Monitor Operation and Maintenance

The operational goal for monitoring water quality is to obtain the most accurate and most complete record possible. The general operational categories include maintenance of the monitoring station and equipment, periodic verification of sensor calibration, troubleshooting of sensors and recording equipment, and thorough record keeping.

A standard protocol is common for the operation of continuous water-quality monitors in nearly all aquatic environments and site characteristics; only the cleaning and calibration steps (steps 3–5 in table 4) differ for determining error as a result of fouling and calibration drift. The standard protocol supports two methods for cleaning and calibration: (1) a method for monitors in well-mixed, stable, or slowly changing aquatic environments; and (2) a method for monitors in stratified or dynamic, rapidly changing conditions, such as those typically found in estuarine environments or in warm,

Table 4. Standard protocol for the operation and maintenance of a continuous water-quality monitor.

1. Conduct site inspection
   a. Record monitor readings, time, and monitor conditions
   b. With an independent field meter, observe and record readings and time near the sensor(s)
2. Remove sonde from the monitoring location
3. Clean sensors
4. Return sonde to the monitoring location
   a. Record monitor readings and time
   b. Using an independent field meter, observe and record readings near the sensor(s)
5. Remove sonde, rinse thoroughly, and check calibration
   a. Record calibration-check values
   b. Recalibrate if necessary
6. Return sonde to monitoring location
   a. Record monitor readings and time
   b. Using an independent field meter, observe and record readings near the sensor(s)

sluggish, biologically active environments. The second method is used when changes in the monitored field measurements are greater than the calibration criteria (see *Monitor Calibration Criteria*), when measured field parameters are rapidly changing, or when measurements are fluctuating (see *Rapidly Changing Conditions*). Rapid change is defined as change that exceeds the calibration criteria (see *Monitor Calibration Criteria*) within 5 minutes.

Standard Protocol

The standard protocol is a series of procedures that must be performed routinely at all continuous water-quality stations (table 4) as fully described in this report. Site characteristics, such as stratification or dynamic, rapidly changing environmental conditions, may make it necessary to modify the standard protocol (see *Rapidly Changing Conditions*). Alternative methods that combine aspects of these techniques for cleaning and calibrating monitors also are possible. Environmental conditions or data-quality objectives may dictate the most appropriate method. For example, under conditions of rapidly rising streamflow or extreme low-flow conditions that lead to rapidly changing field parameters, measurements that are more accurate and perhaps safer working conditions may be obtained by using a modified protocol for rapidly changing environmental conditions. Experience and knowledge of site conditions will aid in the choice of cleaning and calibration methods.

Maintenance

Maintenance frequency generally is governed by the fouling rate of the sensors, and this rate varies by sensor type, hydrologic and environmental conditions, and season. The performance of temperature and specific conductance sensors tends to be less affected by fouling than the DO, pH, and turbidity sensors. The use of wiper or shutter mechanisms on modern turbidity instruments has substantially decreased fouling in some aquatic environments. For sites with data-quality objectives that require a high degree of accuracy, maintenance can be weekly or more often (table 5). Monitoring sites with nutrient-enriched waters and moderate to high temperatures may require maintenance as frequently as every third day. In cases of severe environmental fouling or in remote locations, the use of an observer to provide more frequent maintenance to the water-quality monitor should be considered.

In addition to fouling problems, monitoring disruptions as a result of recording equipment malfunction, sedimentation, electrical disruption, debris, ice, pump failure, or vandalism also may require additional site visits. Satellite telemetry can be used to verify proper equipment operation on a daily basis and can aid the field hydrographer in recognizing and correcting problems quickly. Satellite telemetry is recommended for sites where lost record will critically affect project objectives.

Specific maintenance requirements depend on the site configuration and equipment. A useful discussion of the maintenance requirements for the flow-through and USGS minimonitor installations is available in Gordon and Katzenbach (1983), but nearly all operational requirements are fulfilled by the completion of the USGS water-quality continuous monitor field-inspection form (Attachment 1). Manufacturer's instructions must be followed for other types of equipment or sensors.

Table 5. General maintenance functions at a water-quality monitoring station.

Daily maintenance functions (for sites equipped with telemetry)
Daily review of sensor function and data download
Battery (or power) check
Deletion of spurious data, if necessary
Maintenance functions during field visits
Calibration of the field meter(s)
Inspection of the site for signs of physical disruption
Inspection and cleaning of sensor(s) for fouling, corrosion, or damage
Inspection and cleaning of deployment tube
Battery (or power) check
Time check
Routine sensor cleaning and servicing
Calibration check (and recalibration, if necessary)
Downloading of data

