TURBIDITY 6.7

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TURBIDITY 6.7

Turbidity, which can make water appear cloudy or muddy, is caused by the presence of suspended and dissolved matter, such as clay, silt, finely divided organic matter, plankton and other microscopic organisms, organic acids, and dyes (ASTM International, 2003a). The color of water, whether resulting from dissolved compounds or suspended particles, can affect a turbidity measurement.

> **TURBIDITY–an expression of the optical properties of a liquid that causes light rays to be scattered and absorbed rather than transmitted in straight lines through a sample.**
>
> — ASTM, 2003a

Although turbidity is not an inherent property of water, as is temperature or pH (Davies-Colley and Smith, 2001), the recognition of turbidity as an indicator of the environmental health of water bodies has increased over the past decade, resulting in a growing demand for high-quality and objective turbidity measurements. To meet this demand, relatively inexpensive, yet sophisticated instruments have been developed that allow for nearly continuous monitoring and data logging of turbidity in natural waters. Gray and Glysson (2003) note the following examples of disparate uses for turbidity data:

- Regulating and maintaining drinking water clarity.
- Determining water clarity for aquatic organisms.
- Indicating visual impairment in water.
- Real-time monitoring that indicates watershed conditions.
- Developing surrogates for concentration of suspended sediment (SSC) and other constituents.
- Monitoring the effects of land development and related human activities and subsequent management of natural resources.
- Determining transport of contaminants associated with suspended materials.

Although technological advances in turbidity measurement have produced a variety of instrument types to meet one or more of these differing objectives, turbidity instruments of different designs commonly do not yield identical or equivalent results. Moreover, the mixing of different source waters or dilutions of environmental samples may not produce linear results when measuring for turbidity because of the variety of factors that contribute to and can have an effect on turbidity. Selection of the appropriate turbidity instrument requires, therefore, consideration of project objectives, data requirements, and the physical and chemical properties of the water body.

This section on turbidity provides protocols and guidelines for selecting appropriate field and laboratory instruments and procedures for instrument calibration and maintenance, turbidity measurement, data storage, and quality assurance that meet stated objectives for U.S. Geological Survey (USGS) data-collection efforts.[1] The use of consistent procedures and instruments within and among projects or programs for which turbidity data will be compared over space and time is crucial for the the success of the data-collection program.

Select instruments carefully after reviewing project objectives and after consulting with cooperating agencies.

- **Report turbidity on the basis of the individual instrument design.**
- **Use identically prepared calibration solutions.**
- **Use consistent techniques and instrumentation throughout a data-collection program.**

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[1] For additional procedures related to continuous, dynamic monitoring of environmental waters, refer to Wagner and others (2000).

EQUIPMENT 6.7.1

When selecting an appropriate instrument for measuring turbidity, consider the potential effects that may result from the various properties of different water bodies. In addition, ensure that the measurement method, instrument design, and the data output are appropriate for the purpose and objectives for which these data are to be collected.

INTERFERENCES AND INSTRUMENT DESIGN 6.7.1.A

A variety of water properties can affect the measurement of turbidity (table 6.7-1). These include the color of dissolved constituents in the water matrix and particulate materials, particle size, and density. Sensor fouling, such as biological growth or scratches on the optical surface of the instrument, tends to produce a negative bias when light beams are blocked, but can produce a positive bias if scratches increase the scatter of the sensor's light beam (table 6.7-2). Likewise, bubbles or gases in the water can cause apparent turbidity (positive bias), and might require special sample preparation or handling to eliminate without changing the particle characteristics of the original sample (consult manufacturer’s recommendations).

To account for the effects of properties of water or interferences on turbidity, many types of instruments have been designed (table 6.7-3), many with multiple light beams or detectors (fig. 6.7-1). For example, although stray light can cause a positive bias in turbidity measurement because of apparent additional reflectance, many newer instruments, particularly those used for dynamic monitoring, are designed to minimize stray light.

For a valid comparison of turbidity data over time, between sites, and among projects, use instruments with identical optical and data-processing configurations.

Table 6.7-1. Properties of water matrices and their expected effect on turbidity measurement

[Negative, a negative effect produces a disproportionately low measurement; IR, infrared; nm, nanometers; positive, a positive effect produces a disproportionately high measurement; ~, approximately. See table 6.7-3 for descriptions of instrument designs.]

Properties of water matrix	Effect on the measurement	Direction of effect on the measurement	Instrument designs to compensate for effect
Colored particles	Absorption of light beam	Negative	• Near IR (780-900 nm) light source • Multiple detectors
Color, dissolved (in the matrix)	Absorption of light beam (if the incident light wavelengths overlap the absorptive spectra within the sample matrix)	Negative	• Near IR (780-900 nm) light source • Multiple detectors
Particle size:	*Wavelength dependent.*		
Large particles	• Scatter long wavelengths of light more readily than small particles	• Positive (for near IR light source, ~820-900 nm)	• White light (broad spectrum) light source
Small particles	• Scatter short wavelengths of light more efficiently than long wavelengths	• Positive (for broad spectrum light source, such as white light)	• Near IR (780-900 nm) light source
Particle Density	Increases forward and backward scattering of light at high densities	Negative	• Multiple detectors • Backscattering

Table 6.7-2. Sampling interferences and their expected effect on turbidity measurement

[Positive, a positive effect produces a disproportionately high measurement; Negative, a negative effect produces a disproportionately low measurement.]

Interference	Effect on the measurement	Direction of effect on the measurement
Stray light	Increases apparent light scatter	Positive
Bubbles from entrained gases	Increases apparent light scatter	Positive
Contamination of calibrants	Increases apparent light scatter	Positive
Optical sensor fouling or scratching	*Particularly with dynamic instruments.* • Possible beam blockage • Possible scratches on optical surfaces	• Negative • Positive
Bubbles	Increases apparent light scatter	Positive
Scratches on cuvette glass	Increases apparent light scatter	Positive

Table 6.7-3. Summary of instrument designs and capabilities, current reproducible technologies, appropriate applications, and approximate limits

[Indicated ranges are for example only and do not exclude the possibility that manufacturers can develop instruments under each design that surpass these ranges. Abbreviations: EPA 180.1, U.S. Environmental Protection Agency (1993) method 180.1; Regulatory, range complies with EPA regulations (unless specified "non-US"); IR, infrared; ISO 7027, International Organization for Standardization (1999) method 7027; nm, nanometers; US, United States]

Design	Prominent feature and application	Typical instrument capability range (nm)	Suggested application range (nm)
Nephelometric non-ratiometric	White light turbidimeters – Complies with EPA 180.1 for low-level monitoring.	0 to 40	0 to 40 Regulatory
Ratiometric white-light turbidimeters	Complies with EPA 180.1 for low-level monitoring. Uses a nephelometric detector as the primary detector, but contains other detectors to minimize effects of color and noise. Can be used for both low- and high-level measurement.	0 to 4,000	0 to 40 Regulatory 0 to 4,000
Nephelometric, near-IR turbidimeters, non-ratiometric	Complies with ISO 7027 – The wavelength (780-900 nm) is less susceptible to effects of color. Good for samples with color and good for low-level monitoring.	0 to 1,000	0 to 11 Regulatory (non-US) 0 to 1,000
Nephelometric near-IR turbidimeters, ratiometric	Complies with ISO 7027. Contains a ratio algorithm to monitor and compensate for variability and color.	0 to 4,000	0 to 40 Regulatory 0 to 4,000
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-ratiometric measurements. This is primarily used in high-level turbidity applications.	10 to 10,000	10 to 10,000
Backscatter/ ratiometric 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.	10 to 10,000	10 to 10,000
Light attenuation (spectro-photometric)	Not applicable for regulatory purposes. Wavelength 860 nm. Highly susceptible to interferences; best applied at low to medium turbidity levels.	20 to 1,000	20 to 1,000
Multiple-beam turbidimeters	Multiple light sources and multiple detectors are used to provide both reference and active signals, with at least four independent measurements being made. The final signal is determined with a ratio algorithm.	0 to 40	0 to 40 Regulatory 0 to 1,000

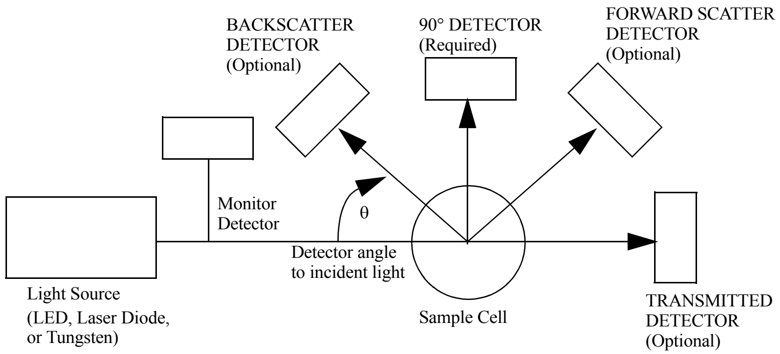

Figure 6.7-1. Photoelectric nephelometer (single-beam design) showing optional additional detectors for ratiometric, backscatter, or transmitted determination of turbidity. [Modified from Sadar (1998)].

One outcome of the availability of different instrument designs is that **turbidity measured using instruments with different optical designs can differ by factors of two or more for the same environmental sample, even with identically calibrated instruments**. Thus, raw data from differently designed instruments should not be considered directly interchangeable—the resultant data are inherently incomparable without additional work to establish relations between instruments over the range of the environmental conditions present.

Such complications underscore the need to clearly determine study objectives before selecting a turbidimeter, and to understand the limitations of the instrument selected. In addition, a carefully planned quality-assurance (QA) protocol is required to identify errors associated with different aspects of the turbidity measurement process. For additional information on turbidity measurement, see Sadar (1998), U.S. Environmental Protection Agency (1999), and the literature provided by instrument manufacturers.

TECHNICAL NOTE (1): Variability in measurements caused by instability in light sources, high particle densities, or color can be reduced by the use of multiple detectors at different angles. Such "ratiometric" instruments compute the turbidity value using a ratio of the light received by the different detectors. Furthermore, because turbidity is an optical measurement, the absorption of light by colored particles or by a colored matrix can cause a reduction in the apparent turbidity. The negative effect from color is minimized by using near-infrared light frequencies as the light source (tables 6.7-1, 6.7-3) or ratiometric techniques.

DATA STORAGE 6.7.1.B

To ensure that USGS turbidity data can be understood and interpreted properly within the context of the instrument used and site conditions encountered, data from each instrument type will be stored and reported in the National Water Information System (NWIS) using parameter codes and measurement reporting units that are specific to the instrument type, with specific instruments designated by the method code. The respective measurement units, most of which also are in use internationally, are listed and defined in table 6.7-4.

- The designations NTU, NTRU, BU, AU, and NTMU signify the use of a broad spectrum incident light in the wavelength range 400-680 nanometers (nm).
- The designations FNU, FNRU, FBU, FAU, and FNMU generally signify an incident light in the range between 780-900 nm.[2]

These reporting units are equivalent when measuring a calibration solution (for example, formazin or polymer beads—see section 6.7.2), but their respective instruments may not produce equivalent results for environmental samples. Additional information on specific instruments is provided in Appendix A, "Data Coding and Storage."

The term "turbidity unit," as used in this manual, refers generically to turbidity measured by instruments of undefined design. Note that manufacturers might, for the foreseeable future, retain the general use of the measurement unit "NTU" when referring to calibrants and equipment.

> **TECHNICAL NOTE (2):** Historically, reporting units included Jackson Turbidity Units (JTU) and Formazin Turbidity Units (FTU). Neither unit is still in common use, due to lack of precision (JTU) and lack of specificity about instrumentation type (FTU).

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[2] ISO 7027 specifically defines the light source for FNU measurements as having a wavelength of 860 nm, with a bandwidth of 60 nm. The angle of the detector must be 90 degrees from incident light, plus or minus 2.5 degrees.

Table 6.7-4. Reporting units corresponding to different turbidity instrument designs

[Parameter code numbers begin with a "P"; nm, nanometers; °, degree; ±, plus or minus; K, kelvin]

Detector geometry	Light wavelength	
	White or broadband (with a peak spectral output of 400-680 nm)	**Monochrome (spectral output typically near infrared, 780-900 nm)**
Single illumination beam light source		
At 90° to incident beam	Nephelometric Turbidity Unit (NTU)[1] (P63675)	Formazin Nephelometric Unit (FNU)[2] (P63680)
At 90° 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) (P63676)	Formazin Nephelometric Ratio Unit (FNRU) (P63681)
At 30° ± 15 to incident beam (backscatter)	Backscatter Unit (BU) (P63677)	Formazin Backscatter Unit (FBU) (P63682)
At 180° to incident beam (attenuation)	Attenuation Unit (AU) (P63678)	Formazin Attenuation Unit (FAU) (P63683)
Multiple illumination beam light source		
At 90° 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) (P63679)	Formazin Nephelometric Multibeam Unit (FNMU) (P63684)

[1] EPA Method 180.1 defines the optical geometry for NTU measurements. The detector angle must be 90° ± 30 to the incident light beam. The light source must be a tungsten lamp with color temperature 2,200 - 3,000 K. (Source: U.S. Environmental Protection Agency, 1993)

[2] ISO 7027 defines the optical geometry for FNU measurements. The detector angle must be 90° ± 2.5 to the incident light beam. The light source must be a light-emitting diode (LED) with wavelength 860 ± 60 nm. (Source: International Organization for Standardization, 1999).

