



National Field Manual for the Collection of Water-Quality Data



Chapter A6 Field Measurements

Section 6.2 DISSOLVED OXYGEN

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Acknowledgments

This National Field Manual for the Collection of Water-Quality Data (National Field Manual) responds to advances in technology and science and to the ever-developing needs for water-quality monitoring. Its aim is to provide scientifically sound guidance to U.S. Geological Survey (USGS) personnel and to document USGS requirements for collecting water-quality data. As a result, the expertise of numerous scientists has been tapped in developing the various chapters of this manual and keeping them current.

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Contents

Acknowledgments	iii
6.2 Dissolved Oxygen	1
6.2.1 Optical (Luminescence) and Amperometric Sensor Methods	2
6.2.1.A Equipment and Field Preparations	4
Equipment Description and Maintenance	4
Field trip preparations	6
6.2.1.B Calibration of Optical and Amperometric Sensors	8
Correction for Atmospheric Pressure and Salinity	10
Selection of Calibration Method	12
Optical (Luminescence) DO Sensors: Calibration Procedures	12
Amperometric (Clark cell) DO Sensors: Calibration Procedures	18
6.2.1.C Measurement	24
Surface water	24
Groundwater	26
6.2.1.D Troubleshooting for Amperometric Instruments	29
6.2.2 Spectrophotometric (Rhodazine-D and Indigo-Carmine) Methods	30
6.2.2.A Equipment and Supplies	31
6.2.2.B Calibration and Interferences	32
6.2.2.C Measurement	33
6.2.3 Iodometric (Winkler) Method	36
6.2.3.A Equipment and Supplies	37
6.2.3.B Measurement	38
6.2.4 Reporting	40
6.2.5 Correction Factors for Oxygen Solubility Concentrations and Salinity	40
Selected References	54

Figures

6.2-1. Factors used to correct reported atmospheric pressures that have been adjusted to sea level	11
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Tables

6.2-1. Equipment and supplies for the optical and amperometric sensor methods of dissolved oxygen determination	6
6.2-2. Factors used to correct reported atmospheric pressures that have been adjusted to sea level	11
6.2-3. Troubleshooting guide for amperometric instruments	29
6.2-4. Equipment and supplies for the spectrophotometric method of dissolved-oxygen determination using Rhodazine-D™ and Indigo Carmine reagents	32
6.2-5. Equipment and supplies for the iodometric (Winkler) method of dissolved-oxygen determination	37
6.2-6. Solubility of oxygen in freshwater at various temperatures and pressures	42
6.2-7. Salinity correction factors for dissolved oxygen in water	48

6.2 Dissolved Oxygen

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The concentration of dissolved oxygen in water is affected by many factors, including ambient temperature, atmospheric pressure, and ion activity (ionic strength of the water body). Accurate dissolved-oxygen (DO) data are essential for understanding and documenting effects on environmental water resources that result from natural phenomena and human activities. Sources of DO in water include atmospheric aeration and photosynthetic activities of aquatic plants. Sinks of DO in water include respiration, aerobic decomposition processes, ammonia nitrification, and other chemical/biological reactions. Many chemical and biological reactions in groundwater and surface water depend directly or indirectly on the amount of available oxygen. The presence of DO in aquatic systems is necessary for the survival and growth of many aquatic organisms and is used as an indicator of the health and geochemical quality of surface-water and groundwater systems.

DISSOLVED OXYGEN: Molecular oxygen (oxygen gas) dissolved in water.

Standard procedures used by the U.S. Geological Survey (USGS) for determining concentrations of DO in surface water and groundwater involve the use of luminescence-based (optical sensor), amperometric (Clark cell¹), or spectrophotometric methods of analysis. The iodometric (Winkler) method (section 6.2.3) no longer is used by the USGS for routine measurement of DO at field sites, but remains a standard method for verifying the results of DO measurements made using other methods.

The selection of field equipment and measurement methods takes into consideration (a) whether equipment will be used at varying and discrete locations and times or be deployed at a single location over a period during which it will be unattended, (b) anticipated environmental conditions, (c) the specific data-quality objectives of the data-collection program, and (d) the inherent benefits of a given technology as applied to given site characteristics and project or program objectives. The measurement methods described are employed by the USGS onsite for routine determination of DO concentrations in fresh to saline surface water and groundwater.

The primary USGS field procedure employed for DO determinations during the past two decades required the use of amperometric sensors until luminescence-based (optical) sensors became more common (around 2005). Although both optical and amperometric methods yield accurate results, optical DO sensors are considered a major technological advance over amperometric sensors because optical DO sensors are more robust in the field environment.

- ▶ Optical and amperometric sensor methods (section 6.2.1) are applicable to the same aqueous environmental conditions. Both sensor technologies are available in single-parameter DO meters or in multi-parameter sondes and can be either handheld for discrete measurements or deployed for longer term, unattended continuous and real-time measurements.

¹ This document refers to the “amperometric” method or sensor interchangeably with the “Clark cell” sensor. Other terms applied to amperometric methods include polarographic and galvanic technology.

- ▶ Spectrophotometric (colorimetric) methods (section 6.2.2) yield consistent results when applied to the determination of DO concentrations in oxygen-depleted waters (for example, in certain aquifers and deep-lake horizons). Noninstrumental colorimetric methods that are available for visually determining DO concentrations to zero milligram per liter (mg/L) can be useful for a quick reconnaissance of DO conditions and an accuracy check of DO sensor performance.
- ▶ The iodometric (Winkler) method (section 6.2.3) is regarded as an accurate and precise method for the calibration of DO sensors and the determination of DO concentration in water, when performed under controlled laboratory conditions. Before sensors that could be immersed directly in the water column became commonly available, USGS personnel were trained to perform Winkler titrations onsite. Standard USGS practice no longer sanctions the transport of field samples offsite for DO determination.

- **Some procedures for equipment operation as recommended in this guidance document may not apply to your equipment because of technological advances or other changes.**
- **Be sure to record any modifications made to the standard USGS procedures given in this field manual.**

6.2.1 Optical (Luminescence) and Amperometric Sensor Methods

Either the optical or amperometric sensor methods can yield accurate results for measurement of DO concentrations under most of the field conditions encountered for routine USGS data-collection activities. Both methods are relatively simple to use, whether deployed for single (discrete) or continuous (unattended) DO measurements in surface water or groundwater. Because of the advantages introduced by advances in applying luminescence technology to DO measurement, optical sensors are generally favored for most standard USGS field operations.

- ▶ **Optical sensors.** The technology used in optical DO sensors involves the measurement of light-emission characteristics of a luminescence-based reaction at the sensor-water interface (see TECHNICAL NOTE 1). In contrast to amperometric sensors:
 - Oxygen is not consumed at the sensor-water interface.
 - The optical sensor is not dependent on water flow; consequently, no stirring mechanism is required at sites with slow or stagnant waters.
 - Optical sensors are stable. They are considerably more robust than amperometric sensors in maintaining calibration over long-term deployment and over a wide range of environmental conditions, and sensor drift over time is minimal when the sensor is kept clean.
 - There are no known sources of interference to the luminescence method in natural aquatic systems. Optical sensors will measure accurately in the presence of hydrogen sulfide (H_2S) and also when deployed in fresh, brackish, and mildly polluted waters. Contact, however, with organic solvents can compromise sensor integrity or performance.
 - Cleaning and maintenance are simplified. The optical sensor contains no anode or cathode to service, and uses no electrolyte solution, amperometric-type membranes, O-rings, or stirrer.

- The maintenance routine and schedule for optical sensors is less frequent than for amperometric sensors. Optical-sensor maintenance is dictated by manufacturer guidelines that are specific to the type of sensor in use and the conditions to which the sensor has been subjected.
 - Optical-sensor luminophore-containing modules² (referred to as sensor caps, probe tips, or luminophore-coated membranes or foil, depending on the manufacturer) are rugged and resistant to punctures or other damage in storm or high-flow conditions, while amperometric (Teflon-membrane) sensors are considerably more vulnerable and require frequent replacement.
 - Compared with the amperometric sensor, the frequency of a calibration check for an unattended (for example, continuously deployed) optical sensor should occur at least every 4 to 8 weeks, which depends primarily on environmental conditions and the age and condition of the luminophore, while the amperometric sensor typically requires recalibration every week or two, depending on environmental conditions.
 - The manufacturers generally recommend annual to biannual replacement of the luminophore-containing module. The modules are easily replaced and should be calibrated or undergo a calibration check after being replaced.

TECHNICAL NOTE 1. The luminescence sensor employs a light-emitting diode (LED) to provide incident light of a specific wavelength, which excites a luminescent-dye molecule substrate (luminophore) of the sensor. After some dissipation of the excitation energy, longer wavelength light is emitted. The intensity of the fluorescence is proportional to the DO concentration because the presence of oxygen can quench, or suppress, the fluorescence response of the dye. Higher DO concentrations result in greater quenching and a decreased fluorescence response. More importantly, the timescale, or lifetime, of the fluorescence reaction is dependent also on the DO concentration and is not dependent on the light intensity of excitation or fluorescence, therefore allowing reliable determination of the DO concentration. Temperature stability during calibration and measurement is extremely important for optical and amperometric sensors alike.

- ▶ **Amperometric sensors** (Clark cell). The amperometric measurement method was the most commonly used field method for DO determination for USGS water data-collection efforts before introduction of the luminescence method. In this method, the DO concentration is determined using a temperature-compensating meter connected to an amperometric-membrane type of sensor or an amperometric sensor bundled with other sensors in a multiparameter sonde.
 - Amperometric sensors require use of membranes and electrolyte solutions (*see* TECHNICAL NOTE 2 below).
 - The method is flow-dependent, requiring that an adequate flow of water (approximately 1 foot per second (ft/s)) passes across the membrane.³ Manual stirring is required when making handheld measurements. Use of an additional stirring mechanism fitted to the sensor or sonde is needed for discrete or continuous measurements at sites with slow or stagnant waters.
 - Contact of the amperometric sensor with hydrogen sulfide (H₂S) interferes with the DO determination by degrading the electrode surfaces under the membrane.

² See TECHNICAL NOTE 1 for definitions of luminescence and luminophore.

³ The “Rapid Pulse” (YSI) sensor, however, does not require a stirrer and was designed to be virtually flow-independent for DO measurement in environmental waters. As of this writing, it is the only amperometric technology designed for this purpose and that allows a two-point calibration.

- Amperometric sensors are vulnerable to changes in temperature and the instrument must be temperature compensating. Be cognizant of the relation between sensor membranes and temperature. The permeability of the membrane changes as a function of temperature, as does the solubility of oxygen in water.
- Method performance can be negatively affected by:
 - calibration drift
 - a loose, wrinkled, or damaged membrane
 - air bubbles in the electrolyte
 - use of expired or contaminated electrolyte solution
 - loose-fitting O-rings and membranes
 - damaged, dirty, or otherwise contaminated electrodes under the membrane
- Extreme temperature change and (or) shock/vibration may cause a shift in the calibration, resulting in biased data.

TECHNICAL NOTE 2. Some manufacturers provide amperometric-sensor membranes of various thicknesses, the selection of which depends on the intended use of the instrument. Select the sensor membrane based on manufacturer's recommendations. Two basic types of membrane design are available: (a) individual membranes and (b) membrane-cap assemblies. Individual membranes are considerably less expensive but require more care and skill to install properly. Sensor performance can be affected by the manner in which individual membranes are installed and conditioned after installation.

6.2.1.A Equipment and Field Preparations

DO instruments (meters and sensors) are available from a number of commercial vendors. Because of differences among manufacturers in the instrument design and instructions for use, calibration, and maintenance, it is important that the user be thoroughly familiar with the instructional manual for the specific instrument system to be used in addition to the guidance given here.

Equipment Description and Maintenance

Meters, sondes, and the DO sensors used in these instruments are sophisticated electronic equipment that require care in handling and operation. Information about the equipment and supplies required for the optical and amperometric methods of determining aqueous DO concentrations is summarized in table 6.2–1.

- ▶ **Amperometric sensor.** The amperometric “instrument system” refers to the entire sensor assembly, including electrolyte solutions, membranes, and thermistors. Protect all sensors and supplies from being jostled during transportation, from sudden impacts, sudden temperature changes, and from extremes of heat and cold below 0 °C.

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- ▶ **Optical sensor.** Guidance for when to replace the luminophore-containing cap or membrane varies among manufacturers and can be based on the specific design and materials used, the environmental conditions to which the sensor is exposed, the age of the sensor, and (or) the amount of time it is deployed. For example:
 - Hach Company states that the need for replacement of the luminophore module depends on environmental factors to which their LDO (Luminescent Dissolved Oxygen) probe is exposed, rather than be scheduled solely on the basis of frequency or length of use. Environmental factors such as photobleaching of the luminophore surface from irradiation (for example, overexposure to sunlight), and substantial changes in water properties such as salinity or atmospheric conditions (air pressure), can affect the need for luminophore-module replacement.
 - YSI Environmental advises annual replacement of the luminophore membrane assembly for their ROX (Reliable Oxygen) optical sensor.
 - In-Situ, Inc. advises that the RDO (Rugged Dissolved Oxygen) sensor cap has a 2-year shelf life from the time of manufacture when not in service, but the cap must be replaced after one year of field deployment.
 - ▶ **Storage of optical and amperometric sensors.** Become familiar with the specific manufacturer's recommendations for short-term (field) and long-term (office) storage.
 - Amperometric sensors should not be allowed to dry out and should be kept moist during storage.
 - Storage of optical sensors in a humid environment differs among manufacturers; consult the manual provided for the sensor.

Table 6.2–1. Equipment and supplies for the optical and amperometric sensor methods of dissolved oxygen determination.¹

[DO, dissolved oxygen; mg/L, milligram per liter; NFM, *National Field Manual for the Collection of Water-Quality Data*; –, minus; +, plus; °C, degrees Celsius; ±, plus or minus]

For amperometric method only
Amperometric instruments must be pressure-compensated (as well as temperature-compensated).
DO sensor membrane replacement kit includes membranes, O-rings, electrolyte (filling) solution; electrode reconditioning supplies; stirring attachment for low- or no-flow waters.
For optical and amperometric measurement methods
Instrument must be equipped with temperature compensation <ul style="list-style-type: none"> • DO instrument and DO sensor or multiparameter instrument with DO capability and digital temperature readout display • Operating range in water, from at least –5 °C to +45 °C • Measure concentrations from 0.05 to 20 mg/L (instrument capability can range to 50 mg/L) • Minimum scale readability (display resolution), preferably 0.01 mg/L DO • Calibrated accuracy within ±0.1 mg/L DO²
Calibration equipment, per manufacturer’s recommendation. ³
Pocket altimeter-barometer or DO instrument with built-in barometer; barometer measures to nearest 1 millimeter of mercury and its calibration has been checked before use.
Thermometer (see NFM 6.1 and 6.8 for calibration-check criteria) (for verification of air and water temperature and accuracy of instrument built-in thermistor).
Zero DO solution. ⁴ Dissolve 1 gram sodium sulfite in 1 liter of deionized water (0.008M solution, prepared fresh just before the field trip or during week of use). ⁵
Flowthrough chamber for determining groundwater DO, if downhole sensor deployment is impractical.
Oxygen-solubility table (table 6.2–6), or access http://water.usgs.gov/software/DOTABLES/ .
Waste-disposal containers.
Spare batteries. <ul style="list-style-type: none"> • Calibration and maintenance log books for DO instrument and barometer. • Calibrated specific conductance sensor, if working in saline or brackish systems.

¹ Modify this list to meet specific needs of the field effort.

² Refer to Wagner and others (2006) for long-term sensor deployment.

³ Equipment needs and additional information specific to each calibration procedure are provided in section 6.2.1.B.

⁴ Optionally, a few crystals of cobalt chloride (CoCl₂) can be added to the solution as a catalyst in order to speed up the reaction; however, routine USGS field operations omit the addition of CoCl₂, as it is a toxic substance, is regulated for proper disposal, and is not a necessary component to achieve a solution of the zero DO. If CoCl₂ will be used, personnel are advised to check the Material Safety Data Sheet for proper handling and disposal of the solution.

⁵ Take special note of the manufacturer’s guidance as applicable to your sensor. Some manufacturers supply the zero-DO solution required or document the specific instructions for preparing the zero-DO solution recommended for their sensors, including an alternative by which nitrogen gas is forced into tap or deionized water to produce a zero-DO solution (consult with the manufacturer’s division of technical support).

Field trip preparations

The service performed on all equipment, whether a full calibration, calibration check, or replacement or repair of parts for the instrument, and whether performed in the office, laboratory, or field, must be accurately recorded and dated in the log book using black or blue non-erasable ink.