Sensor Inspection and Calibration Check

The purposes of sensor inspection are to verify that a sensor is working properly, to provide an ending point for the interval of water-quality record since the last maintenance visit, and to provide a beginning point for the next interval of water-quality record. This is accomplished by recording the initial sensor readings in the environment, cleaning the sensors, recording the cleaned-sensor readings in the environment, performing a calibration check of sensors by using appropriate calibration standards, and recalibrating the sensors if the readings are outside the ranges of acceptable differences (see *Monitor Calibration Criteria*). A final environmental sensor reading is required after the calibration check or after recalibration. The difference between the initial sensor reading and the cleaned-sensor reading is the sensor error caused by fouling; the difference between the cleaned-sensor readings in calibration standard solutions of known quality represents sensor error caused by calibration drift. If the calibrated sensor cannot be recalibrated or does not agree with the calibrated field meter, the faulty sensor must be repaired after verifying that the readings of the field meter are not in error (see *Troubleshooting Procedures*). The alternative is to replace the monitoring sonde or sensor with a calibrated backup unit and repair the malfunctioning monitor in the laboratory or return it to the manufacturer for repair. All information related to the sensor inspection must be recorded on a field form (Attachment 1), which then is the basis for data corrections made during the record-processing stage. Complete and thorough documentation of the sensor inspection is required.

Steady-State Conditions

The standard protocol (table 4) is used for servicing sensors in stable or slowly changing (in one direction) environmental conditions. Slowly changing is defined as changes in field measurements during maintenance that are less than the calibration criteria (see *Monitor Calibration Criteria*). Readings to determine error caused by fouling and calibration drift are made while the monitor is deployed. The initial sensor readings (before cleaning) of the monitoring equipment are compared to readings from a calibrated field meter ideally located at the same measuring point in the aquatic environment. The sonde is then removed for servicing while the field meter remains in place. The initial sensor reading becomes the ending point of the data record since the last servicing, and the field meter reading provides a sense of the reasonableness of the monitor readings and an indication of potential electronic calibration drift and fouling errors. Field meter readings should be recorded every 5 minutes, or more frequently if necessary.

Upon removal from the water, the monitoring sensors are inspected for signs of chemical precipitates, stains, siltation, or biological growths that may cause fouling. These observations are recorded in the field notes before cleaning, and then the individual sensors are cleaned according to the manufacturer's specifications. The cleaned sonde or sensor is then returned to the water, and the final (cleaned) sensor readings and field meter readings and times are recorded in the field notes after the sensor has equilibrated. If the conditions are steady state, the field meter readings should not change substantially during the time that the monitoring sensors are cleaned. The observed difference between the initial sensor reading and the cleaned-sensor reading is a result of fouling (chemical precipitates, stains, siltation, or biological growths). After all cleaned-sensor readings are recorded, the monitoring sensors are again removed from the water, calibration is checked in calibration standard solutions, and the readings are recorded (and recalibrated if necessary); the difference between the cleaned-sensor readings in calibration standard solutions and the expected reading in these solutions is the result of sensor-calibration drift error. The sonde is recalibrated if necessary and replaced in the aquatic environment, and a set of initial readings is taken as the start of the new record.

Except for temperature sensors, the field meter readings are not used directly in record computation; the field meter is used only as a tool to assess cross-section variability and environmental changes that may occur while the monitor is being serviced. If the environmental conditions are slowly changing while the monitor is being serviced and do not fluctuate, the fouling and calibration drift error can be computed with consideration being given to these environmental changes (see *Data-Processing Procedures*).

Rapidly Changing Conditions

The standard protocol with minor modifications (table 6) is used when environmental conditions change rapidly or when measurements are fluctuating (increasing and decreasing; fig. 4). Rapid change is relative to the length of time needed to service the monitor and generally is defined as change that exceeds the calibration criteria within 5 minutes (see *Monitor*

Table 6. Modified standard protocol for the operation and maintenance of a continuous water-quality monitor at a site with rapidly changing conditions.

1. Conduct site inspection
    a. Record monitor readings, time, and monitor conditions
    b. With an independent field meter, observe and record readings and time near the sensor(s)
2. Remove sonde from the monitoring location
3. Place the sonde and a field meter in an insulated 5-gallon bucket filled with ambient water
    a. Record monitor readings, time, and monitor conditions
    b. With an independent field meter, observe and record readings and time near the sensor(s)
4. Clean sensors
5. Return sonde to the insulated 5-gallon bucket
    a. Record monitor readings and time
    b. Using an independent field meter, observe and record readings and time near the sensor(s)
6. Remove sonde, rinse thoroughly, and check calibration
    a. Record calibration-check values
    b. Recalibrate if necessary
7. Return sonde to monitoring location
    a. Record monitor readings and time
    b. Using an independent field meter, observe and record readings near the sensor(s)

Calibration Criteria). Rapidly changing conditions typically occur in lakes and estuaries; a steep salinity or DO vertical gradient can result in large changes in salinity or DO over very short vertical distances. Internal water movement may further destabilize the gradient, and boat movement in choppy waters can make it impossible to replace the monitor or hold the field meter in one location. This effectively prevents comparison of pre-cleaned and cleaned-sensor readings to determine fouling per the standard protocol under steady-state conditions. Hazardous working conditions, especially in estuaries or large lakes, may limit the time that can be spent at the site and may require removal of the sonde and replacement after servicing. These situations require the use of a modified standard protocol for rapidly changing conditions (table 6). Such conditions also can occur in small streams or rivers, when rapidly increasing streamflow or extremely low streamflow conditions lead to rapidly changing field parameters that prevent comparison of pre-cleaned and cleaned-sensor readings in the stream. Experience and knowledge of site conditions will aid in the choice of servicing methods.

