sediment concentration, should be developed, endorsed by the Subcommittee on Sedimentation, and widely advertised to encourage methods and instrumentation development.
8. Collection and Computation of Sediment-Surrogate Records: Develop standardized procedures for the collection of sediment-surrogate data. This should include protocols for instrument calibration and criteria for acceptance of the derivative sediment data. A standard procedure for computation of sediment-discharge records should be developed for all sediment-surrogate records utilizing the fullest set of data.
9. Technical Needs for Turbidity Measurements: The agencies responding to the questionnaire identified several technical needs related to turbidity including:
    a. Improve the understanding of the relation between turbidity, total suspended solids, suspended-sediment concentration, channel stability, and biological impairment.
    b. Establish reference conditions for fluvial sediment, and a means of measuring significant departure from reference conditions.
    c. Develop a consistent data-collection protocol and less expensive probes that can be rapidly deployed and are stable in the field.
    d. Obtain more long-term stream discharge, suspended-sediment, bedload, and bed-material data.

INTRODUCTION TO THE PROCEEDINGS OF THE FEDERAL INTERAGENCY WORKSHOP ON TURBIDITY AND OTHER SEDIMENT SURROGATES

by John R. Gray, G. Douglas Glysson, James H. Eychaner, and Chauncey W. Anderson

According to the U.S. Environmental Protection Agency (USEPA) (2002), siltation, also referred to as sedimentation, remains one of the most widespread pollutants affecting assessed rivers and streams, interfering with aquatic habitat, drinking water treatment processes, and recreational uses of rivers, lakes, and estuaries. Accelerated sedimentation can affect fisheries by reducing water clarity, spawning areas and rearing ponds, food sources, and habitat complexity (bedforms). In addition to affecting aquatic life, accelerated sedimentation can result in channel aggradation, can increase stream channel width/depth ratios, and can cause bank erosion and failure. Sediment can adversely affect drinking water supplies by causing taste and odor problems by fouling treatment systems and by depositing in reservoirs, resulting in loss of storage capacity. In recreational waters, high levels of suspended sediment reduce aesthetics, impair swimming, fishing, and boating, and may result in safety problems and concerns. In contrast to accelerated sedimentation, sediment supply-limited systems have sediment deficits that manifest as bank and channel scour, entrenchment, and loss of habitat.

The need for reliable, cost-effective, spatially and temporally consistent data on sediment content and clarity of our Nation's waters has never been greater. Traditional uses of these data in the United States (U.S.) have focused on engineering considerations relevant to the design and management of reservoirs and in-stream hydraulic structures, and dredging. Over the last two decades, information needs have expanded to include those related to contaminated sediment management, dam decommissioning and removal, environmental quality, stream restoration, geomorphic classification and assessments, physical-biotic interactions, the global carbon budget, and regulatory requirements of the Clean Water Act, including the USEPA's Total Maximum Daily Load (TMDL) Program.

Ironically, the substantial increase in these data needs has coincided with a general decline in national-level sediment-data collection as inferred by a two-decade decrease in the number of sites at which the U.S. Geological Survey (USGS) collects daily records of suspended-sediment transport. The number of these sites increased rapidly after 1945, peaking at 360 in 1982 (Glysson, 1989; Osterkamp and Parker, 1991). By 1998, the number had fallen by 65 percent to 125 sites. In 2002 the USGS operated 147 daily sediment stations, 42 of which were in Puerto Rico. Puerto Rico operated one sediment station in 1982. Excluding the statistics for the Puerto Rico sediment stations operated in 1982 and 2002 from consideration yields a 71-percent decrease in the number of daily USGS sediment stations over the 2-decade period ending in 2002 (U.S. Geological Survey, 2002). Among the factors cited for the decline in the number of USGS daily sediment stations was the need for less expensive and more accurate fluvial-sediment data collected using safer, less manually intensive techniques (Gray and others, 2002). These statistics are likely indicative of a general decline in collection of nationally consistent, quality-assured fluvial sediment data, in that the USGS bears primary responsibility for acquisition and management of the Nation's water data including suspended-sediment, bedload, and bottom-material data (Glysson and Gray, 1997). Any decrease in sediment monitoring should be of particular concern to the Nation in that the physical, chemical, and biological sediment damages in North America were estimated to total about $16 billion in 1998 (Osterkamp and others, 1998).

The methodologies for manually collecting and analyzing fluvial sediment data in the U.S. (Edwards and Glysson, 1999) and internationally (Yuqian, 1989) are well established. However, these methods entail frequent site visits, particularly during higher flows, followed by laboratory processing and subsequent analysis of large data sets (Larsen and others, 2001). Currently, sediment discharges calculated from manually sampled data—and even from data obtained by devices that automatically collect samples of the water-sediment mixture—require substantial temporal concentration interpolation to provide the requisite data continuity, and normally lack uncertainty estimates.

More recent automatic and manual methods for inferring the fluvial sedimentary properties and clarity of the Nation's surface waters remain comparatively poorly established. Of the many methods being evaluated for quantifying water clarity or inferring selected sedimentary properties of surface waters (Gray and others, 2003), turbidity (Wilde and Gibs, 1998) is the most common measure for water clarity and as a surrogate[1] for inferring suspended-sediment concentrations (SSC) (Bent and others, 2000) in the U.S. Turbidity is caused by organic and inorganic fractions including silt and clay particles, fine particulate organic matter, organic compounds, dyes, and plankton. In general, any suspended or dissolved particle that is capable of causing light to be scattered or absorbed should be expressed in a turbidity measurement. Measurement of turbidity offers a relatively rapid and inexpensive method for determining the clarity of aquatic ecosystems. Turbidity can be used to evaluate the general condition and productivity of the system or can simply provide a means for identifying problem ("red flag") areas for watershed planning and for targeting intensive investigations. Turbidity measurements also may be useful in studies of sediment transport, ecological processes, and environmental regulation and control. In certain ecoregions, turbidity may be a reliable means of estimating SSC and (or) causes of physical impairment. Turbidity represents an integration of the various factors that cause light to be absorbed or scattered, and in that sense is considered a bulk optical property of water.

Other sediment surrogate techniques, including those based on laser-optic, digital-optic, acoustic, and pressure-differential technologies are increasingly being deployed. However, along with turbidity, there is an expressed need for a better understanding and standardization of data produced by these technologies. This was the impetus for the "Turbidity and Other Sediment Surrogates Workshop," held April 30-May 2, 2002, in Reno, Nevada. The Workshop (Glysson and Gray, 2002), sponsored by the Federal Interagency Subcommittee on Sedimentation ("Subcommittee on Sedimentation") as described by Glysson and Gray (1997), brought together a diverse group of about 130 representatives from government, academia, and the private sector with interests in measuring turbidity and using of other surrogates for estimation of SSC and other characteristics of suspended sediment. A list of those registered for the Workshop and their respective professional affiliation is included in appendix 1.

The primary goals of the Workshop were to determine a technically supportable, unambiguous definition of turbidity; determine proper use of turbidity meters to infer SSC from turbidity, and identify capabilities and limitations of other equipment or techniques that might be used for in-situ measurement of SSC.

The mandate of the Workshop was to provide to the Subcommittee on Sedimentation:

- A status of turbidity and other surrogates for quantifying selected physical properties of surface water, and
- Clear and tractable recommendations on how to use turbidity and other selected measurement techniques to provide reliable, quality-assured information on water clarity and selected sedimentary characteristics of the Nation's surface waters.

That information was informally provided to those members of the Subcommittee on Sedimentation present at an ad hoc meeting on May 2, 2002, immediately following the Workshop.

The general goals of the Workshop related to turbidity were to:

- Communicate and illustrate potential problems associated with measurements of optical properties [or turbidity] of water.
- Propose a technically supportable, unambiguous definition for turbidity.
- Establish agreed-upon measurements (lab and field) for defining the optical properties of water for engineering and (or) biological applications.
- Define the method of operation of a turbidimeter to collect data to estimate SSC in surface water, and the ancillary data needed to interpret those data.
- Identify the conditions for which turbidimeter data can be used to reliably estimates SSC data.
- Define methods to convert measured turbidity values to SSC values, and determine approximate variance in results.

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[1]As used in this report, a surrogate is an environmental measurement than can be reliably correlated with an in-stream characteristic, such as concentration or particle-size distribution of fluvial sediment, or those for selected water-quality constituents. Surrogate data are typically easier, less expensive, and (or) safer to collect than the target variable.

- Define variability between measurements from turbidimeters calibrated to the same standards and measuring a variety of natural waters.

The general goals of the Workshop related to other sediment-surrogate technologies were to define:

- The state-of-the-art of selected surrogate techniques for the collection of SSC and other characteristics of surface water.
- Approximate criteria and (or) conditions under which each technology is a reliable surrogate measurement techniques for SSC and other sedimentary characteristics of surface water.

The April 30th introductory plenary session was followed by two concurrent sessions on:

- Broad topical issues related to turbidity – led by James H. Eychaner, U.S. Geological Survey, Sacramento, CA.
- Other sediment surrogates – led by John R. Gray, U.S. Geological Survey, Reston, VA.

The goal of the concurrent sessions was to describe the history and status of their respective topics, and to serve as a prelude for four concurrent breakout sessions that convened on the mornings of May 1-2, 2002.

The titles of the breakout sessions were:

- **Breakout Session 1**: Definition of Optical Methods for Turbidity and Data Reporting.
- **Breakout Session 2**: Use of Optical Properties to Monitor Turbidity and Suspended-Sediment Concentration.
- **Breakout Session 3**: Computing Suspended-Sediment Records Using Surrogate Measurements.
- **Breakout Session 4**: Other Fluvial-Sediment Surrogates.

The breakout session leaders were charged with providing a summary of their full findings and recommendations to a final plenary session held on the afternoon of May 2, 2002. Summaries of the respective topics include:

- Clear statements of the background, key elements, and relevant considerations,
- Lists of key problems and limitations, and
- Sets of clear recommendation on how to proceed, if at all.

Additionally, results from tests measuring the turbidity of blind sediment samples which took place as part of the Workshop, and results from a questionnaire on use of turbidity by States and Tribes that was ultimately completed in January 2003 under the auspices of the Workshop, supplement results from the breakout sessions.

This report describes the status and recommendations related to turbidity and other sediment surrogates from the Federal Interagency Turbidity and Other Sediment Surrogates Workshop. Extended abstracts supporting most of the presentations at the Workshop are included in appendix 2 of this report and are available on-line at http://water.usgs.gov/osw/techniques/turbidity.html.

Each major activity associated with the Workshop that produced one or more products—the four breakout sessions, the blind sediment sample measurement tests, and the results from the questionnaire on use of turbidity by States and Tribes—was addressed and summarized in a manner unique to the subject matter, the nature in which information was shared, and in the style of the activity leaders. In an attempt to avoid losing the intent and thrusts of the each activity, these summaries are provided in the following sections without consideration to consistency in format. Some information included herein—most notably that related to the questionnaire—was derived after the Workshop.

The USGS-authored extended abstracts in appendix 2 were reviewed and approved for publication by the USGS. Other extended abstracts in appendix 2 did not go through the USGS review processes and therefore may not adhere to USGS editorial standards.

It is the intention of the Subcommittee on Sedimentation to evaluate the Workshop's findings and recommendations and to develop an action plan to implement those recommendations that the Subcommittee endorses. Hence, this Workshop represents the beginning of a process to provide national standardization for measurement and use of turbidity and other sediment-surrogate data.

Acknowledgements: The authors wish to thank the Subcommittee on Sedimentation for its support for the Turbidity and Other Sediment Surrogates Workshop. We also wish to thank the Hach Company and APS Analytical Standards, Inc., for providing the quality-control standards used in the Workshop; the USGS Branch of Quality Systems for providing the quality-control samples used in the blind sediment sample turbidity test measurements; Annette Ledford, Nana Frye, and Bernadette Ward of the USGS for their support in preparing for and putting on the Workshop; the Nevada District of the USGS for their support in organizing and conducting the Workshop field trip; Morris Flexner of the U.S. Environmental Protection Agency, Region 4, Science and Ecosystem Support Division, and Eric Somerville of Nutter & Associates, Athens, Georgia for their reviews and comments on the questionnaire results; and Iris Collies and Genevieve Comfort for their astute editorial support.

BREAKOUT SESSION 1: DEFINITION OF OPTICAL METHODS FOR TURBIDITY AND DATA REPORTING

by Andrew C. Ziegler

A majority of Workshop attendees participated in breakout session 1, including representatives from Federal and State agencies and private-sector manufacturers of equipment and standards. The session was tasked with providing information and recommendations on the use of turbidity as an environmental measurement of surface water. The session's specific goals were to:

1. Draft a definition of turbidity.
2. Describe the current limits of the technology as a surrogate for suspended sediment.
3. Draft data-reporting requirements.
4. Describe the comparability of different methods.
5. Summarize and develop recommendations to the Subcommittee on Sedimentation for development and use of turbidity and optical measurements as a surrogate for selected characteristics of suspended sediment and other sediment-associated constituents.