Field-measurement instruments are to be maintained on a regular schedule and performance-tested before field deployment, as described below:

1. Check all electrical connections and the charge on the batteries, as applicable for the instrument in use.
2. Thermistors/thermometers must be calibrated and field checked before use, as described in NFM 6.1 (“Temperature”).

3. Perform a 100-percent saturation calibration check (see section 6.2.1.B). This performance check does not negate the need for onsite sensor calibration at oxygen saturation.
4. Perform a zero-DO sensor-performance check.
 - a. Prepare the zero-DO sodium sulfite solution (see table 6.2–1).
 - b. Before immersing sensor in the zero-DO solution, it is imperative to **remove the wiper** (or sponge) from the unit to avoid saturating it with the sodium sulfite solution. (Not all instruments have a DO sensor wiper.)
 - c. Rinse sensor and wiper thoroughly and then reinstall wiper elements. Multiple and thorough rinses with deionized water are necessary to restore the sensor to proper operating condition and prevent bias to subsequent measurements.
5. Review the care and maintenance guidance provided by the manufacturer for the specific sensor being used; instructions can differ appreciably depending on the instrument type, make, and model.
 - a. **Optical DO-sensor instrument:** Check the condition and (or) deployment history of the luminophore-containing sensor module, referring to the manufacturer’s guidance for replacement of the luminophore module.
 - Depending on the instrument, sensor modules are replaced annually or at least every 2 years, even if the probe is idle.
 - If the instrument reading exceeds 0.2 mg/L in the zero-DO solution, check DO again with a freshly prepared zero-DO solution; if a greater than 0.2 mg/L reading persists, contact the instrument manufacturer and inquire if the luminophore module should be replaced.
 - b. **Amperometric instrument:**
 - Inspect the instrument closely, checking for loose, wrinkled, or torn membrane; air bubbles beneath the membrane; a loose O-ring, and a tarnished or discolored cathode or anode. If any of these problems are detected, do not use the sensor until it has been serviced according to the manufacturer’s guidance.
 - If the instrument reading exceeds 0.2 mg/L in the zero-DO solution, check DO again with a freshly prepared zero-DO solution; if a greater than 0.2 mg/L reading persists, replace the sensor membrane and electrolyte (if present) or repair.
 - **Membrane type** – Consult manufacturer recommendations to select a sensor membrane of the thickness required for the field operation. (Only one membrane thickness is available for some amperometric sensor makes or models.)
 - **Membrane replacement** – After replacing, the new membrane should be allowed to condition over a given period of time before sensor calibration and deployment.
 - Depending on the manufacturer and whether replacement involves using the O-ring or membrane-cap method, conditioning time depends on the type of membrane. Conditioning of membranes with O-rings, for example, generally ranges from a minimum of 2 hours up to 6 hours. For greater stability during calibration, allow the new membrane to condition overnight before calibration and use.
 - Membranes in caps are prestretched and require less conditioning.

- For continuous monitoring applications with field-replaceable sensors, either condition the replacement sensor before the site visit, or replace the sonde with a second, clean and calibrated sonde and perform maintenance of the replaced sonde at the office.
 - When the sonde is deployed for discrete measurement, and conditions necessitate use of a new membrane before the recommended overnight conditioning time, more frequent calibration checks and possibly recalibration may be needed to ensure accurate DO measurements.⁴ This is not recommended for continuous monitoring applications.
6. Remember to document field preparations and all instrument tests and adjustments in the meter log book. **Do not use an instrument that fails calibration.**

CAUTION:

Before handling sodium sulfite, cobalt chloride, or any other chemicals, refer to safety precautions on the Material Safety Data Sheet (MSDS) for that chemical.

6.2.1.B Calibration of Optical and Amperometric Sensors

Sensor-based instrument systems used to determine DO in water must be calibrated properly before being deployed. Proper calibration procedures are necessary to ensure the overall accuracy and precision of DO measurements. Amperometric sensors are more likely to require frequent calibration than optical sensors. While equipment manufacturers advise performing the calibration in the office laboratory before going onsite, USGS protocols call for onsite calibration checks and possible recalibration at the field site, as necessary to meet the specific data-quality requirements of the project.

The accuracy required by the project for sites at which DO will be determined and the capabilities of the selected instrument will govern whether a one-point calibration will be sufficient or a two-point calibration should be used. In addition, some manufacturers of the DO equipment commonly used for USGS data-collection efforts recommend testing of the equipment in a laboratory setting to determine the accuracy of room-temperature calibrations compared with measurements made under the anticipated warmer or colder field conditions. Project personnel are advised to be familiar with recommendations from the manufacturer of their equipment.

- ▶ **One-point calibration.** The main goal of the one-point calibration procedure is to create a 100-percent saturated oxygen environment where the DO sensor (optical or amperometric) and its regulating thermistor are at the same temperature. Amperometric sensors used in multiparameter instruments, for the most part, are capable of only a one-point calibration).⁵
 - **Procedure 1** (Air calibration chamber in air)
 - **Procedure 2** (Calibration with air-saturated water)
 - **Procedure 3** (Air calibration with a wet towel)

⁴ One sensor manufacturer recommends running the DO sensor for at least 15 minutes after a membrane change or if the electrodes were reconditioned. Check the manual or handbook of your instrument for corroboration.

⁵ The “Professional Plus” multiparameter instrument (YSI Incorporated) with amperometric sensor can be calibrated at zero DO and 100 percent saturation. Other such instruments also may be in production.

- **Procedure 4** (Air calibration chamber in water). Unlike Procedures 1, 2, and 3, this procedure currently is applied to amperometric instrument systems only. The potential applicability of this procedure to calibration of optical sensors is a topic of discussion and review that can be followed in the chapter 6 section of the NFM Comments and Errata page (<http://water.usgs.gov/owq/FieldManual/mastererrata.html>).
- ▶ **Two-point calibration (for optical sensors).** The two-point calibration typically involves calibration of the sensor at 100 percent saturation, followed by calibration at zero DO. Only specific makes and models of optical DO sensors have the capacity to be calibrated to two points. The two-point calibration adds complexity to the calibration process and is not recommended by all manufacturers of optical sensors. Be sure first to understand the instrument capabilities and then determine the best course of action for your field work.
 - For routine applications, it is advisable to rely on a zero-DO performance check rather than a zero-DO recalibration, which would risk corrupting the manufacturer's zero-DO calibration.
 - Use of a two-point calibration should be considered if (a) the calibration is needed to satisfy the data-quality objectives of the project,⁶ (b) oxygen concentrations of less than 1 mg/L are likely to be encountered and zero-DO performance tests fail at this concentration level, or (c) the calibration is deemed necessary by experienced field personnel knowledgeable of site conditions.
 - Before starting or planning for a two-point calibration, it is advisable to consult the manufacturer's instructions or technical support for the specific optical DO sensor being used.
 - If using a two-point DO calibration, calibrate the DO sensor only after calibrating other field-measurement sensors to prevent possible interference of the sodium sulfite (zero-DO) solution with the calibration of the other sensors. Complete the DO calibration at 100 percent saturation before the zero calibration.
- ▶ **Sensor-performance checks.** Verifying sensor performance (calibration checks) is a required standard procedure in USGS field operations (*see* section 6.2.1.A)
 - All DO sensors have the capability to undergo a performance check at zero DO as well as at saturation.⁷
 - Verifying instrument performance at zero DO and using the two-point calibration can be particularly important for data accuracy when the instrument will be used to measure low DO concentrations (for example, DO less than 5 mg/L).

Do not use an instrument that fails to calibrate properly.

⁶ Although optical instruments undergo zero-calibration procedures by the manufacturer, the accuracy of factory calibrations may not satisfy the data-quality objectives of some USGS field studies.

⁷ It should be underscored that manufacturers uniformly caution against zero recalibration of sensors but allow for zero DO checks, stipulating the need to thoroughly rinse the zero-solution from the sensor.

Correction for Atmospheric Pressure and Salinity

Calibration procedures include corrections for atmospheric pressure and ionic strength (ionic strength is estimated from the conductivity or salinity measurement for routine field applications). Atmospheric pressure, the temperature of the water or water vapor, and the ionic strength (estimated by conductivity or salinity) of the water must be known to determine the theoretical amount of oxygen that can be dissolved in water. **Record all calibration information in instrument log books and copy calibration data onto field forms at the time of calibration.**

TECHNICAL NOTE 3. DO sensors do not actually measure oxygen in milligrams per liter or parts per million. Both of these expressed concentrations are based on calculations that relate instrument reading with the temperature and salinity of the sample water. The actual sensor measurement is proportional to the ambient partial pressure of oxygen, which can be displayed either as percent saturation or in milligrams per liter, depending on user input.

Ambient atmospheric pressure is true atmospheric pressure at the measurement site, not that which has been adjusted to sea level. Atmospheric pressure reported by the National Weather Service generally is not the true (ambient) value. National Weather Service atmospheric readings usually are adjusted to sea level and must be adjusted back to the elevation of the weather station. Upon request, a weather station may provide ambient atmospheric pressure.

- ▶ Determine the ambient atmospheric pressure to the nearest 1 millimeter (mm) of mercury. A calibrated pocket altimeter-barometer typically has been used to determine atmospheric pressure; however, many instruments that now are in common use include an internal barometer.
- ▶ Check the accuracy of all field barometers before each field trip (including barometers built into instrument systems) and record readings and adjustments in the instrument log book. If possible, check barometer accuracy while at an official weather station. If this is not an option, adjust the official weather station barometric pressure to the elevation at the field site at which the barometer reading is being recorded.
- ▶ To correct weather-station readings adjusted to sea level to ambient atmospheric pressure: subtract appropriate values shown (table 6.2–2, fig. 6.2–1) from atmospheric readings adjusted to sea level (shown in millimeters of mercury).

Although atmospheric pressure does not decrease linearly with increases in elevation, linear interpolation is acceptable within the elevation ranges given in table 6.2–2. Alternatively, plot the values from table 6.2–2 and extrapolate subtraction factors directly from the graph (fig. 6.2–1). Section 6.2.5 contains the table of oxygen solubility at various temperatures and pressures.

Most modern multiparameter instruments (see NFM 6.8) incorporate a pressure-temperature and salinity compensation algorithm in their firmware for DO measurements; the instruments have a built-in conductivity sensor that corrects the DO-concentration (in milligrams per liter) data for salinity automatically. For instruments that are not equipped with a conductivity/specific conductance (SC) sensor, a manual salinity correction of the DO data would be required.

- ▶ If a user-specified salinity correction is needed, **the preferred USGS method is to apply salinity correction factors after calibrating and** measuring DO concentration of the environmental water body (see section 6.2.5). Interactive tables are available for user-specified temperature, pressure, and salinity at <http://water.usgs.gov/software/DOTABLES/>.

- **When a manual salinity** correction is made by the user during calibration, the instrument requires recalibration for each field variation in salinity (*see* section 6.2.5).

TAKE NOTE: If using a multiparameter sonde that includes a calibrated conductivity sensor, salinity corrections to the DO concentration reading (in mg/L) are performed automatically in the sonde; that is, the DO sensor communicates with the SC sensor.

Table 6.2–2. Factors used to correct reported atmospheric pressures that have been adjusted to sea level.

[NGVD, National Geodetic Vertical Datum of 1929]

Elevation of weather station (in feet, NGVD)	Value to subtract (millimeters of mercury)
0	0
1,000	27
2,000	53
3,000	79
4,000	104
5,000	128
6,000	151

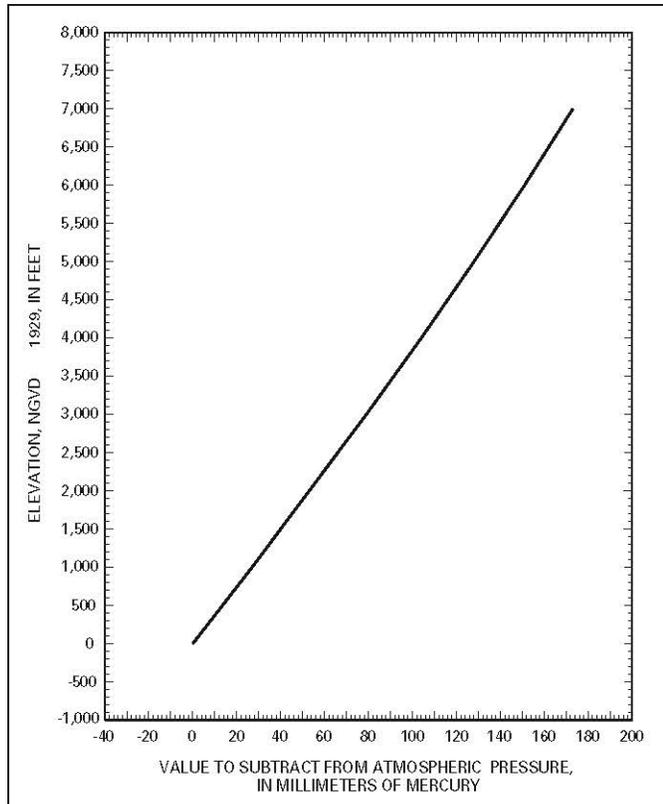


Figure 6.2–1. Factors used to correct reported atmospheric pressures that have been adjusted to sea level. NGVD 1929, National Geodetic Vertical Datum 1929.

Selection of Calibration Method

A saturated-oxygen calibration of DO sensors is recommended uniformly by manufacturers, regardless of which of the following methods is used: Air Calibration Chamber in Air (Procedure 1), Calibration in Air-Saturated Water (Procedure 2), or Air Calibration with a Wet Towel (Procedure 3). With minor modifications, these procedures can be applied to a one-point calibration of either luminescent-sensor (optical) or amperometric instruments (not all instruments allow or can accommodate a two-point calibration). A fourth method, Air Calibration Chamber in Water (Procedure 4), is described in the section on calibration for amperometric sensors. Although Procedure 4 has, in some cases, been applied when calibrating optical sensors, the pressure differentials and aqueous vapor properties at various temperatures experienced at the field site increases the potential for undetected water droplets on the thermistor and luminophore membrane and the risk for larger measurement error compared with the other calibration methods described below. It is important to refer to the manufacturer-provided guidance, as each of the procedures has inherent advantages and disadvantages and may include instrument-specific sources of error.

- ▶ The saturated-water method (Procedure 2) tends to be favored by manufacturers for calibrations in an office laboratory because it ensures equilibration of the temperature sensor with the DO amperometric membrane or the optical luminescence-coated sensor. Procedure 2 is considered to provide the best accuracy for calibration of optical sensors.
- ▶ The air calibration with a wet towel method (Procedure 3) is performed at the field site and is the method recommended most commonly by manufacturers for calibrating the amperometric (Clark cell) sensor, given advances in instrument technology. While the Wet Towel method can be used in the calibration of optical as well as amperometric sensors, the Air Calibration Chamber in Water method is applicable to amperometric sensors only. In previous versions of this field manual, the Air Calibration Chamber in Water (Procedure 4) method was published as “Procedure 3.”

- **Check DO meter calibration at each field site.**
- **Calibration of amperometric sensors should be checked each time after an instrument has been powered off and recalibrated, as necessary.**

Optical (Luminescence) DO Sensors: Calibration Procedures

The introduction of luminescence technology to DO field instruments has improved and simplified the data-collection process for field determination of DO. In addition to being more rugged, having fewer interferences, and undergoing decreased calibration drift relative to amperometric sensors, optical DO sensors tend to be more accurate, with accuracy specifications of ± 0.1 mg/L or 1 percent after calibration.⁸ This level of accuracy is best achieved by calibrating under controlled conditions in a laboratory or simulated laboratory environment.

⁸ USGS field scientists have corroborated the accuracy of the optical sensor to 0.05 mg/L DO by using repeated comparisons of results with the Rhodazine-D spectrophotometric method described in section 6.2.2 of this field manual (Gerolamo Casile, U.S. Geological Survey, written commun., 2012). These results can be entered into the USGS NWIS database.