The modified standard protocol for rapidly changing conditions (table 6) generally follows the standard protocol (table 4) except that all measurements are made in ambient water collected in an ice cooler or insulated 5-gallon bucket that provides a stable environment for readings. First, sonde readings and time are recorded; the sonde is carefully removed from the water with minimal disturbance to any biological growth or sedimentation, inspected for signs of chemical precipitates, stains, siltation, or biological growths that may cause fouling, and placed in the bucket. The observations of fouling are recorded in the field notes. A calibrated field meter is

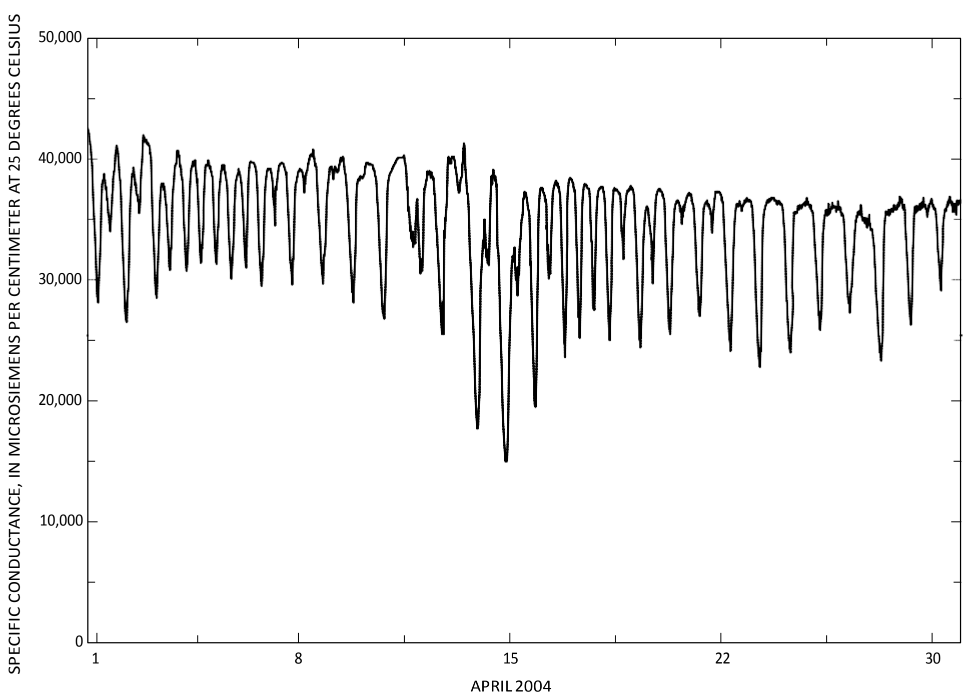

Figure 4. Example of rapidly changing recorded values of specific conductance at U.S. Geological Survey streamgaging station 02300554, Little Manatee River at Shell Point near Ruskin, Florida.

placed in the bucket next to the sonde, and pre-cleaned sensor readings and times are recorded. Field meter readings should be recorded every 5 minutes, or more frequently if necessary. The sonde is removed from the bucket and cleaned according to the manufacturer's specifications. The cleaned sonde is then returned to the bucket. After the sensors have equilibrated, the cleaned-sensor readings, field meter readings, and times are recorded in the field notes. The observed difference between the pre-cleaned sensor reading and the cleaned-sensor reading is a result of fouling. After all cleaned-sensor readings are recorded, the sensor calibration is checked in calibration standards, and the readings are recorded. The difference between the cleaned-sensor readings in calibration standard solutions and the expected reading in those solutions is caused by sensor calibration drift error. The sonde is recalibrated if necessary and replaced in the aquatic environment, and a set of initial readings is taken to represent the start of the new record. If turbidity is being measured, it may be more appropriate to use tap or distilled water rather than ambient water in the insulated bucket because of the possibility of turbid particles settling out in still water.

Because of the inherently variable nature of turbidity, measurements of turbidity in the stream before and after cleaning the sensor may not provide an accurate measure of fouling. A more accurate determination of fouling of turbidity sensors can be made by making pre-cleaning measurements in a bucket of clean tap or distilled water. Fouling is then determined by comparing measurements of turbidity in the bucket after cleaning the sensor, taking into consideration any changes in turbidity in the bucket, with measurements by a field meter.

Alternative Methods for Servicing a Monitor

Other modifications to the standard protocol may be desirable based on data-quality objectives, site characteristics, and field conditions. The optimal method for determining fouling is to record pre-cleaned and cleaned-sensor readings at the field site in a stable environment. In hazardous field situations, such as working from a boat in choppy waters, it may be difficult to perform accurate calibration checks. It may be more practical to exchange the sonde with a clean, calibrated sonde. One example of an alternative method for servicing a monitor is water-quality sonde exchange, in which fouling is determined by pre-cleaned and cleaned-sensor readings at the site but calibration checks are made off site, and the sonde is replaced with another clean, calibrated sonde. Once the sonde is cleaned, calibration checks can be performed elsewhere if care is taken in transporting the sonde; however, calibration of replacement sondes should be performed at or near the field site, especially if DO is being measured. If conditions prevent field calibration, the replacement sonde should be calibrated in the office or laboratory, and a minimal one-point calibration check must be performed on site or in a nearby mobile laboratory.