Extended abstracts (see Appendix 2) relating to the subject matter of breakout session 1 included:

"Issues related to use of turbidity measurements as a surrogate for suspended sediment," Presented by Andrew C. Ziegler, U.S. Geological Survey.

"Biological aspects of turbidity and other optical properties of water," Presented by G. Chris Holdren, U.S. Bureau of Reclamation.

"Turbidity instrumentation – An overview of today's available technology," Presented by Mike Sadar, Hach Company.

"Turbidity studies at the National Water Quality Laboratory," Presented by M. Patricia Pavelich, U.S. Geological Survey.

"The contribution of suspended organic sediments to turbidity and sediment flux," Presented by Mary Ann Madej, U.S. Geological Survey.

"Guidelines and standard procedures for monitoring turbidity," Presented by Richard J. Wagner, U.S. Geological Survey.

"Continuous in-situ measurement of turbidity in Kansas streams," Presented by Patrick P. Rasmussen, U.S. Geological Survey.

"Turbidty calibration standards evaluated from a different perspective," Presented by Kemon Papacosta, APS Analytical Standards, Inc.

"Determination of total and clay suspended-sediment loads from instream turbidity data in the North Santiam River Basin, Oregon, 1998-2000," Presented by Mark A. Uhrich, U.S. Geological Survey.

Results of Session 1 and recommendations to the Federal Interagency Subcommittee on Sedimentation are summarized herein. The recommendations include a definition of turbidity, technology limits as a surrogate for suspended sediment, a summary of data-reporting requirements and comparability of different methods for measuring the optical properties of water. A new method is proposed that describes the requirements to measure and report the optical properties of natural water and wastewater conducive to developing means for estimating SSC.

Definition of Turbidity

There was concurrence that a new method for measurement of optical properties in natural water and wastewater is needed. There was concurrence to adopt the current standard for the definition of turbidity contained in D 1889-00, Standard Test Method for Turbidity in Water (ASTM International, 2002).

Turbidity—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. (Turbidity of water 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.)

Additionally, there was concurrence that the scope of the proposed new method should include and describe a variety of issues, including:

1. Determination of turbidity in environmental water and wastewater.
2. Method applicability to the measurement of turbidity from 0.5 to 10,000 (or more) turbidity units. The ASTM International low-level turbidity method (D 6885-03; ASTM 2003) complements the methods proposed here; see table 1.
3. Determination of turbidity can be conducted in situ with portable, flow-through sample cells, or with laboratory meters.
4. Additional bulk optical methods may be useful to supplement measurements of light scatter.
5. It is anticipated that turbidity measurements may be useful in studies of suspended sediment, ecological processes, and environmental regulation and control.
6. Quality-assurance/quality-control (QA/QC) measures should be addressed in the method.

Current technologies, appropriate applications, and approximate limits are described in table 1. These limits do not exclude the possibility that turbidimeter manufacturers can develop instruments under each design that surpass these ranges. Instrument traceability is a primary need for future understanding and comparability.

Within the new standard, a guide to subsets of the method should be provided. The method should provide a hierarchical decision tree for selection of an instrument for a specific application (table 1). Examples should be included in a section on "Significance and Use."

- Decision Tree A: Knowing something about a sample set, what instrument should be chosen?
- Decision Tree B: With a specific instrument, what water should be measured?"

The new method should specify that the different instruments and models will yield different turbidity results and generally should not be expected to be equivalent. These differences can be viewed as limitations of the current technology.

Limits of the technology as a surrogate for suspended sediment

Different instruments and models will yield different turbidity results and generally should not be expected to be equivalent. Within the new method description, there is a need to:

a. Resolve comparability of units, if only to guide the selection of instrument by desired measurement range.
b. Provide guidance on how to use this collection of instruments to detect and control environmental change.
c. Recognize that turbidity measurements are not directly convertible to SSC or TSS data. Relations that can be developed are site-specific and vary with various characteristics of the suspended material.
d. Specify typical properties of water and sediment, and potential interferences to turbidity measurement and their probable affects (tables 2 and 3, respectively).
e. Specify that an inventory of instrument types, appropriate applications, and applicable turbidity unit ranges (table 1) be included in the method. Information in table 1 is not offered as definitive. Distinguish between factors that may negatively affect the quality of the instrumental results in observing turbidity from factors that the measurements are attempting to observe.

Table 1. Summary of instrument designs and capabilities, current reproducible technologies, appropriate applications, and approximate limits (modified after Sadar; see appendix 2)

[Indicated ranges are examples only and do not exclude the possibility that manufacturers can develop instruments under each design that surpass these ranges. NTU is nephelometric turbidity units; µm is micrometer.]

Design	Prominent Feature and Application	Typical Instrument Capability Range (NTU)	Suggested Application range (NTU)
Nephelometric non-ratio	White light turbidimeters – Comply with USEPA Method 180.1 (U.S. Environmental Protection Agency, 1999) for low-level monitoring.	**0.0 to 40**	**0.0 - 40 Regulatory**
Ratio White Light turbidimeters	Complies with USEPA Long Term Inhanced Surface Water Treatment Rule (U.S. Environmental Protection Agency, 1998), and American Public Health Association, American Water Works Association, and Water Pollution Control Federation (1995). Uses a nephelometric detector as the primary detector, but contains other detectors to minimize interference. Can be used for both low- and high-level measurement.	**0 - 4,000**	**0 - 40 Regulatory** **0 - 4,000 other**
Nephelometric, near-IR turbidimeters, non-ratiometric	Complies with International Organization for Standardization 7027 (1999) – The wavelength (860-890 µm) is less susceptible to color interferences. Good for samples with color and good for low-level monitoring.	**0 - 1,000**	**0 – 11 Regulatory (non-U.S.)** **0 - 1,000 other**
Nephelometric near-IR turbidimeters, ratiometric	Great Lakes Instruments, method 2 (U.S. Environmental Protection Agency, 1999), International Organization for Standardization 7027 (1999) and USEPA approved. Compliant and contains a ratio algorithm to monitor and compensate for interferences.	**0 - 1,000**	**0 - 40 Regulatory** **0 to 1,000 other**
Surface Scatter Turbidimeters	Not applicable for regulatory purposes. Turbidity is determined through light scatter from or near the surface of a sample. The detection angle is still nephelometric, but interferences are not as substantial as nephelometric non-ratio measurements. This is primarily used in high-level turbidity applications	**10 - 10,000**	**10 - 10,000**
Back-Scatter/Ratio Technology	Not applicable for regulatory purposes. Backscatter detection for high levels and nephelometric detection for low levels. Backscatter is common with probe technology and is best applied in high turbidity samples.	**100 - 10,000**	**100 - 10,000**
Light attenuation (spectrophotometric)	Not applicable for regulatory purposes. Wavelength 860 µm. Highly susceptible to interferences, best applied at medium turbidity levels	**20 - 1,000**	**20 - 1,000**

Table 2. Typical properties of water and sediment and their effects on turbidity measurements (modified after Sadar; see appendix 2)

Property	Effect on the measurement
Absorbing particles (colored particles)	Negative bias (reported measurement is lower than actual turbidity).
Color in the matrix	Negative if the incident light wavelengths overlap the absorptive spectra within the sample matrix.
Particle size	Either positive or negative (wavelength dependent). Large particles scatter long wavelengths of light more readily than small particles. Small particles scatter short wavelengths of light more efficiently than long wavelengths.
Particle density	Negative bias (reported measurement is lower than actual turbidity).

Table 3. Common interferences and their effects on turbidity measurements (modified after Sadar, see appendix 2)

Interference	Effect on the measurement
Stray light	Positive bias (reported measurement is higher than actual turbidity).
External particle contamination	Positive bias (reported measurement is higher than actual turbidity). Principally at low levels, less than 1 unit.
Sensor fouling	Particularly with in-situ instruments. Negative bias for beam blockage. Possible positive or negative bias for scratches on optical surfaces.
Bubbles or spikes from entrained gases	Positive bias.

Instrument standards

The new method should require that calibration standards be traceable to formazin prepared from scratch. The method should specify that ASTM/USEPA-approved formazin or polymer standards be used as primary calibration standards. ASTM/USEPA-approved polymer standards are instrument specific and can have large differences in response, depending on the instrument. Instrument manufacturer protocols and required calibration standards should be used.

Data-reporting requirements and the comparability of different methods

The new method should specify that reporting units for methods and instruments be differentiated (table 4). Data reporting should consider and include incident light wavelength, orientation and number of detectors, instrument manufacturer, model number, calibration measurement documentation, reporting of variability, and other relevant factors (see table 4).

Because of instrument differences, it must be recognized that retrospective data mining for comparison with new measurements may require site-specific correlation studies and depends on knowledge of the detector used previously. Documentation of the percentage difference between older and newer methods is needed. For example, do NTU and FAU measurements differ by less than 40 percent across a number of different water matrices? References for published reports that compare turbidity data collected with different instruments and (or) methods should be included.

Users will be aided by knowledge of qualitative comparisons between measurements in different units. Although differences may be commonly detectable, the magnitude of differences may have no management significance. It is likely that the differences between methods will have significant site-to-site variability. Recording ancillary information about the visual appearance of samples is recommended; that is, does the water have visible color or is it extremely dark? Consider guidance for laboratories on dilution as a qualitative check for validity of initial readings. It is likely that the color of particles can affect the readings even with meters that use differential modes.

Table 4. Proposed turbidity reporting units for waters and wastewaters (modified after Sadar (see appendix 2), and from information presented at the Workshop by James H. Eychaner)

Detector geometry	Light source	
	White	Monochrome
Single illumination beam		
At 90^o to incident beam	Nephelometric Turbidity Unit (NTU)	Formazin Nephelometric Unit (FNU)
At 90^o and other angles. An instrument algorithm uses a combination of detector readings, which may differ for values of varying magnitude.	Nephelometric Turbidity Ratio Unit (NTRU)	Formazin Nephelometric Ratio Unit (FNRU)
At 0^o to incident beam (backscatter)	Nephelometric Backscatter Unit (NBU)	Formazin Backscatter Unit (FBU)
At 180^o to incident beam (attenuation)	Nephelometric Attenuation Unit (NAU)	Formazin Attenuation Unit (FAU)
Multiple illumination beams		
At 90^o and possibly other angles to each beam. An instrument algorithm uses a combination of detector readings, which may differ for values of varying magnitude.	Nephelometric Turbidity Multibeam Unit (NTMU)	Formazin Nephelometric Multibeam Unit (FNMU)

Each reporting unit is defined by reference to the same standard suspensions of formazin, so measurements of environmental waters would be expected to have similar numerical values for any of these units. The characteristics of water that cause turbidity, however, differ fundamentally from formazin crystals and between environmental settings. Experience shows that instruments of different types, even when calibrated with identical standards, can produce readings that differ by factors of 2 or more for the same environmental sample.

Data obtained from these different methods should be differentiated. Because of the fundamental ambiguity, and until a uniform industry standard for the measurement and storage of the optical properties of water is developed in the U.S., turbidity data reported in any of these units must be supplemented by identifying the manufacturer and model number of the instrument or by providing equivalent information about the frequency, bandwidth, and path length of the illumination beam. Lastly, it should be recognized that new methods and techniques will need to be developed for the use of turbidity and other measurements as surrogates for suspended-sediment and associated chemical constituents.

BREAKOUT SESSION 2: USE OF OPTICAL PROPERTIES TO MONITOR TURBIDITY AND SUSPENDED-SEDIMENT CONCENTRATION

by David H. Schoellhamer

Breakout session 2 was responsible for developing recommendations on the design and implementation of a turbidity/sediment monitoring station and network using optical sensors. The session focused on four key elements to a successful monitoring program:

1. Sampling design that satisfies the study objectives,
2. Sensor installation that considers positioning, fouling, and maintenance,
3. Good calibration of sensors, and
4. Accurate, timely, and efficient processing of time-series data.

Many hydrologic monitoring programs measure optical properties of water to determine SSC, turbidity, suspended load, and concentrations and loads of constituents associated with sediment. This is typically done with in-situ sensors that automatically measure either light transmission or scattering on a nearly continuous basis. The output from the sensors is calibrated to the desired parameter. In a number of cases, this approach has worked very well. There are, however, problems and limitations to this approach.

Extended abstracts (see Appendix 2) relating to the subject matter of breakout session 2 included:

"Real-time water-quality monitoring in Kansas," Presented by Patrick P. Rasmussen, U.S. Geological Survey.

"Continuous turbidity monitoring in streams of northwestern California," Presented by Rand Eads, U.S. Forest Service.

"Lessons learned from turbidity field monitoring of 12 metropolitan Atlanta streams," Presented by Paul D. Ankorn, U.S. Geological Survey.

"Methods for continuous automated turbidity monitoring in British Columbia, Canada," Presented by Judith R. Burke, British Columbia Ministry of Sustainable Resource Management.