TECHNICAL NOTE 4. Optical DO sensors often contain internal calibration information from the manufacturer. Although some manufacturers advise that no further calibration is warranted, the accuracy of factory calibrations do not necessarily satisfy the data-quality objectives required for USGS applications. **Because the validity of a calibration can substantially affect the overall accuracy and precision of DO measurements, users are advised to check the calibration frequently in order to meet specific data-quality objectives.**

- ▶ Because the optical DO sensors are not subject to drift, shock, or temperature extremes, the office-performed calibration is likely to remain stable after transport to the field; nevertheless, calibrations must be verified at the field site.⁹
- ▶ The Rhodazine-D spectrophotometric and iodometric methods for DO measurement described in sections 6.2.2 and 6.2.3, respectively, have been used to check the calibration of these instruments (see footnote 8).
- ▶ All calibration information is to be recorded in instrument-specific log books and the calibration data copied onto field forms at the time of calibration. Some instruments produce calibration reports generated by manufacturer-specific firmware; such reports that can be downloaded should be reviewed and incorporated in the instrument log book.
- ▶ Procedure 1 (air calibration chamber in air), Procedure 2 (calibration with air-saturated water) and Procedure 3 (air calibration with a wet towel) are described below for calibration of optical sensors at 100 percent saturation.
 - Refer to the NFM Comments and Errata, chapter 6, for the potential applicability of the “air calibration chamber in water” method to calibration of optical sensors (<http://water.usgs.gov/owq/FieldManual/mastererrata.html>).
 - A description of the “air calibration chamber in water” method is given below as Procedure 4 in the section titled "Amperometric (Clark cell) DO Sensors: Calibration procedures".

Procedure 1: Air calibration chamber in air

This procedure (which is similar to Procedure 3) is commonly used for calibrating **handheld** optical DO instruments. Calibration chambers either are built into the instrument case or are provided as separate components by the manufacturer. **Use the calibration chamber that is provided or recommended by the manufacturer.**

1. Wet the inside of the calibration chamber with water and then pour out the water, leaving a few drops.
 - a. Remove any water droplets on the temperature and optical sensors.
 - b. Insert the sensor into the chamber (this ensures 100 percent humidity).
 - If using a screw-on calibration cup, make sure it is loose and not making an airtight seal in order to maintain ambient pressure.
 - Keep the calibration assembly in a stable temperature environment and out of direct sunlight.

⁹ Laboratory calibration is favored by manufacturers in general, who advise that DO instruments rarely should require recalibration in the field.

2. Allow 10 to 15 minutes for the air to saturate with water vapor and for the DO sensor and the air inside the calibration chamber to equilibrate. If appropriate for the instrument being used, run the instrument during the equilibration period.
3. Using a calibration-checked altimeter-barometer, read the ambient atmospheric pressure checked to the nearest 1 mm of mercury.
4. Monitor the temperature and DO outputs in the calibration chamber, observing readings until the instrument readings stabilize. Read the temperature to the nearest 0.1 °C.

TECHNICAL NOTE 5. To maximize accuracy, a recommended practice is to maintain or approximate air temperatures during calibration that are within 10 °C of the ambient temperature of the water to be measured (see Procedure 3 – Wet Towel Method).

5. If calibrating to a given DO concentration rather than calibrating to a condition of 100 percent saturation, use table 6.2–6 or the online software DOTABLES (<http://water.usgs.gov/software/DOTABLES/>) to determine DO saturation at the calibration temperature and atmospheric pressure.
6. Following the manufacturer’s instructions, adjust the calibration control until the instrument reads the DO saturation value determined from the oxygen-solubility table.
 - If using an instrument that allows calibration simply to a 100-percent saturation condition, all that may be needed is to provide the ambient atmospheric pressure for the instrument to determine (with internal software) the resulting DO concentration.
7. Verify that the instrument reading is within ± 0.2 mg/L or 2 percent of the computed saturation value, or use more stringent accuracy criteria that reflect the data-quality requirements of the study.
8. Remove the sensor from the calibration chamber to check if water droplets were on the optical tip or membrane during calibration; water droplets on the sensor tip or membrane and on the temperature sensor can cause improper calibration.
 - **Recalibrate the instrument if water droplets were present.**
 - Having followed all the steps above, the DO sensor is now calibrated and ready for use.
9. Record calibration information in instrument log books and transfer calibration data into electronic records or onto paper field forms at the time of calibration.

During saturated-air calibration, it is necessary to keep water droplets off of the optical sensor module (luminescence tip or membrane) and temperature probe.

Procedure 2: Calibration with air-saturated water

This procedure, in which the DO sensor or instrument system is calibrated in water that is saturated with oxygen at a known temperature and ambient atmospheric pressure, generally is preferred by manufacturers for optical-sensor calibration.¹⁰ Procedure 2 is considered the most accurate for optical measurements of DO because the saturated water ensures that all equipment parts equilibrate with water temperature simultaneously, and the method eliminates the need to check for water droplets on the optical tip/membrane or temperature sensor. Great care is required, however, to ensure that the water is indeed saturated with oxygen.

Equipment: Calibration with Air-Saturated Water	
1	5-gallon bucket or manufacturer-provided aeration chamber
1	10-gallon-aquarium air pump with two outlets
1	10-foot-length of aquarium pump tubing
2	Gas-diffusion (air) stones

For this procedure, producing aerated water under controlled laboratory conditions is preferred; calibrate the DO sensor in the office laboratory before departing for the field site (step 4a below).

1. In the laboratory, fill a 5-gallon bucket to three-quarters full with tap water.
2. Attach the pump tubing to the pump and then the two air stones to the ends of the tubing. Place the tubing with air stones at the bottom of the filled bucket.
3. Turn on the pump and aerate the water for a minimum of 30 minutes.¹¹
Tip: The pump could be left to operate continuously (24/7) in order to have a ready supply of air-saturated water on hand for calibration in the laboratory or for transport and calibration in the field.
4. **Calibration**—Take care to keep air bubbles off of the optical sensor (the luminescence tip or membrane).
 - a. For laboratory calibration, place the DO sensor (or multiparameter sonde) in the bucket and allow 5 to 10 minutes for the sensor to come to thermal equilibrium with the aerated water. Take care not to place the sensor over or in the bubbles from the air stone!
 - b. For field calibration of a handheld DO sensor:
 - Fill a 1-gallon (approximately 4-liter) container to three-quarters full with the laboratory-aerated water for transport to the field. In the field vehicle, shake the container vigorously for 2 minutes to fully aerate the water and immerse the DO sensor. Allow about 5 minutes for the sensor to come to thermal equilibrium with the aerated water.
 - Alternatively, use the Wet Towel Method (Procedure 3).
5. Read and record the temperature of the calibration water to the nearest 0.1 °C.

¹⁰ Some manufacturers provide the necessary aeration equipment with the instrument.

¹¹ Previous versions of this procedure described in this field manual specified that a sensor or sonde be immersed in the water while the water is being aerated with a battery-operated aquarium pump. Owing to uncertainties in pump quality, battery power, and possible supersaturation, this technique is not universally recommended by the manufacturers who reviewed this protocol and has been modified accordingly. If the former procedure is used, it is imperative to avoid placing the sensor in the stream of air bubbles.

6. Using a calibration-checked altimeter-barometer, determine the ambient atmospheric pressure to the nearest 1 mm of mercury.
7. Using oxygen-solubility table 6.2–6 or the online software DOTABLES (<http://water.usgs.gov/software/DOTABLES/>), determine the DO saturation value at the measured temperature and atmospheric pressure of the calibration water. (Refer to section 6.2.5 and table 6.2–7 for salinity corrections.)
8. Verify that the instrument reading is within ± 0.2 mg/L or 2 percent of the computed saturation value. Alternatively, use more stringent accuracy criteria that reflect the data-quality requirements of the study. If the field calibration or calibration check fails to meet the established criterion, (a) use a different instrument (if available), and (b) do not collect or report data using an instrument that has failed calibration.
9. Record calibration information in instrument log books and transfer calibration data into electronic records or onto paper field forms at the time of calibration.

For accurate calibration, ensure that the water is 100 percent saturated with oxygen (see step 4b above).

Procedure 3: Air calibration with a wet towel

For many multiparameter instruments a 100-percent humidity environment can be created by wrapping a moist towel around the sensor guard and inserting into a plastic bag. The Wet Towel Method is almost identical to Procedure 1, the main difference being that the sensor (or sonde) guard will be wrapped in a wet towel instead of being inserted into a calibration cup or chamber.

Equipment: Calibration with a Wet Towel	
1	Towel, sized so that it will wrap around the sensor at least two full wraps
1	Trash bag, clear or white plastic

1. Bring sensor to thermal equilibrium.
 - a. If attempting to match the temperature of the water being monitored (for example, stream, lake, or groundwater), place the sensor directly in the water body (alternatively, for groundwater, into a flowthrough cell through which well water is being pumped continually).
 - b. Allow 5 to 10 minutes for thermal equilibration of the sensor with ambient water temperature until temperature readings have stabilized.
2. Once temperature readings are stable, soak the towel either (a) in the water for DO measurement, or (b) with tap or deionized water.

3. Remove the towel, wring it out, and then wrap the wet towel completely around the sensor guard, cup, or chamber, two full wraps or more.
 - As you wrap the sensor, ensure that no water droplets are either on the temperature sensor or on the luminescent sensor (sensor tip or membrane).
 - Place the wrapped sensor into the plastic bag and keep it out of direct sunlight in order to keep the temperature from changing.
4. Allow 10 to 15 minutes for the air to saturate with water vapor and for the DO sensor and the air inside the towel (calibration chamber) to equilibrate. Run the instrument during the equilibration period, if so directed by manufacturer instructions.
5. Using a calibration-checked altimeter-barometer, read the ambient atmospheric pressure checked to the nearest 1 mm of mercury.
6. Monitor the temperature and DO outputs and observe readings until the instrument stabilizes. Read the temperature to the nearest 0.1 °C.
7. If calibrating to a DO concentration rather than to 100 percent saturation, use the oxygen-solubility table 6.2–6 or the online software DOTABLES (<http://water.usgs.gov/software/DOTABLES/>) to determine the DO saturation concentration at the measured temperature and atmospheric pressure.
8. Following the manufacturer’s instructions, adjust the calibration control until the instrument reads the DO saturation value determined from the oxygen-solubility table.
 - If using an instrument that allows calibration only to 100 percent saturation, all that may be needed is to provide the ambient atmospheric pressure and the instrument will determine the resulting DO concentration internally.
 - Verify that the instrument reading is within ± 0.2 mg/L or 2 percent of the computed saturation value, or use more stringent accuracy criteria that reflect the data-quality requirements of the study.
9. Remove the sensor from the towel and check if any water droplets were on the membrane. Water droplets on the membrane and temperature probe can cause improper calibration.
 - **Recalibrate the instrument if water droplets are observed.**
 - Having followed all the steps above, the DO sensor is now calibrated and ready for use.
10. Record calibration information in instrument log books and transfer calibration data into electronic records or onto paper field forms at the time of calibration.

Amperometric (Clark cell) DO Sensors: Calibration Procedures

The calibration and operation of amperometric instruments differ among instrument types, makes, and models—refer to the instrument manual provided by the manufacturer. Calibration for amperometric sensors typically is performed using one of the following procedures for a one-point calibration at 100 percent saturation:

- ▶ Procedure 1 (Air Calibration Chamber in Air)
- ▶ Procedure 2 (Calibration with Air-Saturated Water)
- ▶ Procedure 3 (Air Calibration with Wet Towel)
- ▶ Procedure 4 (Air Calibration Chamber in Water)

Manufacturers recommend different calibration frequencies for membrane-electrode (amperometric) DO meters. Depending on equipment capabilities, instrument performance and data quality can be enhanced by checking sensor performance; that is, making calibration checks as frequently as needed or as directed by project protocols. Sensor manufacturers generally agree that optimum performance and data quality will be obtained by frequent calibration and performance checks. Sensor performance checks at zero DO are implemented routinely by trained USGS field personnel (see section 6.2.1.B).

Tip: Many amperometric DO sensors require the meter to be powered on for 10 to 15 minutes before calibration (and use) to stabilize the probe. Refer to the manufacturer's instrument-specific guidelines for the requirements of your instrument.

Procedure 1: Air calibration chamber in air

This procedure, similar to Procedure 3, is the most commonly used method for amperometric instruments. Calibration chambers are either built into the instrument case or are provided as separate components by the manufacturer. **Use the calibration chamber provided or recommended by the manufacturer.**

1. Wet the inside of the calibration chamber with water, then pour out the water (but leave a few drops).
2. Remove any water droplets on the sensor membrane and temperature sensor, then insert the sensor into the chamber (this ensures 100 percent humidity).
 - If using a screw-on calibration cup, ensure it is loose (not making an airtight seal) to avoid causing a change in the pressure around the sensor compared to the onsite barometric pressure. Alternatively, consider using the Wet Towel Method (Procedure 3).
 - Be sure to keep the DO assembly in a stable temperature environment and out of direct sunlight, as applicable for the instrument in use.
3. Allow 10 to 15 minutes for the air to saturate and for the DO sensor and the air inside the calibration chamber to equilibrate. Apply power to the instrument during the equilibration period, as applicable for the instrument in use.
4. Using a calibration-checked altimeter-barometer, read the ambient atmospheric pressure checked to the nearest 1 mm of mercury.

5. Monitor the temperature and DO outputs in the calibration chamber and observe readings until the instrument stabilizes. Read the air temperature in the chamber to the nearest 0.1 °C. To the degree possible, the temperature in the chamber should approximate the temperature of the water body in which DO will be determined within about 10 °C.

TECHNICAL NOTE 6. Most instrument manufacturers recommend calibrating at temperatures that are at least within 10 °C of the ambient water temperature. The most accurate calibration will be achieved if the temperature difference between the environmental water and the calibration chamber is minimized as much as possible (see Procedure 3, the Wet Towel Method, for additional information). In addition, the manufacturers of DO equipment that currently (2013) is in common use for USGS data-collection efforts advise testing the equipment in a laboratory setting to determine the accuracy of room-temperature calibrations compared with measurements made under the anticipated warmer or colder field conditions.

6. If calibrating to a DO concentration rather than to a 100-percent saturation condition, use the oxygen-solubility table 6.2–6 or the online software DOTABLES (<http://water.usgs.gov/software/DOTABLES/>) to determine the DO saturation value at the measured temperature and atmospheric pressure.
7. Following the manufacturer’s instructions, adjust the calibration control until the instrument reads the DO saturation value determined from the oxygen-solubility table.
 - If using an instrument that allows calibration simply to a 100-percent saturation condition, all that may be needed is to provide the ambient atmospheric pressure and the instrument will determine the resulting DO concentration internally.
 - Verify that the instrument reading is within ± 0.2 mg/L or 2 percent of the computed saturation value, or use more stringent accuracy criteria that reflect the data-quality requirements of the study. If the criteria are not met, repeat the calibration procedure after checking for water droplets in step 2 above.
8. Remove the sensor from the calibration chamber and again check for water droplets on the membrane. Water droplets on the membrane and temperature sensor can cause improper calibration.
 - **Recalibrate the instrument if water droplets are observed.**
 - Having followed all the steps above, the DO sensor is now calibrated and ready for use.
9. Record calibration information in instrument log books and transfer calibration data into electronic records or onto paper field forms at the time of calibration.

Procedure 2: Calibration with air-saturated water

In this procedure, the DO sensor or instrument system is calibrated in water that is saturated with oxygen at a known temperature and ambient atmospheric pressure. **Manufacturers advise that the calibration with air-saturated water is best done in the laboratory under controlled conditions.**¹²

Equipment: Calibration with Air-Saturated Water	
1	5-gallon bucket or manufacturer-provided aeration chamber
1	10-gallon-aquarium air pump with two outlets
1	10-foot-length of aquarium pump tubing
2	Gas-diffusion (air) stones

1. In the laboratory, fill the 5-gallon bucket about three-quarters full with tap water.
2. Using two air stones, saturate the water for at least 30 minutes before use. However, some manufacturers recommend that the pump be left on continuously (24/7) so that the water is always saturated and ready to use.
3. Place the DO sensor in the water, avoiding contact with the bubble stream, and allow the sensor to come to thermal equilibrium.
4. Read the temperature of the calibration water to the nearest 0.1 °C.
5. Using a calibration-checked altimeter-barometer, determine the ambient atmospheric pressure to the nearest 1 mm of mercury.
6. **Move the sensor so as to ensure a 1 foot per second (ft/s) flow across the membrane;** alternatively, use a sensor that is equipped with a stirrer. Ensure that sufficient flow passes over the DO sensor during the saturated-water calibration method as well as when making a field measurement.
 - Move the sensor to stir the water, using either a horizontal stirring motion or a “teabag” dipping motion. Take care not to remove the sensor from the water.
 - The DO reading may rise as the water is stirred.
 - **After the DO reading has peaked and is stable, start to calibrate the DO sensor.**
 - Maintain this flow rate while monitoring measurements and adjusting the instrument calibration.

TECHNICAL NOTE 7. The various types of amperometric sensors can have different levels of flow dependency; however, the 1 ft/s flow is not detrimental to sensors with little or no flow dependence.

7. Using the oxygen-solubility table 6.2–6 or the online software DOTABLES (<http://water.usgs.gov/software/DOTABLES/>), determine the DO saturation value at the measured temperature and atmospheric pressure of the calibration water. (Refer to section 6.2.5 and table 6.2–7 for salinity corrections.)