INSTRUMENT SELECTION AND MAINTENANCE 6.7.1.C

Owing to potential differences in turbidity readings resulting from different instrument types, it is critical that when selecting turbidimeters, investigators carefully consider the objectives of the study and the uses of the resulting data. Considerations include:

- Whether the program will be regulatory in nature (typically applies in a drinking water context).
- The expected range in turbidity and the portions of that range that will be the most important to measure with accuracy.
- The need for consistency of method and comparability among data sources (whether data from one site need to be comparable with data from another site or with historical data).
- Which potential interferences are the most important to quantify or otherwise take into account (tables 6.7-1 through 6.7-4).

Within the United States, turbidity is regulated by the U.S. Environmental Protection Agency (USEPA) only for water that is intended for use as drinking water. In some cases, States use turbidity for regulations associated with the Clean Water Act (U.S. Environmental Protection Agency, 2002a). To date, the USEPA has approved the following three methods to measure turbidity in drinking water: (1) EPA Method 180.1 (U.S. Environmental Protection Agency, 1993), based on white-light nephelometric instrument designs; (2) GLI Method 2 (U.S. Environmental Protection Agency, 1999; Great Lakes Instrument Company, undated), which uses a dual-beam and dual detector technology with an 860 nm light-emitting diode (LED) light source to compensate for color and reduce erratic readings; and (3) Hach Method 10133 (U.S. Environmental Protection Agency, 2002b), an inline process-stream method that is unlikely to be used within USGS. Owing to a nonlinear response of these technologies at high turbidities, their applicable range in drinking water is from 0 to 40 turbidity units. Instrument designs that conform to EPA Method 180.1 or GLI Method 2 may perform poorly (including nonlinear responses) at turbidities that commonly occur in nature (greater than 40 turbidity units). Also, white-light instruments typically consume more power than monochrome instruments, so access to the regional power grid is commonly required. For these methods, waters with turbidities greater than 40 must be diluted before measuring. **For studies involving the measurement of turbidity in finished drinking water, either EPA Method 180.1, GLI Method 2, or Hach Method 10133 must be used**. (This requirement commonly is applied when determining ground-water turbidity in water from wells used for human consumption.)

> **TECHNICAL NOTE (3)**: One other method, ISO 7027 (International Organization for Standardization, 1999), has been defined for waters with low turbidity and is in use in Europe and elsewhere; however, as of 2003, ISO 7027 had not been accepted by USEPA for compliance with drinking-water regulations in the United States.

USEPA-approved methods generally are not required when providing data for regulatory purposes in accordance with the Clean Water Act (U.S. Environmental Protection Agency, 2002a). For example, nonregulatory methods can be used to determine changes in turbidity of surface water resulting from resource management actions, or to correlate turbidity with regulated constituents such as suspended sediment (Uhrich and Bragg, 2003), nutrients, or bacteria (Christensen and others, 2000). For such data-collection efforts, it may be possible to use alternative instrument designs that are targeted towards specific study objectives and that will accommodate the range of natural conditions that occur in the water body. **Before selecting a methodology and the corresponding instrumentation, determine if USEPA-compliant methodologies are necessary.** Given the breadth of applications for measuring turbidity, no particular sampling consideration can be defined as the most important in all cases; however, **consistency of instrument types and calibration procedures within monitoring programs or among individual projects is one of the most important aspects to consider when designing a data-collection program that will include turbidity.**

Nephelometry: the measurement of light scattering using a light detector 90 degrees from the incident light (USEPA, 1999).

Decision Considerations for Instrument Selection

Numerous factors are involved when deciding on the type(s) of equipment that are appropriate for a given study. A major consideration in the selection of a turbidity instrument is whether turbidity will be measured under **static** or **dynamic** conditions. Water samples that are removed from the source and are measured with benchtop meters are considered static. Submersible sensors allow turbidity measurement under dynamic water conditions, using either instantaneous profiling techniques or a deployed instrument for continuous monitoring.

Measurements taken under static conditions compared to those taken under dynamic conditions differ primarily because static-measurement techniques do not completely account for particle settling, whereas dynamic-measurement techniques more accurately reflect the dynamic nature of particle movement within the water body. Such differences are particularly pronounced when coarse silt or sand-sized particles are present. Also, temperature changes in the sample during transport from source water to laboratory can cause differences between measurements taken on a static sample (benchtop instrument) and measurements taken under dynamic (in situ or pumped) conditions. Some benchtop instruments do, however, provide flowthrough chambers that keep the sample in motion to approximate the dynamic conditions in the original water body.

As discussed previously, instrument selection begins with a thorough consideration of study objectives, and continues with questions about the use of the data, the type of water body and its sources of turbidity, and the way in which the data will be collected and stored. A decision tree (fig. 6.7-2) is provided below to help guide the selection process. In the decision process described below, numbers 1 through 3 pertain to information in fig. 6.7-2; numbers 4 and 5 provide additional guidance.

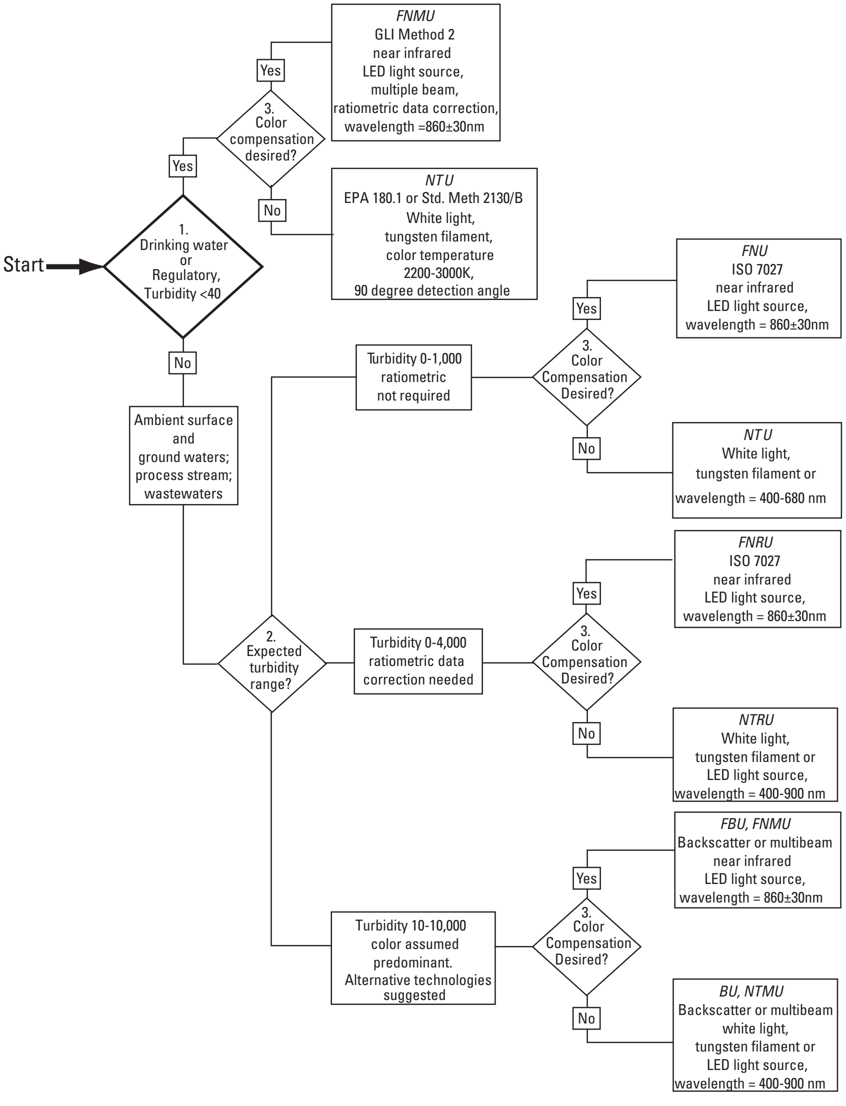

Figure 6.7-2. Decision tree to determine appropriate instrumentation designs for intended turbidity measurements.

Decision Considerations (considerations 4 and 5 are not shown in fig. 6.7-2)**:**

1. **Is the study regulatory in nature?**
   If "Yes," go to step **3** (fig. 6.7-2).
   If "No," continue to step **2** (fig. 6.7-2).

   If the study involves regulation of drinking water, the instrument choices are limited by the methods accepted by the USEPA for drinking water. If the study involves State regulations (for example, those proposed under provisions of the Clean Water Act), the regulations may require the use of one or more specific instrument designs, which cannot be anticipated in this protocol.

   If the study does not involve turbidity in drinking water or other specially designated instrument types, consider using instrument designs that accommodate a broader range of environmental conditions.

2. **What is the expected range in turbidity, or what part of the range is most important to measure accurately?**

   For turbidities in the range of 0-1,000 units, single-detector nephelometric measurement may work adequately if the instrument is calibrated in the same range as the sample. As particle densities increase, however, the backward scattering of light particles increases to the point that it can cause interference with single-detector nephelometry, resulting in a negative effect on the measurement or an unstable reading (table 6.7-1). Multiple detectors at different angles can be used, with the turbidity value determined by a ratio of the light received by the different detectors. Ratioing helps to reduce noise in the turbidity signal, especially at ultra-low turbidities or when particle densities are high. Instruments that utilize backscatter detection also can help compensate for such effects at high turbidities. Backscatter is particularly important above 1,000 units. The effect of particle size should be considered too. Positive effects on turbidities for water sources with predominantly large or small particle sizes can be minimized with careful consideration of the study objectives, the water source, and instrument requirements.

3. **Is the water source colored by dissolved or particulate materials, and should the color be part of the measured turbidity?**

   Color in water samples, from dissolved or particulate materials (or both), can cause a negative effect (Sutherland and others, 2000) on measured turbidity (table 6.7-1). In some cases, it could be desirable to quantify this decrease by using an instrument with a broad-spectrum or white-light source that would be sensitive to color changes. Alternatively, when measuring changes in turbidity that are unrelated to color, instruments with a near-infrared light source should be used.

4. **Will the measurement be done by dynamic means or by a benchtop measurement of samples removed from the source?**

   In most cases, it is preferable to measure turbidity directly within the water source or in a pumped sample (dynamically), rather than taking a sample from which an aliquot must then be measured using a benchtop (static) method. Dynamic measurement is preferred to static measurement because of problems with representative subsampling, settling of solids and temperature changes in static samples, and interferences such as condensation or scratches on sample cuvettes. Dynamic techniques usually are required for continuous monitoring, and the sensors often can be combined with other sensors that measure additional properties, such as temperature, specific conductance, dissolved oxygen, and pH. In some cases, however, dynamic readings are not feasible or desired (for example, if a measurement is needed of a composite sample or in a laboratory setting). Most instruments used for static measurements are not capable of being used for dynamic measurements; whereas some instruments used for dynamic measurements can be immersed in a water sample and the measurement taken statically.

5. **What resolution is required in the resulting data?**

   For turbidity data that primarily will be in the low (less than 5 turbidity units) or ultra-low (less than 1 unit) ranges, the necessary resolution may be down to the 100th or 10th decimal place, whereas for turbidities greater than 40 units, resolution to the nearest 5, 10, or even 100 reporting units might be adequate. After determining the primary instrument design requirements, consult literature or online sources of individual instrument manufacturers for information on available resolution.

Once a particular instrument design and set of reporting units (table 6.7-4) have been selected, the user evaluates the literature and cost information from instrument manufacturers to decide on the most appropriate model. Although rapid changes in optical and sensor technology preclude the inclusion of specific manufacturers' models in figure 6.7-2, Appendix table A-1 provides a partial list of available models according to instrument design and reporting units, current as of April 2004, which can be used in combination with figure 6.7-2 to narrow the options for the choice of an instrument to meet a specific set of study objectives.