"OBS calibration and field measurements," Presented by Thad Pratt, U.S. Army Corps of Engineers.

"Ten years of continuous suspended-sediment concentration monitoring in San Francisco Bay and Delta," Presented by David H. Schoellhamer, U.S. Geological Survey.

A goal of the session was to develop a set of recommendations on how to design and implement a turbidity/sediment monitoring station and network using optical sensors. The session identified common problems and produced several general recommendations given below.

During the breakout session presentations, it became apparent that the case-study projects were separately solving similar problems. Collectively, there was a great deal of experience and knowledge in the group, but the knowledge and skills learned during a project are often not available to other investigators. Therefore,

> **General Recommendation 1**: *Better technology transfer is needed between groups. Recommended solutions include creating a steering committee similar to that for Acoustic Doppler Current Profilers, appointing a 'turbidity-surrogate' coordinator, publishing a newsletter, creating and maintaining a web-based compilation of information, supporting user groups and on-line help, and transferring industrial technology to the environmental field. Documentation of methods is also needed.*

Environmental conditions, problems addressed by studies, and study objectives differ among projects, and these dictate sampling design, including instrumentation and data-quality objectives.

> **General Recommendation 2**: *In order to ensure that previous experience is utilized to help satisfy study objectives, sampling design plans should be reviewed by stakeholders and peers, and upon request, could be reviewed by the aforementioned steering committee.*

These data are difficult to collect and quality assurance is required. For example, it is difficult to be assured that a point measurement collected by an in-situ sensor is representative of the desired quantity, such as a discharge-weighted cross-sectionally averaged value. There is also a conflict between producing quality data and providing real-time data to stakeholders and the public, which is often a study objective. Continuous monitoring of optical properties of surface waters is a developing technology and quality assurance guidelines will evolve as the technology matures.

> **General Recommendation 3:** *A testing and development program is needed to evaluate existing sensors (the U.S. Environmental Protection Agency has an evaluation program) and future sensors and to develop reliable and accurate methods for sensor deployment, calibration, and data processing, including real-time data.*

Turbidity is a crucial parameter to water-quality regulation, but it is not a well-defined quantity. Different sensors and standards will produce different results. This ambiguity complicates the development of a turbidity monitoring program and the application of resulting data.

> **General Recommendation 4:** *Guidelines for calibrating a turbidity sensor to formazin and other materials are needed. The existing USGS water-quality monitoring guidelines (Wagner and others, 2000) should be updated to reflect recent advances in turbidity- and surrogate-data collection. Both primary and secondary turbidity standards should be available through a central lab clearinghouse that tests the standards to ensure quality. Database data descriptors for internal and external use should provide a detailed description of the turbidity methodology (optical properties, range, and calibration method).*

> **General Recommendation 5**: *The public and users of these data need to be informed of the issues involved in producing the data, including assumptions, limitations, methods, and applicability.*

This can best be accomplished by effectively disseminating improved turbidity guidelines and the knowledge gained by individual studies, the steering committee, and the testing and development program.

BREAKOUT SESSION 3: COMPUTING SUSPENDED-SEDIMENT RECORDS USING SURROGATE MEASUREMENTS

by Gardner C. Bent and Lawrence A. Freeman

Introduction

The goals of breakout session 3 were to:

1. Establish guidelines for evaluating current and future suspended-sediment surrogate technologies with respect to accuracy and precision in computation of suspended-sediment records,
2. Propose acceptance criteria for surrogate data sets used in computing records using surrogate measurements,
3. Identify limitations with respect to computing records,
4. Estimate time frames for overcoming limitations, and
5. Provide recommendations for using surrogate technologies to assist in computing records.

Extended abstracts (see Appendix 2) relating to the subject matter of breakout session 3 included:

"Estimation of suspended sediment flux in streams using continuous turbidity and flow data coupled with laboratory concentrations," Presented by Jack Lewis, U.S. Forest Service.

"The use of rating (transport) curves to predict suspended sediment concentration: A matter of temporal resolution," Presented by Arthur J. Horowitz, U.S. Geological Survey.

"Comparison of estimated sediment loads using continuous turbidity measurements and regression analysis," Presented by Victoria G. Christensen, U.S. Geological Survey.

"Determination of total and clay suspended-sediment loads from instream turbidity data in the North Santiam River Basin, Oregon; 1998-2000," Presented by Mark A. Uhrich, U.S. Geological Survey.

A goal of many sediment-monitoring programs is to estimate suspended-sediment discharges on daily or other timescales. Most daily suspended-sediment discharge records computed by the USGS are based on an analysis of concentration data collected on a daily or more frequent basis and a time series of streamflow at 15-minute intervals (Porterfield, 1972; Koltun and others, 1994; McKallip and others, 2001). This type of sampling design, however, can be affected by resource limitations, such as financial and human resource constraints and operational limitations associated with equipment and logistical issues. The combination of these limitations may result in unacceptably large data gaps for computing reliable sediment-discharge records. Sediment discharges during periods lacking concentration values for samples are estimated based on a number of tools, including the relation between SSC and streamflow (sediment-transport curves), which is used to compute the suspended-sediment discharge.

The accuracy and precision of suspended-sediment discharge records are commonly in question because it is not feasible to collect continuous SSC samples. Accuracy and precision likely would be more problematic in environments where suspended-sediment concentrations can vary widely over short time periods (several minutes to daily), and where more frequent concentration sampling than daily cannot be attained. Continuous sediment-surrogate data on a constant time step of 15 minutes and (or) a variable time step based on rapidly changing surrogate data and stream stage would help estimate the short time periods of extremely variable SSC as well as periods of little to no concentration data (missing record). Thus, sediment-surrogate data could provide a more accurate estimate of SSC for computation of suspended-sediment discharge records than traditional computation methods discussed previously.

A number of sediment-surrogate measurements have been proposed and are being tested to supplement streamflow for quantitative estimation of SSC. Thus, this breakout session was tasked with assessing the ability of available technologies that provide a surrogate of SSC for computing suspended-sediment discharge records. This breakout session did not include discussion of the technical details, merits, and limitations of optical methods, such as turbidity and optical backscatter measurements, which were addressed in an accompanying breakout session, or other methods, such as acoustic backscattering, optical laser scattering, digital optics, and pressure differential techniques (which are discussed in the subsequent breakout session 4 summary).

Background

The potential benefits of collecting sediment-surrogate data and their use in computing suspended-sediment discharge records were demonstrated during the breakout session by Christensen and others (appendix 2); Lewis (appendix 2); and Uhrich (Determination Of Total And Clay Suspended-Sediment Loads From Instream Turbidity Data In The North Santiam River Basin, Oregon; 1998-2000; appendix 2). All three extended abstracts reported increased accuracy in suspended-sediment discharge records using turbidity as a surrogate for calculating SSC compared to traditional records-computation methods. Although Melis and others (see appendix 2) demonstrated that laser-based sensor data provide a good estimate of SSC and particle-size distributions, their work did not include use of the laser-based sensor data in records computation. In addition, the use of sediment surrogates in records computation was presented for a variety of hydrologic conditions and environments throughout the U.S. The use of sediment-surrogate data in records computation has been presented only for turbidity and laser technologies in this breakout session. The applicability of the others sediment-surrogate technologies in use for records computation has not been demonstrated currently.

If increased accuracy for less than daily to quarterly time periods is not of interest, but annual or longer time periods of suspended-sediment discharge are, then the use of sediment surrogates in suspended-sediment discharge records computation may not be needed. Horowitz (appendix 2) reported that suspended-sediment discharge on a yearly or longer time period could be accurately predicted using traditional sediment-transport curves. The example presented was for the Mississippi River at Thebes, Illinois, which is a very large drainage area where SSC would not be expected to vary widely over short time periods (several minutes to daily). In substantially smaller drainage basins, where concentrations can vary widely over short time periods, the collection of continuous sediment-surrogate data should increase the accuracy of the computed suspended-sediment discharges. In many streams and rivers, approximately 90 percent of sediment transport occurs in 10 percent of the time, and increased accuracy to compute suspended-sediment discharge during these time periods would likely be beneficial.

Use of sediment surrogates could also be beneficial in (1) decreasing the number of SSC samples needed, (2) evaluating concentration variability on a shorter time period (particularly during runoff events), and (3) triggering automatic pumping samplers for collection of concentration samples. However, the use of sediment surrogates does not preclude the need for collecting traditional suspended-sediment samples and for numerous calibration samples [cross-sectional samples collected using the Equal-Width Increment (EWI) or Equal-Discharge Increment (EDI) methods with concurrent samples at the sensor(s)] (Edwards and Glysson, 1999). Lewis (appendix 2) reports that the relation between turbidity and SSC can vary significantly between runoff events, and thus requires concentration samples during numerous events. Horowitz (appendix 2) reports that the operation and maintenance costs of sediment-surrogate sensors can be relatively high. Thus, the use of sediment surrogates may not reduce the cost of installing and operating a suspended-sediment station, nor reduce the cost of suspended-sediment discharge records computation.

All sediment-surrogate sensors should be evaluated in the laboratory for sensor calibration, sensor electronic drift, and so forth prior to installation in the field. During field installation of sediment-surrogate sensor(s), proper procedures should be followed for locating, cleaning, and calibrating the sensor(s). Additionally, SSC samples must be collected regularly over the range of streamflow and over time at the sensor location and across the cross section. During suspended-sediment records computation, detailed notes must be taken to evaluate all sediment-surrogate data records for factors that include sensor fouling, sensor cleaning, sensor calibration, sensor electronic drift (Wagner and others, 2000). These points cannot be emphasized enough, as uncorrected data errors will be transferred into the final computation of suspended-sediment discharge. During periods of missing and poor sediment-surrogate data (uncorrectable sensor fouling, values outside of the recommended range of a sensor, and so forth) and no SSC samples, records computations can be made based on relations between concentration and streamflow (sediment-transport curves).

Recommendations

1. Establish a program to evaluate selected sediment-surrogate sensors. This should include the following information:

   - manufacturer's specifications of sensor,
   - actual lab performance of sensor, and
   - field limitations of sensor.

2. Standard operating procedures should be developed for the collection of sediment-surrogate data. This should include but not be limited to:

   - information on determining the best location for a sensor(s),
   - cleaning of the sensor(s),
   - calibration of the sensor(s),
   - the need for regular collection of suspended-sediment samples at the sediment-surrogate sensor(s) location over the range of streamflow and over time,
   - the need for the collection of EWI or EDI samples (Edwards and Glysson, 1999) for determination of the cross-sectional coefficient over the range of streamflow and over time, and
   - examination of sedimentary characteristics such as percent fines or grain-size distributions when sources of sediment may have changed (for example, during landslides or other known, infrequent events).

The Subcommittee on Sedimentation or their designees in Federal, State, and local agencies, and the private sector should lead development of these procedures. The procedures should be incorporated into future revisions of the report by Porterfield (1972) and USGS Office of Surface Water Technical Memorandum No. 91.15 (1991) should be updated. The procedures should be provided on a web site and offered through the USGS, National Training Center Course - Sediment Records Computation and Interpretation (U.S. Geological Survey, 2003a). The ability to reliably compute records of sediment discharge is predicated on an adequate understanding data-collection procedures, such as is offered through the USGS, National Training Center Course - Sediment Data-Collection Techniques (U.S. Geological Survey, 2003b)

3. A standard suspended-sediment discharge records computation procedure should be developed for all sediment-surrogate records.

The USGS computer program Graphical Constituent Loading Analysis System (GCLAS; McKallip and others, 2001) should be modified for the estimation of SSC from sediment-surrogate data. GCLAS should include but not be limited to analyses procedures presented by Lewis (appendix 2). These modifications to GCLAS and the GCLAS program should be provided on a web site. The modified program should be offered through the USGS, National Training Center Course - Sediment Records Computation and Interpretation.

BREAKOUT SESSION 4: OTHER FLUVIAL-SEDIMENT SURROGATES

by Jeffrey W. Gartner, David S. Mueller, Gary R. Wall, and John R. Gray

Breakout session 4 was responsible for providing information and recommendations on techniques for monitoring characteristics of suspended sediments other than the more traditional and relatively ubiquitous methods such as optical backscatter and turbidity. The session's specific goals were to define the present status of several sediment-surrogate methods (laser optic, acoustic backscatter, pressure differential, and digital optic) for estimating SSC, including:

1. appropriate conditions (size distribution and (or) concentration) under which each might be used;
2. important limitations and advantages;
3. possible/probable/potential accuracy, if known; and
4. priority (where appropriate) for potential research for any of the techniques that are not currently accepted or widely used.

Extended abstracts (see Appendix 2) relating to the subject matter of breakout session 4 included:

"Testing laser-based sensors for continuous, in situ monitoring of suspended sediment in the Colorado River, Grand Canyon, Arizona," Presented by Theodore S. Melis, U.S. Geological Survey.