¹² Field calibrations with battery-powered pumps are not recommended by manufacturers who reviewed this report (see footnote 11). Trained USGS field personnel have, however, demonstrated success using Procedure 2 in the field.

8. Verify that the instrument reading is within ± 0.2 mg/L or 2 percent of the computed saturation value, or use more stringent accuracy criteria that reflect the data-quality objectives of the study.
 - Having followed all the steps above, the DO sensor is now calibrated and ready for use.
9. Record calibration information in instrument log books and transfer the calibration data into electronic records or onto paper field forms at the time of calibration.

For accurate calibration, ensure that the water is 100 percent saturated with oxygen.

Procedure 3: Calibration with a Wet Towel

This method is almost identical to Procedure 1, the main difference being that the sensor (or sonde) guard will be wrapped in a wet towel instead of being inserted into a calibration cup or chamber.

Equipment: Wet-Towel Calibration	
1	Towel, sized so that it will wrap around the sensor at least two full wraps
1	Trash bag, clear or white plastic

1. Bring the sensor to thermal equilibrium.
 - If attempting to match the temperature of the water being monitored (for example, stream, lake, or groundwater), place the sensor directly in the water body (alternatively, for groundwater, into a flowthrough cell through which well water is being pumped continually).
 - Allow 5 to 10 minutes for thermal equilibration of the sensor with the ambient water temperature until temperature readings have stabilized.
2. Once temperature readings are stable, soak the towel either (a) in the environmental water for DO measurement, or (b) with tap or deionized water.
3. Remove the towel, wring it out, and wrap the wet towel completely around the sensor guard, cup, or chamber, two full wraps or more.
 - As you wrap the sensor, **ensure that no water droplets are either on the temperature sensor or on the sensor tip or membrane.**
 - Place the wrapped sensor into the plastic bag and **keep it out of direct sunlight** to keep the temperature from changing.
4. Allow 10 to 15 minutes for the air to saturate with water vapor and for the DO sensor and the air inside the towel (calibration chamber) to equilibrate. Run the instrument during the equilibration period, if so directed by manufacturer instructions.
5. Using a calibration-checked altimeter-barometer, read the ambient atmospheric pressure to the nearest 1 mm of mercury.
6. Monitor the temperature and DO outputs and observe readings until the instrument stabilizes. Read the temperature to the nearest 0.1 °C.

7. If calibrating to a specific DO concentration rather than to 100 percent saturation, use the oxygen-solubility table 6.2–6 or the online software DOTABLES (<http://water.usgs.gov/software/DOTABLES/>) to determine the DO saturation value at the measured temperature and atmospheric pressure.
8. Following the manufacturer's instructions, adjust the calibration control until the instrument reads the DO saturation value determined from the oxygen-solubility table.
 - If using an instrument that allows calibration to 100 percent saturation, all that may be needed is to provide the ambient atmospheric pressure and the instrument will determine the resulting DO concentration internally.
 - Verify that the instrument reading is within ± 0.2 mg/L or 2 percent of the computed saturation value, or use more stringent accuracy criteria that reflect the data-quality requirements of the study or program.
9. Remove the sensor from the towel and check if any water droplets are on the membrane. Water droplets on the membrane or temperature sensor can cause improper calibration.
 - **Recalibrate the instrument if water droplets are observed.**
 - Having followed all the steps above, the DO sensor is now calibrated and ready for use.
10. Record calibration information in instrument log books and transfer calibration data into electronic records or onto paper field forms at the time of calibration.

Water droplets on the DO membrane and thermistor will result in improper calibration. Recalibration is required if water droplets are observed.

Procedure 4: Air calibration chamber in water

A specialized air-calibration chamber permits calibration of the DO sensor at the temperature of the water in which DO concentration is to be measured. This calibration procedure minimizes errors caused by temperature differences; for example, at sites having field conditions with a wide disparity between ambient air and water temperature. For many multiparameter water-quality instruments, the manufacturer-provided groundwater flow cell may be modified and used as an air calibration chamber in water.¹³ The modification requires the cell to be mounted on the sonde with one port of the cell tightly plugged and the other port vented to the atmosphere with tubing. The method is subject to large errors, especially in cold temperatures, if the port is not adequately vented to the environment. **Before using this method, check with the manufacturer for its applicability to the instrument to be used.**

1. Insert the sensor probe and calibration chamber into the surface water or groundwater to be measured. Once the temperature readings stabilize (allow 10 to 15 minutes), remove the sensors and calibration chamber from the water to be measured. Empty the calibration chamber, leaving a few drops of water.
 - Check for and remove any water droplets on the sensor membrane and the thermistor.
 - Insert the DO sensor into the wet chamber (this ensures 100 percent humidity).

¹³ Air calibration chambers for in-water calibrations no longer are available on the open market (for example, the YSI 5075A calibration chamber is no longer manufactured).

- Check that the port is adequately vented, that no water can leak into the calibration chamber, and that droplets of water are not adhering to the membrane and thermistor. The water droplets reduce the rate of oxygen diffusion through a membrane, producing erroneous results.
2. Immerse the calibration chamber into the water to be measured. Allow 10 to 15 minutes for the air temperature inside the chamber to equilibrate with the water (see TECHNICAL NOTE 6 in Procedure 1).
 - For streams, choose an area of the stream that closely approximates mean stream temperature. In shallow streams, try to place the chamber in an area that represents the stream but that is shaded from direct sunlight.
 - For groundwater, use temperature-stabilized purge water or other clean water having a temperature that closely approximates that of the groundwater.
3. Using a calibration-checked pocket altimeter-barometer, determine the ambient atmospheric pressure to the nearest 1 mm of mercury.
4. Read the temperature within the chamber to the nearest 0.1 °C, using a calibrated thermometer (NFM 6.1).
 - The temperature inside the chamber should approximate the water temperature.
 - If the two temperatures do not match, allow additional time for equilibration of the chamber with the water temperature.
 - If the temperature of the chamber still does not approximate the water temperature, the thermistor in the DO sensor might be malfunctioning. Compare water temperature measured by the DO meter and a calibrated field thermometer. If the two measurements vary by more than ± 0.5 °C, the calibration should be discontinued and the DO meter thermistor should be repaired following the manufacturer's recommendations.
5. Use table 6.2–6 (section 6.2.5) to determine the DO saturation value at the measured water temperature and atmospheric pressure. If a salinity correction will be applied during calibration, consult the instructions in section 6.2.5 and table 6.2–7.
6. Following the manufacturer's instructions, set or adjust the calibration control until the instrument reads a DO saturation value determined from oxygen solubility (table 6.2–6).
 - Verify that the instrument reading is within ± 0.2 mg/L of the computed saturation value, or use more stringent accuracy criteria per the data-quality objectives of the study.
 - Verify that no water droplets are on the membrane or thermistor. **Recalibrate the instrument if water droplets are observed.**
 - Having followed all the steps above, the DO sensor is now calibrated and ready for use.
 - Remove the sensor from the calibration chamber for cleaning and storage.
7. Record calibration information in instrument log books and transfer calibration data into electronic records or onto paper field forms at the time of calibration.

Water droplets on the DO membrane and thermistor will result in improper calibration. Recalibration is required if water droplets are observed.

6.2.1.C Measurement

The solubility of oxygen in water depends on the partial pressure of oxygen in air, the temperature of the water, and the content of dissolved solids in the water.

- ▶ The higher the atmospheric pressure and the lower the temperature and conductivity, the more oxygen can be dissolved in the water.
- ▶ Degassing, mineral precipitation, and other chemical, physical, and biological reactions can cause the DO concentration of a water sample to change substantially within minutes after sample collection. These sample reactions are especially important when sampling groundwater that is not in equilibrium with the atmosphere.

The solubility of oxygen in water decreases as salinity increases. Correction factors for salinity normally are applied after measuring DO for single-point samples; however, for continuously deployed DO probes on multiparameter instruments that include calibrated specific-conductance sensors, it is wise to activate the instrument's internal salinity correction algorithms to account for a dynamically changing environment. Information that pertains to oxygen solubility and salinity is given in section 6.2.5, including the link to an on-line program that generates tables of DO solubility values and (or) salinity correction factors over a range of user-specified temperature, pressure, and salinity or specific conductance (<http://water.usgs.gov/software/DOTABLES/> accessed March 11, 2013).

Surface water

Standard determinations of DO in riverine surface water represent the cross-sectional median or mean concentration of dissolved oxygen at the time of observation.

- ▶ Multiparameter instruments (sondes) are in common use for USGS measurement of DO and other field properties, both for in situ discrete measurements in surface water and for short- or long-term deployment in streams, lakes and reservoirs, and other bodies of surface water. Refer to NFM 6.8, Wagner and others (2006), and manufacturer guidance for additional information regarding the siting and use of multiparameter instruments.
- ▶ Measuring the DO concentration at one distinct point in a cross section is valid only for flowing water with a cross-sectional DO variation of less than 0.5 mg/L. Discerning such variation requires a reconnaissance cross-section measurement. **Measurements made at multiple locations in the cross section are recommended as a routine practice, when possible.**
- ▶ Determining DO concentration for a single channel at the centroid of flow at the midpoint of the vertical only represents the cross section under ideal mixing conditions.
- ▶ Do not measure DO in or directly below sections with turbulent flow, in still water, or from the bank, unless these conditions represent most of the reach or are required to fulfill study objectives.
- ▶ Verify whether or not the instrument in use applies salinity corrections automatically. If not, apply a salinity correction to the saturation values after the DO measurement, referring to section 6.2.5 and table 6.2–7.

**Dissolved oxygen must be measured in situ.
Never measure DO in subsamples from a sample splitter or other vessel.**

Follow the steps below to measure DO in surface water:

1. Calibration checks:
 - Check that the thermistor is accurate and that its calibration has been certified by the USGS Water Science Center within the past 12 months; more frequent calibration checks are performed in the field, depending on the field conditions encountered (see NFM 6.1.2.B for specifics).
 - Check the performance of the DO sensor at saturation and zero DO (refer to section 6.2.1.B).
 - If a calibration adjustment is necessary or if it is required to address program protocols, data-quality requirements, or site-specific conditions, calibrate the DO sensor onsite, in accordance with the procedures described in section 6.2.1.B.
2. Examine the variation in DO measured at multiple locations along the cross section (if this reconnaissance step was performed) to help select the sampling method (NFM 6.0):
 - **Flowing, shallow stream**—Wade to the location(s) where DO is to be measured.
 - **Stream too deep or swift to wade**—Lower a weighted DO sensor with a calibrated temperature sensor from a bridge, cableway, or boat.
 - Do not attach the weight directly to the sensors or sensor cables, because this could damage the sensors or sensor cables.
 - To avoid damaging sensors or cables, contact the instrument manufacturer or vendor for information regarding the weights approved for use with the instrument and how to attach them.
 - **Still-water conditions**—Measure DO at multiple depths at several points in the cross section (see TECHNICAL NOTE 8).
 - **Lakes and reservoirs**—Measure DO at a series of specific depths to determine a vertical profile at each location of interest (see TECHNICAL NOTE 8).

TECHNICAL NOTE 8. For amperometric sensors: If the water velocity at the point of measurement is less than about 1 ft/s, use a stirring device to increase the flow velocity.¹⁴

- To hand stir, raise and lower the sensor at a rate of about 1 ft/s, but do not break the surface of the water. The stir-by-hand method may not be appropriate in lakes, reservoirs, or slow-moving waters (for example, bayous); these water bodies may be stratified at the point of measurement, making accurate DO measurements impossible with a non-stirred amperometric DO probe. This could be especially problematic in areas where DO concentrations change substantially over short distances, such as near the thermocline or bottom sediments.
 - High stream velocity also can cause erroneous DO measurements.
-

3. Immerse the DO and temperature sensors directly into the water body and allow the sensors to equilibrate to the water temperature (no less than 60 seconds).
4. Record the temperature without removing the sensor from the water.

¹⁴ Refer to footnote 3 if using a YSI “Rapid Pulse” sensor, for which a stirrer is not needed.

5. After the instrument reading has stabilized, record the median DO concentration (see NFM 6.0). The reading should stabilize to within ± 0.2 mg/L.
6. For EWI, EDI, or multiple-vertical measurements, proceed to the next station in the cross section and repeat steps 3 through 5. When measurements for the stream have been completed, remove the sensor from the water, rinse it with deionized water, and store it according to the manufacturer's instructions.
7. Record DO concentrations on the field forms:
 - **In still water**—Median of three or more sequential values.
 - **EDI**—Mean value of all subsections measured (use the median if measuring one vertical at the centroid of flow).
 - **EWI—Mean (or median)** of all subsections measured.

Groundwater

Before the concentration of DO in groundwater can be determined, standing water must be evacuated from the well to ensure that measurements of DO concentration in the well will be representative of formation-water concentration. An adequate well purge ensures the flow of freshwater from the formation into the well (refer to NFM 4.2 and NFM 6.0.3.A for detailed information). Measurement of ambient DO concentrations in groundwater additionally requires use of equipment and procedures that avoid aeration and mitigate losses or gains of dissolved gases in the water being sampled. A bailed sample, for example, is inadmissible for DO measurement because the field sample-decanting process exposes the sample to the atmosphere (NFM 6.0.3); this provision likewise applies to any type of sampling device from which the sample is brought in contact with air when transferred to a measurement or analysis vessel.

Project or program data-quality requirements and objectives, site characteristics, and equipment availability will dictate whether (a) measurements will be made *in situ* (DO measured downhole) or *ex situ* (DO measured above land surface, the inline-flow procedure), and if (b) optical, amperometric, or spectrophotometric methods will be used for DO measurement. This section addresses the use of optical and amperometric sensors, for which the lower threshold for measurement of aqueous DO concentrations is from 1 to 2 mg/L, depending on the instrument being used and the accuracy required.¹⁵ **If the anticipated DO concentration is less than 1.0 mg/L, consider use of spectrophotometric methods (section 6.2.2).**¹⁶

- ▶ If using an optical-sensor instrument at DO less than 1.0 mg/L, first perform a zero-DO calibration check or calibration (instrument permitting), and document the results.
- ▶ When anticipating DO concentrations in the hypoxic or suboxic range on a routine or regular basis,
 - Optical sensor: Readings to 0.05 mg/L should be verified using the methods described in sections 6.2.2 or 6.2.3. The presence of hydrogen sulfide, however, will not affect the accuracy of the measurement.
 - Amperometric sensor: The sensor can be adversely affected by hydrogen sulfide and misread the true DO value.

¹⁵ The accuracy of DO measurements to 0.05 mg/L with an optical sensor has been field verified against Rhodazine-D spectrophotometric measurement on numerous occasions by USGS field-methods instructors (Gerolamo Casile, U.S. Geological Survey, oral commun., 2012).

¹⁶ Note that spectrophotometric methods for determining DO concentration generally are not approved by the U.S. Environmental Protection Agency for regulatory assessments.

Refer to NFM sections 6.0.1 and 6.0.3 for guidance related to the selection, preparation, and procedures for in situ and ex situ measurement of field-determined properties. Study objectives and site characteristics will dictate the specific method selected. Select the field-measurement system that best fits the requirements for the data-collection effort.

- ▶ **Downhole (in situ) measurement** (see NFM 6.0.3.B). Submersible multiparameter sondes and single-parameter sensors are deployed downhole to the targeted depth interval. Deployment typically involves data collection for a single field trip. The sonde or sensor sometimes is deployed for unattended monitoring, but the appropriate conditions and protocols must be followed (see NFM 6.8). Use of the optical DO sensor makes longer-term deployment more practical, compared to that of the amperometric sensor.
- ▶ **Inline flowthrough cell/chamber (ex situ) measurement.** Sample is pumped directly (inline) to an airtight, transparent chamber or manufacturer-provided cell having either (1) leak-proof ports (compression fittings) that accommodate either the optical or amperometric DO single-parameter sensor (and other single-parameter sensors), or (2) a multiparameter sonde instrumented with either an optical or amperometric DO sensor. NFM 6.0, figure 6.0–3, diagrams a flowthrough cell system; figure 6.0–5 charts downhole and inline sampling processes.¹⁷
 - Sample is transferred using a positive-displacement submersible pump fitted with high-density plastic or fluorocarbon-polymer tubing that is relatively gas impermeable.
 - Use of transparent materials for the tubing and chamber is needed to allow checking for air bubbles in the water stream or adhering to the sides of the tubing and flowthrough cell or chamber (that have been introduced as an artifact of the sampling procedure, as distinguished from gas bubbles that are native to the formation water). Such air bubbles add significant error to low-level DO measurements and should be excluded (A.F. White, U.S. Geological Survey, written commun., 1993).
 - Protect exposed sample tubing and the flow-through cell or chamber from direct sunlight.