Figure 6.7-2 shows that differences among instrument designs have resulted in a wide array of options for measuring turbidity. Although these options provide flexibility and the capability to tailor the data-collection program to the needs of each particular study, they also present problems for data comparison among studies with differing objectives or water sources, particularly if different equipment is used in the studies. When data are to be compared among different programs or studies, sending duplicate samples to a laboratory such as the National Water Quality Laboratory (NWQL) provides a reference for quality-assurance purposes and is recommended (the NWQL, for example, simulates dynamic measurement using a flowthrough chamber with its benchtop meters). If a dynamic measurement is used for determining field turbidities, it can be useful to compare these data with results obtained from a laboratory-analyzed sample, as long as the properties contributing to the sample turbidity do not degrade during storage and transit (see section 6.7.3).

Dynamic measurement is the preferred method for determining the turbidity of a water body, provided that this method is consistent with study objectives and other study protocols. Dynamic measurement more accurately reflects surface-water conditions than static determination because particle settling in cuvettes is avoided.

Signal-Processing Options

Because turbidity measurements can be highly variable, a range of signal-processing options may be available with different instruments. Some instruments can provide statistics such as the maximum, minimum, mean, median, range, and variance of many readings over a timespan of a few seconds. These statistics can be useful for reducing variability in recorded turbidities, for understanding sources of turbidity, or for diagnostic purposes. Instruments that use proprietary algorithms can provide functions intended to reduce spikes in instantaneous data, sometimes employing user-defined variables such as time constants and spike thresholds. Such algorithms can provide a smoother signal than simple instantaneous measurements; however, because the algorithms may not be published, these data must be used with care and in consideration of the data-quality objectives of the study. Note that if the instrument uses signal averaging to smooth the data output, the instrument response to changes in turbidity readings can be slowed. **Select the output you desire in accordance with study objectives and data-storage and transmittal requirements.**

Maintenance of Turbidity Instruments

The equipment and supplies commonly used for field measurement of turbidity are listed in table 6.7-5. These include supplies generally needed for the maintenance, storage, and cleaning of the selected instrument. Routine maintenance of turbidity instrumentation is critical, particularly for continuously deployed, dynamic applications.

Table 6.7-5. Equipment and supplies used for measuring turbidity

[Modify this list to meet the specific needs of the field effort. Abbreviations: ≤, less than or equal to; mm, millimeter; mL, milliliter]

- Turbidimeter, spectrophotometer, or submersible-sensor instrument (such as a multiparameter instrument with a turbidity sensor).[1]
- Calibration turbidity stock solutions and standards
  - Formazin stock suspension, commercially obtained or prepared from scratch with hydrazine sulfate and hexamethelenetetramine chemicals, or
  - Instrument-specific polymer solutions containing styrene divinylbenzene beads.
- Sample cells (cuvettes), clear colorless glass (supplied from instrument manufacturer).
- Inert (dry) gas (for example, nitrogen) and gas-delivery apparatus; tanks must be fitted with regulators and filter.
- Sample bottle (preferably an amber bottle that does not sorb suspended material).
- Silicon oil, optical grade (with same index of refraction as sample cells; supplied by instrument manufacturer).
- Paper tissues, extra lint free.
- Turbidity-free water, deiononized water filtered through a ≤ 0.2 mm filter membrane with precision-sized pores.
- Bottle to hold turbidity-free water, cleaned and rinsed three times with filtered water.
- Volumetric flask, Class A, 100 mL or 500 mL.
- Volumetric pipet, Class A, 5.0 mL and pipet filler.

[1] See text, figure 6.7-2, and table 6.7-3 for description of appropriate instrument types.

- Before field use of water-quality instruments, become familiar with the manufacturer's instructions for calibration, operation, and maintenance.
- The maintenance program must include:
    - Regular cleaning of optical surfaces. Use a lint-free cloth, soft toothbrush, or paintbrush and deionized water for cleaning optical surfaces. Exercise care so as not to damage optical surfaces. Optical surfaces of some instruments may be more easily damaged than others — check manufacturer’s recommendations before proceeding with cleaning and use.
    - For deployed, dynamic monitoring, the cleaning frequency should be approximately every 2 to 4 weeks. More frequent cleaning is necessary where biofouling is particularly apparent.
    - Verification that wipers are operational. Change wiper pads when they are excessively dirty or worn; avoid hindering or forcing wiper movement, or scratching optical surfaces.
    - Washing sample cuvettes after each use (wear powderless, disposable laboratory gloves and use a lint-free cloth).
    - Regular calibration or verification against secondary calibration solutions.
    - Examination of collected data for indication of instrument malfunction.
- Test all field instruments in an office or laboratory before use. Record all maintenance and repairs in the instrument logbook.

CALIBRATION 6.7.2

To ensure the collection of reliable turbidity data, carefully follow the standard calibration procedures described below and the instructions from the instrument manufacturer. Even identically calibrated turbidimeters can produce significantly different readings of native-water sources for instruments of different designs. All turbidity instruments are designed to produce equivalent responses to “scratch” formazin (prepared in the office laboratory), the accepted reference solution, despite differences among the designs. The calibration process provides a common point for standardization, and if turbidity were an inherent physical property, then measurements of environmental waters would be expected to have similar numerical values for any instrument. However, the varying particle and color characteristics of environmental waters differ fundamentally from formazin crystals. This has led manufacturers to develop calibration solutions that in some cases are tailored to specific instruments, potentially increasing the magnitude of error if solutions are used improperly. **Where turbidity data are to be compared within or among data-collection projects, the consistent use of sampling, calibration, and measurement equipment and techniques is necessary.**

The USGS follows conventions for turbidity determination established by ASTM International (2003a), which defines three levels of calibration solutions (calibrants) - “Reference Turbidity” solutions, “Calibration Turbidity” solutions, and “Calibration Verification” solutions or solids.

- The **Reference Turbidity** solution is a calibrant that a skilled analyst synthesizes reproducibly from traceable raw materials. All other calibrants are traced back to this solution. The reference standard for turbidity is formazin made from scratch (see below for preparation instructions), a polymer with repeating units of $C_2H_4N_2$.
- **Calibration Turbidity** solutions are those that are used to adjust instrument readout, and must be traceable and equivalent to the reference turbidity calibrant to within accepted statistical errors.

TECHNICAL NOTE (4): Acceptable calibration turbidity solutions include dilutions of formazin made from scratch (scratch formazin), commercially prepared stabilized formazin (such as StablCal®, available from Hach Company in formulations of 4,000 turbidity units and lower)[3], and styrene divinylbenzene beads (SDVB) (such as AMCO-AEPA-1® polymer)[3]. Although stabilized formazin calibrants have a much longer shelf life than solutions diluted from scratch formazin, settling of formazin crystals can still be observed when they sit unused. Calibrants made from SDVB have a more uniform grain size than formazin and tend to settle less over time, but often are custom developed for specific instruments and must be purchased accordingly.

- **Calibration Verification** calibrants are those used to perform instrument checks in the field. Calibration verification calibrants may include but are not limited to calibration turbidity solutions. Sealed or solid materials should not be used to adjust instrument performance.

Calibration turbidity solutions and calibration verification calibrants can be instrument specific. Be careful to check the manufacturer's instructions. Use of calibrants with instruments for which they are not designed can introduce significant errors.

All evidence indicates that formazin and stabilized formazin are safe to use as primary turbidity standards when good laboratory practices are followed (Sadar and others, 1998). Standard safety procedures, including wearing laboratory coats, glasses, and gloves, are considered adequate protection for routine use of formazin. The primary hazard from the formazin solution is physical irritation. Of the components in formazin, only formaldehyde will evaporate and

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[3] The use of brand names in this report is for example purposes only and does not constitute an endorsement by the U.S. Geological Survey.

cause exposure through the air; however, its concentration in this mixture is well below what is considered to be a health risk. Concentrations in formazin solutions diluted below 4,000 turbidity units will result in exposures that are reduced even further. For more information, see the Material Safety Data Sheet (http://www.ilpi.com/msds/index.html#Internet) or Sadar and others (1998).

TECHNICAL NOTE (5): The raw materials used in the synthesis of scratch formazin do present potential safety concerns. These materials, specifically hydrazine sulfate and hexamethylenetetramine (hexamine), are currently (2004) listed as a suspected carcinogen and an experimental mutagen, respectively. Hydrazine sulfate also is a strong reducing agent and as such requires standard laboratory safety precautions (avoid inhalation, ingestion, and contact with skin, and work in a fume hood). In water, it separates into free hydrazine and sulfuric acid. An excess of hexamethylenetetramine reacts with acid to produce formaldehyde at neutral pH. The formaldehyde then reacts with dissolved hydrazine to produce the formazin polymer. The final product, 4,000 turbidity-unit formazin suspension, contains 3.2 parts per million hydrazine sulfate, 0.1 percent formaldehyde, 0.2 percent formazin, 0.5 percent ammonium sulfate, and 4.7-percent hexamethylenetetramine. Laboratory rats were fed 4,000-NTU formazin at 5,000 mg/kg body weight with no toxic effect (Sadar and others, 1998)

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Avoid inhalation and ingestion of or skin contact with hydrazine sulfate when preparing formazin solutions. Work in a fume hood.

6.7.2.A CALIBRATION SOLUTION: USE, PREPARATION, AND DILUTION

A stock formazin solution may be prepared in the laboratory or may be purchased from a manufacturer. Serial dilutions are made to achieve the desired calibration interval. **Commercially prepared calibration turbidity solutions are recommended for routine instrument calibration to avoid any safety and quality-assurance concerns.**

Under circumstances in which study personnel need to prepare a stock turbidity suspension, precise laboratory practices are required in order to achieve consistent results.

- Always use turbidity-free water (deionized water passed through a filter media of less than or equal to 0.2 μm) at 20-25°C for mixing dilutions or suspensions.
- Prepare the stock turbidity suspension monthly and calibrant dilutions immediately prior to instrument calibration. **Calibrant solutions made from diluted scratch formazin are stable for only a few hours to a few days, depending on the concentration** (ASTM, 2003b)**. With the exception of 4,000 NTU formazin, commercial calibration solutions such as StablCal® or AMCO-AEPA-1® must not be diluted because changes will occur in the suspension matrix that will render the dilutions nonlinear.**
- Store reagents, as appropriate, in a dust-free cabinet or refrigerator.

Inconsistent techniques used to dilute calibrants and variable temperatures can add significant measurement error.

To prepare a 4,000 turbidity-unit formazin stock suspension[4]:

1. Wearing laboratory powderless disposable gloves, quantitatively transfer 5.0 g of reagent-grade hydrazine sulfate [$(NH_2)_2 \bullet H_2SO_4$] into approximately 400 mL of turbidity-free water in a 1-L volumetric flask.
2. Quantitatively transfer 50.0 g of reagent-grade hexamethylenetetramine [$(CH_2)_6N_4$] into approximately 400 mL of turbidity-free water in a separate, clean flask; stopper and swirl until the $(CH_2)_6N_4$ is completely dissolved. Filter through a 0.2-µm filter into a clean flask.
3. Quantitatively transfer the filtered hexamethylenetetramine into the flask containing hydrazine sulfate (from step 1). Dilute solution to the 1-L mark with turbidity-free water. Stopper and mix for at least 5 minutes, but no more than 10 minutes.
4. Let stand for 24 hours at 25° ± 1°C to develop the 4,000 turbidity-unit suspension.
5. Transfer the solution to an opaque, light-blocking, polyethylene bottle and store refrigerated. The 4,000 turbidity-unit stock suspension is stable for about a year, if stored at 20-25°C in amber polyethylene bottles.

To prepare 500 mL of a 400 turbidity-unit calibrant solution, dilute the 4,000 turbidity-unit stock solution by a 1:10 ratio as follows:

1. Mix 50 mL of the 4,000 turbidity-unit stock solution in a 500-mL flask.
2. Dilute to the mark with turbidity-free water and mix.
3. Transfer the solution to an opaque, light blocking, polyethylene bottle and store refrigerated. The 400 turbidity-unit stock solution is stable only for about one day.

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[4] Refer to ASTM International (2003a) for detailed instructions.

To prepare a 40 turbidity-unit calibrant solution, dilute the 400 turbidity-unit solution by a 1:10 ratio as follows:

1. Mix 10 mL of the 400 turbidity-unit stock solution in a 100-mL flask.
2. Dilute to the mark with turbidity-free water and mix.
3. Transfer the solution to an opaque, light-blocking, polyethylene bottle. **Prepare the calibrant suspension on the day the calibrant is needed, use it immediately after preparation, and discard unused calibrant. The 40 turbidity-unit stock solution is stable only for about 1 day.**

When chemicals to be used for preparation of reagents are received, mark the dates of receipt and expiration on the container. When a calibrant is prepared, label the container with the contents, date of preparation, expiration date, and preparer's initials. Store formazin in a cool, dark place (a storage cabinet or frost-free refrigerator). After use, pour waste calibration solutions into a labeled glass or plastic container for proper disposal.

Reagents and calibrants must not exceed their shelf life.