"Use of acoustic instruments for estimating total suspended solids concentrations in streams – The south Florida experience," Presented by Eduardo Patino, U.S. Geological Survey.

"Estimation of suspended solids concentrations based on acoustic backscatter intensity: Theoretical background," Presented by Jeffrey W. Gartner, U.S. Geological Survey.

"Surrogate techniques for suspended-sediment measurement," Presented by Daniel G. Wren, University of Mississippi.

A summary of the recommendations of the breakout session is shown in table 5.

Participants in breakout session 4 found that no single technique or instrument is capable of estimating SSC under all conditions. All four of the methods examined show promise, although some have limited application. Additional testing is required to determine if, and under what conditions, these methods may be suitable for use in determining SSC. An unfulfilled goal of the breakout session was to address the degree of accuracy required for estimates of SSC. Participants in this session concluded that in understanding sediment transport processes, less accurate data with higher temporal and (or) spatial resolution may be more useful than a limited number of more accurate measurements. Subsequent to the Workshop, accuracy guidelines were developed (Gray and others, 2002) for sediment-concentration measurements for a laser-diffraction instrument. The guidelines have been adopted by the Technical Committee, Federal Interagency Sedimentation Project (Federal Interagency Sedimentation Project, written commun., 2003).

OTHER SUSPENDED-SEDIMENT MONITORING TECHNIQUES

Techniques for monitoring SSC evaluated by participants in the breakout session included acoustic backscattering, optical laser scattering, digital optics, and pressure differential techniques. The majority of these methods are categorized as research techniques, the exception being optical instruments using the principle of laser light scattering (diffraction).

Acoustic Backscatter (ABS): Techniques that estimate mass concentration of suspended material from acoustic backscatter have been tested since the 1980's, although the method is presently applied to a very limited extent. The method has the advantage of being non-intrusive and providing a profile of SSC when an acoustic Doppler velocity profiler is employed for measurements, however the relation between acoustic frequency and particle size limits the size range for which the method is appropriate (Reichel and Nachtnebel, 1994; Lynch and others, 1994; Schaafsma and others, 1997). In addition, changes in size distribution increase errors associated with the acoustic backscatter method similar to all single frequency instruments; thus, careful calibration techniques are critical. Post-processing algorithms used are complex, requiring compensations for hydrologic properties such as temperature, salinity, and pressure, as well as instrument characteristics such as frequency, power, and transducer design. Application is yet to be outinely used and additional testing under various conditions is needed.

Laser Diffraction: Commercially available instruments for both laboratory and in-situ measurements using laser diffraction are available for determining size distribution of suspended material. Some of these can be used to determine SSC if particle density is known. Unlike single frequency optical instruments such as those that operate on optical backscatter (OBS) principles, these instruments are not subject to potential inaccuracies associated with changes in particle size of suspended materials. Laser diffraction instruments designed for in-situ measurements may be deployed unattended to provide a high-resolution time series of particle size distribution. However, there are limitations associated with high particle concentration and size range based on the laser path length and optical detectors used by individual instruments. Additionally, biological fouling degrades measurements by all types of in-situ optical instruments.

Digital Optical: Prototype digital-optical systems that employ cameras and computer software to determine number and size of suspended particles are in development; in-situ versions are yet to be built or tested. Nevertheless, digital optical systems requiring little or no calibration may ultimately replace visual accumulation and pipette laboratory techniques for analysis of particle size distributions.

Pressure Differential: The last technique examined by participants in breakout session 4 employs dual pressure transducers to infer SSC from density. The method has been field tested with mixed results (Larsen and others, 2001). The technique has generally been successful at concentrations above about 50,000 milligrams per liter (mg/L), but needs additional field evaluation in the range of 10,000-50,000 mg/L.

General Recommendations

In addition to information contained in the instrument matrix shown in table 5, the following general recommendations were made to improve the ability to estimate SSC. It is well understood that these recommendations may require additional funding. However, it is believed that the potential benefits of implementing these recommendations outweigh their cost; if necessary, additional source(s) of funding should be sought. Those recommendations include the following four suggestions.

1. **Sediment Monitoring Instrumentation and Analysis Research Program**: The active support of a sediment monitoring instrument and analysis research program (SMIARP) is recommended. This would include expanding capabilities at several existing gages for testing and evaluating instruments and techniques (including, but not limited to, bulk optic, digital optic, laser, acoustic, pressure differential) as tools to address problems of determining mass concentration and other selected characteristics. SMIARP gages informally exist now in three hydrologically distinct regions within the United States (Gray and others, 2003). SMIARP sites are based on the premise that the whole is greater than the sum of parts. That is, more progress might be made by concentrating effort with new instruments and new techniques so that necessary tools are available for such endeavors as comparisons among instruments, determining ground-truth data, and understanding complex sedimentary processes.
2. **Topical Expert Advisors**: Establishment and fostering of group(s) of topical expert advisors is recommended. These advisors (private, Federal, State, academic) could be called on to provide guidance and recommendations to the Subcommittee on Sedimentation, as well as

researchers and others applying new techniques and technology in the field. Such experts might be called on to review the potential success of efforts to determine SSC using various techniques. One example of such a group within the USGS is the Hydroacoustics Work Group (U.S. Geological Survey, 2003c), which, among other activities, provides guidance and training to users of acoustic velocity instruments within and outside the USGS.

3. **Improved Communication**: Improved communications to distribute information about emerging technologies applicable to determination of SSC is recommended by establishing a mechanism such as a list server or web site. Useful information that could be distributed would include successes, failures, field experiences, and general problems encountered using various techniques to estimate selected characteristics of suspended sediment.
4. **Data Accuracy**: The establishment and promulgation of criteria for suspended-sediment data accuracy is recommended.

SUMMARY

Evaluations of these methods indicate that there probably is no single technique or instrument capable of estimating SSC under all conditions. Variations in hydrologic conditions, as well as particle compositions, mass concentrations, and size distributions of suspended material, among other things, may require use of multiple frequency instruments or even multiple instrument types to determine mass concentrations to a reasonable degree of accuracy. Yet to be determined is what degree of accuracy is needed for a given situation. In all cases other than direct measurement through use of isokinetic water samplers, some method of instrument calibration is required to determine mass concentration.

In general, all methods evaluated show promise, although some applications are more limited than others. Additional testing is needed for all four methods, particularly those in development. This testing should include side-by-side evaluations of various instruments and techniques, as described above in the recommendation to establish SMIARP sites.

Additionally, several underlying themes recurred during discussions. Those themes included the following points. First, ascertaining the success or failure of a given technology is more desirable than doing nothing. Second, in understanding sediment transport processes, less accurate data with higher temporal and (or) spatial resolution are better than a limited number of more accurate measurements. Finally, it is necessary to define the error bars of the resulting answer and define what is an acceptable reduction in accuracy for increased temporal and (or) spatial resolution.

Table 5. Technology information matrix

[mm is millimeter; mg/L is milligrams per liter; > is greater than]

TECHNOLOGY	ACOUSTICS
MEASUREMENT	Acoustic backscatter (ABS) of suspended particles.
MEASUREMENT USE	Suspended-sediment concentration (SSC) at a point or water column profile.
INSTRUMENT(S)	Acoustic Doppler instruments, AQUAscat (Aquatec Subsea Ltd., 2003), possibly others.
MANUFACTURER(S)	Nortek (2003), RD Instruments (2003), SonTek/YSI (2003), Aquatec Subsea Ltd., and others .
MEASUREMENT LOCATION	Point and/or (vertical and horizontal) profile.
STATUS, PROGRESS, AND TRENDS	Field testing of use of acoustic backscatter from Doppler instruments begun in 1980s continues. Evaluation of Sediview (software for SSC estmation from acoustic Doppler current profiler) (DRL Software Ltd., 2003) by USGS Hydroacoustics Work Group (U.S. Geological Survey, 2003c) - sediment subgroup.
APPROPRIATE SIZE AND CONCENTRATION	Size range is frequency dependent (for example, 40 to 400 microns with 1,200 kilohertz), other frequencies are available.
SENSOR(S)	Acoustic transducer.
SOURCES OF INFORMATION	Hydroacoustics Work Group - sediment subgroup. Sediment Laboratory, University of Mississippi. Manufacturer on-line information. Literature search.
PROBLEMS, STRENGTHS, WEAKNESSES, AND LIMITATIONS	Problems and Limitations: Provides only concentration and not information on particle size, lacks available field tests, and needs development or improvement of software packages. Also has single frequency instrument and particle size limitations. Strengths: Generally unaffected by biological fouling, provides profiles, and measures most of the x-section. Technique is a qualitative tool for selecting sampling locations.
ACCURACY	Perhaps as good as +/- 5-10 percent.
SET PRIORITY IF RESEARCH TECHNIQUE	Sediment monitoring instrument and analysis research program (SMIARP) concept should be used to research the feasibility of using different technologies for estimating SSC. Algorithm(s) development needed.
RECOMMENDATIONS AND GOALS	Determine possible field applications. Evaluate other technologies such as to cross-check results of acoustic instruments. Establish SMIARP sampling protocol. Evaluate multi-frequency concept. Communicate with experts working on the use of acoustic technology to find out what has been done and what is available.

Table 5. Technology information matrix.--Continued

TECHNOLOGY	OPTICAL (LASER DIFFRACTION)
MEASUREMENT	Diffraction of light by suspended particles.
MEASUREMENT USE	In situ: Grain size and volumetric concentration (also light transmission, pressure, and temperature with some instruments). SSC with assumed particle density. Laboratory: Grain size and "obscuring" of light transmission.
INSTRUMENT(S)	In situ: LISST-100 (Laser In-Situ Scattering and Transmissometry) (Sequoia Scientific Inc., 2003) (32 size bins), LISST-25 [Sauter (surface area moment) mean for size)], LISST-25X (Sauter means for both sand and fines). Manually Deployed: LISST-SL (Same as LISST-100 above). Laboratory: LS100Q (140 size bins), 230 (140 size bins) and others.
MANUFACTURER(S)	In situ: Sequoia Scientific Inc. (2003). Laboratory: Beckman-Coulter Inc. (2003) and Malvern Instruments (2003) (Other manufacturers may be available).
MEASUREMENT LOCATION	In situ: Point (or small volume) instrument (can also be raised and lowered through water column). Manually Deployed: Point measurements or used across section.
STATUS, PROGRESS, AND TRENDS	In situ: Size distribution measurements tested by manufacturer and users in both lab and field settings; mass concentration depends on careful choice of particle density. Manually Deployed: Cooperative Research and Development Agreement (CRADA) between USGS and Sequoia Scientific, Inc (2003)) device in development. Laboratory: Size distribution only; comparisons with sieve derived data and standardized distributions tested by manufacturer and users.
APPROPRIATE SIZE AND CONCENTRATION	In situ and Manually Deployed: 0 to perhaps 5000 mg/L (concentration limits depend on particle size distributions); 1.5 - 500 microns possibly up to 1500 microns with new instrument in development. Laboratory: 0.04 - 2000 microns; concentration is not available by lab units unless volume context and density are known during analysis.
SENSOR(S)	Ring detectors.
SOURCES OF INFORMATION	Manufacturer on-line information. Literature search.
PROBLEMS, STRENGTHS, WEAKNESSES, AND LIMITATIONS	In situ (Limitations): Cost, concentration and particle size limitations, biological fouling, point data only, user must define density to determine mass concentration. In situ (strengths): Potential for real time data, fine temporal resolution and continuous sampling is possible, provides grain size with no other in-situ variable. Manually Deployed: Same as above but not available yet. Laboratory: Same as in situ but does not provide concentration values. High concentration samples usable with dilutions.
ACCURACY	Manually Deployed: Unknown until prototype developed but potentially same as LISST-100. In situ: Particle-size distribution 5-15 percent on basis of published results from laboratory tests (Gartner and others, 2001). Laboratory: See manufacturer specifications.
SET PRIORITY IF RESEARCH TECHNIQUE	High Priority: Side by side testing in field at several sediment monitoring instrumentation research program sites covering a wide range of natural conditions is desirable.
RECOMMENDATIONS AND GOALS	Continue field and laboratory testing with verification data collected using suitable methods; employ side by side testing of instruments.