Data-quality objectives may require even further modifications of the standard protocol. In this case, the sonde is carefully removed from the monitoring location, and pre-cleaned and cleaned-sensor readings are made off site in a less hazardous environment to determine fouling, and calibration checks are made for calibration drift. All modifications to the steady-state protocol introduce the possibility of immeasurable errors into the process and may preclude identifying calibration drift error and fouling error separately. Consideration of these errors should be taken into account when rating the accuracy of the record (see *Final Data Evaluation*).

Monitor Calibration Criteria

When calibration checks reveal only a small amount of calibration drift, it may not be necessary to recalibrate the instrument (Gordon and Katzenbach, 1983). Under field conditions, the operating accuracy of the equipment has limits. Within these acceptable limits (calibration criteria), adjustments to calibration may not improve overall data accuracy. The calibration criteria for water-quality monitors (table 7) are based on stabilization criteria defined by Wilde and Radtke (2005). The criteria take into consideration the lower accuracy of some continuous water-quality sensors. In practice, a calibration check of cleaned sensors using calibration

Table 7. Calibration criteria for continuous water-quality monitors.

[±, plus or minus value shown; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; %, percent; mg/L, milligram per liter; pH unit, standard pH unit; turbidity unit is dependent on the type of meter used]

Measurement	**Calibration criteria** (variation outside the value shown requires recalibration)
Temperature	±0.2 ºC
Specific conductance	±5 µS/cm or ±3% of the measured value, whichever is greater
Dissolved oxygen	±0.3 mg/L
pH	±0.2 pH unit
Turbidity	±0.5 turbidity unit or ±5% of the measured value, whichever is greater

standards is compared to the calibration criteria. If calibration drift is within the calibration criterion, the sensor is considered stable and recalibration is not required.

Field Cleaning of Sensors

During the cleaning process, care should be taken to ensure that the electrical connectors are kept clean and dry. Water in the connector pins can cause erratic readings. For this reason, a container of compressed air is a useful component of field-cleaning supplies. Most commercially available temperature sensors can be cleaned with a detergent solution and a soft-bristle brush. Film on the sensor that resists removal usually can be removed by soaking the sensor in a detergent and water solution (Ficken and Scott, 1989), but the manufacturer's recommended cleaning procedures must be followed carefully for multiparameter sensor systems.

Radtke and others (2005) recommend cleaning specific conductance sensors thoroughly with de-ionized water before and after making a measurement. Oily residue or other chemical residues (salts) can be removed by using a detergent solution. Specific conductance sensors can soak in detergent solution for many hours without damage. Oil or other residues can be removed by dipping the sensor in a solvent or diluted hydrochloric acid solution (5 percent), but the manufacturer's recommendations must be checked before using acid solution or solvents on sensors. The sensor must never be in contact with acid solution for more than a few minutes. Carbon and stainless-steel sensors can be cleaned with a soft brush, but platinum-coated sensors must never be cleaned with a brush.

Routine cleaning of DO sensors involves using a soft-bristle brush to remove silt from the outside of the sensor, wiping the membrane with a damp, lint-free cotton swab (available at local electronics stores), and rinsing with de-ionized water. The sensor usually is covered with a permeable membrane and filled with a potassium chloride solution. The membrane is fouled easily and typically will need to be replaced every 2 to 4 weeks. When the membrane is replaced, the potassium chloride solution must be rinsed out of the sensor with de-ionized water followed by several rinses with potassium chloride solution before the sensor is refilled. The membrane must be replaced with care so that the surface of the membrane is not damaged or contaminated with grease, and no bubbles are trapped beneath the membrane. The surface of the membrane should be smooth, and the membrane should be secured tightly with the retaining ring. The sensor must be stored in water for a minimum of 2 to 4 hours, preferably longer, to relax the membrane before installation and calibration. The time required to relax the membrane requires either replacing the DO sensor membrane with a pre-relaxed membrane and recalibrating or replacing the membrane and revisiting the site for calibration later. The retaining ring must be replaced annually or more frequently to prevent loss of electrolytes. Replacing the retaining ring when membranes are changed ensures a tight seal.

The gold cathode of the DO sensor also can be fouled with silver over an extended period of time, and a special abrasive tool usually is required to recondition the sensor. A fouled anode, usually indicated by the white silver electrode turning gray or black, can prevent successful calibration. As with the cathode, the sensor anode usually can be reconditioned following the manufacturer's instructions. Following reconditioning, the sensor cup must be rinsed, refilled with fresh potassium chloride solution, and a new membrane installed.

The pH electrode must be kept clean, and the liquid junction (if applicable) must be free flowing in order to produce accurate pH values (Radtke and others, 2003). The body of the electrode should be thoroughly rinsed with de-ionized water before and after use. In general, this is the only routine cleaning needed for pH electrodes; however, in cases of extreme fouling or contamination, the manufacturer's cleaning instructions must be followed.