CALIBRATION PROCEDURES 6.7.2.B

Although calibration principles are similar whether using static or dynamic sensors, in practice the steps taken can be different.

- Benchtop meters use a small, 15- to 25-mL sample holding cell, or "cuvette," which is inserted into the measurement chamber. This results in a static measurement unless additional flowthrough equipment is used.
  - Values must be read from the meter before particle settling can affect the measured turbidity.
  - If particle settling of sand or silt occurs before the measurement can be completed, the sample results must be recorded in the database to reflect the possible bias in the

data. (For input to the USGS NWIS database, the results would be coded with an "E" remark, indicating the value is an "Estimate" only.)

- — The cuvettes used for calibrating static turbidimeters are identical to those used in the meter when taking a turbidity reading.

- ▶ Submersible meters collect data by immersing a turbidity sensor in the sample media, but are calibrated using a separate chamber that allows the sensor to be immersed in the calibrant.

Benchtop (static) turbidimeter calibration

The calibration instructions and procedures that follow are general and should be modified to apply to the instrument being used—check manufacturer's instructions. Refer to table 6.7–5 for a list of supplies commonly used for turbidity measurement.

To calibrate a benchtop turbidimeter:

1. Prepare formazin suspensions as described above.
    - Allow stock solutions to come to room temperature.
    - Calibrate each instrument range using at least two calibrant concentrations, and three or more if the instrument allows it. Use calibrant solutions that bracket the range of the turbidity anticipated in the sample solution.
    - Prepare dilute calibrant fresh from the stock at the time of use—after dilution, the stock suspension is stable only for a few hours.
    - Formazin-based calibrants should be resuspended by inverting the calibrant 25 times (1-second inversion cycle), followed by a 2- to 10-minute wait to allow for bubble removal. Calibrants of 40 turbidity units or less will remain suspended for up to 30 minutes; calibrants greater than 40 turbidity units may require more frequent resuspension.
    - **Do not use calibrants with flocculated suspensions**.
2. Turn on the turbidimeter and allow it to warm up. (Check manufacturer's instructions for equipment startup.)

3. Select the desired turbidity range. Use a calibration range to equal the high value of calibrant for the range of interest.

4. Rinse a clean, dry, scratch-free cell with the highest concentration of the calibrant for the instrument range setting or range of interest. Index-mark the cell to ensure consistent orientation within the instrument. (See manufacturer's instructions for index-marking the cell.)

    a. Hold the sample cell by the rim (top lip), not beneath the lip.
    b. Pour calibrant into the sample cell to the fill mark.
    c. Wipe the exterior of the cell using a soft, lint-free cloth or tissue to remove moisture (condensation) from cell walls.
    d. Apply a thin layer of silicon oil onto the exterior of the cell to reduce condensation on the cell and to mask slight scratches and nicks. Apply silicon oil uniformly onto the blank cell if it will be used on the cell filled with calibrant (follow manufacturer's recommendations).
    e. Before inserting the cell containing calibrant into the instrument, ensure that no air bubbles are present in the cell. If necessary, degas the sample according to manufacturer's instructions. Air bubbles can cause significant positive bias in turbidity measurements (table 6.7-1).

5. Orient the calibration cell in the cell holder according to the index marks—**the calibration cell and sample cell must have identical orientation** when in the instrument-measurement chamber.

6. In the instrument logbook, record the instrument value for each calibrant. Most modern turbidimeters contain calibration curve-fitting capabilities specific to that instrument, allowing the instrument to produce sample readings that may be used directly. If the meter does not have this capability, you will need to construct a calibration curve to correct sample readings to the calibrated turbidity. To determine turbidity using a calibration curve (see American Public Health Association, 1998, for more details on this procedure):

   a. Record the instrument response to a range of calibration solutions bracketing the expected turbidity of the sample.
   b. Create a graph showing the value of the instrument response (x-axis) against the turbidity value of the calibration solutions (y-axis).
   c. Using linear regression, plot a line that encompasses the plotted values.
   d. For water samples, input the instrument reading on the x-axis and read the corresponding corrected turbidity value from the y-axis, or determine the corrected y-value from the regression equation on the instrument reading.

7. (Adjust the calibration control until the value on the meter equals the value of the calibrant used.

8. Repeat steps 4-7 as recommended by the instrument manufacturer for calibration solutions bracketing the range of expected turbidities. Use calibrants representing at least two different turbidities, including the expected maximum and minimum. Ensure that calibrants are within the linear portion of the instrument's operating range.

Submersible (dynamic) turbidity sensor calibration

Most dynamic turbidimeters and multiparameter instruments with turbidity sensors are microprocessor based, with the calibration parameters stored in instrument memory. Turbidity values of the calibrants are user selectable in some instruments, but others have internally established calibration ranges that cannot be changed.

- ▶ Check calibrants in the 1–5 turbidity-unit (low-level) range to assess the actual performance of the instrument near the detection limit; **instrument reliability often decreases at turbidities less than 2 turbidity units—**consult the manufacturer's specification for the expected accuracy of the measurement.

- Refer to Wagner and others (2000) for instructions on record keeping when cleaning and calibrating continuously deployed instruments, and for acceptable tolerances. Monitor the output carefully to ensure that turbidity readings are stable before confirming the calibration.
- **Calibrate the instrument using calibration turbidity solutions before leaving for the field**. While in the field, check instrument performance periodically using a calibration or verification calibrant and turbidity-free water.
- The optical surface of the sensor must be clean before beginning the calibration procedure. In deployed, continuous monitoring situations, pipes or other structures that house the sensor also may require periodic cleaning.

To calibrate a submersible turbidity sensor *(modify the general instructions that follow as necessary so that they are compatible with the manufacturer's instructions)***:**

1. Prepare a sufficient volume of the selected calibration solution or verification calibrant, as described previously. The volume of calibrant required could be 500 mL for some instruments, particularly if the entire sonde bundle will be immersed.
2. **Select Procedure (A) or (B).** The same procedure, once tested and selected, also should be applied to instruments used in future studies against which the data could be compared.

   Procedure A. Immersion of the entire sonde (bundle of field-measurement sensors, including the turbidity sensor) requires larger volumes of calibrant; calibrant is vulnerable to contamination and dilution. The sonde sensor guard may need to be removed.

   Procedure B. Immersion of turbidity sensor only—depending on sonde configuration, isolation of the turbidity sensor and achieving a bubble-free optical surface could be difficult. This technique minimizes the volume of calibrant required for calibration.
3. Determine the number of calibration points to be used (a minimum of two, but three is preferred) and configure the instrument for this number of points, if applicable.

4. For a zero turbidity-unit calibrant (or turbidity-free water):
    a. Rinse sonde/sensor with deionized water, followed by a portion of the turbidity calibrant.
    b. Immerse sensor in calibrant, or add enough calibrant to cover the sensor in the calibration chamber.
    c. Agitate the sonde/sensor repeatedly to remove bubbles from the optical surface (activate mechanical wiper, if present).
    d. Set sensor vertically on a flat surface or use a ringstand to hold it.
    e. Monitor turbidity readings for 1 to 2 minutes or longer to ensure that readings are stable (consult manufacturer's recommendations and signal-processing information). Record the pre-calibration value in the instrument logbook or on the field sheet.
    f. Confirm the calibration value or adjust the instrument calibration using the manufacturer's instructions.
    g. Remove the sonde/sensor and dry thoroughly to minimize dilution or contamination of the next calibrant.
    h. Discard the calibrant into a labeled waste container and hold for proper disposal.
    i. If measurement of color-derived turbidity is not desired, filter (using a 0.2-µm pore-size filter) an aliquot of the sample water and use the filtered water in place of turbidity-free water.

5. Using a second calibrant with a value near the maximum of the expected turbidity range, repeat steps 4(a-i). Repeat again with a third calibrant near the middle of the expected range if increased accuracy is desired and instrument software permits. If the software does not permit a three-point calibration, the third calibrant can nonetheless be used to document the accuracy of the calibrated instrument near the middle of the expected range. If an "out of range" error is displayed, verify the intended calibrant value and start again with the first (zero) calibrant solution. Repeat the calibration procedure if the measurement is not within the specification. Record all calibration and verification measurements in the instrument logbook.

6. On a one-time basis, determine the maximum value that can be reported by the instrument by holding a lint-free cloth over the optical sensor and recording the turbidity. Use this value as an indicator that turbidity might have been greater than the range of the instrument during measurements in a water body.

Spectrophotometric turbidimeter calibration

Spectrophotometric turbidity measurements, sometimes referred to as absorbtometric or attenuation turbidity, are useful to indicate relative values or to monitor changes in turbidity with time. Spectrophotometers, however, measure light transmission (rather than light scattering) using a narrow, short-wavelength light source, are inaccurate for absolute turbidity measurement, and are unrated for instrument sensitivity. Most of the spectrophotometers used for measuring turbidity are benchtop or portable instruments, so sample handling is similar to that described for benchtop (static) turbidimeters.

- ▶ Use spectrophotometry as an indication of optical properties in water only upon careful review of study objectives and alternative available technology.
- ▶ Instrument response is negative (that is, the detector response decreases) with increasing turbidity, which is the opposite of traditional turbidity and backscatter instrument responses. Report results in Attenuation Units (AU) or Formazin Attenuation Units (FAU), depending on the light source (table 6.7-4). (The overwhelming majority of available spectrophotometric turbidity instruments use FAU.)

Spectrophotometers commonly have a stored program for turbidity that has been factory calibrated and that can be verified but not adjusted. Check the instrument output against that of a different instrument every few weeks while the instrument is in use. Check the relative accuracy of the turbidity measurement before leaving for the field by inserting calibration turbidity solutions covering the FAU range needed. Accounting for a change in reporting units, calibration steps for spectrophotometric determination are identical to those for static measurement of turbidity, including the possible need for constructing a calibration curve (see instructions under **Benchtop (static) turbidimeter calibration**, steps 1-8).

MEASUREMENT 6.7.3

Three methods for field-measurement determinations of turbidity are described in this section: static (or benchtop) determination (6.7.3.A); dynamic (submersible) determination (6.7.3.B); and spectrophotometric (absorptometric) determination (6.7.3.C). Procedures for the use of turbidity instruments are similar for various surface-water and ground-water applications. The sampling methods used and the considerations needed for accurate representation of the intended water conditions, however, depend on the objectives and intended data use of the study and on site type and conditions. Routine sampling of streams by the USGS typically involves isokinetic, depth-integrated sampling methods (NFM 4.1; NFM 6.0.2). Much of the routine sampling of ground water at wells by the USGS involves well purging (NFM 4.2; NFM 6.0.3).

- ▶ Before making a turbidity determination, ensure that the instrument to be used has been cleaned and calibrated properly, and that the calibration process has been accurately documented (section 6.7.2).
- ▶ Biased or erroneous readings can result from numerous factors, including unmatched cell orientation, colored sample solutions, gas bubbles, condensation, and scratched or dirty sample cells (see tables 6.7–1 and 6.7–2). Condensation on the sample cell commonly occurs when the water sample is much colder than the air temperature.
- ▶ **Turbidity measurement is time sensitive and therefore should be completed on-site (preferably in situ)** to avoid effects from (a) biodegradation, growth, settling, or sorption of particulates in the sample; or (b) precipitation of humic acids and minerals (carbonates and hydroxides, for example) caused by changes in sample pH during transport and holding.
- ▶ If temporary storage of samples is necessary, collect samples in clean amber bottles, keep out of sunlight, and chill at or below 4°C to prevent biodegradation of solids or biological growth. The holding time must not exceed 24 hours (ASTM International, 2003a).

Turbidities in surface waters can range widely, even within the same water body, depending on local hydrology, sources of sediment or colored materials, and disturbance regimes. Although drinking-water sources often have background turbidities of less than 1 turbidity unit, it is not unusual to measure turbidities of 1,000 or greater, depending on stream and weather conditions (Uhrich and Bragg, 2003). Protocols for determining turbidities in surface waters typically must account for making reliable measurements that span turbidities over one to three orders of magnitude. Use either a dynamic or static method, employing either discharge-weighted, pumped-sample, or grab-sample procedures, as appropriate for site characteristics and study objectives (NFM 6.0). Repeat the measurement three to five times to ensure accuracy and replication within the precision of the instrument.

6.7.3.A STATIC (BENCHTOP) DETERMINATION

The methods described below encompass both white-light nephelometry that meets USEPA specifications for drinking water, and other static methods (for example, ISO 7027) that do not meet USEPA specifications. EPA Method 180.1 is applicable in the range of turbidity from 0 to 40 NTU without dilution, and from about 40 to 1,000 NTU with dilution (U.S. Environmental Protection Agency, 1993). **Note that dilution of environmental samples that contain particulate materials or exhibit other nonlinearity properties can introduce significant errors from subsampling; therefore, dilution is discouraged.** Consult table 6.7–3 and the Appendix, table A–1, because reporting units will vary with the instrument type used. The static method assumes the turbidimeter recently has been calibrated properly with a calibration or verification solution (section 6.7.2).