Table 5. Technology information matrix.--Continued

TECHNOLOGY	DIGITAL OPTICAL
MEASUREMENT	Number and size of suspended particles.
MEASUREMENT USE	SSC can be calculated with an assumed density.
INSTRUMENT(S)	Camera and personal computer.
MANUFACTURER(S)	USGS prototype (from commercial camera systems).
MEASUREMENT LOCATION	Point.
STATUS, PROGRESS, AND TRENDS	Laboratory unit has been beta-tested, field units are designed but not built - potentially could be ready for beta-testing in 3 years.
APPROPRIATE SIZE AND CONCENTRATION	0.004 mm to about 4 mm, but the instrumentation can be specialized based on a combination of lens and concentration.
SENSOR(S)	Digital cameras supported by portable computer.
SOURCES OF INFORMATION	Daniel J. Gooding, USGS, Cascades Volcano Observatory, Vancouver, Washington.
PROBLEMS, STRENGTHS, WEAKNESSES, AND LIMITATIONS	Problems: Concentration limits; instruments are still being constructed, developer needs funding and technical support. Strengths: Replace visual accumulation (VA) and pipette lab techniques, reasonable price, made to match the agency need.
ACCURACY	<1 percent for particle size, SSC based on density estimate.
SET PRIORITY IF RESEARCH TECHNIQUE	Conduct an instrument test of SEDIGRAF (Matthes and others, 1992) and Beckman Coulter (2003) LS-100 (laser) using both reference materials and duplicate samples - arrange 2-3 labs to be involved, circulate a draft work (study) plan to review, prepare reference materials with sand concentration variability. Compare pilot instrument with both SEDIGRAF and LS-100 - again design workplan/review/accept plan, prepare reference materials and duplicates, evaluate results.
RECOMMENDATIONS AND GOALS	Complete the prototype instrument, test instrument versus VA and/or pipette in laboratory setting. Test equipment for temporal endurance and daily stability.

Table 5. Technology information matrix.--Continued

TECHNOLOGY	PRESSURE DIFFERENTIAL
MEASUREMENT	Differential fluid density.
MEASUREMENT USE	SSC between sensors with temperature compensation.
INSTRUMENT(S)	Dual Pressure Sensors.
MANUFACTURER(S)	Design Analysis Associates, (DAA), 2003; Hope Hydrology, The Netherlands (2003).
MEASUREMENT LOCATION	Vertical, Bank-mounted (or pier, etc.).
STATUS, PROGRESS, AND TRENDS	Tested in Puerto Rico and University of Georgia; also The Netherlands and elsewhere. Puerto Rico tests had mixed results, concluding that perhaps 2.5 - 5 percent or greater sediment by weight is required for the technology to "work". University of Georgia laboratory test variance within 13 percent; field variance about 50 percent. Technology from The Netherlands purported to function with 95 percent accuracy at 0.01 percent sediment by weight. Technique needs more work.
APPROPRIATE SIZE AND CONCENTRATION	Appears somewhat or totally insensitive to size distribution (must be confirmed); appropriate for high concentrations. Used in lab and field applications.
SENSOR(S)	Pressure transducers, variable voltage output.
SOURCES OF INFORMATION	DAA, Logan, Utah (2003); Hope Hydrology, The Netherlands (2003); University of Georgia; USGS (Larsen and others, 2001).
PROBLEMS, STRENGTHS, WEAKNESSES, AND LIMITATIONS	Probably not applicable at low concentrations (less than a few thousand mg/L). Turbulence may cause additional inaccuracies, but may be dampened with new algorithms. Works best at high concentrations where other techniques fail.
ACCURACY	Lab: good (±5 percent) Field: to be determined (function of concentration).
SET PRIORITY IF RESEARCH TECHNIQUE	Confirm capabilities - Hope Hydrology (2003), University of Georgia Test device in high-concentration system, Paria River at Lees Ferry, Arizona.
RECOMMENDATIONS AND GOALS	Niche is in higher concentration systems, probably > 50,000 mg/L Need tests at range of 10,000 - 50,000 mg/L, to above 100,000 mg/L Need to look at other industrial, chemical, oceanographic technology that measures fluid density Need to evaluate cost and accuracy of other transducers

SUMMARY OF BLIND SEDIMENT REFERENCE SAMPLE MEASUREMENT SESSION

by Mark N. Landers

The focus of the Turbidity and Other Sediment Surrogates Workshop, April 30-May 2, 2002, included issues associated with the definition and measurement of turbidity, and with the use of turbidity as a surrogate for physical and chemical properties of water. These issues include the variance in measured turbidity and factors that affect measurement results. The Workshop included a separate session to illustrate the variance in measurements of turbidity for laboratory-prepared blind reference samples performed by some Workshop attendees. The results of the blind reference sample measurement session were intended to be indicative rather than quantitative.

The session involved calibration of instruments and measurement of blind reference samples. Fourteen Workshop attendees participated, using nine different types of turbidimeters. Participants in this session were provided with instructions and a form to record their calibration and measurement results[1]. Calibration standards were graciously provided by commercial suppliers. Meters were calibrated following manufacturer recommended practice. Participants recorded their meter specifications (manufacturer and model), and calibration standard specifications (standard type, value, and units). Participants who calibrated with standards from different manufacturers had differences of less than 5 percent from one standard to the next.

Variability with calibration standards is small compared to other sources of variance.

Three lots of blind reference samples were prepared, representing three sediment size distributions and two concentrations. The reference samples were prepared by the USGS, Branch of Quality Systems (U.S. Geological Survey 2003d). Concentrations and material size distributions were not identified on the numbered sample bottles to ensure unbiased measurement. The measurement sheet included measurement instructions. Participants recorded the blind sample bottle identifier, the time, instrument reading, and units for each sample. Most participants sampled one blind sample from each of the three lots. Results are summarized in table 6 and show graphically in figure 1.

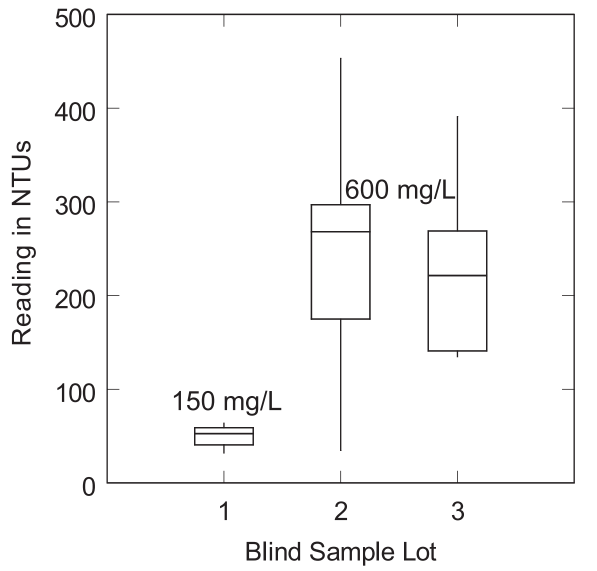

Figure 1. Box and whisker plots depicting the variance reported in turbidity in blind reference samples measure by workshop participants for three blind-sample lots. NTU is nephelometric turbidity unit.

The results show a large variance in measured turbidity under the conditions of the Workshop sampling session. Variance in results could be introduced by

[1] <u>*Blind Measurement Notes, as given on Workshop session measurement form:*</u>

Minimize mixing and sub-sampling errors. Mix sample thoroughly in bottle before transferring to sample container. If possible, measure entire bottle to reduce sub-sampling errors. Obtain reading quickly to reduce errors due to settling. Take instantaneous rather than averaged readings.

many sources including factors associated with the operator, measurement technology, sub-sampling, and other factors in an uncontrolled environment. Although this Workshop session does not represent controlled conditions, the environment is more controlled than that typically experienced in the field, and more controlled than that experienced if each person were in a different field condition.

The results indicate that higher sediment concentrations will result in greater measurement uncertainty. This is apparent in comparing the measurement range and standard deviation of Lot 1 (150 mg/L) with that of Lots 2 and 3 (600 mg/L). The results also indicate that larger percentages of sand within a given concentration may result in a lower reading of turbidity.

Results are not shown for differences between instrument manufacturers. Differences in readings due to the instruments could not be directly distinguished from differences due to other factors in this session. The overall results support the general Workshop findings that reliable, repeatable definitions and methods for turbidity measurement are difficult to develop.

Table 6. Characteristics of blind reference samples analyzed by participants at the Turbidity and Other Sediment Surrogates Workshop, April 30 – May 2, 2002

[mg/L is milligrams per liter; µm is microns; NTU is nephelometric turbidity unit]

	Blind Sample Lot 1	**Blind Sample Lot 2**	**Blind Sample Lot 3**
Sediment Concentration	150 mg/L	600 mg/L	600 mg/L
Sediment Size Characteristics	Fines: <62µm	Fines: <62µm Sands: 63-200µm	Fines: <62µm Sands: 63-200µm
Percent Sands	0	6-7	20
Number of Measurements	12	15	14
Median of Measured Turbidity (NTU)	53	268	221
Standard Deviation of Measured Turbidity (NTU)	11	112	85

USES OF TURBIDITY BY STATES AND TRIBES

by Bruce A. Pruitt

ABSTRACT

As part of the Subcommittee on Sedimentation's "Turbidity and Other Sediment Surrogates Workshop," April 30-May 2, 2002, a questionnaire on uses of turbidity was submitted to water-quality coordinators for all State and some Tribal agencies. The questionnaire was designed to address key issues related to turbidity, including water-quality standards, technology, ranges observed, water bodies, seasonal variability, calibration and sampling protocols, and use of other measures of fluvial and suspended sediment.

All but 5 of the 40 agencies that responded indicated having established either narrative or numeric standards for turbidity under their jurisdictions. In addition to water-quality standards, several agencies are using either turbidity or TSS to identify sediment-impaired streams or stream reaches with application to developing sediment TMDLs.

Water clarity was identified by the agencies as the parameter of primary interest when measuring turbidity. Several agencies have correlated either turbidity or TSS with habitat or aquatic life. Several agencies indicated having noticed a seasonal variability in turbidity that is possibly related to an increase in plankton in the water column and not runoff. Reported ranges in turbidity vary widely, ranging from below detection limits to over 10,000 NTU.

The large majority of agencies use instruments operating on the bulk optical properties of water-sediment mixtures, including turbidimeters, optical backscatter meters (OBS), and optical transmissometers to infer turbidity, and analyses of grab samples to provide the comparative SSC or TSS data. Some agencies are using flow-integrated sampling techniques depending upon the project objectives.

The majority of the agencies that measure turbidity use formazin as a calibration standard and USEPA Method 180.1 for analysis (U.S. Environmental Protection Agency, 1999). The majority of the agencies used either Oracle, STORET, or a "local" database or spreadsheet for data storage and analysis. The agencies identified several technical needs related to turbidity, including improving the relation between turbidity, TSS, SSC, channel stability, and biological impairment; establishing reference fluvial sediment conditions and means of measuring significant departure from reference conditions; improving depth-integrated isokinetic samplers; and developing a consistent procedure and less expensive probes that can be rapidly deployed and are stable in the field. In addition, most agencies agreed that additional long-term, stream-discharge, suspended and bedload data are needed, and that the USEPA should revise Method 180.1 on turbidity (U.S. Environmental Protection Agency, 1999) to include state-of-the-art instrumentation capable of measuring higher concentrations of turbidity without making sample dilutions.

INTRODUCTION

Suspended sediment is considered a pollutant and in excessive amounts can affect water quality and designated uses of water. Accelerated sedimentation can affect the growth and development of fisheries by reducing spawning areas and food sources, by adding fill in rearing ponds, and by reducing habitat complexity (bedforms). In addition to affecting aquatic life, accelerated sedimentation can result in aggradation, increase the stream channel width/depth ratio, and cause bank erosion and failure. Sediment can adversely affect drinking water supplies by causing taste and odor problems, foul treatment systems, and fill reservoirs resulting in loss of storage capacity. In recreational waters, high levels of suspended sediment reduce aesthetics, impair swimming, fishing, and boating, and may result in safety problems and concerns. In contrast to accelerated sedimentation, sediment deficits or sediment "starved" streams (e.g., below dams) can result in bank and channel scour, entrenchment, loss of habitat, and can adversely affect stream cross-sectional and planform geomorphology.

Because it is expensive and labor intensive to collect and analyze suspended-sediment samples on a frequent basis, measurement of turbidity offers a relatively rapid and inexpensive means of determining the clarity of aquatic ecosystems. Turbidity can be used to evaluate the general condition and productivity of the system or simply provide a means of identifying problem areas ("red flag") for watershed planning and targeting intensive investigations. In certain ecoregions, turbidity may be a reliable means of estimating SSC, TSS, and (or) causes of physical impairment.

Turbidity in water bodies is caused by both organic and inorganic fractions including silt and clay particles, fine particulate organic matter, organic compounds, and plankton. In general, any suspended or dissolved particle that is capable of causing light to be scattered or absorbed will be expressed in turbidity measurements.

Problem

Several problems and sources of error are associated with measuring turbidity. First and foremost is error associated with turbidimeter calibration. Calibration standards are inherently unstable, may vary from solution to solution and batch to batch, and may degrade readily causing variation in data. Optical lenses and cubettes are susceptible to scratches, and thus constitute a potentially significant source of error, depending upon their material, design, and cleaning device or procedure. The presence of dirt, debris, air bubbles, and ambient light also provide potentially significant sources of error associated with measuring turbidity. In addition, a high degree of uncertainty can be anticipated when comparing data using different technology, physics, and laboratory methods for measuring turbidity. Finally, errors can be associated with how, when, and where the sample is collected. Consequently, data quality, interpretation, and application will vary with the calibration, instrumentation, and field and laboratory methods employed. Prior to this survey, the variability in interstate measurement nationwide and use of turbidity had not been thoroughly compared and evaluated.