Do not measure groundwater DO concentration in a sample extracted from a bailer or other sampling device that results in sample exposure to the atmosphere.

Follow the steps below to measure DO in groundwater:

1. Calibration checks: Check the performance of the DO sensor at saturation and zero DO (refer to section 6.2.1.B).
 - Check that the thermistor gives an accurate reading and that its calibration has been verified by the USGS Water Science Center within the past 12 months (see NFM 6.1).
 - Check the performance of the DO sensor at saturation and zero DO (refer to section 6.2.1.B).
 - If field calibration is necessary or if it is required to address program protocols, data-quality requirements, or site-specific conditions, calibrate the DO sensor in accordance with the procedures and restrictions described in section 6.2.1.B.

¹⁷ See section 6.0, “General Information and Guidelines,” in chapter 6 of this field manual (http://water.usgs.gov/owq/FieldManual/Chapter6/6.0_contents.html).

2. Install the DO equipment (see NFM 6.0 for more detailed instructions):
 - **Downhole system**—Lower the DO and temperature sensors to the measuring point, followed by the pump, to monitor DO variation during purging. When an amperometric sensor is used, water needs to flow past the sensor at a velocity of no less than 1 ft/s; attach a mechanical stirrer, if necessary, to maintain this velocity. The optical sensor is not flow dependent.
 - **Inline flowthrough system**—Refer to NFM 6.0 for installation guidelines. If sensors are to be installed in a flowthrough cell or chamber, install the DO sensor immediately downstream of the point of sample inflow. For a system using a multiparameter instrument sonde, install the sonde in the flowthrough cell provided by the manufacturer and in accordance with manufacturer instructions. Be sure to:
 - Install the DO sensor through an airtight grommet, if using a chamber instrumented with single-parameter sensors. Check that the seal around the DO sensor is intact and that the sensors are properly immersed.
 - Shield the sample tubing and flowthrough cell/chamber from direct sunlight to minimize changes to sample temperature (this step is most critical for users of amperometric sensors).
 - Dislodge and flush entrained air bubbles from the tubing walls and flowthrough chamber by tapping the tubing with a blunt tool (see TECHNICAL NOTE 9 below). Note that air bubbles are an indication of air leakage into the sampling system and should be distinguished from gas bubbles that could be native to formation water chemistry.
 - Check for and eliminate backpressure in the flowthrough chamber.
3. **If using an amperometric instrument**, be sure to maintain constant, laminar flow past the DO sensor (refer to footnote 3). Measure and record DO at regular intervals throughout purging. Allow the sensors to equilibrate with groundwater for 5 minutes or more at the flow rate to be used for sampling.
4. Check the stability (measurement variability) of DO toward the end of purging. The stability criterion is met when five consecutive readings made at regularly spaced intervals of 3 to 5 minutes or more are within ± 0.2 mg/L. (For each reading, monitor fluctuations for 30 to 60 seconds and record the median value, if necessary.) If the ± 0.2 mg/L criterion is not met, increase the purge period in accordance with study objectives and continue to record measurements at regularly spaced time intervals.
5. Report sample DO as the median of the final five DO readings recorded. Record on field forms any difficulty with stabilization.
6. Remove the sensor from the water and rinse it with deionized water.

Air bubbles in the lines and flowthrough chamber can add substantial error to DO readings in low DO or oxygen depleted groundwater.

TECHNICAL NOTE 9. Anomalously high DO measurements commonly are caused by aeration of groundwater during pumping. This can result from air leakage through loose fittings on production-well pumps (for example, turbine pumps) and also if drawdown in the aquifer introduces air into the cone of depression or through well-screen perforations. To avoid these problems, review information about the pump, well-construction and drawdown data, and previous data records (A.F. White, U.S. Geological Survey, written commun., 1993).

6.2.1.D Troubleshooting for Amperometric Instruments

The troubleshooting suggestions given in table 6.2–3 are for amperometric instruments and are not exhaustive; consult the manufacturer of your amperometric instrument for additional guidance. For problems with calibration or measurement using optical sensors, periodically wipe the sensor with a wet cloth. Do not wipe the Teflon membrane; rather, remove water droplets by shaking or other means. Wiping the Teflon membrane may scratch the membrane, resulting in erroneous readings. If problems with the amperometric sensor persist, consult the manufacturer. Faulty batteries can cause erratic readings.

- ▶ Check the voltage of the batteries.
- ▶ Start with good batteries in the instrument and carry spares.

Table 6.2–3. Troubleshooting guide for amperometric instruments.

Symptom	Possible cause and corrective action
Instrument drifts or takes excessive time to stabilize	<ul style="list-style-type: none"> • Thermal equilibrium of water and sensor has not been reached—wait longer. • Weak batteries—replace. • DO sensor needs maintenance—recondition.
Erratic instrument readings	<ul style="list-style-type: none"> • Break in cable—replace cable. • Faulty connection at instrument or sensor—clean contact and tighten. • Hole in membrane—replace membrane, recondition. • Air bubble in sensor—recondition sensor. • Weak batteries—replace.
Instrument too slow to react	<ul style="list-style-type: none"> • Gold or silver cathode tarnished—buff with pencil eraser, manufacturer-provided polishing paper, and recondition sensor. • Fouled membrane—replace membrane and recondition sensor.
Instrument will not read zero in sodium sulfite solution	<ul style="list-style-type: none"> • Solution contains oxygen—make fresh solution. • Instrument still does not read zero—replace membrane and recondition sensor.
Instrument cannot be calibrated to read standards	<ul style="list-style-type: none"> • Unable to adjust upward—check to see if more than one membrane is on the sensor. • Unable to adjust downward (membrane is probably too tight or too thin)—replace membrane.
Instrument reads inaccurate temperature	<ul style="list-style-type: none"> • Faulty thermistor or cable—repair or replace.

6.2.2 Spectrophotometric (Rhodazine-D and Indigo-Carmine) Methods

Various spectrophotometric methods (*see* TECHNICAL NOTE 10) are available for determining DO over a broad range of concentrations. The information given in this section, however, is limited to the application of spectrophotometric analysis of Rhodazine-D¹⁸ and Indigo-Carmine reagents for determining DO concentrations in relatively oxygen-deficient (hypoxic) and anoxic¹⁹ waters; that is, DO concentration from about 2 to zero mg/L.²⁰ The option to measure DO by spectrophotometry in the higher concentration ranges generally is selected when field conditions limit use of optical or amperometric sensor methods. (Non-instrumental analyses of Rhodazine-D and Indigo-Carmine reagent indicators also are available for measuring aqueous DO concentrations, but the analysis can be subject to considerable operator variability, is not applicable to standard USGS field protocols, and is thus beyond the scope of this guidance.)

TECHNICAL NOTE 10. The purpose of photometry is to measure light in a way that takes the sensitivity of human visual system into account. Photometry only measures in the visible spectral region from 360 nm to 830 nm, where human eyes are sensitive. Spectrophotometry is the quantitative measurement of the reflection or transmission properties of a material as a function of wavelength. The National Institute of Standards and Technology (NIST) maintains the national scales for reflectance and transmittance in the ultraviolet, visible, and near-infrared spectral regions; that is, 250 nm to 2,500 nm (*see* <http://www.nist.gov/pml/div685/grp03/photometry.cfm>, and <http://www.nist.gov/pml/div685/grp03/spectrophotometry.cfm>).

Spectrophotometric methods for DO measurement have been used in USGS field work for measuring DO in oxygen-depleted groundwater and can be adapted for work in oxygen-depleted zones of lakes and reservoirs, but are not approved by the U.S. Environmental Protection Agency for application to regulatory assessments. The Rhodazine-D spectrophotometric method for determining DO in groundwater was introduced by White and others (1990) as a means for obtaining accurate DO data for groundwater at a time when sensor methods lacked the capability of in situ measurement.

- ▶ The Rhodazine-D spectrophotometric method is applicable to a range from 0.1 to 1.0 mg/L dissolved oxygen in aqueous environments. The Rhodazine-D (phenzone dye) compound, in reduced form, reacts with dissolved oxygen to form a deep rose to red-purple reaction product.
- ▶ Low-level Indigo-Carmine spectrophotometric methods are applicable to DO concentration ranges from either 0.006 to 0.8 or 0.2 to 2.0 mg/L, depending on the specific manufacturer kit (“ampul” or “ampoule” kit) being used for the range of interest. Indigo Carmine reacts with the dissolved oxygen present in the sample to form a highly colored blue reaction product.
- ▶ As mentioned previously, USGS technical staff have documented optical sensor measurements²¹ at DO concentrations of 0.05 mg/L and Rhodazine-D spectrophotometric readings to be of comparable accuracy. To date, these findings have not been published or verified using different types of optical sensors. Before measuring and reporting hypoxic to anoxic DO concentration data from optical

¹⁸ Rhodazine-D™ is a proprietary product of CHEMetrics, Inc. (White and others, 1990).

¹⁹ Hypoxic: *Hypoxia* – “A condition in which natural waters have a low concentration of dissolved oxygen (about 2 milligrams per liter compared with a normal level of 8 to 10 milligrams per liter). Stevenson and Wyman (1991); <http://toxics.usgs.gov/definitions/hypoxia.html>. *Anoxic*, in this document, refers to water that has a very low concentration of dissolved oxygen (that is, less than 0.5 milligrams per liter) (U.S. Geological Survey, 2010; <http://toxics.usgs.gov/definitions/anoxic.html>), or total deprivation of oxygen (U.S. Environmental Protection Agency, 2009).

²⁰ The information for the concentration range of the spectrophotometric methods discussed was provided from and reviewed by technical specialists representing CHEMetrics, Inc. and the Hach Company. See <http://www.chemetrics.com> and www.hach.com.

²¹ Unpublished data. Comparisons were made using an In-Situ Inc. TROLL 9500 Profiler equipped with a rugged dissolved oxygen (RDO) optical sensor (Gerolamo Casile, U.S. Geological Survey, oral commun., 2012).

sensors, the capability and accuracy of the optical sensor in this low DO-concentration range needs to be documented by making side-by-side measurements onsite to compare results with values obtained using a spectrophotometric method.

6.2.2.A Equipment and Supplies

The Rhodazine-D and Indigo-Carmine spectrophotometric methods were designed to minimize atmospheric interaction with the water sampled. Two sampling systems commonly are used: (1) an in situ (submersible or downhole) sampler, such as the assemblies discussed in White and others (1990), and (2) a plastic overflow cell through which sample water is pumped (see equipment and supplies in table 6.2–4).

The sampling system is configured to utilize a self-filling ampoule system with the Rhodazine-D or Indigo Carmine reagent vacuum-sealed inside. DO concentration is determined instrumentally on the resultant solution using a spectrophotometer or photometer. The ampoule kits and spectrophotometer (or photometer) are available commercially. The spectrophotometer (or photometer) selected must be able to be adjusted, either manually or automatically, to the appropriate wavelength of incident light needed for the determination of DO in the resultant colored sample, based on the reagent used. Applicable spectrophotometers, photometers, and ampoule kits are available commercially from various companies and for a variety of concentration ranges.

- ▶ The accuracy of commercially available reagent kits may not be included with the equipment or supplies purchased. Always check with the manufacturer regarding the accuracy of the specific test kit(s) of interest.
- ▶ The accuracy of the test kits will typically be a function of the concentration range of DO in the sample.
- ▶ A spectrophotometer is used to measure the amount of light that a sample absorbs. The instrument operates by passing a beam of light through a sample and measuring the intensity of light received by a detector (<http://www.chm.davidson.edu/vce/spectrophotometry/Spectrophotometry.html>).
- ▶ Some spectrophotometers are precalibrated specifically for the products or kits developed by the kit manufacturer. If using a spectrophotometer that is not precalibrated for the products being used, calculate the DO concentration using the regression equations provided by the manufacturer of the reagent kit.

Table 6.2–4. Equipment and supplies for the spectrophotometric method of dissolved-oxygen determination using Rhodazine-D™ and Indigo Carmine reagents.[mm, millimeter; DO, dissolved-oxygen concentration; mg/L, milligrams per liter; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius]

Portable spectrophotometer (or photometer)
Appropriate reagent kits for the expected DO range of the environmental condition
Blank ampoule (zero DO), included in each kit
Submersible sampling tool, used in situ, to meet criteria described in White and others (1990). For example, <ul style="list-style-type: none"> • Manganous sulfate reagent • Plastic sampler device (overflow cell), length of C-flex tubing, and sample pump
Safety gloves, glasses, and apron
Waste disposal container
White background sheet
Deionized water (maximum conductivity of 1 $\mu\text{S}/\text{cm}$)
Bottle, squeeze dispenser, for deionized water
Lint-free wipes to remove moisture from surface of the ampoule

6.2.2.B Calibration and Interferences

DO is measured as percent absorbance by the spectrophotometer. A calibration chart typically is provided with each chemical reagent kit, along with a regression formula to convert absorbance to micrograms per liter ($\mu\text{g}/\text{L}$) of DO for use with a spectrophotometer that does not perform the conversion in its firmware. Most current spectrophotometers and photometers available for measurement of dissolved oxygen are precalibrated for direct readout of DO concentration in milligrams per liter.

- ▶ Ensure that an appropriate blank ampoule is used to zero the spectrophotometer (or photometer).
- ▶ Additional calibration is needed if the method will be used to determine DO in heavily contaminated or acidic waters. This can be done by equilibrating a water sample with known partial pressures of atmospheric oxygen (White and others, 1990). Atmospheric oxygen standards are available from suppliers of gas chromatography equipment.

These chemical reagent-based methods are not subject to salinity or dissolved-gas interferences (ASTM D5543-09, ASTM D 888-12, White and others, 1990; Gilbert and others, 1982). Interferences from total salinity, major dissolved inorganic species, dissolved gases, or temperature are typically negligible with this method. However, color and turbidity in the environmental sample may interfere with both the Rhodazine-D and Indigo-Carmine methods, causing positively biased results. If using these methods in colored or turbid water, first conduct an assessment of the amount of bias attributable to such effects.

- ▶ Rhodazine-D. The spectrophotometric method using Rhodazine-D reagent is affected by the presence of oxidizing agents, including chlorine, ferric and cupric ions, and hexavalent chromium, resulting in high-biased DO readings (White and others, 1990).²²
 - The presence of cupric copper and ferric iron at a concentration less than 50 $\mu\text{g}/\text{L}$ may cause a bias of less than 1 $\mu\text{g}/\text{L}$; at 100 $\mu\text{g}/\text{L}$ concentration, cupric copper may cause a bias of 5 $\mu\text{g}/\text{L}$, and ferric iron may cause a bias of 7 $\mu\text{g}/\text{L}$.
 - Sample pH at or below a pH of 2 may cause erroneous results.

²² See also http://www.chemetrics.com/products/pdf/oxygen_rhodazined.pdf, accessed September 20, 2012.

- A hydroquinone concentration greater than 200 µg/L is a positive interferent and its oxidation byproduct, benzoquinone, causes a false positive result. The effect from oxidizing agents can be corrected if the concentrations of the interfering species are known (White and others, 1990).
- ▶ Indigo Carmine. The spectrophotometric method using Indigo Carmine reagent²³ is affected by ferric iron, hypochlorite (chlorine), and chromate, which can cause a false positive at concentrations equal to or greater than 10 mg/L.
 - Cupric copper interferes positively at or above 100 mg/L.
 - Seawater may cause the reagent to precipitate.

6.2.2.C Measurement

USGS spectrophotometric measurement procedures have been tested and quality assured for the determination of DO concentration using the Rhodazine-D and Indigo-Carmine reagents provided in commercially available kits supplied by the CHEMetrics and Hach companies, respectively.²⁴ While the instructions provided by the manufacturers generally should be followed, augmented instructions and information are provided below to ensure that DO measurement meets USGS standards for accuracy and reproducibility. USGS personnel are advised to make the adjustments described here to the manufacturer-provided instructions.

Rhodazine-D and Indigo-Carmine reagents react with DO to produce an oxidized complex characterized by deep-rose or brightly blue-colored reaction products, respectively. The color intensity is proportional to the concentration of the initial DO present. **Timing is very important for colorimetric analyses made with a spectrophotometer.** Follow the explicit instructions for the waiting time after the sample mixes with the reagent. The reaction with the reagents occurs almost instantaneously for both the Rhodazine-D and Indigo-Carmine methods. Color development continues after the time interval specified for these methods because oxygen from the atmosphere continuously diffuses into the sample through the broken ampule tip.