Benchtop determination of turbidity is especially susceptible to negative bias from particle settling. Visually check for the presence of coarse material (sand or coarse silt) in the sample. Gently agitate the sample, then set it down. **If particles rapidly settle to the bottom (within 3-5 seconds), then coarse materials are present and the sample cannot be measured accurately using the static method.** Static measurements made on such samples therefore must be coded to indicate that accuracy is qualified when being entered into a database. In the USGS NWIS database, for example, the results should be entered with an “E” remark code.

Preliminary steps for benchtop turbidity determination:

1. Warm up the turbidimeter according to the manufacturer's instructions. Put on powderless laboratory gloves.
2. Rinse a clean, dry, scratch-free, index marked cell with a turbidity calibrant within the range of interest.
3. Gently agitate the calibrant, pour the calibrant into the sample cell to the fill mark, and dry the cell exterior with a lint-free cloth.When using a meter recently calibrated with an acceptable calibrant turbidity solution (formazin or styrene-divinylbenzene polymer—see section 6.7.2), a verification calibrant may be used for this check measurement.
4. Follow the manufacturer's instructions for readout of turbidity value and record the turbidity of the calibrant used and the turbidity value measured in the calibration logbook. If readings are not within specifications for the indicated range, recalibrate the instrument for the turbidimeter using accepted calibration turbidity solutions.

Most turbidimeters will correct initial sample readings directly into a final reading based on the stored calibration. If the meter does not have this capability, take the values from a previously constructed calibration curve.

For samples with turbidity less than 40 turbidity units:

1. Measure sample turbidity immediately or as soon as possible upon sample withdrawal.
   a. If discrete subsamples are to be taken from a churn splitter or other sample-compositing device, remove samples for turbidity measurement along with other whole water samples. Avoid pouring the sample into a cuvette from a bottle, if possible. If not possible, then invert the bottle 25 times using a 1-second inversion cycle and pour off the sample immediately to capture suspended particles.

   b. For drinking water, use an instrument that complies with EPA Method 180.1 or GLI Method 2. Measurements are reported in NTU for EPA 180.1, or in FNMU for GLI Method 2. (See table 6.7–4 to select the appropriate parameter code.)

2. Rinse a freshly cleaned cell with the sample to be tested.
3. For a **discrete (static) sample**, complete the following sequence of steps (through step 4a) without hesitation (skip to step 4 for flowthrough cell measurement).
   a. Gently invert—do not shake—the sample 25 times (ASTM, written commun., undated) to completely disperse the solids, taking care not to entrain air bubbles. Allow air bubbles to disappear before filling the sample cell.
   b. Rapidly pour the sample into a sample cell to the line marked (to the neck if there is no line). Do not touch cell walls with fingers.
   c. Remove condensation from the cell with a clean, soft, lint-free cloth or tissue. If condensation continues, apply a thin coating of silicon oil to the outside of the cell about every third time the cell is wiped dry of moisture. Allow samples to equilibrate to ambient temperature, if necessary, before subsampling to help minimize condensation problems. Note: warming the sample may change particle associations in the water matrix.
   d. Before inserting the sample cell into the meter, ensure that no air bubbles are present in the cell. If necessary, degas the sample according to the manufacturer's instructions. Air bubbles can cause significant positive bias in turbidity measurements (table 6.7–1).
   e. Orient the calibration cell in the cell holder according to the index marks—the calibration cell and sample cell must have identical orientation when in the instrument measurement chamber.

Be sure that sample cells are index marked to indicate orientation. Match orientation so that cells yield the same value when light passes through.

4. Determine the measured turbidity value of the sample directly from the instrument scale or by using the instrument value and calibration curve, as is appropriate for the instrument being used. For samples with less than 1 turbidity unit, see **TECHNICAL NOTE 6** under step 4d.
    a. Record the very first readings after placement of the sample cell in the measurement chamber. If readings are unstable, then particle settling may be occurring. If so, gently re-invert the cell 25 times and record at least three readings over a short, defined time interval (for example, 30 seconds to 1 minute).
    b. Repeat at least twice with fresh sample, until three or more sample values fall within ±10 percent.
    c. Samples that contain significant color should be diluted if using EPA Method 180.1 (for samples with turbidity greater than 40 units see below *"For samples, including drinking water, with turbidity greater than 40 turbidity units," step 3).* **Results of diluted samples must be qualified with a "d" in the "Value Qualifier Code" field for data entered into the USGS NWIS database.**
    d. Report the median of the three or more sequential readings that fall within ±10 percent.

TECHNICAL NOTE (6): When using low-level reporting scales, you may need to subtract a correction factor from the reading to correct for stray light. For example, the Hach Company reports the correction for the 0.2-NTU scale to be on the order of 0.04 NTU for the Hach 2100P. The stray-light correction is determined by reading turbidity from an empty instrument (without cuvette).

5. Record the data in reporting units described in table 6.7–4, using the method code that describes the specific instrument in use (Appendix table A–1). If particle settling or instability in initial readings was a problem, the results must be qualified as an estimate by using an "E" remark code for data entered into NWIS QWDATA.

For samples, including drinking water, with turbidity greater than 40 turbidity units:

1. Select an appropriate instrument. (See table 6.7–4 to select the appropriate USGS parameter code.)
    - For drinking water, use EPA Method 180.1, a compliant instrument, and NTU reporting units; alternatively, select the GLI Method 2, a compliant instrument, and FNMU reporting units. Reporting units for these methods must be remarked with an "E" code in NWIS for turbidities greater than 40.
    - For study objectives other than drinking water, choose instruments according to information provided in figure 6.7–2 and table 6.7–3.
2. Obtain a discrete sample.
    - For drinking-water samples, proceed to step 3.
    - For non-drinking-water samples, skip to step 4.
3. For drinking-water samples, dilution is required to comply with USEPA regulations.
    a. Dilute the sample with one or more equal volumes of turbidity-free water until turbidity is less than 40 turbidity units after mixing and degassing.
    b. Record the volume of turbidity-free water used for dilution. Follow steps 1-5 from the previous section for samples with turbidity less than 40 turbidity units.
    c. Skip to step 5, below
4. For non-drinking-water samples (where USEPA compliance is not required), with 100 and 1,000 turbidity-unit ranges only — place a cell riser (if available) into the cell holder before inserting the sample cell. This decreases the length of the light path in order to improve the linearity of measurements. **Do not use the cell riser for the lower turbidity ranges.**
    a. For turbidimeters with adjustable ranges and signal-processing capabilities (for instance, ratio mode to compensate for high particle densities), select the desired configuration (table 6.7–3) and operate according to manufacturer's recommendations. Some instruments will automatically switch to different modes (for example, ratio mode) or to a different light source. Record instrument mode on field sheets.
    b. Select the desired range on the turbidimeter.

Dilutions can introduce errors if coarse material is present or if the sample matrix changes with the addition of diluant. When making dilutions, perform at least three at approximately 80, 50, and 20 percent of the original concentration. Record the turbidity of each dilution and determine if they are linear and correlate positively with the percentage diluted. If the response is nonlinear, alternative instrument designs that better compensate for interferences should be considered. Do not forget to adjust the turbidity value of diluted samples using the dilution factor.

5. Fill the cell with sample water:
   a. Hold the cell by the rim (top lip), not beneath the lip.
   b. Gently agitate the sample 25 times. Without hesitation, carefully but rapidly pour sample water into the cell to the fill mark.
   c. Wipe the exterior of the cell using a soft, lint-free cloth or tissue to remove moisture (condensation) from cell walls.
   d. If necessary, apply a thin layer of silicon oil (table 6.7–1) onto the exterior of the cell to reduce condensation on the cell and mask slight scratches and nicks.
   e. If rapid particle settling is occurring, steadily invert the cell 25 times, taking care not to shake too vigorously, which could entrain gases in the sample.

6. Record the sample turbidity.

Most modern turbidimeters will adjust initial sample readings directly into a final reading based on the previous calibration. If the meter does not have this capability, you will need to read values from a calibration curve constructed previously. See step 6 under "Benchtop (static) turbidimeter calibration" for instructions on constructing and using calibration curves.

a. Record the very first readings after placement of the sample cell in the measurement chamber. If readings are unstable, particle settling may be occurring: gently re-invert the cell 25 times and record at least three readings over a defined time interval (for example, 30 seconds to 1 minute).
b. Repeat at least twice with fresh sample until three or more sample values fall within ±10 percent.
c. Samples that contain significant color should be diluted if using EPA Method 180.1. **Results of diluted samples must be qualified with a "d" in the "Value Qualifier Code" field for data entered into the USGS NWIS database.**
d. Report the median of the three or more sequential readings that fall within ±10 percent.

For diluted water samples, the measured turbidity must be converted based on the amount of dilution, according to the following equation:

$$T_s = T_d \times \frac{(V_o + V_s)}{V_s} ,$$

where T_s= turbidity of the environmental sample, T_d=turbidity of the diluted sample, V_o = volume of turbidity-free water in the diluted mixture, and V_s= volume of the environmental sample in the diluted mixture.

EXAMPLE: If five volumes of turbidity-free water were added to one volume of sample, and the diluted sample showed a turbidity of 30 units, then the turbidity of the original sample is computed as 180 units.

e. Report turbidity as follows, using method codes as described in Appendix table A–1[5]:
   - For EPA Method 180.1, use NTU.
   - For GLI Method 2, use FNMU.
   - For non-diluted, non-USEPA-compliant measurements, use the reporting units described in table 6.7–4.

In contrast to surface waters, natural turbidity in ground water generally is less than 5 turbidity units. Natural ground-water turbidity of up to 19 turbidity units has been reported for some environmental settings (Nightingale and Bianchi, 1977; Strausberg, 1983; Puls and Powell, 1992). Contaminated ground-water systems, however, can have considerably higher turbidity (Wells and others, 1989; Gschwend and others, 1990; Puls and Powell, 1992; Backhus and others, 1993). Measuring turbidity in ground water requires special considerations and procedures. For effervescent ground water, a degassing apparatus may be required; follow manufacturer’s instructions.

- ▶ **During well development—**Monitor turbidity caused by well installation, recording consecutive measurements to document decreases in turbidity as development proceeds.
- ▶ **During well purging—**Monitor changes in turbidity by taking sequential readings until purging criteria are met (NFM 6.0). The final stabilized turbidity value should be equal to or less than the value recorded at the end of well development. A decrease in turbidity values during purging can indicate mitigation of subsurface disturbance caused by well installation and by deployment of data-collection equipment in the well.
- ▶ **For dynamic measurement—**Report the median of the three or more sequential measurements that meet the ±10-percent criterion for stability (NFM 6.0).
- ▶ **For discrete-sample measurement using a turbidimeter or spectrophotometer:**
  - — **Bailers are not recommended** for collecting turbidity samples, as bailer deployment can increase turbidity.
  - — Do not collect the discharge passing through the flowthrough chamber in which pH, conductivity, or other field-measurement sensors are installed.

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[5] Diluted samples must be qualified with a “d” in the “Value Qualifier Code” field when entering data into NWIS.

- — **Pump the ground-water sample** directly from the sample discharge line into a precleaned glass or polyethylene sample-collection bottle.
- — Subsample into a cuvette and measure turbidity according to instructions for static determination (steps 3-5 above).

Multiparameter instruments can be used with a flowthrough chamber (instead of being deployed in situ) for monitoring ground-water field measurements. See the section below on dynamic determination of turbidity.

6.7.3.B DYNAMIC (SUBMERSIBLE-SENSOR) DETERMINATION

Determination of turbidity using a submersible sensor or sensor in a multiparameter sonde is useful for site-specific water-quality studies. Such turbidity data can be used for watershed investigations, for example, for determination of visual impairment (Davies-Colley and Smith, 2001), for correlation with other constituents (such as concentrations of suspended sediment, total phosphorus, or for bacteria – see Christensen and others, 2000; Uhrich and Bragg, 2003), or for long-term monitoring. Turbidity sensors for these applications utilize a variety of different light sources and other options to compensate for interferences (fig. 6.7–2, table 6.7–3).

Multiparameter instruments with internal batteries and memory can be used in surface-water studies that require long-term deployment. Guidelines for long-term instrument deployment fall under the topic of continuous monitors, and are beyond the scope of this section—refer to the manufacturer’s instructions and recommendations, and to guidance documents such as Wagner and others (2000).