Objective

A questionnaire on uses of turbidity was submitted to State and Tribal water-quality coordinators. The objectives of the questionnaire were to determine:

1. How turbidity is being used in addressing water-quality issues including water-quality criteria.
2. What water bodies are being measured using turbidity, including ranges observed.
3. What technology is being used to measure turbidity. How turbidity meters are being calibrated.
4. How future turbidity measurements could be improved.

The query also included questions pertaining to TSS, SSC, bedload, and particle-size analysis. The blank questionnaire used in this national query is attached as appendix 3.

Results

A combination of 40 States/Tribes (hereafter referred to as "agencies") responded to the questionnaire. The primary turbidity-specific objective of the majority of the agencies was to establish water-quality criteria or standards for turbidity that were protective of aquatic life and designated for beneficial uses such as fishing and recreation (table 7). Only five of the agencies have no turbidity standard. Of those five, Arizona replaced its turbidity standard with a SSC standard. The majority of the agencies have established, at a minimum, narrative language for turbidity such as "substantial visual contrast," "free from color and turbidity," or "reduced light transmission." More than half of the responding agencies have established numeric standards for turbidity, which range from "not to exceed" over background or ambient conditions, to "maximum allowable levels." Some agencies have established numeric standards that are basin-specific, while others vary with water bodies or presence of salmonids. Several agencies are using either turbidity or TSS to identify sediment-impaired streams or stream reaches, for example, to confirm Clean Water Act 303(d)-listed stream segments and develop sediment-related TMDL studies.

Primarily, water clarity was identified by the agencies as the parameter of interest when measuring turbidity.

Six agencies are also using turbidity as a surrogate for SSC, siltation, or erosion (tables 8 and 9). Nine agencies have correlated either turbidity or TSS with habitat or aquatic life. Streams and lakes were identified as water bodies where most turbidity measurements have been conducted. However, 9 agencies have measured turbidity in wetlands and 14 agencies have measured turbidity in either estuarine or marine ecosystems. Thirteen agencies have noticed a seasonal variability in turbidity unattributed to runoff that is possibly related to an increase in plankton in the water column.

Reported ranges in turbidity vary widely among reporting agencies. However, reported ranges in mountain regions are generally lower than other physiographic regions. For instance, Arkansas reported turbidity levels of less than 1 NTU in the Ozark Mountains to over 400 NTU in the Mississippi Delta area. Idaho reported 0 to 50 NTU in the Rocky Mountains to over 500 in the Snake River watershed. Many of the agencies that cover Piedmont and Coastal Plain physiographies reported turbidity levels over 1,000 NTU, and in some cases over 10,000 NTU.

The large majority of agencies are using data derived from environmental grab samples in conjunction with measurements of the bulk optical properties of the water-sediment mixture, including turbidimeters, optical backscatter meters (OBS), and optical transmissometers (table 9). Seven agencies are using optical transmission, and three agencies are using Secchi disk (Carolina Coastal Science, 2003). Six agencies are collecting samples by either grab sampling or integrated sampling depending upon the project objectives. In addition, six agencies are using automated, single-point sampling methods. The majority of the agencies that measure turbidity use formazin as a calibration standard and USEPA Method 180.1 for analysis. Six agencies are adjusting the temperature to 25ºC prior to measuring turbidity in the laboratory.

Six agencies are measuring particle-size distribution by a wet sieve method, and one agency plans to use laser technology in the near future. Most are using the TSS analytical procedure (APHA, 1995)to produce their sediment data. However, Arizona and New Mexico use the SSC measurement technique (ASTM International, 2002), and California plans to measure SSC in the future. The majority of the agencies that measure TSS use USEPA Method 160.2. No agencies are presently measuring bedload. The majority of the agencies used either Oracle, STORET, or a “local” database or spreadsheet for data storage and analysis.

Discussion

Several instruments and methods are available to quantify SSC in water bodies with various degrees of accuracy and precision. Historically, measurement of turbidity has been the primary method used by agencies to infer SSC (or TSS), and narrative and (or) numeric standards have been established for turbidity in water bodies. As with most measures of fluvial and suspended sediment, uncertainty associated with measuring turbidity is high and is associated with calibration, technology used, sample handling, interference, and how, when and where the sample is collected. However, measurement of turbidity provides, in part, a relatively rapid and inexpensive means of prioritizing stream reaches on a watershed scale, formulating watershed strategic plans, identifying local sources of sediment, and developing correlations and surrogates with suspended sediment and aquatic life.

Conclusions and Recommendations

The results of the questionnaire indicate that nearly all agencies measuring turbidity are interested primarily in water clarity and establishing water-quality criteria protective of designated or beneficial uses. Narrative standards are related to visual contrast, suspended solids, or light transmission. Numeric standards range from 0.1 NTU in marine waters (Hawaii) to 150 NTU (Louisiana and Maryland) in freshwater streams (may not exceed at any time).

Generally, agencies have observed lower turbidity l evels in mountainous physiographic regions as compared to piedmont and coastal plain physiographic regions. Particle-size distribution, particle shape, suspended fine particulate organic carbon, and clay mineralogy may account for the bulk of the interphysiographic variability.

Caution should be exercised when comparing turbidity data collected by different agencies. Data quality, interpretation, and application will vary with the calibration, instrumentation, and field and laboratory methods employed.

Most agencies indicated that more effort should be devoted toward improving the relation between turbidity, TSS, SSC, channel stability, and biological impairment. In addition, many agencies expressed a need for establishing reference fluvial-sediment conditions and means of measuring significant departure from reference conditions. Improvements need to be made in depth-integrated isokinetic samplers. Many agencies were in favor of a consistent procedure and less expensive probes that can be deployed rapidly and are stable in the field. Several agencies expressed the need for additional long-term, stream discharge, and suspended-sediment and bedload data. Most agencies agreed that the USEPA should revise the method on turbidity (Method 180.1) to include state-of-the-art instrumentation capable of measuring higher concentrations of turbidity without making sample dilutions.

Table 7. State turbidity standards and their primary use.

State	Turbidity Standard	Parameter of Interest /Other Uses
AL	Shall be no turbidity of other than natural origin that will cause substantial visible contrast with the natural appearance of waters or interfere with any beneficial uses which they serve. Shall not exceed 50 nephelometric turbidity units (NTU) above background.	Water clarity
AR	Shall be no distinctly visible increase in turbidity of receiving waters attributable to municipal, industrial, agricultural, other waste discharges or instream activities. Numeric standard varies from 10 to 75 NTU depending upon basin.	Water clarity and suspended sediment
AZ	Recently replaced turbidity standard with suspended-sediment concentration (SSC).	Surrogate for sedimentation
CA	Narrative ocean plan objectives: 1) no reduction in natural light; 2) no undesirable discoloration of ocean waters.	Water clarity
CT	Shall not exceed 5 NTU over ambient levels.	Water clarity; siltation and erosion
DE	Not to exceed natural levels by more than 10 NTU.	Scatter and absorption
FL	All classes: # 29 NTU above natural background conditions.	Water clarity and light absorption
GA	All waters shall be free from turbidity, which results in a substantial visual contrast in a water body due to a man-made activity.	n/a
HI	Inland water criteria: wet season, 5 NTU (geometric mean); dry season, 2 NTU; specific basins vary from 0.1 (ocean waters) to 4.0 NTU.	Light scatter
IA	Turbidity of the receiving water shall not be increased by more than 25 NTU by any point source discharge.	Water clarity
ID	Turbidity below any applicable mixing zone set by the Department shall not exceed background turbidity by more than 50 NTU instantaneously or more than 25 NTU for more than 10 consecutive days.	Water clarity
IN	No standard.	Water clarity
ME	Transparency as a water quality standard	Water clarity, color, total solids

Table 7. State turbidity standards and their primary use. --Continued

State	Turbidity Standard	Parameter of Interest /Other Uses
MN	Class 2A waters: shall not exceed 10 NTU; Class 2B waters: shall not exceed 25 NTU	Water clarity
MS	Cannot be more than 50 NTU above background	Water clarity
MT	Class A-1: No increase above naturally occurring turbidity is allowed; Class B-1 and C-1: 5 NTU maximum allowable increase above background; Class B-2 and C-2: 10 NTU maximum allowable increase above background.	Water clarity
NC	Turbidity in receiving water shall not exceed 50 NTU in streams not designated as trout waters and 10 NTU in streams, lakes or reservoirs designated as trout waters; for lakes and reservoirs not designated as trout waters, the turbidity shall not exceed 25 NTU; if turbidity exceeds these levels due to natural background conditions, the existing turbidity level cannot be increased.	Water clarity
NE	To be aesthetically acceptable, waters shall be free from human-induced pollution which causes: ...floating, suspended, colloidal, settleable materials that produce objectionable films, colors, turbidity....	Water clarity and light scatter
NH	Class A waters: shall contain no turbidity, unless naturally occurring; Class B waters: shall not exceed naturally occurring conditions by more than 10 NTU; Waters identified in RSA 485-A, III, shall contain no turbidity of unreasonable kind or quality.	Water clarity, light absorption
NJ	FW2/SE3 waters: maximum 30-day average of 15 NTU, maximum of 50 NTU at any time; SE1/ SE2 waters: Maximum 30-day average of 10 NTU, maximum of 30 NTU at any time; SC waters: Levels shall not exceed 10 NTU.	Changes in water quality and indication of vertical and lateral mixing
NM	Shall not reduce light transmission to the point that the normal growth, function, and reproduction of aquatic life is impaired or that will cause substantial visible contrast with the natural appearance of the water; Numeric standard varies from 10 to 50 NTU depending upon basin.	Water clarity and surrogate for erosion
NV	Pyramid Lake Paiute Tribe: 10 NTU proposed	Water clarity
NY	No increase that will cause a substantial visible contrast to natural conditions. Class GA waters: Shall not exceed 5 NTU.	Water clarity
OH	No standard.	n/a
OK	Turbidity from other than natural sources shall be restricted to not exceed: for cool water aquatic community/trout fisheries, 10 NTU; lakes, 25 NTU; and other surface waters, 50 NTU.	Water clarity
OR	No more than 10 percent cumulative increase in natural stream turbidities shall be allowed with exceptions for emergencies.	Light scatter

Table 7. State turbidity standards and their primary use. --Continued

State	Turbidity Standard	Parameter of Interest /Other Uses
RI	Class A waters: none in such concentrations that would impair any usages specifically assigned to this class. Turbidity not to exceed 5 NTU over background; Class B, B1 and C waters: none in such concentrations that would impair any usages specifically assigned to this class. Turbidity not to exceed 10 NTU over natural background.	Water clarity
SC	Trout streams are not to exceed 10 NTU or 10 percent above natural conditions; Lakes and reservoirs are not to exceed 25 NTU; Other freshwaters are not to exceed 50 NTU; All saltwater classes are not to exceed 25 NTU, including Shellfish Harvesting Waters.	Water clarity and NPS indicator
SD	No standard.	n/a
TN	Shall be no turbidity or color in such amounts or of such character that will materially affect fish and aquatic life.	n/a
UT	Not to increase by more than 10 NTU.	Water clarity
VA	No standard.	Water clarity
VT	Class A(1) and (2) waters: not to exceed 10 NTU; Class B waters: not to exceed 10 and 25 NTU in cold water and warm water fish habitat, respectively.	n/a
WI	No standard.	Light scatter, surrogate for total suspended solids (TSS)
WV	Shall not exceed 10 NTU over background when the background is 50 NTU or less, or have more than a 10 percent increase in turbidity (plus 10 NTU minimum) when the background turbidity is more than 50 NTUs.	n/a
WY	Cold water fisheries and drinking water supplies classes 1, 2AB, 2A, and 2B: 10 NTU; Warm water or nongame fisheries classes 1, 2AB, 2B, and 2C: 15 NTU with exceptions for North Platte River and short-term increases in turbidity.	Water clarity

Table 8. Agency turbidity program elements

Agency	Data Base	Affected Programs[1]	NTU Correlations[2]	NTU Ranges	TSS or SSC[3], (mg/L)	Water Bodies[4]	Observed Seasonal Variablity
AL	local data-base, STORET (future)	ambient monitoring program	no		no	S,L,E,M	no
AR	STORET	WQS	no	<1 (Ozark) to >400 (Delta)	TSS (BDL to >300)	S,L	yes, algal blooms
AZ	Oracle, STORET	303(d)	biota	streams:1-1000 lakes: 2-160	SSC (80 mg/l WQS)	S,L	yes, algal blooms
CA	local spdsht.		yes	>1	TSS (SSC for SWAMP)	S,L,W,E,M	yes, algal blooms
CT	USGS, local database		no	1-75	TSS (<10)	S	no
DE	STORET, local spdsht		TSS, N, P, habitat	1-923	TSS (1-378)	S,L,E,M	yes, algal blooms
FL	Oracle, STORET	WQS, TMDL, GW purge	no		no	S,L,W,E,M, GW	
HI	local spdsht.	TMDL	no	0.1 to 430	TSS (0.5-70 normally; >700 (storm-flow))	S	no
IA	STORET	WQS, TMDL	no			S,L	yes, nutrient-enriched streamss
ID	local spdsht.		TSS vs NTU	0-500+ Snake; Rockies:0-50	TSS	S,L,E	yes, algal blooms
IN	local data-base		no	0-800	TSS	S,L	yes, algal blooms