Turbidity sensors are extremely susceptible to fouling; thus, frequent maintenance trips may be necessary to prevent fouling of the turbidity sensor in an aquatic environment high in sediment, algae accumulation, larvae growth, or other biological or chemical debris. Mechanical cleaning devices, such as wipers or shutters that remove or prevent accumulation, are available for modern sensors. In environments that cause severe algal fouling, however, algae can accumulate on the wiper pad preventing complete removal of algal fouling from the optical lens and resulting in erratic turbidity data. Similarly, inorganic or organic debris can lodge in shutters, allowing fouling to accumulate and preventing efficient operation of the sensor. If the turbidity sensor is not equipped with a mechanical cleaning device that removes solids accumulation or a shutter that prevents accumulation on the lens before readings are recorded, reliable data collection is very difficult.

Sensors first should be inspected for damage, ensuring that the optical surfaces of the probe are in good condition. The wiper pad or other cleaning device also should be inspected for wear and cleaned or replaced if necessary. Before placing the turbidity sensor in standards, the optic lens should be carefully cleaned with alcohol by using a soft cloth to prevent scratching (or as recommended by the manufacturer), rinsed three times with turbidity-free water, and carefully dried. If the readings are unusually high or erratic during the sensor inspection, entrained air bubbles may be present on the optic lens and must be removed.

Field Calibration of Sensors

A water-quality monitoring sensor or sonde should be calibrated in the laboratory before installation at a field location and checked for calibration at the field site. Calibration in the laboratory or the field is done only by using calibration standards of known quality. During field visits, calibration of all sensors should be checked with two standard solutions that bracket the range of expected environmental conditions and a third standard near the ambient environmental conditions before any adjustments are made to the monitor calibration.

Field calibration is performed if the cleaned-sensor readings obtained during the calibration check differ by more than the calibration criteria (table 7). Spare monitoring sondes or sensors are used to replace water-quality monitors that fail calibration after troubleshooting steps have been applied (see *Troubleshooting Procedures*). All calibration equipment and supplies must be kept clean, stored in protective cases during transportation, and protected from extreme temperatures.

Temperature Sensors

Modern temperature sensors are quite sturdy and accurate, and the manufacturers generally make no provisions for field calibration of the temperature sensor. Temperature readings are compared between the sensors and thermometers that have been certified by the local USGS Water Science Center with an NIST-traceable thermometer as described by Radtke and others (2004). Temperature accuracy is especially important because of the effect of temperature on the performance of other sensors. Before a field trip, the Water Science Center certification labels on thermometers or thermistors should be checked to ensure that the certification is current and that the thermometer or thermistor is appropriate for use in extreme field conditions.

The temperature sensor and the calibrated field thermistor are placed adjacent to each other, preferably in flowing water or an insulated bucket of water. If a liquid-in-glass thermometer is used, it must be the total-immersion type. Sufficient time for temperature equilibration must elapse before a reading is made. The two temperature sensors must be read and the temperatures recorded instantaneously. If the monitoring temperature sensor fails to agree within $\pm$0.2 °C, troubleshooting steps must be taken; if troubleshooting fails, the sensor must be replaced. The faulty sensor or sonde should be returned to the manufacturer for proper calibration, repair, or replacement.

Specific Conductance Sensors

Calibration of specific conductance sensors should be checked with three calibration standard solutions of known quality before any adjustments are made, thus providing data for possible three-point calibration drift corrections (see *Application of Data Corrections*). Calibration checks must be made with two standard solutions that bracket the expected range of environmental conditions and a third standard solution near the ambient specific conductance value of the water. In addition, the zero response of the dry sensor in air should be checked and recorded to ensure linearity of sensor response at low values. If sensor-cleaning processes fail to bring a specific conductance sensor within the calibration criteria (table 7), the sensor must be recalibrated. Field calibration differs among the types of instruments, but most sensors generally are calibrated with only one or two standards. The manufacturer's calibration procedures should be followed.

Expiration dates and lot numbers for the standard solutions must be recorded and the standard solution bottles allowed to equilibrate to the temperature of the aquatic environment (by immersing in the water for 15 to 30 minutes). After three calibration standard solutions are checked and recorded (without making any adjustments), the monitor is recalibrated, if necessary, by using the appropriate calibration standard solutions and following the manufacturer's calibration procedures. The sensor, thermistor or thermometer, and measuring container must be rinsed three times with a standard solution. Gentle tapping will ensure that no air bubbles are trapped on the sensor. Fresh standard solution is poured into the calibration cup; the temperature setting is adjusted, if necessary; the specific conductance values, calibration standard values, and temperature are read and recorded in the field notes and the monitoring instrument log. A temperature correction may be necessary if the monitor does not have automatic temperature correction (Radtke and others, 2005).

Standard solution that has been used is discarded into a waste container, and the procedure is repeated using a second or third standard solution to check linearity of sensor response. If the sensor readings differ from the standards by more than 5 μS/cm or 3 percent, whichever is greater, the calibration sequence must be repeated. If the second calibration sequence still differs by more than the calibration criteria, troubleshooting techniques must be attempted (see *Troubleshooting Procedures*). If these steps fail, the sonde or monitoring sensor must be replaced and the backup instrument calibrated.