Some submersible turbidity sensors can be adjusted to operate within differing turbidity ranges. For example, although the maximum turbidity based on factory settings is just over 1,000 FNU, the YSI 6026 can be factory adjusted to read turbidities up to 4,000 FNU, allowing readings to be obtained that would otherwise be off scale. The adjustment, however, is specific to the individual instrument, with calibration being non-linear between 1,000 and 4,000 FNU; hence, readings in this high range are not reproducible between instruments (M. Lizotte, YSI Environmental, written commun., May 2003). Any such adjustments made to an instrument's operating range must be documented in the instrument's logbook and in applicable field notes.

Dynamic determination generally reflects the dynamic conditions in a water body more accurately than static measurements of discrete samples because it avoids problems of particle settling. Instrumentation of this type, however, is not approved by the USEPA for evaluating drinking water.

The following procedures apply to in situ determination and to determination of turbidity in a flowthrough chamber:

1. Calibrate the instrument in the laboratory or office using a calibration solution before leaving for the field (see section 6.7.2).
2. At the field site, verify that the instrument has retained its calibration within 5 percent. If it fails verification, then the instrument must be recalibrated.
3. Follow procedures for selection of surface-water and ground-water sampling locations and for dynamic (**Procedure A**) or flowthrough-chamber (**Procedure B**) field measurements, as described in NFM 6.0.

   Procedure A: Dynamic measurement—Immerse the multi-parameter sonde or single turbidity sensor in the water body.

   Procedure B: Flowthrough chamber (ground water only)—Secure chamber cover over sonde/sensor to form an air-tight and water-tight seal. Discharge the first sample aliquot to waste, then open the connection to the flowthrough chamber and pump a sample from the water source to the flowthrough chamber according to instructions in NFM 6.0.3.

4. Activate the instrument to display turbidity values in real time.
5. Agitate the turbidity sensor to remove bubbles from the optical surface: move the sensor up and down or in a circular pattern and (or) activate the wiper mechanism, if available.
6. Monitor turbidity readings as described for other field measurements in NFM 6.0.
    - Allow at least 2 minutes before recording the required number of sequential readings. Some instruments may require as much as 10-20 minutes warmup time.
    - Stability is reached if values for three (for in situ procedure) to five (for flowthrough-chamber procedure) or more sequential readings, spaced at regular time increments, are within 10 percent.
7. Record turbidity readings on the field form and in field notes, including the instrument manufacturer and model. Use reporting units appropriate for the instrument, as described in tables 6.7–3 and 6.7–4.
8. **Surface-water sites—**Repeat steps 5–7 for dynamic measurements (**Procedure A**) at each vertical to be measured. Determine the number of vertical locations; refer to NFM 6.0.2.A and NFM 4.1.
9. Before leaving the field, clean the sonde/sensor with a thorough rinse of deionized water and place it in the storage vessel. Most instruments require a small amount of deionized water to be stored in the storage vessel with the sensors. **Follow the manufacturer's recommendations for storage of sondes/sensors.**
10. Record data in the database in reporting units as described in table 6.7–4, using method codes specific to the instrument in use (Appendix table A–1).
11. If turbidities are higher than the instrument range, dilutions will be necessary. Turbidity will need to be measured with static methods. Take a representative sample and dilute it with one or more equal volumes of turbidity-free water, recording the volume of water used for dilution. In such cases, **qualify the resulting data with a "d" in the "Value Qualifier Code" field in NWIS**.
12. **Quality control.** Periodically check instrument performance by placing a primary or secondary calibration solution in the instrument storage vessel and comparing the standard value with the reading displayed. Record in the instrument maintenance logbook all the readings obtained.

SPECTROPHOTOMETRIC DETERMINATION 6.7.3.C

The attenuation method described below uses a field spectrophotometer to provide a relative measure of the sample turbidity. The spectrophotometer directs a beam of light through the sample at a specific wavelength and measures the amount of transmitted light reaching the "transmitted" detector (fig. 6.7–1). The decrease in the detected light intensity caused by absorption or scattering in the sample is calibrated to accepted calibration turbidity solutions (see 6.7.1.C). Spectrophotometric measurement of turbidity yields readings in AU or FAU, depending on the light source.

- **This method is not approved by the USEPA** and is subject to many interferences. It is a useful method, for example, if the purpose for the turbidity determination is as an indicator of ambient or "stabilized" conditions during well development or purging.
- **Turbidity values less than 50 FAU—the range for most surface water and ground water—are inaccurate using this method** and the procedure is recommended only as a measure of relative turbidity among different samples.

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An FAU is equivalent to an NTU when measuring formazin, but they are not necessarily equivalent when measuring water samples or other types of standards. Relations among different instrument types are site specific. Be careful to enter absorption-derived turbidity values into the data base using the appropriate reporting units, parameter codes, and method codes according to tables 6.7–3 and A–1.

To make spectrophotometric determinations of turbidity:

1. Before starting, check operating instructions for the specific instrument in use.
2. Enter the stored program number for turbidity, if any. Record the light wavelength used. A wavelength of 860 nm (bandwidth 60 nm) is specified by ISO 7027 for reporting in FAU.
3. Use a set of clean, matched 10-mL sample cells.
4. Calibrate according to instructions in the instrument's operating manual (see section 6.7.2).
5. If recently calibrated, take check measurements using calibration solutions that bracket the range anticipated in the sample solution. **Clean the 10-mL cell after using calibrants.**
6. Fill one cell to the 10-mL mark with turbidity-free water and cap with a stopper. NOTE: If measurement of color-derived turbidity is not desired, filter (using a 0.2-µm pore-size filter) an aliquot of the sample water and use this water in place of turbidity-free water.
7. Place blank sample into the cell holder, close the light shield, and verify a zero reading.
8. Fill the other cell to the 10-mL mark with sample water and cap with a stopper. Gently invert 25 times to suspend all particulates.
9. Carefully place sample into the cell holder and close the light shield. Record this reading in AU or FAU.

QUALITY-ASSURANCE PROCEDURES 6.7.4

Quality-assurance procedures should be developed in accordance with the objectives of the sampling or monitoring plan. The primary emphasis should be on quantifying the sources of variability and bias in turbidity measurements that can affect the utility of the data being collected. **Where turbidity from one water source will be compared with turbidity from another source or against a numerical criterion, the use of consistent procedures, instrumentation, and supplies is critical.**

VARIABILITY 6.7.4.A

Sources of variability include the different instruments in use (even similar models), differing subsampling techniques, different operators, spatial and temporal variations in the water body being measured, and different sampling procedures being used. The data resulting from static turbidity determinations also can be negatively biased from particle settling.

Variability in turbidity can be quantified through repeated measurements of turbidity at different times, using different instrumentation, or using different methods. In some cases it might be useful to compare results of a field-turbidity measurement with that of a laboratory-analyzed sample. Keep in mind, however, that sample properties that affect turbidity can degrade during sample transit and storage (see section 6.7.3). The following are examples of tests that can be performed periodically for quality control of some sources of variability in turbidity determinations.

- ▶ **Static determination**
  - — **Measurement variability:** For one cuvette with sample and gently agitate to keep particulates in suspension. Measure the turbidity and remove the cuvette from the turbidimeter. Repeat at least three times, using the same cuvette. Record each reading and determine the standard deviation of the measurements. Consider submitting replicate samples for laboratory analysis. These procedures may not adequately characterize measurement variability that is caused by particle settling.

- **Subsampling variability:** For one water sample, agitate the sample, then withdraw an aliquot into the cuvette, measure turbidity, discard the sample, and clean the cuvette. Repeat at least three times. Record each reading and determine the standard deviation of the measurements.
- **Operator variability:** Split one water sample into two or more subsamples using a churn splitter. Have different operators prepare cuvettes and measure turbidity on the subsamples. Consider submitting samples for laboratory analysis.
- **Sampling variability:** Collect at least two independent samples from the source using standard techniques. Prepare turbidity cuvettes for each sample and measure turbidity.

▶ **Dynamic Determination**

- **Cross-sectional variability:** At a field site, measure turbidity at a number of verticals across the stream width (see NFM 4 and 6.0). Compare against measurements at the centroid, stream margins, locations for continuous monitors, different depths, or against a static measurement from a composite sample using a meter that is optically compatible with the dynamic meter. Keep in mind that the static measurement will likely be biased low if sand or coarse silt are present.
- **Measurement variability:** At a field site, repeat turbidity measurements three or more times at the same location, one after another. Record these values after removing the meter from the water. Use the same instrument for each set of measurements. Consider submitting samples for laboratory analysis.
- **Operator variability:** At a field site, have two or more people determine turbidity at the established measurement location. Use the same instrument for each set of measurements, although it can be calibrated by each person independently to incorporate all sources of variability.

If sand or coarse silt are present in the sample, qualify your static-determination data being entered into NWIS with an "E" remark code.

BIAS 6.7.4.B

Sources of bias can include effects on measurements from various properties of water (table 6.7–1), interferences (table 6.7–2), sampling and subsampling techniques, instrument drift, biofouling, sensor damage, different operators, and different protocols being employed. Bias in turbidity is quantified through measurements of turbidity against known calibration solutions, at different times, using different instrumentation, or with different methods. This is particularly important before and after a measurement series, either in a laboratory or when servicing a continuous monitor in the field. Following are examples of quality-assurance tests that can be performed periodically for static or dynamic determinations of turbidity.

- **Instrument Drift**: After a series of measurements and prior to calibration, measure turbidity using known calibrants, including turbidity-free water or zero-turbidity calibration solution and a calibration (or “check”) solution near the maximum calibrated range. Record the turbidity before making any adjustments to instrument calibration. Bias is computed as the percent difference between readings before calibration and readings at the same range after calibration. Instrument drift is most important to document in continuous monitoring applications.
- **Fouling**: After a series of measurements and before calibration, measure source-water turbidity using known calibrants, including turbidity-free water or zero-turbidity calibration solution and a calibration (or “check”) solution near the maximum calibrated range. Record data. Clean the cuvette or submersible sensor and repeat measurements of source water and calibrants. Record data. Calculate bias as the percent difference between the calibrant reading of the uncleaned sensor and the cleaned sensor.
- **Operator Bias:** Similar to Operator Variability (above), bias can result from inconsistencies in methods among different operators. Split one water sample into two or more subsamples using a churn splitter. Have different operators prepare cuvettes and measure turbidity on the subsamples. Consider submitting samples to a laboratory for analysis. Calculate bias as the percent difference between the turbidity readings obtained by the different operators.

6.7.5 DATA REPORTING AND INTERPRETATION

To minimize comparison of data derived from substantially different instrument designs, USGS turbidity data are stored according to the instrument designs and reporting units indicated in table 6.7–4, with the method codes describing the specific instrument used. Parameter codes associated with instrument design and reporting units, and method codes associated with individual instruments are detailed in Appendix table A–1. Method codes are used with these data to provide information that can be used to understand potential differences in turbidity data.

In some cases, instruments are designed to operate in different modes (for example ratiometric or non-ratiometric). Such instruments are listed multiple times in Appendix table A–1, corresponding to different parameter codes to distinguish their different settings. Be careful to document all instrument settings and dilution factors, and use parameter codes and method codes appropriate for instrument settings. For data storage in NWIS, samples with noticeable sand or coarse materials that were measured by static techniques must be qualified as Estimates with an “E” in the Remark code, and diluted samples must be entered with a “d” in the Value Qualifier Code field.

Guidelines for reporting turbidity measurements to the nearest acceptable digit according to EPA Method 180.1, GLI Method 2, ASTM, and ISO 7027 methods are listed in table 6.7–6. The indicated values represent the least significant digit in the measurement. Reported turbidity values should be rounded to this level of precision. For example, a value of 43.12 units displayed by an instrument would be reported as 45 under USEPA guidelines, but as 43 under ASTM guidelines. In contrast, a value of 13.42 units displayed by an instrument would be reported as 13 under all the guidelines. For most applications, the USGS will conform to ASTM guidelines unless data were specifically collected for drinking-water compliance (using either EPA Method 180.1, GLI Method 2, or ISO 7027).

Traditionally, the USGS has censored data below 2 NTU as not-detected (less than 2). However, improvements in instrument capabilities have resulted in greater reliability at this low end. Based on input from instrument manufacturers, ASTM has chosen to report data below 1 to the nearest 0.05 unit, and to the nearest 0.1 for data ranging between 1 and 10. Because turbidities in this range should be free of appreciable color or settleable materials, static methods should provide reasonable comparisons with dynamic methods. Before publishing such data, study personnel should consider submitting samples of low-turbidity water to the NWQL or other laboratory for confirmation of low-end resolution and reproducibility.

Additionally, the high end of an instrument's range should be determined. Data greater than this value should be censored as greater than the maximum value. For dynamic sensors on a submersible sonde, cover the optics with a piece of lint-free cloth and record the resulting turbidity. Confirm this value with the manufacturer's recommendations. Qualify data having the maximum value by showing a ">" remark code in NWIS.