Table 8. Agency turbidity program elements --Continued

Agency	Data Base	Affected Programs[1]	NTU Correlations[2]	NTU Ranges	TSS or SSC[3], (mg/L)	Water Bodies[4]	Observed Seasonal Variablity
KY	STORET	red flag	no	0 (pristine) - 11,000 (slurry spills)	TSS (0 to >400)	S,L,W	higher value in spring & summer
LA	FOCUS and STORET (presently); Oracle (future)	WQS, TMDL	no	BDL to 3000	TSS (BDL to 9166, one time event)	S,L,E,M	yes, rainy season during winter and spring
MA	local data-base	Red flag increase >5 NTU	none		TSS	S,L	limited seasonal data
MD		NPDES	none	none	TSS (45 WQS)	All with NPDES Permits	no response
ME		WQS, TMDL	TSS vs. aquatic life		TSS	S,L	yes, lakes
MI			no		TSS	S,L	no
MN	STORET		no	0.2-720	TSS (0.6-3594)	S,L,W	no
MS	local data-base	WQS	no	1.0-694	TSS	S,L,W,E,M	no
MT	STORET	WQS	NTU vs. aquatic life; NTU vs. TSS	1.0-225	TSS	S,L,W	yes, lakes (Secchi disk)
NC	STORET	WQS, red flag	no	0-12,000	TSS	S,L,E	no
NE	STORET		no	1-2552	TSS (5-592)	S,L	yes, algal blooms
NH	STORET	WQS, red flag for TSS	no, but planned	0-5	no	S,E	no
NJ	STORET		no			S,E	

Table 8. Agency turbidity program elements --Continued

Agency	Data Base	Affected Programs[1]	NTU Correlations[2]	NTU Ranges	TSS or SSC[3], (mg/L)	Water Bodies[4]	Observed Seasonal Variablity
NM			TSS, PSC vs. biota	lotic: 0-10000; lentic:0-300	TSS, SSC planned	S,L	no
NV, Pyramid Lake Paiute Tribe	hardcopy only	WQS, T and E fish species	no	0-40	no	S,W	no
NY, State	local database	WQS	no	1 to 600; 1 to 100 common	TSS	S	no
NY, Mohawk	local spdsht.		Fish & habitat	0.5-24	no	S	no
OK	Oracle		no	5-800	TSS	S,L	no
OR	STORET	WQS, TMDL, red flag	NTU vs. TSS	1-1000	TSS (1-12,000)	S,L,E	yes, algal blooms
RI	local database		none	0.4 to 114.8	TSS (0.1 to 119)	S,L,E	no response
SC	STORET	WQS, TMDL	no	0.1 to 18,346	TSS (0.1 to 840)	S,L,E	not assessed
TN	local database	WQS	NTU vs. aquatic life (future use)	0.1 to 957	TSS	S	not assessed
UT	STORET	WQS	no	0-1000	TSS (0-1000)	S,L	not assessed
VA	Oracle		no		TSS	S,L,W,E,M	not assessed
VT							
WI	STORET		>100 NTU, aquatic life	1 to 400 NTU		S,W	not assessed

Table 8. Agency turbidity program elements --Continued

Agency	Data Base	Affected Programs[1]	NTU Correlations[2]	NTU Ranges	TSS or SSC[3], (mg/L)	Water Bodies[4]	Observed Seasonal Variablity
WV	local data-base	WQS, total metals inter-pretation	tested TSS vs. macroin-vertebrate (no relation-ship observed)		TSS (3.7 to 7.9)	S	not observed in small, high-gradient streams
WY		WQS	no	0 to >1000	TSS	S,L	not assessed

Notes:

[1]WQS = water quality standard; T= Threaten; E = Endangered

[2]TSS = total suspended solids; N = nitrogen; P = phosphorus; NTU = nephelometric turbidity units; PSD = particle size distribution

[3]SSC = suspended sediment concentration; BDL = below detection limits

[4]S = stream; L = lake; W = wetlands; E = estuary; M = marine; GW = ground water

spdsht. = spread sheet

TMDL = Total Maximum Daily Load

GW = ground water

NPDES = National Pollutant Discharge Elimination System Permitting Program

SWAMP = Surface Water Ambient Monitoring Program

> = greater than

< = less than

mg/L = milligrams per liter

"red flag" = turbidity used for initial screening of possible water-quality problem

Table 9. Agency turbidity procedural elements

Agency	NTU Technology 1	PSD[2]	Sample Type[3]	Bedload	SOP[4]	SSC or TSS	Calibration Standard	Temp. Adjusted	Interfer-ences
AL	OBS	no	grab	no	180.1	160.2	formazin	no	color
AR		no	grab		SM			no	no
AZ	OBS	PSD	grab, auto-mated	no	180.1	TSS, SSC	formazin	no	no
CA	Secchi disk	wet sieve	grab, auto-mated	no		TSS now SSC future			no
CT	OBS, OT	no	grab, IS	no	180.1		formazin, multi-point	no	no
DE	OBS	no	grab, auto-mated	no	180.1	TSS	manu. specs	room temp.	no
FL	OBS	no	grab	no	180.1		formazin	yes	no
HI	OBS	no	grab	no	180.1	TSS	manu. specs		no
IA	OBS	no	grab and pumped	no				no	no
ID	OT	no	grab	no	180.1	TSS			algae, white water
IN	OBS, OT	no	grab	no	180.1, ISO 7027	TSS, 160.2	multi-point	no	no
KY	OBS	no	grab	no	180.1	160.2		no	no
LA	OBS	no	grab	no	180.1	160.2	multi-point	no	color
MA	OBS, OT	no	grab	no	ISO 7027, SM	TSS	polymer	no	no

Table 9. Agency turbidity procedural elements --Continued

Agency	NTU Technology [1]	PSD[2]	Sample Type[3]	Bedload	SOP[4]	SSC or TSS	Calibration Standard	Temp. Adjusted	Interfer-ences
MD		no		no	180.1	TSS	no response		no
ME		no	grab and IS						no
MI	Secchi disk	no	grab	no	160.2	TSS			no
MN	Secchi disk	no	grab, auto-mated	no	180.1	160.2	Formazin, multi-point		color
MS	OBS	no	grab	no	manu. methods	TSS	formazin	temp. adj. in lab	no
MT	OBS	yes, wet sieve	IS	no		TSS	multi-point	temp. adj. to 25EC	no
NC	OBS	no	grab	no	SM	TSS	polymer, multi-point	yes, to 25EC	no
NE		no	grab	no					no
NH	OT	no	grab	no	180.1	no	manu. stds		no
NJ		wet sieve, Laser (future)	grab, Niskin bottle	no response	180.1	TSS, 160.2	manu. specs		no
NM		no, sieve substrate	grab, IS	no, start next year	180.1	TSS (160.2) SSC	0,20, 100, 800 NTU formazin, others	no	color
NV	OBS	no	in situ	no	no	no	2-point	no	no
NY, State	OBS	no	grab and IS	no	180.1	TSS, 160.2		no	no
NY, Mohawk		no	grab	no	180.1	No	single-point	no	color

Table 9. Agency turbidity procedural elements --Continued

Agency	NTU Technology [1]	PSD[2]	Sample Type[3]	Bedload	SOP[4]	SSC or TSS	Calibration Standard	Temp. Adjusted	Interfer-ences
OK	OBS	no	grab, IS	no	180.1		3-point	no	no
OR	OBS, OT	yes, wet sieve	grab and auto-mated	no	180.1	TSS	multi-point	no	no
RI	no response	no response	no response	No response	no response	no response	no response	no	no
SC	OBS	no	grab	no	SM	TSS (160.2)	formazin, multi-point	yes	no
TN	OBS	no	grab	no	180.1	no		yes	no
UT	OBS	no	grab	no	180.1	TSS	formazin	no	no
VA		no	grab	no	180.1	TSS (SM)	multi-point calibration	yes	color
WI	OBS	no	grab		manu. methods	no	single-point	no	no
WV	OT	no			180.1	TSS		room temp.	no
WY	OBS	no	grab	no	180.1	no	multi-point	no	no

Notes:
[1]OBS = optical backscatter meter; some—possibly most—questionnaire respondents included turbidimeters under the OBS category.
OT = optical transmissometer; some questionnaire respondents may have included turbidimeters under the OT category.
Secchi = Secchi disk.
[2]PSD = particle-size distribution.
[3]IS = integrated sampling (Edwards and Glysson, 1999).
[4]180.1 = USEPA method on turbidity analysis; SM = Standard Methods for the Examination of Water and Wastewater.
[5]160.2 = USEPA method on total suspended solids analysis.

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APPENDIXES

Appendix 1: List of Registrants and Respective Affiliation for the "Turbidity and Other Sediment Surrogates Workshop," April 30-May 2, 2002, Reno, NV.

LAST NAME	FIRST NAME	AGENCY	CITY	ST	ZIP CODE
Agrawal	Yogesh	Sequoia Scientific, Inc.	Redmond	WA	98052
Allander	Kip	USGS	Carson City	NV	89706
Anderholm	Scott	USGS	Albuquerque	NM	87109
Anderson	Chauncey	USGS	Portland	OR	97216
Anderson	Jeff	USDA/FS	Fresno	CA	93710
Ankcorn	Paul	USGS	Atlanta	GA	30360
Barteaux	Chris	FTS	Victoria	BC	V9B-6B2
Bartlett	Phil	FTS	Victoria	BC	V9B-6B2
Bent	Gardner	USGS	Northborough	MA	01532
Bernard	Jerry	USDA-NRCS	Washington	DC	20013
Berris	Steven	USGS	Carson City	NV	89706
Blumer	Stephen	USGS	Lansing	MI	48911
Bohman	Larry	USGS	Norcross	GA	30092
Bragg	Heather	USGS	Portland	OR	97216
Brooks	Amy	USGS	Portland	OR	97216
Buchanan	Paul	USGS	Sacramento	CA	95819
Burke	Judith	Waterose Envir. Services	Sooke, Canada	BC	V0S 1N0
Carey	Bill	BLM	Lakewood	CO	80228
Carlton	Spencer	Hydrolab Corp	Austin	TX	78754
Christensen	Victoria	USGS	Lawrence	KS	66049
Cleveland	Jonathan	ABB, Inc.	Carson City	NV	89706
Curran	Janet	USGS	Anchorage	AK	99508
Daly	John	Wedgewood Technology	San Carlos	CA	94070
D'Aversa	Mary	BLM	Eugene	OR	97440
Davis	Broderick	FISP	Vicksburg	MS	39180
DeCarlo	Eric	U of Hawaii	Honolulu	HI	96822
Demas	Charles	USGS	Baton Rouge	LA	70816
Dickey	Terry	Hydrolab Corp	Austin	TX	78754
Dorken	Brad	CA Forestry & Fire Prot	Redding	CA	96001
Dunkle	John	In-Situ Inc	Laramie	WY	82070
Eads	Rand	USFS	Arcata	CA	95521
East	Jeffery	USGS	Houston	TX	77004
Ellis	Colleen	Humboldt St University	Arcata	CA	95521
Eng	Dan	US Army Engineer	Vicksburg	MS	39180
Evans	Jonathan	USGS	Baltimore	MD	21237
Eychaner	James	USGS	Sacramento	CA	95826
Ferrari	Ronald	BOR	Lakewood	CO	80226
Fielder	Rick	YSI, Inc.	Yellow Springs	OH	45387
Freeman	Lawrence	USGS	Marina	CA	93933
Fulford	Janice	USGS	Stennis Space Ctr	MS	39529
Ganju	Neil	USGS	Sacramento	CA	95819
Garcia	Kerry	USGS	Carson City	NV	89706
Gartner	Jeffrey	USGS	Menlo Park	CA	94025
Glysson	G. Douglas	USGS	Reston	VA	20192
Gray	John	USGS	Reston	VA	20192
Hardy	Mark	USGS	Boise	ID	83702
Hauck	Bill	TMWA	Sparks	NV	89431

Appendix 1: List of Registrants and Respective Affiliation for the "Turbidity and Other Sediment Surrogates Workshop," April 30-May 2, 2002, Reno, NV. --Continued