Dissolved Oxygen Sensors

Dissolved oxygen in water is related to temperature, atmospheric pressure, and salinity. Calibration of DO sensors should be checked at 100-percent saturation and with a fresh zero-DO solution before any adjustments are made. Lewis (2005) provides detailed steps for four different calibration procedures: (1) air-calibration chamber in water, (2) air-saturated water, (3) air-calibration chamber in air, and (4) iodometric (Winkler) titration. The first three procedures calibrate DO to 100-percent saturation by an amperometric method. Based on measured temperature and atmospheric pressure, the saturated DO is obtained from a reference table developed by Weiss (1970) as described in U.S. Geological Survey (1998) and reproduced by Lewis (2005). An interactive program also is available for producing a table of DO saturation values (*http://water.usgs.gov/software/dotables.html*) to the nearest 0.1 or 0.01 mg/L over user-defined ranges of temperature and barometric pressure and a table of salinity-correction factors over user-defined ranges of specific conductance. Ambient atmospheric pressure must be determined with a calibrated pocket barometer to the nearest 1 mm of mercury. The fourth method, the iodometric titration method, measures DO in an unknown sample directly (by a dye color change upon reduction of available oxygen) to determine the sample concentration to which the DO sensor is calibrated. The appropriate procedure depends on the type of monitoring equipment. The manufacturer's calibration procedures must be followed closely to achieve a calibrated accuracy of ±0.3 mg/L concentration of DO. Calibration of field barometers should be checked before each field trip, preferably by checking with an official weather station (Lewis, 2005).

Most DO sensors can be calibrated only with a one-point calibration, usually at 100-percent saturation, although some sondes have the capability of a two-point calibration, at zero-percent and 100-percent saturation. For the sondes that are calibrated only at 100-percent saturation, the DO sensor response is checked in a zero-DO sodium-sulfite solution. A fresh zero-DO standard solution should be prepared before each field trip, as described by Lewis (2005).

Calibration in the field presents a problem because replacement of the Teflon® membrane may be required frequently, and the replaced membrane must be allowed to "relax" in water for 2–4 hours before calibration (Lewis, 2005). One solution to this problem is to carry into the field clean and serviced spare DO sensors, stored in water (or moist, saturated air). The replacement DO sensors then can be calibrated in the field, thus avoiding an interruption in the record and a return site visit.

Luminescent-based DO sensors are calibrated by the manufacturer, and the manuals indicate that calibration may not be required for up to a year. When calibrated, the user should follow the manufacturer's guidance. Regardless of the manufacturer's claims, the user must verify the correct operation of the sensor in the local measurement environment. The standard protocol for servicing should be used for luminescent-based DO sensors to quantify the effects of fouling and calibration drift. Lewis (2005) advises users to make frequent calibration checks and to recalibrate as frequently as required to meet the specific data-quality objectives. Recalibration should not be necessary if calibration checks show the sensor to be in agreement with the calibration criteria (table 7).

pH Sensors

Field calibration of pH sensors often is a time-consuming process that requires patience. Expiration dates for the pH-4, 7, and 10 buffer solutions must be checked, and spare pH sensors or backup sondes will need to be prepared in case replacement of the sensors is required.

Upon arrival at the field site, tightly capped buffer solutions are immersed in the aquatic environment to allow time for temperature equilibration, usually 15 to 30 minutes. Prior to replacement or calibration of the pH sensor, the cleaned sensor should be checked for calibration drift in all three buffer solutions. If the pH sensor readings exceed the calibration criteria (table 7), the monitoring sensor must be calibrated as described by the manufacturer's instructions.

Temperature effects on pH buffer solutions vary with individual solutions, and the temperature-correction factor must be verified with the manufacturer. Examples of common pH buffer solution variances with temperature are given in table 8. The pH sensor reading must be standardized to the temperature-corrected pH value.

Table 8. Example of the effects of temperature on pH calibration standard solutions.

[ºC, degree Celsius; all pH values are in standard pH units. Temperature-compensation values for pH may vary with buffer manufacturers; refer to manufacturer's specifications for actual buffer values]

Temperature (°C)	pH buffer solution nominal value		
	4.01	7.00	10.00
0	4.00	7.14	10.30
5	4.00	7.10	10.23
10	4.00	7.07	10.17
15	4.00	7.04	10.11
20	4.00	7.02	10.05
25	4.01	7.00	10.00
30	4.01	6.99	9.96
35	4.02	6.98	9.92
40	4.03	6.98	9.88

For most sondes, a two-point calibration is used. A relative zero is established with a pH-7 buffer and the slope is set with a pH-4 or pH-10 buffer. A three-point calibration may be used for some sondes. To begin calibration, the pH sensor, thermistor or thermometer, and calibration cup are rinsed with pH-7 buffer solution, which is then discarded along with all subsequent rinsates in a waste container. Fresh pH-7 buffer solution is poured into the rinsed calibration cup, and the instruments are allowed to equilibrate for at least 1 minute before the buffer solution is discarded and fresh pH-7 buffer solution is poured into the calibration cup. The solution is slowly swirled in the calibration cup, ensuring that the pH sensor and thermistor are fully immersed and that values have stabilized. The temperature, pH, and associated millivolt reading (if available) are measured and recorded, along with lot numbers and expiration dates of the pH buffers. This standardization process is repeated with fresh pH-7 buffer solution until two successive values of the temperature-adjusted pH-7 readings are obtained.