Table 6.7–6. Guidelines for reporting turbidity units

[For ASTM and USGS measurements, refer to table 6.7–3 for reporting units based on instrument design. **Abbreviations:** USGS, U.S. Geological Survey; ASTM, ASTM International; EPA 180.1, U.S. Environmental Protection Agency method 180.1 (1993); GLI, Great Lakes Instruments; ISO 7027, International Organization for Standardization method 7027 (1999); NTU, nephelometric turbidity units; FNMU, Formazin Nephelometric Multibeam Units; FNU, Formazin Nephelometric Units; N/A, not applicable;<, less than; ≥, equal to or greater than]

Turbidity Reading	USGS	ASTM	EPA 180.1 (NTU)	GLI Method 2 (FNMU)	ISO 7027 (FNU)
0–<1	0.05	0.05	0.05	0.05	0.01
1–<10	.1	.1	.1	.1	.1
10–<40	1	1	1	1	1
40–<100	1	1	5	5	N/A
100–<400	10	10	10	10	N/A
400–<1,000	10	10	50	50	N/A
≥1,000	50	50	100	100	N/A

6.7.6 TROUBLESHOOTING

Consult the instrument manufacturer for additional guidance if the suggestions shown on table 6.7–7 do not remedy the problem encountered.

Table 6.7–7. Troubleshooting guide for field turbidity measurement

Symptom	Possible cause and corrective action
Erratic reading	• Check voltage of the batteries: replace weak batteries with new batteries. • Condensation on cell wall of static turbidimeter: see "Moisture" symptom. • Bubbles in sampling system or on optical surface of sensor: tap sample line to flowthrough cell or chamber systems to dislodge bubbles; adjust degassing apparatus; remove bubbles on sonde/sensor system by agitating the unit repeatedly or by activating the wiper mechanism.
Unusually high or low turbidity	• Bubbles in sampling system or on optical surface of sensor: see "Erratic reading" symptom. • Fouling of optical surfaces. Clean with lint-free cloth or toothbrush. • Wiper mechanism is "parking" on optical surfaces. Use software to reset wiper, or replace wiper mechanism (may require factory repair). • Inappropriate turbidimeter for environmental conditions. See tables 6.7–1, 6.7–2, and 6.7–3, or figure 6.7–2 to determine most appropriate turbidimeter type.
Calibration value "out of range"	• Contaminated calibrant solution or value entered incorrectly. Verify intended calibrant value and start over. If problem persists, try using a different batch of calibrant solution.
Readings first appear stable, then begin to increase inexplicably	• Check for moisture on cell wall: see "Moisture" symptom.
Moisture condensation on cell wall (static turbidimeter or spectrophotometer)	• Wipe cell dry with soft, lint-free cloth. • Apply a thin veneer of silicon oil (first check instrument manufacturer’s instructions). • Add gas sweep to system.
Blank samples or reference material standards do not read accurately	• Check that the cells are oriented as instructed. • Check age/expiration of calibrant solutions. • Check accuracy against that of another instrument.

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Appendix A. Data Coding and Storage

PLEASE NOTE: The information on Table A-1 is current as of August 2004. An Excel spreadsheet of this information is updated periodically and can be accessed at: http://water.usgs.gov/owq/turbidity/turbidity.pcodes_mcodes.update.xls

Table A–1. Parameter codes and method codes corresponding to instrument designs, reporting units, and selected instruments

[For guidance on appropriate instrument design refer to figure 6.7-2. For specific instrument specifications, contact manufacturers directly. **Abbreviations**: PCODE, parameter code; NTU, nephelometric turbidity unit; N/A, not applicable or unavailable; NTRU, nephelometric turbidity ratio unit; BU, backscatter unit; AU, attenuation unit; NTMU, nephelometric turbidity multi-beam unit; FNU, formazin nephelometric unit; FNRU, formazin nephelometric ratio unit; FBU, formazin backscatter unit; FAU, formazin attenuation unit; FNMU, formazin nephelometric multibeam unit; nm, nanometer; °, degree; EPA 180.1, U.S. Environmental Protection Agency method 180.1; ASTM D1899–00, ASTM International method D1899–00; ISO 7027, International Organization for Standardization method 7027; GLI M2, Great Lakes Instruments Company Method 2; >, greater than; <, less than; **±,** plus or minus]

Instrument design	Reporting unit	Method comments	PCODE	Method[1] (Instrument name, mandatory)	Method code	Method source	Static/ dynamic/ process	Comments
White or broadband (480-680 nm) light source; 90° detection angle, one detector.	**NTU**	**Compliant with EPA 180.1, Hach 10133, and ASTM D1899-00.** **Primarily for drinking water applications or low turbidity. Measurement should not be > 40 NTU.**	63675	HACH, sensor model 2100 AN (Ratio OFF), NTU	A	EPA 180.1	Static	Flowthrough accessory provides more dynamic measurement, making readings more stable.
				HACH, sensor model 2100 N (Ratio OFF), NTU	B	EPA 180.1	Static	Flowthrough accessory provides more dynamic measurement, making readings more stable.
				HACH, sensor model 1720 C, NTU	C	EPA 180.1	Process	
				HACH, sensor model 1720 D, NTU	D	EPA 180.1	Process	
				HACH, sensor model 1720 E, NTU	E	EPA 180.1	Process	
				HACH, sensor model Filter Track 660, NTU	F	Hach 10133	Process	
				HACH, sensor model SS6, NTU	G	N/A	Process	Not EPA 180.1 approved
				HF Scientific, Sensor Model Micro100 (Light source WHITE), NTU	H	EPA 180.1	Static	
				HF Scientific, Sensor Model Micro200, NTU	I	EPA 180.1	Process	
				HF Scientific, Sensor Model DRT-15CE, NTU	J	EPA 180.1	Static (Portable)	
				HF Scientific, Sensor Model Micro 1000 (light source WHITE, Ratio OFF), NTU	K	EPA 180.1	Static	Flowthrough accessory provides more dynamic measurement, making readings more stable. Instrument option allows choice of ratiometric or non-ratiometric mode.
				ICM, Sensor Model 11150, NTU	L	EPA 180.1	Static	
				ICM, Sensor Model 11152, NTU	M	EPA 180.1	Static (Portable)	
				LaMotte Instruments Sensor Model 2008, NTU	N	EPA 180.1	Static	

Table A–1. Parameter codes and method codes corresponding to instrument designs, reporting units, and selected instruments

[For guidance on appropriate instrument design refer to figure 6.7-2. For specific instrument specifications, contact manufacturers directly. **Abbreviations**: PCODE, parameter code; NTU, nephelometric turbidity unit; N/A, not applicable or unavailable; NTRU, nephelometric turbidity ratio unit; BU, backscatter unit; AU, attenuation unit; NTMU, nephelometric turbidity multi-beam unit; FNU, formazin nephelometric unit; FNRU, formazin nephelometric ratio unit; FBU, formazin backscatter unit; FAU, formazin attenuation unit; FNMU, formazin nephelometric multibeam unit; nm, nanometer; °, degree; EPA 180.1, U.S. Environmental Protection Agency method 180.1; ASTM D1899–00, ASTM International method D1899–00; ISO 7027, International Organization for Standardization method 7027; GLI M2, Great Lakes Instruments Company Method 2; >, greater than; <, less than; **±**, plus or minus]

Instrument design	Reporting unit	Method comments	PCODE	Method[1] (Instrument name, mandatory)	Method code	Method source	Static/ dynamic/ process	Comments
White or broadband (480-680 nm) light source; 90° detection angle, one detector. (*continued*)	**NTU (*continued*)**	**Compliant with EPA 180.1, Hach 10133, and ASTM D1899-00.** **Primarily for drinking water applications or low turbidity. Measurement should not be > 40 NTU.**	63675	Orbeco-Hellige, Sensor Model 965-10A, NTU	O	EPA 180.1	Static	
				Orbeco-Hellige, Sensor Model 966-01, NTU	P	EPA 180.1	Static (Portable)	
				WTW Measurement Systems, Sensor Model 550, NTU	Q	EPA 180.1	Static	
				Turbiquant Sensor Model 1500 T, NTU	R	EPA 180.1	Static	
				Turbiquant Sensor Model 3000 T (Ratio OFF), NTU	S	EPA 180.1	Static	
				Other, unspecified	Z	N/A	N/A	Only for interim storage while method codes are being generated for new instruments.
White or broadband (480-680 nm) light source; 90° detection angle; Multiple detectors with ratio compensation.	**NTRU**	**Compliant with EPA 180.1 and ASTM D1899-00 for turbidities < 40 NTRU.** **Use ratio mode on applicable NTU instruments with turbidity > 40.**	63676	HACH, Sensor Model 2100 AN (Ratio ON), NTRU	A	EPA 180.1	Static	
				HACH, Sensor Model 2100 N (Ratio ON), NTRU	B	EPA 180.1	Static	
				HACH, Sensor Model 2100 P, NTU	C	EPA 180.1	Static (Portable)	
				HF Scientific, Sensor Model Micro 1000 (light source WHITE, Ratio ON), NTRU	D	EPA 180.1	Static	
				LaMotte Instruments, Sensor Model 2020, NTRU	E	EPA 180.1	Static	
				Turbiquant Sensor Model 3000 T (Ratio ON), NTRU	F	EPA 180.1	Static	
				WTW Measurement Systems, Sensor Model 555, NTRU	G	EPA 180.1	Static	
				Other, unspecified	Z	N/A	N/A	Only for interim storage while method codes are being generated for new instruments.

Table A–1. Parameter codes and method codes corresponding to instrument designs, reporting units, and selected instruments

[For guidance on appropriate instrument design refer to figure 6.7-2. For specific instrument specifications, contact manufacturers directly. **Abbreviations**: PCODE, parameter code; NTU, nephelometric turbidity unit; N/A, not applicable or unavailable; NTRU, nephelometric turbidity ratio unit; BU, backscatter unit; AU, attenuation unit; NTMU, nephelometric turbidity multi-beam unit; FNU, formazin nephelometric unit; FNRU, formazin nephelometric ratio unit; FBU, formazin backscatter unit; FAU, formazin attenuation unit; FNMU, formazin nephelometric multibeam unit; nm, nanometer; °, degree; EPA 180.1, U.S. Environmental Protection Agency method 180.1; ASTM D1899–00, ASTM International method D1899–00; ISO 7027, International Organization for Standardization method 7027; GLI M2, Great Lakes Instruments Company Method 2; >, greater than; <, less than; **±,** plus or minus]

Instrument design	Reporting unit	Method comments	PCODE	Method[1] (Instrument name, mandatory)	Method code	Method source	Static/ dynamic/ process	Comments
White or broadband (480-680 nm) light source; 30 ± 15° detection angle (Backscatter).	**BU**	**Applicable for high particle densities**	63677	HACH, Sensor Model 2100 AN (light source WHITE, Backscatter ON), BU	X	N/A	Static	
				HF Scientific, Sensor Model Micro 1000 (light source WHITE, Ratio OFF, Backscatter ON), BU	Y	N/A	Static	
				Other, unspecified	Z	N/A	N/A	Only for interim storage while method codes are being generated for new instruments.
White or broadband (480-680 nm) light source; 180° detection angle (Attenuation).	**AU**	**Instrument response negatively correlated with particle density**	63678	HACH, Sensor Model 2100 AN (light source WHITE, Attenuation ON), BU	X	N/A	Static	
				HF Scientific, Sensor Model Micro 1000 (light source WHITE, Ratio OFF, Attenuation ON), AU	Y	N/A	Static	
				Other, unspecified	Z	N/A	N/A	Only for interim storage while method codes are being generated for new instruments.
White or broadband (480-680 nm) light source; multiple light sources. Detectors at 90° and possibly other angles to each beam.	**NTMU**	**Instrument algorithm uses a combination of detector readings, which may differ for values of varying magnitude**	63679	Other, unspecified	Z	N/A	N/A	Only for interim storage while method codes are being generated for new instruments.