- ▶ Do not extend the waiting times specified in the Rhodazine-D and Indigo-Carmine methods, but adhere to them strictly.
- ▶ Excessive mixing of the ampule before reading the spectrophotometer also may introduce atmospheric oxygen, which can bias the results, resulting in erroneous readings.

Follow the steps below to measure DO using the spectrophotometric method:

1. Familiarize yourself with instructions from the manufacturer for the kit to be used and adjust the instructions to incorporate the procedures that follow, as applicable.
2. Accounting for site characteristics and study objectives, purge the well following guidelines in NFM 4.2.
3. Set the spectrophotometer to an appropriate wavelength for the kit being used. When using a manufacturer-designated DO photometer (or spectrophotometer), verify whether or not introduction of the ampoule provided in the kit will trigger the correct wavelength setting automatically.

²³ ASTM D 888-12; ASTM D 5543-09; Gilbert and others (1982).

²⁴ Instructions from the Hach Company and CHEMetrics Inc. for selected colorimetry-based methods at DO concentration ranges relevant to routine USGS sampling were selected for testing because USGS field personnel currently use the equipment and reagent kits from these companies.

4. Zero the spectrophotometer using the blank provided in the kit (follow the manufacturer's instructions).²⁵
5. When collecting the sample:
 - Prevent sample aeration. Use a positive-displacement submersible pump and high-density plastic or fluorocarbon polymer sample tubing that is relatively gas impermeable, if possible, throughout measurement.
 - Operate equipment to mitigate losses or gains of dissolved gases. (Consult NFM 6.0 for proper downhole and inline flowthrough-chamber sampling procedures.)
6. Select your sample-collection method: Use either a downhole or overflow-sampler device.
 - *Go to Step 7* for the downhole sampling tool method,²⁶ *or*
 - *Go to Step 8* for the plastic overflow-sampler device with a suitable pump method.
7. **Downhole system:** After purging the well (NFM 4.2), follow steps 7a through d.
 - a. Carefully immerse a reagent-containing ampoule on the sampling tool that is attached to a wire line.
 - b. At the desired depth of sample collection (in a well or in surface water), break the scored tip of the ampoule by using a sharp upward tug on the sampling tool.
 - This permits sample water to be drawn into the ampoule.
 - During transit to the surface, progressively decreasing pressure in the ampoule prevents cross contamination from overlying water through the ampoule tip.
 - c. Withdraw the ampoule from the sampling device and invert once to mix the contents of the ampoule, allowing the bubble to travel from end to end; follow the kit-specific instructions regarding the number of ampoule inversions.²⁷
 - Take care that this process does not introduce atmospheric oxygen into the ampoule.
 - Make sure the time required to bring the ampoule to the surface does not exceed the waiting times specified by the method. (This method may work best for shallow wells).
 - d. Wipe all liquid from the exterior of the ampoule, using a lint-free tissue. Skip to step 9.
8. **Overflow device:** After purging the well (NFM 4.2), follow steps 8a through f.
 - a. Connect the plastic overflow-sampling device (table 6.2–4) to the outlet of the pump tubing with C-flex tubing 3 feet (ft) or less in length. The overflow device is used to break the ampoule in the flowing stream of water.
 - If using the **Rhodazine-D** method, the kit is equipped with the appropriate overflow sampling device needed to crack the ampoule.

²⁵ Native water may be used if this option is provided by the kit manufacturer.

²⁶ A downhole sampling tool is described by White and others (1990).

²⁷ Instructions provided by kit manufacturers specify inverting the ampoule several times with the bubble traveling from end to end to facilitate mixing of reagent and sample. USGS field observations, however, indicate that vigorous or repeated mixing can introduce atmospheric oxygen and bias the measurement (Gerolamo Casile, U.S. Geological Survey, written commun., 2013).

- If using the **Indigo-Carmine** method, adapt the Rhodazine-D instructions as follows, instead of using the directions provided²⁸:
 - Obtain a plastic funnel with a funnel size of approximately 1 cup.
 - Adapt the funnel to the end of a length of C-flex tubing. This funnel, while overflowing, will allow the tip of the Indigo-Carmine ampoule to be broken very close to where the sample water flows in.

TECHNICAL NOTE 11. Use optically clear materials to enable seeing whether bubbles are entrained in the tubing or flow cell (chamber). Air bubbles that adhere to the sides of the tubing and chamber will add significant error to low-level DO measurements (A.F. White, U.S. Geological Survey, written commun., 1993).

- b. Reduce the pumping rate to achieve an even, nonturbulent, laminar rate of flow (for groundwater, about 500 milliliters per minute) that is used for sample collection. While pumping, allow the sampling device to overflow during sample collection.
 - Check for air bubbles in or adhering to the tubing and flowthrough cell (chamber).
 - Tap the tubing with a blunt tool to dislodge entrained air bubbles.
 - c. Insert the glass ampoule, tip first, into the overflowing sampling device so that the tapered tip is at the bottom of the device, close to the point of water inflow.
 - d. Snap the tip by gently pressing the upper end of the ampoule toward the wall of the sampling device.
 - The vacuum ampoule will draw in the sample water, leaving a small bubble at one end.
 - Ensure that the ampoule is full before proceeding to step e; this will prevent entraining excess atmospheric oxygen and thereby producing erroneous readings.
 - e. Withdraw the ampoule from the sampling device and invert to mix the contents of the ampoule, allowing the bubble to travel from end to end; follow the kit-specific instructions regarding the number of ampoule inversions (see footnote 27).
 - f. Wipe all liquid from the exterior of the ampoule, using a lint-free tissue.
9. Insert the ampoule directly into the spectrophotometer cell holder, either immediately after retrieval or as specified in the kit-specific instructions.
10. Read concentration or absorbance:
- a. Make spectrophotometer readings, adhering as strictly as possible to the manufacturer-specified time interval.
 - **Rhodazine-D**—Record the reading within the time interval directed by the kit manufacturer (for example, within 30 seconds when using the CHEMetrics ampoule kit).

²⁸ The Hach Company Indigo Carmine kit instructs placing the sample tube at the bottom of an overflowing beaker, then breaking the ampoule near the sample tubing at the bottom of the beaker. Tests conducted by USGS personnel indicated that substituting the directions in step 8a substantially improve measurement accuracy and reproducibility. (Gerolamo Casile, U.S. Geological Survey, written communication, 2013).

- **Indigo-Carmine**—Record the reading within the time interval directed by the kit manufacturer.
- b. If using a spectrophotometer that does not convert absorbance values of DO measurements to milligrams per liter for the kit being used, use regression equations to make the conversion (see White and others, 1990).
11. **Quality control:** Consider utilizing multiple determinations to document the precision and (or) accuracy of the DO concentration to be reported.
- Repeat steps 9 and 10 twice in rapid succession to document measurement precision.
 - To document the variability of DO concentrations within the water system being measured, repeat steps 4 through 10 on three sequentially collected samples.

Do not exceed the time interval specified for completion of color development.

6.2.3 Iodometric (Winkler) Method

The USGS currently uses the Alsterberg-Azide modification to the Winkler titration procedure for iodometric determination of DO. The precision of measurements using the iodometric method should be within at least ± 0.05 mg/L²⁹ when performed by experienced analysts (American Public Health Association, 2005).

- ▶ The iodometric (Winkler) method no longer is being used routinely as a standard field method for measurement of DO in USGS investigations because (1) the accuracy and reproducibility achievable are dependent on the experience and expertise of the data collector, (2) potential environmental interferences (for example, the presence of nitrite, ferrous and ferric iron, and organic matter) require advanced knowledge of the chemistry of the sample, and (3) field conditions can make preventing exposure of the sample to atmospheric oxygen difficult. Nevertheless, the iodometric method is recognized as a reliable standard for producing accurate results when correctly implemented.
- ▶ The iodometric (Winkler) method is widely accepted in the scientific community and is used to check the calibration of, and the measurements made with, electrometric DO instrument systems.
 - The Winkler method was used to verify the accuracy of optically and amperometrically determined DO concentrations reported by the USGS in an oil spill investigation, in accordance with a request by the U.S. Environmental Protection Agency (Wilde and Skrobialowski, 2011).
 - Checking the calibration of electrometric instruments using the Winkler procedure is performed in a controlled (that is, laboratory) environment. The DO instrument is calibrated with air-saturated deionized water in which the DO concentration has been determined by the Winkler method; the DO instrument is then adjusted to the concentration determined from the titration.
 - If a saline solution is used to approximate the environmental water, do not apply a salinity correction factor.

²⁹ Based on a standard deviation (SD) of ± 0.02 mg/L for a three SD accuracy of ± 0.06 mg/L.

6.2.3.A Equipment and Supplies

Equipment and supplies needed for the iodometric method are listed in table 6.2–5. The procedure involves the use of reagents available in premeasured pillow packets from commercial suppliers. Alternatively, reagents may be prepared by a chemist or titration technician, as described in American Public Health Association (2005).

- ▶ The accuracy of commercially obtained reagent packets may differ among manufacturers and other preparers of the reagents and should be recorded in field notes.
- ▶ Clean all equipment before use.

Table 6.2–5. Equipment and supplies for the iodometric (Winkler) method of dissolved-oxygen determination.

[mL, milliliter; *N*, normal; $\mu\text{S/cm}$, microsiemens per centimeter at 25 degrees Celsius; NFM, *National Field Manual for the Collection of Water-Quality Data*]

Beaker, 2,000 mL, glass or Teflon
Bottles for biochemical oxygen demand (BOD) analysis, glass stoppered, 300 mL
Stirrer, magnetic
Stirring bars, Teflon coated
Cylinder, graduated, 250 mL
Flask, Erlenmeyer, 250 mL
Buret, 25-mL capacity with 0.05-mL graduations and Teflon stopcock
Buret, support stand
Buret, clamp, double
Chemical reagents: ¹ <ul style="list-style-type: none"> • Alkaline iodide-azide reagent • Manganous sulfate reagent • Sulfamic acid granules • Sodium thiosulfate, 0.025 <i>N</i> titrant • Starch indicator solution
Clippers, for opening reagent pillows
Appropriate safety gloves, glasses, and apron
Waste disposal container
White background sheet
Deionized water (maximum conductivity of 1 $\mu\text{S/cm}$)
Bottle, squeeze dispenser, for deionized water
Thermometer, calibrated (see NFM 6.1 for selection and calibration criteria)
Pocket altimeter-barometer, calibrated, or DO-measurement equipment that includes barometer

¹ Use either commercially prepared reagent pillow packets or analyst-prepared reagents, depending on the data-quality requirements of the study.

6.2.3.B Measurement

This section describes how to make an iodometric determination of DO concentration.

- ▶ When the purpose of using the Winkler method is to check calibration of an amperometric or luminescent-sensor instrument, start at step 1 below and continue to the end. For quality control, steps 5 and 6 are written so as to verify the Winkler determination in duplicate. This is standard practice and should be followed.
- ▶ If making a Winkler determination for the DO concentration of an environmental sample, start at step 5, substituting the sample water for deionized water (DIW). Collect the sample and perform the titration as described below on at least two subsamples to provide the appropriate quality control. When filling the BOD bottles, a minimum of three bottle volumes of sample should pass through the bottle to collect the final volume.
 - **In surface water:** To fill the bottles, use of a sewage sampler is recommended. If a hand-held method is needed, fill the bottles in the water body by tilting them slightly to allow the bottle to slowly fill in a manner so as to avoid turbulence, bubbling, or otherwise entraining air. Keep the filled bottles submerged (in the surface-water body) for about 30 seconds. Next, while the bottle is submerged, insert the stopper firmly in the bottle, taking care not to trap air bubbles.
 - **In groundwater:** A laminar-flow sample is pumped inline from the well into the bottle, from the bottom to overflowing the top of the bottle and in a manner so as to avoid any turbulence and bubbles. Allow the sample to overflow for at least 30 seconds. Next, while still overflowing, insert the stopper firmly into the bottle, taking care not to trap air bubbles.
 - Pour off excess water that is trapped on the lip of the stoppered bottle.
 - Follow step 6 procedures as described below, substituting the sample-filled biochemical oxygen demand (BOD) bottles.
- ▶ Results of two iodometric titrations should agree within 0.1 mg/L. If they do not agree, repeat the titration on one or more additional subsamples until this quality-assurance criterion is met.

Follow the steps below to check calibration of an optical or amperometric DO instrument using the Winkler Alsterberg-Azide titration:

1. Fill a clean 2,000-mL beaker with deionized water that is near DO saturation. The water temperature should be close to the ambient (field or laboratory) temperature.
2. Prepare the DO-sensing instrument for operation, in accordance with the manufacturer's instructions.
3. Place the DO sensor in a beaker of DIW. If using an amperometric sensor, maintain a water velocity of at least 1 ft/s flowing passed the sensor. If the sensor is not equipped with a stirring mechanism, use a magnetic stirrer.
4. Monitor the DO concentrations of the DIW with the DO instrument and record the value after the readings have stabilized.
5. Carefully fill two clean BOD bottles with three or more bottle volumes of DIW from the beaker, taking care not to introduce any air bubbles by slowly overflowing the bottles adequately to remove any trapped air bubbles.
6. Determine the DO concentration of the DIW in each BOD bottle, as follows:

- a. Add one each of the following dry reagent pillow packets³⁰
 - Alkaline iodide-azide (white powder).
 - Manganous sulfate (pinkish-colored powder).
- b. Recap the bottle **to prevent air bubbles from being trapped in the bottle.**
- c. Invert the bottle 25 times or more to completely dissolve the reagents.
 - An orange-brown flocculent indicates the presence of DO.
 - Allow the flocculent to settle halfway down the bottle (approximately 5 minutes).
 - Invert the bottle 25 times again; let the flocculent settle again until the upper half of the solution is clear.
- d. Add one reagent pillow of sulfamic acid (see footnote 30).
- e. Recap the bottle without introducing air or air bubbles. Invert the bottle 25 times until all of the flocculent and granules are dissolved, leaving a yellow color.
- f. Fill a clean 25-mL buret with 0.025 *N (Normal)* sodium thiosulfate titrant. Remove any air bubbles from the delivery tube beneath the stopcock and zero the meniscus.
- g. Using either a clean 200-mL pipet or a 200-mL volumetric flask, measure 200 mL of the sample and dispense the sample into a clean, wide-mouth Erlenmeyer flask.
- h. Place the flask on a magnetic stirrer. Carefully insert a clean Teflon stirring bar and stir the sample at a moderate rate without aerating the sample.
- i. Add increments of sodium thiosulfate titrant until the color turns pale straw-yellow.
- j. Add 1 to 2 mL of starch indicator solution. (This causes the sample to turn dark blue.)
- k. Very slowly add more sodium thiosulfate titrant until the sample just turns clear. (A white background behind or below the flask will help to see the color change.)
- l. Record the volume of sodium thiosulfate titrant used, in milliliters.
 - For a 200-mL sample, the volume of titrant added is directly proportional to the amount of DO in milligrams per liter.
 - To calculate DO for a sample volume greater or less than 200 mL,

$$DO \text{ (mg / L)} = \left(\frac{200}{\text{sample volume}} \right) \times \text{titrant added, in mL} \quad (1)$$

- m. Record the DO value. Rinse the equipment thoroughly with deionized water.

7. **Quality control.** Titration values for the duplicate samples should agree within 0.1 mg/L.
 - If they do not agree, repeat the titration process (steps 5 and 6a through 6m, above) on one or more additional subsamples until this quality-assurance criterion is met.
 - Record the final, quality-assured value for DO concentration.

³⁰ Laboratory-prepared reagents might be prepared instead, depending on data-quality requirements, if titration will be performed by an analyst.

8. Recheck the field instrument for proper functioning, following the manufacturer's recommendations and instructions.
 - Consult the manufacturer if the field instrument does not calibrate properly.
 - Do not use an instrument that fails calibration.

6.2.4 Reporting

USGS personnel are instructed to enter the DO value on the field form indicating method (optical, amperometric, spectrophotometric, or iodometric) used for DO determination.

- ▶ DO concentrations for the amperometric and optical-sensor methods are measured to the nearest 0.01 mg/L, but currently are reported to the nearest 0.1 mg/L.
- ▶ DO concentrations for the spectrophotometric/Rhodazine-D and Indigo-Carmine methods are reported to the nearest 0.01 mg/L.
- ▶ **Note that the percentage of DO saturation in water can be greater than 100.** When the concentration exceeds 20 mg/L, check manufacturer's specifications and:
 - Report ">20 mg/L" if the manufacturer's instrument range specifications do not exceed 20 mg/L.
 - Report concentration values up to the maximum specified limit if the manufacturer's instrument range specifications exceed 20 mg/L.
 - Report "> the listed numerical limit" if the concentration exceeds the manufacturer's specified instrument range.