The pH sensor, thermistor or thermometer, and calibration cup are rinsed with de-ionized water, and the standardization process is repeated with a pH-4 or pH-10 buffer solution to establish the response slope of the pH sensor. A buffer that brackets the expected range of pH values in the environment should be selected. The second temperature-corrected pH value, temperature, millivolt readings, lot numbers, and expiration dates are recorded, and the pH sensor, thermistor or thermometer, and calibration cup are rinsed with de-ionized water. The pH-7 buffer solution is then used to rinse, fill, and check the pH-7 calibration measurement. If the pH sensor reading is 7 ±0.1 pH units, the slope adjustment has not affected the calibration. If the accuracy standard is not met, the calibration and slope adjustment steps must be repeated. If repeated calibration and troubleshooting steps fail, the pH sensor or monitoring sonde must be replaced.

Once the slope-adjustment step is completed satisfactorily, the third buffer solution can be used as a check for calibration range and linearity of electrode response. The temperature and pH values are read and recorded along with the lot numbers and expiration dates of the pH buffers; however, the ±0.1 pH accuracy should not be expected to be achieved over the full range from pH-4 to pH-10 for a monitoring sensor. The third buffer should be within ±0.2 pH unit value.

Waters with specific conductance values less than 100 μS/cm may require special low-ionic strength buffers and pH sensors. The extra preparations, precautions, and troubleshooting steps necessary for using these buffers and sensors to measure low-ionic strength waters are described in Busenberg and Plummer (1987).

Turbidity Sensors

Field inspection or calibration of the turbidity sensor is made by using approved calibration turbidity and calibration verification solutions and by following the manufacturer's calibration instructions as described in Anderson (2004). Turbidity standard solutions with various ranges are available commercially, and most sensor manufacturers recommend either formazin-based or SDVB-polymer standards for calibrating turbidity sensors. Formazin-based standard solutions can be diluted by using a dilution formula; however, errors may be introduced during the dilution process, thus reducing the accuracy of the standard solution. Turbidity-free water, used in the preparation of standard solutions, dilution, and rinsing, should be prepared as described in Anderson (2004). Checking or calibrating the turbidity sensor must occur in an environment in which stable readings can be obtained. Such an environment minimizes movement of the standard solutions, wind, or direct sunlight as much as possible. Care should be taken to avoid interference from the bottom of the calibration vessel. Follow the manufacturer's recommendations for calibration.

Calibration of the turbidity sensor should be checked in three standard solutions before any adjustments are made. If the sensor readings exceed the calibration criteria (the greater of ±5 percent or 0.5 turbidity unit) during the inspection process, the sensor must be calibrated. A three-point calibration process is recommended, covering the expected range of values, although some instruments may be limited to calibration with only one or two standards. If instrument calibration allows only a two-step process, two primary standard solutions covering the expected range must be used for calibration and a third midpoint standard solution is used to check for linearity. Similarly, if the instrument calibration requires only turbidity-free water and one standard solution, another midpoint standard solution must be used to check for linearity.

Large particles, leaves, twigs, or other natural debris may interfere with the measurement of true turbidity by causing spikes in the data. Most turbidity sondes designed for continuous deployment have a filtering algorithm coded in the instrument software that eliminates such spikes. The data-processing algorithms may be programmed in the sensor software with no options for user input. User-defined variables, such as time constants and spike thresholds, may be permitted using proprietary algorithms. Anderson (2004) describes some instruments that have the capability of providing such statistics as maximum, minimum, mean, median, range, and variance of multiple readings over a time span of a few seconds. These statistics can be useful for reducing variability in recorded turbidity readings, for understanding sources of turbidity, or for diagnostic purposes. Anderson (2004) cautions that algorithms that are intended to reduce spikes in instantaneous data 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. Because signal averaging to smooth the data output alters the instrument response to changes in turbidity readings, true changes in turbidity may not be measured.

Troubleshooting Procedures

When a field parameter cannot be calibrated with standard solutions, the hydrographer must determine if the problem is with the sensor or the monitor and make the necessary corrections to ensure that the monitor is operational. The hydrographer should carry spare sensors and sondes so that troubleshooting can be accomplished at the time of the service visit. Troubleshooting in the field can prevent the need for extra trips and greatly reduce record loss and the amount of time spent in processing records in the office. A successful service trip results in a properly calibrated and fully functional monitor. Some of the more common problems that are encountered in the field when servicing monitors are listed in table 9.

Table 9. Troubleshooting problems with water-quality monitors.