Hawe	Patrick	BLM	Salem	OR	97306
Henry	Kent	In-Situ Inc	Laramie	WY	82070
Holdren	Chris	BOR	Denver	CO	80225
Horowitz	Arthur	USGS	Atlanta	GA	30360
House	Jon	USGS	Medford	OR	97501
Hudson	Marilyn	BOR	Yuma	AZ	85364
Hyer	Kenneth	USGS	Richmond	VA	23228
Jepsen	Richard	Sandia Nat'l Labs	Carlsbad	NM	88220
Johnson	Gary	USGS	Urbana	IL	61801
Jones	Blaine	Napa County RCD	Napa	CA	94559
Jones	Patty	BLM	Challis	ID	83226
Justus	Billy	USGS	Little Rock	AR	72211
Kerestes	John	USGS	Atlanta	GA	30360
King	Robin	USGS	Urbana	IL	61801
Kroening	Sherri	USGS	Altamonte Springs	FL	32714
Kuhnle	Roger	USDA-ARS	Oxford	MS	38655
Kuszmar	David	NCRWQCB	Santa Rosa	CA	95403
Lambing	John	USGS	Helena	MT	59601
Landers	Mark	USGS	Atlanta	GA	30360
Latysh	Natalie	USGS	Lakewood	CO	80225
Ledda	Trisha	APS	Redwood	CA	94063
Lewis	Jack	USDA/FS	Arcata	CA	95521
Lico	Michael	USGS	Carson City	NV	89706
Lizotte	Michael	ENDECO/YSI	Marion	MA	,02738
Lundgren	Robert	USGS	Bismarck	ND	58501
Madej	Mary Ann	USGS	Arcata	CA	95521
Majedi	Brenda	USGS	Baltimore	MD	21237
Marr	Stephanie	USGS	San Antonio	TX	78249
McDonald	John	YSI, Inc.	Yellow Springs	OH	45387
McKee	Lester	SFEI	Oakland	CA	94621
Melis	Theodore	Grand Canyon Center	Flagstaff	AZ	86001
Miller	Von	USGS	Iowa City	IA	52240
Montgomery	John	NM Dept. of Environment	Santa Fe	NM	87502
Moyer	Douglas	USGS	Richmond	VA	23228
Mueller	David	USGS	Louisville	KY	40299
Nalley	Greg	USGS	Iowa City	IA	52240
O'Halloran	Denis	USGS	Carnelian Bay	CA	96160
Olsen	Catherine	CWQCB	Truckee	CA	96161
O'Neal	C. Wayne	FISP	Vicksburg	MS	39180
Owen	Christopher	Apprise Technologies	Duluth	MN	55806
Papacosta	Kemon	APS	Redwood	CA	94063
Parchure	Trimbak	US Army Corps	Vicksburg	MS	39180
Parrish	Janet	USEPA Region 9	San Francisco	CA	94105
Patino	Eduardo	USGS	Fort Myers	FL	33901
Pavelich	M. Patricia	USGS	Denver	CO	80225
Phillips	Jeff	USGS	West Valley City	UT	84119
Potyondy	John	USDA	Fort Collins	CO	80526
Pratt	Thad	US Army	Vicksburg	MS	39180
Pruitt	Bruce	Nutter and Associates	Athens	GA	30605

Appendix 1: List of Registrants and Respective Affiliation for the "Turbidity and Other Sediment Surrogates Workshop," April 30-May 2, 2002, Reno, NV. --Continued

Rasmussen	Patrick	USGS	Lawrence	KS	66049
Richards	Kevin	USGS	Middleton	WI	53562
Risler	Palma	USEPA	San Francisco	CA	94105
Robinson	James	IBWC	El Paso	TX	79902
Rowe	Timothy	USGS	Carson City	NV	89706
Ryan	Sandra	USDA	Laramie	WY	82070
Rybicki	Nancy	USGS	Reston	VA	20192
Sadar	Mike	Hach Company	Loveland	CO	80539
Sando	Steve	USGS	Huron	SD	57350
Sarver	Kathleen	USGS	Charlotte	NC	28217
Schmidt	Larry	USDA/FS	Fort Collins	CO	80526
Schnoebelen	Doug	USGS	Iowa City	IA	52240
Schoellhamer	David	USGS	Sacramento	CA	95819
Schroder	LeRoy	USGS	Lakewood	CO	80225
Schroeder	Jim	BLM	Carson City	NV	89721
Sorenson	Stephen	USGS	Reston	VA	20192
Spatz	Peter	USGS	Cheyenne	WY	82001
Swietlik	William	USEPA	Washington	DC	20460
Tollner	Ernest	U of Georgia	Athens	GA	30602
Uhrich	Mark	USGS	Portland	OR	97216
Wagner	Richard	USGS	Tacoma	WA	98402
Wall	Gary	USGS	Troy	NY	12180
Warner	Richard	U of Kentucky	Lexington	KY	40546
Wellman	James	USGS	Tulsa	OK	74133
Wiele	Stephen	USGS	Tucson	AZ	85719
Williamson	Joyce	USGS	Rapid City	SD	57702
Wingate	George	BLM	Susanville	CA	96130
Wren	Daniel	U of Mississippi	University	MS	38677
Wright	Scott	USGS	Sacramento	CA	95819
Yang	Chih	BOR	Denver	CO	80227
Young	Christi	BOR	Denver	CO	80225
Ziegler	Andrew	USGS	Lawrence	KS	66049
Zlomke	Robert	Napa County RCD	Napa	CA	94559

APS, APS Analytical Standards, Inc
BLM, U.S. Bureau of Land Management
BOR, U.S. Bureau of Reclamation
CWQCB, California Water Quality Control Board
FISP, Federal Interagency Sedimentation Project
IBWC, International Boundary Water Commission
NCRWQCB, North Coast Regional Water Quality Control Board
Napa County RCD, Napa County Resource Conservation District
SFEI, San Francisco Esturary Institute
TMWA, Truckee Meadow Water Authority
US Army, U. S. Army Corps of Engineers
USDA, U.S. Department of Agriculture
USDA/FS, U.S. Department of Agriculture, Forest Service
USDA-ARS, U.S. Department of Agriculture, Agricultural Research Service
USDA-NRCS, U.S. Department of Agriculture, Natural Resources Conservation Service
USEPA, United States Environmental Protection Agency
USGS, United States Geological Survey

Appendix 2. Extended abstracts submitted as part of the "Turbidity and Other Sediment Surrogates Workshop," April 30-May 2, 2002, Reno, NV.

The extended abstracts of U.S. Geological Survey authors were reviewed and approved for publication by the U.S. Geological Survey. Articles submitted by others did not go through the U.S. Geological Survey process, and therefore may not adhere to our editorial standards or stratigraphic nomenclature. However, all articles were edited for consistency in appearance. The use of trade names in any article does not constitute endorsement by the U.S. Geological Survey. Authors and titles for the extended abstracts, which can be accessed directly at URL: http://water.usgs.gov/osw/techniques/TSS/listofabstracts.htm, are listed below.

Extended Abstracts (in alphabetical order)

Agrawal, Y.C., and Pottsmith, H.C., New isokinetic version of the LISST technology targest needs of the Federal Subcommmittee on Sedimentation

Ankorn, P.D., and Landers, M.N., Lessons learned from turbidity field monitoring of 12 metropolitan Atlantic streams

Burke, J.R., Methods for continuous automated turbidity monitoring in British Columbia, Canada

Christensen, V.G., Rasmussen, P.P., and Ziegler, A.C., Comparison of estimated sediment loads using continuous turbidity measurements and regression analysis

Eads, Rand, Continuous turbidity monitoring in streams of northwestern California

Gartner, J.W., Estimation of suspended solids concentrations based on acoustic backscatter intensity: Theoretical background

Glysson, G.D., and Gray, J.R., Total suspended solids data for use in sediment studies

Gray, J.R., The need for surrogate technologies to monitor fluvial-sediment transport

Holdren, G.C., Biological aspects of turbidity and other optical properties of water

Horowitz, A.J., The use of rating (transport) curves to predict suspended sediment concentration: A matter of temporal resolution

Lewis, Jack, Estimation of suspended sediment flux in streams using continuous turbidity and flow data coupled with laboratory concentrations

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Appendix 3: Questionnaire used to provide information on "Uses of Turbidity by States and Tribes," as part of the "Turbidity and Other Sediment Surrogates Workshop," April 30-May 2, 2002, Reno, NV.

Uses of Turbidity by USEPA Regions, States, and Tribes

The development of a strategy to standardize the measurement, application, and interpretation of turbidity and other measures of fluvial sediment has been needed for several decades. In order to address this critical issue, the USGS is sponsoring a Turbidity and Other Sediment Surrogates Workshop on April 30 to May 2, 2002 in Reno, Nevada. The objectives of the workshop are to:

1. Establish an operational definition for turbidity;
2. Establish a standard measurement(s) (lab and field) for defining the optical properties of water for both engineering and biological use;
3. Identify and define the various physics including state-of-the-art technology used in turbidity measurements;
4. Define the state-of-the-art methods for collecting surrogates for suspended-sediment characteristics (e.g., Suspended-Sediment Concentration (SSC) vs. turbidity); and
5. Recommend different technologies of turbidity to specific applications.

Your input is critical in addressing key issues related to application and interpretation of turbidity and other fluvial sediment methods. Consequently, we are especially interested in how turbidity and other measures of fluvial sediment are presently being used by your agency. Your participation in this questionnaire will greatly improve the ability of the workshop participants to meet the objectives and expectations of the workshop. In turn, your involvement will ensure that issues of interest to you related to the subject are addressed during the workshop.

Please take a few minutes to fill out the following questionnaire and return to me via email by April 12, 2002.

Contact Information:

Name: ____
Title: ____
State Agency or Tribe:_________________________________
Program Element: _____________________________________
Address: ____
Business Telephone No. ________________________________
Email: ____

***Turbidity Use*:**

1. How is turbidity being used (i.e., as a water quality criterion, TSS or SSC vs. turbidity relationships, as a "red flag" to potential problem areas)?

   What parameters are you actually interested in when measuring turbidity (e.g., light scatter by particles, light absorption by particles and (or) color, water clarity (vertical and (or) horizontal))?

2. What programs, regulations, or policy does it affect (e.g., water quality standards, beneficial uses, TMDLs)? *If used as water quality standard, please specify below, attach your standard via email, or fax to my attention at (706) 354-7925* (narrative and (or) numeric criterion as it relates to a beneficial use or use classification).

3. Have you made correlations or correspondence between turbidity (or TSS or SSC) and aquatic ecology (e.g., biological impairment, fish IBI, MBI (HBI, NCBI, etc. for macroinvertebrates)? If so, please explain.

Briefly, what ranges of turbidity (NTU) have you observed? *Please specify Ecoregion and type of water body.*

Do you analyze for TSS or SSC?____ If so, what ranges of TSS or SSC? *Please specific Ecoregion and type of water body and percent fines and sand fractions.*

4. In what water bodies are you presently using turbidity measurements (please check all appropriate)?

Rivers ______Lakes ______Wetlands ______
Estuaries ______Marine ______
Other ____

5. Have you noticed seasonal variation in turbidity that is not related to discharge or increases in sources (e.g., summer algal blooms, chlorophyll a)? Explain.

6. What database(s) are your turbidity data being stored? TSS or SSC (if different)?

If being archived, are there any critical ancillary information included (e.g., meter type, season, standards, environmental conditions, Ecoregion)?

Technology:

7. What type of technology are you presently using to measure turbidity?

Acoustic scattering sensors_______
Optical backscatter sensors_______
Optical transmissometers_________
Collimated laser illumination_______
Differential pressure sensor_______
Other:

8. What manufacturer(s) of turbidimeter(s) are you presently using?

9. Are you conducting particle size class analysis?_____ If so, what instrumentation and method (wet sieve, laser, etc.)?

10. What method(s) of environmental sampling are you using for turbidity (e.g., integrated samplers, automated pumping-type samplers, grabs, etc.)?

11. Are you collecting bedload?__________ If so, what type and size of device (e.g., Helley-Smith, 6-inch)?

Calibration:

12. What standard operating procedure(s) are you using for turbidity (e.g., USEPA Method 180.1, ISO7027)? Please be specific?

13. Are you analyzing for total suspended solids (TSS) or suspended-sediment concentration (SSC)? What standard(s) are you using?

14. What standard(s) do you use or recommend for turbidimeter calibration? Single-point or multiple-point calibration?

15. Do you adjust your environmental sample to a standard temperature prior to measuring turbidity (e.g., 25EC)?

Interferences:

16. What interferences have you observed while measuring turbidity (e.g., color, phytoplankton, chlorophyll, etc.)?

17. Have you attempted to correct turbidity measurements for interferences?

Future Needs:

18. In your opinion, what improvements should be made to turbidity technology? Sampling methods and procedures?

19. Particle size class analysis?

20. TSS or SSC?

21. In the future, what data needs (or data gaps) related to measurement of fluvial sediment do you anticipate (e.g., stream discharge, bedload, suspended load)?