Table A–1. Parameter codes and method codes corresponding to instrument designs, reporting units, and selected instruments

[For guidance on appropriate instrument design refer to figure 6.7-2. For specific instrument specifications, contact manufacturers directly. **Abbreviations**: PCODE, parameter code; NTU, nephelometric turbidity unit; N/A, not applicable or unavailable; NTRU, nephelometric turbidity ratio unit; BU, backscatter unit; AU, attenuation unit; NTMU, nephelometric turbidity multi-beam unit; FNU, formazin nephelometric unit; FNRU, formazin nephelometric ratio unit; FBU, formazin backscatter unit; FAU, formazin attenuation unit; FNMU, formazin nephelometric multibeam unit; nm, nanometer; °, degree; EPA 180.1, U.S. Environmental Protection Agency method 180.1; ASTM D1899–00, ASTM International method D1899–00; ISO 7027, International Organization for Standardization method 7027; GLI M2, Great Lakes Instruments Company Method 2; >, greater than; <, less than; **±,** plus or minus]

Instrument design	Reporting unit	Method comments	PCODE	Method[1] (Instrument name, mandatory)	Method code	Method source	Static/ dynamic/ process	Comments
Near infra-red (780-900 nm) or monochrome light source; 90° detection angle; one detector.	**FNU**	**ISO 7027 compliant (at < 40 FNU).** **Compensates for color in sample.** **Includes most submersible sensors used for profiling and continuous monitoring.**	63680	Eureka Environmental, Sensor Model Trimeter, FNU	A	ISO 7027	Dynamic	
				Forest Technology Systems, Sensor Model DTS-12, FNU	B	ISO 7027	Dynamic	
				Greenspan, Sensor Model TS 100, FNU	C	ISO 7027	Dynamic	
				Greenspan, Sensor Model TS 300, FNU	D	ISO 7027	Dynamic	
				Greenspan, Sensor Model TS 1200, FNU	E	ISO 7027	Dynamic	
				HACH, Sensor Model 2100 N IS (Ratio OFF), FNU	F	ISO 7027	Static	With Infrared filter installed downstream of white light source
				HACH, Sensor Model 2100 AN IS (Ratio OFF), FNU	G	ISO 7027	Static	With Infrared filter installed downstream of white light source
				HACH, Sensor Model 1720 D/L, FNU	H	ISO 7027	Static (Portable)	
				HACH, Sensor Model Optiquant, FNU	I	ISO 7027	Static	
				HACH, Sensor Model Pocket Turbidimeter, FNU	J	ISO 7027	Static	
				HF Scientific, Sensor Model Micro TPI, FNU	K	ISO 7027	Static	
				HF Scientific, Sensor Model Micro100 (light source INFRARED), FNU	L	ISO 7027	Static	
				HF Scientific, Sensor Model Micro 1000 (light source INFRARED, Ratio OFF), FNU	M	ISO 7027	Static	
				Hydrolab, Sensor Model Datasonde 4, FNU	N	ISO 7027	Dynamic	
				In-Situ, Sensor Model MP TROLL 9000, FNU	O	ISO 7027	Dynamic	

Table A–1. Parameter codes and method codes corresponding to instrument designs, reporting units, and selected instruments

[For guidance on appropriate instrument design refer to figure 6.7-2. For specific instrument specifications, contact manufacturers directly. **Abbreviations**: PCODE, parameter code; NTU, nephelometric turbidity unit; N/A, not applicable or unavailable; NTRU, nephelometric turbidity ratio unit; BU, backscatter unit; AU, attenuation unit; NTMU, nephelometric turbidity multi-beam unit; FNU, formazin nephelometric unit; FNRU, formazin nephelometric ratio unit; FBU, formazin backscatter unit; FAU, formazin attenuation unit; FNMU, formazin nephelometric multibeam unit; nm, nanometer; °, degree; EPA 180.1, U.S. Environmental Protection Agency method 180.1; ASTM D1899–00, ASTM International method D1899–00; ISO 7027, International Organization for Standardization method 7027; GLI M2, Great Lakes Instruments Company Method 2; >, greater than; <, less than; **±,** plus or minus]

Instrument design	Reporting unit	Method comments	PCODE	Method[1] (Instrument name, mandatory)	Method code	Method source	Static/ dynamic/ process	Comments
Near infra-red (780-900 nm) or monochrome light source; 90° detection angle; one detector. *(continued)*	**FNU** *(continued)*	**ISO 7027 compliant (at < 40 FNU). Compensates for color in sample. Includes most submersible senors used for profiling and continuous monitoring.** *(continued)*	63680	McVan, Sensor Model Analite NEP 160-3 (90°), FNU	P	ISO 7027	Dynamic	
				McVan, Sensor Model Analite NEP 195, FNU	Q	ISO 7027	Dynamic	
				McVan, Sensor Model Analite NEP 390, FNU	R	ISO 7027	Dynamic	
				McVan, Sensor Model Analite NEP 391, FNU	S	ISO 7027	Dynamic	
				McVan, Sensor Model Analite NEP 395, FNU	T	ISO 7027	Dynamic	
				McVan, Sensor Model Analite NEP 396, FNU	U	ISO 7027	Dynamic	
				McVan, Sensor Model Analite NEP 495, FNU	V	ISO 7027	Dynamic	
				McVan, Sensor Model Analite NEP 9000, FNU	W	ISO 7027	Process	
				McVan, Sensor Model Analite NEP 9500, FNU	X	ISO 7027	Process	
				Orbeco-Hellige, Sensor Model 965-IR, FNU	Y	ISO 7027	Process	
				Orbeco-Hellige, Sensor Model 966-IR, FNU	9	ISO 7027	Process	
				Turbiquant Sensor Model 1000 IR, FNU	0	ISO 7027	Static	
				Turbiquant Sensor Model 1500 IR, FNU	1	ISO 7027	Static	
				Turbiquant Sensor Model 3000 IR (Ratio OFF), FNU	2	ISO 7027	Static	
				YSI Environmental, Sensor Model 6026, FNU	3	ISO 7027	Dynamic	
				YSI Environmental, Sensor Model 6026-4000, FNU	4	ISO 7027	Dynamic	YSI 6026 sensor factory adjusted to allow readings and calibration to 4000 FNU

Table A–1. Parameter codes and method codes corresponding to instrument designs, reporting units, and selected instruments

[For guidance on appropriate instrument design refer to figure 6.7-2. For specific instrument specifications, contact manufacturers directly. **Abbreviations**: PCODE, parameter code; NTU, nephelometric turbidity unit; N/A, not applicable or unavailable; NTRU, nephelometric turbidity ratio unit; BU, backscatter unit; AU, attenuation unit; NTMU, nephelometric turbidity multi-beam unit; FNU, formazin nephelometric unit; FNRU, formazin nephelometric ratio unit; FBU, formazin backscatter unit; FAU, formazin attenuation unit; FNMU, formazin nephelometric multibeam unit; nm, nanometer; °, degree; EPA 180.1, U.S. Environmental Protection Agency method 180.1; ASTM D1899–00, ASTM International method D1899–00; ISO 7027, International Organization for Standardization method 7027; GLI M2, Great Lakes Instruments Company Method 2; >, greater than; <, less than; **±,** plus or minus]

Instrument design	Reporting unit	Method comments	PCODE	Method[1] (Instrument name, mandatory)	Method code	Method source	Static/ dynamic/ process	Comments
Near infra-red (780-900 nm) or monochrome light source; 90° detection angle; one detector. *(continued)*	**FNU** *(continued)*	**ISO 7027 compliant (at < 40 FNU). Compensates for color in sample. Includes most submersible sensors used for profiling and continuous monitoring. *(continued)***	63680	YSI Environmental, Sensor Model 6136, FNU	5	ISO 7027	Dynamic	
				WTW Measurement Systems, Sensor Model 350 IR, FNU	6	ISO 7027	Static (Portable)	
				WTW Measurement Systems, Sensor Model 550 IR, FNU	7	ISO 7027	Static	
				WTW Measurement Systems, Sensor Model VisoTurb 700 IQ, FNU	8	ISO 7027	Static	
				Other, unspecified	Z	N/A	N/A	Only for interim storage while method codes are being generated for new instruments.
Near infra-red (780-900 nm) or monochrome light source; 90° detection angle; multiple detectors; ratio compensation.	**FNRU**	**ISO 7027 compliant (at < 40 FNU). Compensates for color in sample. Ratio mode provides added color compensation and stability at high particle densities**	63681	HACH, Sensor Model 2100 AN IS (Ratio ON), FNRU	A	ISO 7027	Static	
				HF Scientific, Sensor Model Micro 1000 (light source INFRARED, Ratio ON), FNRU	B	ISO 7027	Static	
				Turbiquant Sensor Model 3000 IR (Ratio ON), FNRU	C	ISO 7027	Static	
				WTW Measurement Systems, Sensor Model 555 IR, FNRU	D	ISO 7027	Static	
				Other, unspecified	Z	N/A	N/A	Only for interim storage while method codes are being generated for new instruments.

Table A–1. Parameter codes and method codes corresponding to instrument designs, reporting units, and selected instruments

[For guidance on appropriate instrument design refer to figure 6.7-2. For specific instrument specifications, contact manufacturers directly. **Abbreviations**: PCODE, parameter code; NTU, nephelometric turbidity unit; N/A, not applicable or unavailable; NTRU, nephelometric turbidity ratio unit; BU, backscatter unit; AU, attenuation unit; NTMU, nephelometric turbidity multi-beam unit; FNU, formazin nephelometric unit; FNRU, formazin nephelometric ratio unit; FBU, formazin backscatter unit; FAU, formazin attenuation unit; FNMU, formazin nephelometric multibeam unit; nm, nanometer; °, degree; EPA 180.1, U.S. Environmental Protection Agency method 180.1; ASTM D1899–00, ASTM International method D1899–00; ISO 7027, International Organization for Standardization method 7027; GLI M2, Great Lakes Instruments Company Method 2; >, greater than; <, less than; **±,** plus or minus]

Instrument design	Reporting unit	Method comments	PCODE	Method[1] (Instrument name, mandatory)	Method code	Method source	Static/ dynamic/ process	Comments
Near infra-red (780-900 nm) or monochrome light source; 30±15° detection angle (Backscatter).	**FBU**	**Applicable for high particle densities where color compensation also is required.**	63682	D&A Instrument Co., Sensor Model OBS-3, FBU	S	N/A	Static	
				D&A Instrument Co., Sensor Model OBS-3A, FBU	T	N/A	Static	
				HACH, Sensor Model 2100 AN IS (light source INFRA-RED, Backscatter ON), FBU	U	N/A	Static	
				HF Scientific, Sensor Model Micro 1000 (light source INFRARED, Ratio ON, Backscatter ON), FBU	V	N/A	Static	
				McVan, Sensor Model Analite NEP 160-1 (180°), FBU	W	N/A	Static	
				McVan, Sensor Model Analite NEP 180 (180°), FBU	X	N/A	Static	
				McVan, Sensor Model Analite NEP 185 (180°), FBU	Y	N/A	Static	
				Other, unspecified	Z	N/A	N/A	Only for interim storage while method codes are being generated for new instruments.
Near infra-red (780-900 nm) or monochrome light source; 180° detection angle (Attenuation).	**FAU**	**ISO 7027 compliant (at > 40 FAU).**	63683	HF Scientific, Sensor Model Micro 1000 (light source INFRA RED, Ratio ON, Attenuation ON), FAU	A	ISO 7027	Static	
				Turbiquant Sensor Model 3000 IR (>40), FAU	B	ISO 7027	Static	
				Other, unspecified	Z	N/A	N/A	Only for interim storage while method codes are being generated for new instruments.

Table A–1. Parameter codes and method codes corresponding to instrument designs, reporting units, and selected instruments

[For guidance on appropriate instrument design refer to figure 6.7-2. For specific instrument specifications, contact manufacturers directly. **Abbreviations**: PCODE, parameter code; NTU, nephelometric turbidity unit; N/A, not applicable or unavailable; NTRU, nephelometric turbidity ratio unit; BU, backscatter unit; AU, attenuation unit; NTMU, nephelometric turbidity multi-beam unit; FNU, formazin nephelometric unit; FNRU, formazin nephelometric ratio unit; FBU, formazin backscatter unit; FAU, formazin attenuation unit; FNMU, formazin nephelometric multibeam unit; nm, nanometer; °, degree; EPA 180.1, U.S. Environmental Protection Agency method 180.1; ASTM D1899–00, ASTM International method D1899–00; ISO 7027, International Organization for Standardization method 7027; GLI M2, Great Lakes Instruments Company Method 2; >, greater than; <, less than; **±,** plus or minus]

Instrument design	Reporting unit	Method comments	PCODE	Method[1] (Instrument name, mandatory)	Method code	Method source	Static/ dynamic/ process	Comments
Near infra-red (780-900 nm) or monochrome light source; multiple light sources. **Detectors at 90° and possibly other angles to each beam.**	**FNMU**	**Instrument algorithm uses a combination of detector readings, which may differ for values of varying magnitude.**	63684	Great Lakes Instruments, Sensor 95 T, FNMU	V	GLI M2	Static	
				Great Lakes Instruments, Sensor Accu4, FNMU	W	GLI M2	Static	
				Hydrolab, Sensor Model 4a, FNMU	X	GLI M2	Dynamic	
				Hydrolab, Sensor Model Quanta 4-beam, FNMU	Y	GLI M2	Dynamic	
				Other, unspecified	Z	N/A	N/A	Only for interim storage while method codes are being generated for new instruments.

[1] Instruments included are those available as of August 2004.