[DO, dissolved oxygen; %, percent]

Symptom	Possible problem	Likely solution
Water temperature		
Thermistor does not read accurately	Dirty sensor	Clean sensor.
Erratic monitor readings	Poor connections at monitor or sensor	Tighten connections.
Monitor slow to stabilize	Dirty sensor	Clean sensor.
Readings off scale	Failure in electronics	Replace sensor or monitor.
Specific electrical conductance		
Will not calibrate	Standard solutions may be old or contaminated	Use fresh standard solutions.
	Electrodes dirty	Clean with soap solution.
	Air trapped around sensor	Thrust sensors up and down and tap gently to expel air.
	Weak batteries	Replace batteries.
Erratic monitor readings	Loose or defective connections	Tighten or replace connections.
Monitor requires frequent calibration	Broken cables	Replace cables.
		Replace monitor.
Dissolved oxygen		
Meter drift or excessive time for monitor to stabilize	Temperature compensator has not equilibrated with temperature of stream	Wait for temperature equilibration.
	Fouled sensor	Clean or recondition.
	Stirrer or pulse mechanism not working properly	Check for obstructions or replace.
Erratic monitor readings	Bad connection at monitor or sensor	Tighten connections.
	Fouled sensor	Clean or recondition.
Monitor slow to stabilize	Gold cathode tarnished	Buff with ink eraser or recondition sensor.
	Fouled membrane	Recondition sensor and replace membrane.
	Silver anode blackened	Replace sensor and soak fouled sensor in 3-percent ammonia for 24 hours.
Monitor will not zero	Zero-DO solution contains oxygen	Add additional sodium sulfite to zero-DO solution.
	Zero-DO solution is old	Mix a fresh solution.
Monitor will not calibrate	Membrane damaged	Replace membrane.
	Electrolyte diluted	Replace membrane and electrolyte.
pH		
Meter will not calibrate	Buffers may be contaminated	Replace buffers.
	Faulty sensor	Replace sensor.
Slow response time	Dirty sensor bulb	Clean sensor.
	Water is cold or of low ionic strength	Be patient.
Erratic readings	Loose or defective connections	Tighten connections.
	Defective sensor	Replace sensor.
Turbidity		
Unusually high or erratic readings	Entrained air bubbles on the optical sensor	Follow manufacturer's directions.
	Damaged sensor	Replace sensor.
	Dirty sensor	Clean, following manufacturer's directions.
	Water in connections	Dry connector and reinstall.

Requirements for Field Notes and Instrument Logs

Field notes and instrument logs are the basis for the accurate and verifiable computation of water-quality monitoring records. Legible, detailed, and in-depth field notes and instrument logs are essential for accurate and efficient record processing. Minimum field-note requirements for water-quality monitors include the following items:

- Station number and name
- Name(s) of data collector(s)
- Date, time, and time datum of each set of measure- ments
- Serial or "W" numbers of field meters and monitor
- Lot numbers and expiration dates of calibration standard solutions
- Purpose of the site visit
- Horizontal and vertical locations of sensors in the cross section
- Recorded monitor values, field values, and correspond- ing time and time datum (pre-cleaned, cleaned, calibra- tion checks, calibrations, and final in-stream readings)
- Cross-section survey data and(or) vertical-profile data (locations of vertical points, measured field parameter values, and measurement times), and monitor values before and after the cross-section survey
- Pertinent gage-height data
- Remarks that describe channel and site conditions, condition of the sensors, and any other pertinent observations
- Battery voltage of monitor at arrival and departure (was battery replaced?)
- Notes on sensor changes or replacements, troubleshoot- ing performed, and other remarks or observations that may aid in further processing of the record

The use of field-note forms that include these items encourages consistency and helps to avoid the costly omission of critical information. The USGS standard field form for continuous water-quality monitors contains a comprehensive checklist for data collection at many water-quality monitor- ing sites (Attachment 1). The current version of the USGS standard field form can be accessed by USGS personnel at *http://water.usgs.gov/usgs/owq/Forms.html*. Modifications of this form or alternative forms must be approved by the USGS Water Science Center water-quality specialist or designated reviewer.

An instrument logbook must be maintained for each field meter and water-quality monitor, and all pertinent information regarding the monitor and field meter must be recorded in the appropriate logbook. Details of instrument calibration—both field and laboratory calibrations—are one of the most important pieces of recorded information. Calibration information can be recorded initially on field forms or in field notebooks, but the information then must be copied into the instrument logbook. Repair or replacement of sondes, sensors, membranes, or modification to the sonde software must be recorded in the instrument logbook. The instrument logbook must contain a complete record of all maintenance in the field, the laboratory, or by the manufacturer. Permanent instrument logs contain critical calibration and maintenance information that documents instrument performance throughout the service life of the instrument. Calibration information that is important to log for record processing includes

- Sensor repair or replacement;
- Calibration dates, times, time datum, and temperatures;
- Calibration standard values, expiration dates, and lot numbers;
- Initial and final monitor-calibration data; and
- Field meter calibration values.

Field notes and calibration information should be clearly written, and all notations must be self explanatory. The goal is to have sufficient information for another individual to be able to independently compute the record with similar results. Clear notes simplify the record computation and final review processes.