6.2.5 Correction Factors for Oxygen Solubility Concentrations and Salinity

Solubility concentrations of oxygen in freshwater at various temperatures and pressures (table 6.2–6) and correction factors for salinity based on specific conductance (table 6.2–7) were generated from the equations of Benson and Krause (1980, 1984) and can be customized to cover the range and decimal places needed; see U.S. Geological Survey Office of Water Quality Technical Memorandum 2011.03 (Myers, 2011). **By accessing "DOTABLES," the interactive software that generated tables 6.2–6 and 6.2–7, the user can self-generate individual values or tables of a specific range of oxygen-solubility and salinity correction factors: <http://water.usgs.gov/software/DOTABLES/>.**³¹

- ▶ To adjust freshwater oxygen-saturation values for the effects of salinity, use correction factors based on chloride concentration or specific conductance. Refer to the manufacturer's instructions for the DO instrument before applying a salinity correction.
- ▶ Correcting DO solubility for saline waters (greater than 2,000 microsiemens per centimeter or 1,000 mg/L chloride) varies with instrument type, calibration method, and the salts in solution.

³¹ DOTABLES is an online program that generates tables of dissolved oxygen (DO) solubility values and (or) salinity correction factors over a range of user-specified values for water temperature, barometric pressure, and salinity or specific conductance. In addition to generating tables, DOTABLES can compute a single-value of oxygen solubility and percent saturation for a specific instance of temperature, pressure, and salinity.

- The correction based on specific conductance (table 6.2–7) is more useful because accurate conductivity can be determined easily from a field measurement.
- Salinity correction factors based on chloride can be calculated using information provided in U.S. Geological Survey Quality of Water Branch Technical Memorandum 79.10 (Pickering, 1979).
- ▶ DO instruments either use an automatic internal salinity correction, a manual salinity control knob for internal correction, or the calibration control knob for manual correction of salinity. Check that instruments with automatic internal salinity correction use approved salinity correction factors.

Example of salinity correction

Suppose a DO measurement is made in water with a temperature of 20.0 degrees Celsius, an atmospheric pressure of 750 millimeters of mercury, and a specific conductance of 8,000 microsiemens per centimeter ($\mu\text{S}/\text{cm}$). The freshwater oxygen solubility from table 6.2–6 is 8.97 mg/L for that temperature and pressure; the salinity correction factor from table 6.2–7 is 0.9733 for that temperature and specific conductance. The solubility of oxygen under these conditions then is:

$$8.97 \text{ mg/L} \times 0.9733 = 8.73 \text{ mg/L} \quad (2)$$

The presence of more dissolved ions in the saline water decreases the oxygen solubility.

- ▶ If calibrating an instrument that does not have an internal salinity compensation algorithm, you could adjust the DO instrument to read 8.73 mg/L for a 100 percent saturation condition.
- ▶ If the DO measurement made with an amperometric or optical sensor under the above conditions were 7.50 mg/L and the DO probe did not have an internal salinity compensation algorithm, then the actual DO concentration should be reported as 7.50 mg/L multiplied by 0.9733, which equals 7.30 mg/L.
- ▶ **Do not use a salinity correction factor for measurements made with the iodometric (Winkler) or spectrophotometric methods.**

Example of percent saturation calculation

To express results as percent saturation, use the following equation:

$$DO \text{ (percent saturation)} = \frac{\text{measured DO (mg / L)}}{DO \text{ (mg / L at 100 percent saturation)}} \times 100 \quad (3)$$

For a salinity-corrected DO measurement of 7.30 mg/L for a sample in which the oxygen solubility (salinity corrected) is 8.73 mg/L as in the above example, the percent DO saturation would be the dividend of 7.30 divided by 8.73, multiplied by 100, which equals 83.6 percent. Note that for measurements with the iodometric (Winkler) or spectrophotometric methods, salinity correction factors are not applied to the measurement concentration.

Table 6.2-6. Solubility of oxygen in freshwater at various temperatures and pressures.

[Solubility shown in milligrams per liter. Values based on published equations by Benson and Krause (1980 and 1984). Temp. deg C, temperature in degrees Celsius; Values for atmospheric pressures from 600 to 695 millimeters of mercury begin several pages forward]

Temp. (deg C)	Atmospheric pressure, in millimeters of mercury																			
	700	705	710	715	720	725	730	735	740	745	750	755	760	765	770	775	780	785	790	795
0.0	13.46	13.56	13.65	13.75	13.85	13.94	14.04	14.14	14.23	14.33	14.43	14.52	14.62	14.72	14.81	14.91	15.01	15.10	15.20	15.30
0.5	13.27	13.37	13.46	13.56	13.65	13.75	13.84	13.94	14.03	14.13	14.23	14.32	14.42	14.51	14.61	14.70	14.80	14.89	14.99	15.08
1.0	13.09	13.18	13.28	13.37	13.46	13.56	13.65	13.75	13.84	13.93	14.03	14.12	14.22	14.31	14.40	14.50	14.59	14.69	14.78	14.87
1.5	12.91	13.00	13.09	13.19	13.28	13.37	13.46	13.56	13.65	13.74	13.84	13.93	14.02	14.11	14.21	14.30	14.39	14.48	14.58	14.67
2.0	12.73	12.82	12.91	13.01	13.10	13.19	13.28	13.37	13.46	13.56	13.65	13.74	13.83	13.92	14.01	14.10	14.20	14.29	14.38	14.47
2.5	12.56	12.65	12.74	12.83	12.92	13.01	13.10	13.19	13.28	13.37	13.46	13.55	13.64	13.73	13.82	13.91	14.00	14.10	14.19	14.28
3.0	12.39	12.48	12.57	12.66	12.75	12.84	12.93	13.02	13.10	13.19	13.28	13.37	13.46	13.55	13.64	13.73	13.82	13.91	14.00	14.09
3.5	12.23	12.31	12.40	12.49	12.58	12.67	12.75	12.84	12.93	13.02	13.11	13.19	13.28	13.37	13.46	13.55	13.63	13.72	13.81	13.90
4.0	12.07	12.15	12.24	12.33	12.41	12.50	12.59	12.67	12.76	12.85	12.93	13.02	13.11	13.20	13.28	13.37	13.46	13.54	13.63	13.72
4.5	11.91	11.99	12.08	12.17	12.25	12.34	12.42	12.51	12.59	12.68	12.77	12.85	12.94	13.02	13.11	13.20	13.28	13.37	13.45	13.54
5.0	11.75	11.84	11.92	12.01	12.09	12.18	12.26	12.35	12.43	12.52	12.60	12.69	12.77	12.86	12.94	13.03	13.11	13.19	13.28	13.36
5.5	11.60	11.69	11.77	11.86	11.94	12.02	12.11	12.19	12.27	12.36	12.44	12.52	12.61	12.69	12.78	12.86	12.94	13.03	13.11	13.19
6.0	11.46	11.54	11.62	11.70	11.79	11.87	11.95	12.04	12.12	12.20	12.28	12.37	12.45	12.53	12.61	12.70	12.78	12.86	12.94	13.03
6.5	11.31	11.39	11.48	11.56	11.64	11.72	11.80	11.88	11.97	12.05	12.13	12.21	12.29	12.37	12.46	12.54	12.62	12.70	12.78	12.86
7.0	11.17	11.25	11.33	11.41	11.49	11.58	11.66	11.74	11.82	11.90	11.98	12.06	12.14	12.22	12.30	12.38	12.46	12.54	12.62	12.70
7.5	11.03	11.11	11.19	11.27	11.35	11.43	11.51	11.59	11.67	11.75	11.83	11.91	11.99	12.07	12.15	12.23	12.31	12.39	12.47	12.55
8.0	10.90	10.98	11.06	11.14	11.21	11.29	11.37	11.45	11.53	11.61	11.69	11.76	11.84	11.92	12.00	12.08	12.16	12.24	12.32	12.39
8.5	10.77	10.84	10.92	11.00	11.08	11.16	11.23	11.31	11.39	11.47	11.54	11.62	11.70	11.78	11.86	11.93	12.01	12.09	12.17	12.24
9.0	10.64	10.71	10.79	10.87	10.94	11.02	11.10	11.18	11.25	11.33	11.41	11.48	11.56	11.64	11.71	11.79	11.87	11.94	12.02	12.10
9.5	10.51	10.59	10.66	10.74	10.81	10.89	10.97	11.04	11.12	11.19	11.27	11.35	11.42	11.50	11.57	11.65	11.73	11.80	11.88	11.95
10.0	10.39	10.46	10.54	10.61	10.69	10.76	10.84	10.91	10.99	11.06	11.14	11.21	11.29	11.36	11.44	11.51	11.59	11.66	11.74	11.81
10.5	10.26	10.34	10.41	10.49	10.56	10.64	10.71	10.78	10.86	10.93	11.01	11.08	11.16	11.23	11.30	11.38	11.45	11.53	11.60	11.68
11.0	10.15	10.22	10.29	10.37	10.44	10.51	10.59	10.66	10.73	10.81	10.88	10.95	11.03	11.10	11.17	11.25	11.32	11.39	11.47	11.54
11.5	10.03	10.10	10.17	10.25	10.32	10.39	10.47	10.54	10.61	10.68	10.76	10.83	10.90	10.97	11.05	11.12	11.19	11.26	11.34	11.41
12.0	9.91	9.99	10.06	10.13	10.20	10.27	10.35	10.42	10.49	10.56	10.63	10.71	10.78	10.85	10.92	10.99	11.06	11.14	11.21	11.28
12.5	9.80	9.87	9.94	10.02	10.09	10.16	10.23	10.30	10.37	10.44	10.51	10.58	10.66	10.73	10.80	10.87	10.94	11.01	11.08	11.15
13.0	9.69	9.76	9.83	9.90	9.97	10.04	10.11	10.19	10.26	10.33	10.40	10.47	10.54	10.61	10.68	10.75	10.82	10.89	10.96	11.03
13.5	9.59	9.65	9.72	9.79	9.86	9.93	10.00	10.07	10.14	10.21	10.28	10.35	10.42	10.49	10.56	10.63	10.70	10.77	10.84	10.91
14.0	9.48	9.55	9.62	9.69	9.76	9.82	9.89	9.96	10.03	10.10	10.17	10.24	10.31	10.37	10.44	10.51	10.58	10.65	10.72	10.79

Table 6.2-6. Solubility of oxygen in freshwater at various temperatures and pressures.—Continued

[Solubility shown in milligrams per liter. Values based on published equations by Benson and Krause (1980 and 1984). Temp. deg C, temperature in degrees Celsius; Values for atmospheric pressures from 600 to 695 millimeters of mercury begin several pages forward]

Temp. (deg C)	Atmospheric pressure, in millimeters of mercury																			
	700	705	710	715	720	725	730	735	740	745	750	755	760	765	770	775	780	785	790	795
14.5	9.38	9.44	9.51	9.58	9.65	9.72	9.78	9.85	9.92	9.99	10.06	10.13	10.19	10.26	10.33	10.40	10.47	10.53	10.60	10.67
15.0	9.27	9.34	9.41	9.48	9.54	9.61	9.68	9.75	9.81	9.88	9.95	10.02	10.08	10.15	10.22	10.29	10.35	10.42	10.49	10.56
15.5	9.18	9.24	9.31	9.38	9.44	9.51	9.58	9.64	9.71	9.78	9.84	9.91	9.98	10.04	10.11	10.18	10.24	10.31	10.38	10.44
16.0	9.08	9.14	9.21	9.28	9.34	9.41	9.47	9.54	9.61	9.67	9.74	9.80	9.87	9.94	10.00	10.07	10.13	10.20	10.27	10.33
16.5	8.98	9.05	9.11	9.18	9.24	9.31	9.37	9.44	9.50	9.57	9.64	9.70	9.77	9.83	9.90	9.96	10.03	10.09	10.16	10.22
17.0	8.89	8.95	9.02	9.08	9.15	9.21	9.28	9.34	9.41	9.47	9.54	9.60	9.66	9.73	9.79	9.86	9.92	9.99	10.05	10.12
17.5	8.80	8.86	8.92	8.99	9.05	9.12	9.18	9.24	9.31	9.37	9.44	9.50	9.57	9.63	9.69	9.76	9.82	9.89	9.95	10.01
18.0	8.70	8.77	8.83	8.90	8.96	9.02	9.09	9.15	9.21	9.28	9.34	9.40	9.47	9.53	9.59	9.66	9.72	9.78	9.85	9.91
18.5	8.62	8.68	8.74	8.80	8.87	8.93	8.99	9.06	9.12	9.18	9.24	9.31	9.37	9.43	9.50	9.56	9.62	9.69	9.75	9.81
19.0	8.53	8.59	8.65	8.72	8.78	8.84	8.90	8.96	9.03	9.09	9.15	9.21	9.28	9.34	9.40	9.46	9.53	9.59	9.65	9.71
19.5	8.44	8.50	8.57	8.63	8.69	8.75	8.81	8.87	8.94	9.00	9.06	9.12	9.18	9.25	9.31	9.37	9.43	9.49	9.55	9.62
20.0	8.36	8.42	8.48	8.54	8.60	8.66	8.73	8.79	8.85	8.91	8.97	9.03	9.09	9.15	9.21	9.28	9.34	9.40	9.46	9.52
20.5	8.28	8.34	8.40	8.46	8.52	8.58	8.64	8.70	8.76	8.82	8.88	8.94	9.00	9.06	9.12	9.18	9.25	9.31	9.37	9.43
21.0	8.19	8.25	8.31	8.37	8.43	8.49	8.55	8.61	8.67	8.73	8.79	8.85	8.92	8.98	9.04	9.10	9.16	9.22	9.28	9.34
21.5	8.11	8.17	8.23	8.29	8.35	8.41	8.47	8.53	8.59	8.65	8.71	8.77	8.83	8.89	8.95	9.01	9.07	9.13	9.19	9.25
22.0	8.04	8.09	8.15	8.21	8.27	8.33	8.39	8.45	8.51	8.57	8.63	8.68	8.74	8.80	8.86	8.92	8.98	9.04	9.10	9.16
22.5	7.96	8.02	8.08	8.13	8.19	8.25	8.31	8.37	8.43	8.48	8.54	8.60	8.66	8.72	8.78	8.84	8.89	8.95	9.01	9.07
23.0	7.88	7.94	8.00	8.06	8.11	8.17	8.23	8.29	8.35	8.40	8.46	8.52	8.58	8.64	8.69	8.75	8.81	8.87	8.93	8.98
23.5	7.81	7.86	7.92	7.98	8.04	8.09	8.15	8.21	8.27	8.33	8.38	8.44	8.50	8.56	8.61	8.67	8.73	8.79	8.84	8.90
24.0	7.73	7.79	7.85	7.90	7.96	8.02	8.08	8.13	8.19	8.25	8.30	8.36	8.42	8.48	8.53	8.59	8.65	8.70	8.76	8.82
24.5	7.66	7.72	7.77	7.83	7.89	7.94	8.00	8.06	8.11	8.17	8.23	8.28	8.34	8.40	8.45	8.51	8.57	8.62	8.68	8.74
25.0	7.59	7.65	7.70	7.76	7.81	7.87	7.93	7.98	8.04	8.10	8.15	8.21	8.26	8.32	8.38	8.43	8.49	8.54	8.60	8.66
25.5	7.52	7.58	7.63	7.69	7.74	7.80	7.85	7.91	7.97	8.02	8.08	8.13	8.19	8.24	8.30	8.35	8.41	8.47	8.52	8.58
26.0	7.45	7.51	7.56	7.62	7.67	7.73	7.78	7.84	7.89	7.95	8.00	8.06	8.11	8.17	8.22	8.28	8.33	8.39	8.44	8.50
26.5	7.38	7.44	7.49	7.55	7.60	7.66	7.71	7.77	7.82	7.88	7.93	7.99	8.04	8.10	8.15	8.20	8.26	8.31	8.37	8.42
27.0	7.32	7.37	7.43	7.48	7.53	7.59	7.64	7.70	7.75	7.81	7.86	7.91	7.97	8.02	8.08	8.13	8.19	8.24	8.29	8.35
27.5	7.25	7.30	7.36	7.41	7.47	7.52	7.57	7.63	7.68	7.74	7.79	7.84	7.90	7.95	8.01	8.06	8.11	8.17	8.22	8.27
28.0	7.19	7.24	7.29	7.35	7.40	7.45	7.51	7.56	7.61	7.67	7.72	7.77	7.83	7.88	7.93	7.99	8.04	8.10	8.15	8.20
28.5	7.12	7.18	7.23	7.28	7.33	7.39	7.44	7.49	7.55	7.60	7.65	7.71	7.76	7.81	7.87	7.92	7.97	8.02	8.08	8.13

Table 6.2-6. Solubility of oxygen in freshwater at various temperatures and pressures.—Continued

[Solubility shown in milligrams per liter. Values based on published equations by Benson and Krause (1980 and 1984). Temp. deg C, temperature in degrees Celsius; Values for atmospheric pressures from 600 to 695 millimeters of mercury begin several pages forward]

Temp. (deg C)	Atmospheric pressure, in millimeters of mercury																			
	700	705	710	715	720	725	730	735	740	745	750	755	760	765	770	775	780	785	790	795
29.0	7.06	7.11	7.16	7.22	7.27	7.32	7.38	7.43	7.48	7.53	7.59	7.64	7.69	7.74	7.80	7.85	7.90	7.95	8.01	8.06
29.5	7.00	7.05	7.10	7.15	7.21	7.26	7.31	7.36	7.42	7.47	7.52	7.57	7.62	7.68	7.73	7.78	7.83	7.89	7.94	7.99
30.0	6.94	6.99	7.04	7.09	7.14	7.20	7.25	7.30	7.35	7.40	7.46	7.51	7.56	7.61	7.66	7.71	7.77	7.82	7.87	7.92
30.5	6.88	6.93	6.98	7.03	7.08	7.13	7.19	7.24	7.29	7.34	7.39	7.44	7.49	7.55	7.60	7.65	7.70	7.75	7.80	7.85
31.0	6.82	6.87	6.92	6.97	7.02	7.07	7.12	7.17	7.23	7.28	7.33	7.38	7.43	7.48	7.53	7.58	7.63	7.69	7.74	7.79
31.5	6.76	6.81	6.86	6.91	6.96	7.01	7.06	7.11	7.16	7.21	7.27	7.32	7.37	7.42	7.47	7.52	7.57	7.62	7.67	7.72
32.0	6.70	6.75	6.80	6.85	6.90	6.95	7.00	7.05	7.10	7.15	7.20	7.25	7.30	7.36	7.41	7.46	7.51	7.56	7.61	7.66
32.5	6.64	6.69	6.74	6.79	6.84	6.89	6.94	6.99	7.04	7.09	7.14	7.19	7.24	7.29	7.34	7.39	7.44	7.49	7.54	7.59
33.0	6.59	6.64	6.69	6.74	6.79	6.84	6.89	6.93	6.98	7.03	7.08	7.13	7.18	7.23	7.28	7.33	7.38	7.43	7.48	7.53
33.5	6.53	6.58	6.63	6.68	6.73	6.78	6.83	6.88	6.93	6.98	7.02	7.07	7.12	7.17	7.22	7.27	7.32	7.37	7.42	7.47
34.0	6.48	6.53	6.57	6.62	6.67	6.72	6.77	6.82	6.87	6.92	6.97	7.02	7.06	7.11	7.16	7.21	7.26	7.31	7.36	7.41
34.5	6.42	6.47	6.52	6.57	6.62	6.67	6.71	6.76	6.81	6.86	6.91	6.96	7.01	7.06	7.10	7.15	7.20	7.25	7.30	7.35
35.0	6.37	6.42	6.47	6.51	6.56	6.61	6.66	6.71	6.76	6.80	6.85	6.90	6.95	7.00	7.05	7.09	7.14	7.19	7.24	7.29
35.5	6.32	6.36	6.41	6.46	6.51	6.56	6.60	6.65	6.70	6.75	6.80	6.84	6.89	6.94	6.99	7.04	7.08	7.13	7.18	7.23
36.0	6.26	6.31	6.36	6.41	6.45	6.50	6.55	6.60	6.65	6.69	6.74	6.79	6.84	6.88	6.93	6.98	7.03	7.08	7.12	7.17
36.5	6.21	6.26	6.31	6.35	6.40	6.45	6.50	6.54	6.59	6.64	6.69	6.73	6.78	6.83	6.88	6.92	6.97	7.02	7.07	7.11
37.0	6.16	6.21	6.26	6.30	6.35	6.40	6.44	6.49	6.54	6.59	6.63	6.68	6.73	6.77	6.82	6.87	6.92	6.96	7.01	7.06
37.5	6.11	6.16	6.20	6.25	6.30	6.35	6.39	6.44	6.49	6.53	6.58	6.63	6.67	6.72	6.77	6.81	6.86	6.91	6.95	7.00
38.0	6.06	6.11	6.15	6.20	6.25	6.29	6.34	6.39	6.43	6.48	6.53	6.57	6.62	6.67	6.71	6.76	6.81	6.85	6.90	6.95
38.5	6.01	6.06	6.10	6.15	6.20	6.24	6.29	6.34	6.38	6.43	6.47	6.52	6.57	6.61	6.66	6.71	6.75	6.80	6.84	6.89
39.0	5.96	6.01	6.05	6.10	6.15	6.19	6.24	6.29	6.33	6.38	6.42	6.47	6.52	6.56	6.61	6.65	6.70	6.75	6.79	6.84
39.5	5.91	5.96	6.01	6.05	6.10	6.14	6.19	6.23	6.28	6.33	6.37	6.42	6.46	6.51	6.56	6.60	6.65	6.69	6.74	6.78
40.0	5.87	5.91	5.96	6.00	6.05	6.09	6.14	6.19	6.23	6.28	6.32	6.37	6.41	6.46	6.50	6.55	6.59	6.64	6.69	6.73

Table 6.2-6. Solubility of oxygen in freshwater at various temperatures and pressures.—Continued

[Solubility shown in milligrams per liter. Values based on published equations by Benson and Krause (1980 and 1984). Temp. deg C, temperature in degrees Celsius]

Temp. (deg C)	Atmospheric pressure, in millimeters of mercury																			
	600	605	610	615	620	625	630	635	640	645	650	655	660	665	670	675	680	685	690	695
0.0	11.53	11.62	11.72	11.82	11.91	12.01	12.11	12.20	12.30	12.40	12.49	12.59	12.69	12.78	12.88	12.98	13.07	13.17	13.27	13.36
0.5	11.36	11.46	11.56	11.65	11.75	11.84	11.94	12.03	12.13	12.22	12.32	12.41	12.51	12.60	12.70	12.80	12.89	12.99	13.08	13.18
1.0	11.21	11.30	11.39	11.49	11.58	11.68	11.77	11.86	11.96	12.05	12.15	12.24	12.34	12.43	12.52	12.62	12.71	12.81	12.90	12.99
1.5	11.05	11.14	11.24	11.33	11.42	11.52	11.61	11.70	11.79	11.89	11.98	12.07	12.17	12.26	12.35	12.44	12.54	12.63	12.72	12.81
2.0	10.90	10.99	11.08	11.18	11.27	11.36	11.45	11.54	11.63	11.72	11.82	11.91	12.00	12.09	12.18	12.27	12.37	12.46	12.55	12.64
2.5	10.75	10.84	10.93	11.02	11.11	11.20	11.29	11.39	11.48	11.57	11.66	11.75	11.84	11.93	12.02	12.11	12.20	12.29	12.38	12.47
3.0	10.61	10.70	10.79	10.88	10.96	11.05	11.14	11.23	11.32	11.41	11.50	11.59	11.68	11.77	11.86	11.95	12.03	12.12	12.21	12.30
3.5	10.47	10.55	10.64	10.73	10.82	10.91	10.99	11.08	11.17	11.26	11.35	11.43	11.52	11.61	11.70	11.79	11.87	11.96	12.05	12.14
4.0	10.33	10.42	10.50	10.59	10.68	10.76	10.85	10.94	11.02	11.11	11.20	11.28	11.37	11.46	11.54	11.63	11.72	11.81	11.89	11.98
4.5	10.19	10.28	10.36	10.45	10.54	10.62	10.71	10.79	10.88	10.97	11.05	11.14	11.22	11.31	11.39	11.48	11.57	11.65	11.74	11.82
5.0	10.06	10.15	10.23	10.32	10.40	10.48	10.57	10.65	10.74	10.82	10.91	10.99	11.08	11.16	11.25	11.33	11.42	11.50	11.59	11.67
5.5	9.93	10.02	10.10	10.18	10.27	10.35	10.43	10.52	10.60	10.68	10.77	10.85	10.94	11.02	11.10	11.19	11.27	11.35	11.44	11.52
6.0	9.80	9.89	9.97	10.05	10.14	10.22	10.30	10.38	10.47	10.55	10.63	10.71	10.80	10.88	10.96	11.04	11.13	11.21	11.29	11.37
6.5	9.68	9.76	9.84	9.93	10.01	10.09	10.17	10.25	10.33	10.42	10.50	10.58	10.66	10.74	10.82	10.91	10.99	11.07	11.15	11.23
7.0	9.56	9.64	9.72	9.80	9.88	9.96	10.04	10.12	10.20	10.29	10.37	10.45	10.53	10.61	10.69	10.77	10.85	10.93	11.01	11.09
7.5	9.44	9.52	9.60	9.68	9.76	9.84	9.92	10.00	10.08	10.16	10.24	10.32	10.40	10.48	10.56	10.64	10.72	10.80	10.87	10.95
8.0	9.33	9.40	9.48	9.56	9.64	9.72	9.80	9.88	9.95	10.03	10.11	10.19	10.27	10.35	10.43	10.51	10.58	10.66	10.74	10.82
8.5	9.21	9.29	9.37	9.44	9.52	9.60	9.68	9.76	9.83	9.91	9.99	10.07	10.14	10.22	10.30	10.38	10.46	10.53	10.61	10.69
9.0	9.10	9.18	9.25	9.33	9.41	9.48	9.56	9.64	9.71	9.79	9.87	9.95	10.02	10.10	10.18	10.25	10.33	10.41	10.48	10.56
9.5	8.99	9.07	9.14	9.22	9.29	9.37	9.45	9.52	9.60	9.67	9.75	9.83	9.90	9.98	10.05	10.13	10.21	10.28	10.36	10.43
10.0	8.88	8.96	9.03	9.11	9.18	9.26	9.33	9.41	9.49	9.56	9.64	9.71	9.79	9.86	9.94	10.01	10.09	10.16	10.24	10.31
10.5	8.78	8.85	8.93	9.00	9.08	9.15	9.23	9.30	9.37	9.45	9.52	9.60	9.67	9.75	9.82	9.89	9.97	10.04	10.12	10.19
11.0	8.68	8.75	8.82	8.90	8.97	9.04	9.12	9.19	9.26	9.34	9.41	9.48	9.56	9.63	9.71	9.78	9.85	9.93	10.00	10.07
11.5	8.58	8.65	8.72	8.79	8.87	8.94	9.01	9.08	9.16	9.23	9.30	9.38	9.45	9.52	9.59	9.67	9.74	9.81	9.88	9.96
12.0	8.48	8.55	8.62	8.69	8.77	8.84	8.91	8.98	9.05	9.12	9.20	9.27	9.34	9.41	9.48	9.56	9.63	9.70	9.77	9.84
12.5	8.38	8.45	8.52	8.59	8.67	8.74	8.81	8.88	8.95	9.02	9.09	9.16	9.23	9.31	9.38	9.45	9.52	9.59	9.66	9.73
13.0	8.29	8.36	8.43	8.50	8.57	8.64	8.71	8.78	8.85	8.92	8.99	9.06	9.13	9.20	9.27	9.34	9.41	9.48	9.55	9.62
13.5	8.19	8.26	8.33	8.40	8.47	8.54	8.61	8.68	8.75	8.82	8.89	8.96	9.03	9.10	9.17	9.24	9.31	9.38	9.45	9.52
14.0	8.10	8.17	8.24	8.31	8.38	8.45	8.52	8.58	8.65	8.72	8.79	8.86	8.93	9.00	9.07	9.14	9.20	9.27	9.34	9.41

Table 6.2-6. Solubility of oxygen in freshwater at various temperatures and pressures.—Continued

[Solubility shown in milligrams per liter. Values based on published equations by Benson and Krause (1980 and 1984). Temp. deg C, temperature in degrees Celsius]

Temp. (deg C)	Atmospheric pressure, in millimeters of mercury																			
	600	605	610	615	620	625	630	635	640	645	650	655	660	665	670	675	680	685	690	695
14.5	8.01	8.08	8.15	8.22	8.29	8.35	8.42	8.49	8.56	8.63	8.69	8.76	8.83	8.90	8.97	9.04	9.10	9.17	9.24	9.31
15.0	7.93	7.99	8.06	8.13	8.20	8.26	8.33	8.40	8.47	8.53	8.60	8.67	8.74	8.80	8.87	8.94	9.00	9.07	9.14	9.21
15.5	7.84	7.91	7.97	8.04	8.11	8.17	8.24	8.31	8.37	8.44	8.51	8.57	8.64	8.71	8.77	8.84	8.91	8.97	9.04	9.11
16.0	7.76	7.82	7.89	7.95	8.02	8.09	8.15	8.22	8.28	8.35	8.42	8.48	8.55	8.61	8.68	8.75	8.81	8.88	8.95	9.01
16.5	7.67	7.74	7.80	7.87	7.93	8.00	8.07	8.13	8.20	8.26	8.33	8.39	8.46	8.52	8.59	8.65	8.72	8.79	8.85	8.92
17.0	7.59	7.66	7.72	7.79	7.85	7.92	7.98	8.05	8.11	8.17	8.24	8.30	8.37	8.43	8.50	8.56	8.63	8.69	8.76	8.82
17.5	7.51	7.58	7.64	7.70	7.77	7.83	7.90	7.96	8.03	8.09	8.15	8.22	8.28	8.35	8.41	8.47	8.54	8.60	8.67	8.73
18.0	7.43	7.50	7.56	7.62	7.69	7.75	7.81	7.88	7.94	8.01	8.07	8.13	8.20	8.26	8.32	8.39	8.45	8.51	8.58	8.64
18.5	7.36	7.42	7.48	7.55	7.61	7.67	7.73	7.80	7.86	7.92	7.99	8.05	8.11	8.18	8.24	8.30	8.36	8.43	8.49	8.55
19.0	7.28	7.34	7.41	7.47	7.53	7.59	7.66	7.72	7.78	7.84	7.90	7.97	8.03	8.09	8.15	8.22	8.28	8.34	8.40	8.47
19.5	7.21	7.27	7.33	7.39	7.45	7.52	7.58	7.64	7.70	7.76	7.82	7.89	7.95	8.01	8.07	8.13	8.20	8.26	8.32	8.38
20.0	7.13	7.20	7.26	7.32	7.38	7.44	7.50	7.56	7.62	7.68	7.75	7.81	7.87	7.93	7.99	8.05	8.11	8.17	8.24	8.30
20.5	7.06	7.12	7.18	7.24	7.31	7.37	7.43	7.49	7.55	7.61	7.67	7.73	7.79	7.85	7.91	7.97	8.03	8.09	8.15	8.21
21.0	6.99	7.05	7.11	7.17	7.23	7.29	7.35	7.41	7.47	7.53	7.59	7.65	7.71	7.77	7.83	7.89	7.95	8.01	8.07	8.13
21.5	6.92	6.98	7.04	7.10	7.16	7.22	7.28	7.34	7.40	7.46	7.52	7.58	7.64	7.70	7.76	7.82	7.88	7.94	7.99	8.05
22.0	6.85	6.91	6.97	7.03	7.09	7.15	7.21	7.27	7.33	7.39	7.45	7.50	7.56	7.62	7.68	7.74	7.80	7.86	7.92	7.98
22.5	6.79	6.85	6.90	6.96	7.02	7.08	7.14	7.20	7.26	7.31	7.37	7.43	7.49	7.55	7.61	7.67	7.72	7.78	7.84	7.90
23.0	6.72	6.78	6.84	6.90	6.95	7.01	7.07	7.13	7.19	7.24	7.30	7.36	7.42	7.48	7.53	7.59	7.65	7.71	7.77	7.82
23.5	6.66	6.71	6.77	6.83	6.89	6.94	7.00	7.06	7.12	7.17	7.23	7.29	7.35	7.40	7.46	7.52	7.58	7.63	7.69	7.75
24.0	6.59	6.65	6.71	6.76	6.82	6.88	6.94	6.99	7.05	7.11	7.16	7.22	7.28	7.33	7.39	7.45	7.51	7.56	7.62	7.68
24.5	6.53	6.59	6.64	6.70	6.76	6.81	6.87	6.93	6.98	7.04	7.10	7.15	7.21	7.27	7.32	7.38	7.44	7.49	7.55	7.61
25.0	6.47	6.52	6.58	6.64	6.69	6.75	6.81	6.86	6.92	6.97	7.03	7.09	7.14	7.20	7.25	7.31	7.37	7.42	7.48	7.53
25.5	6.41	6.46	6.52	6.57	6.63	6.69	6.74	6.80	6.85	6.91	6.96	7.02	7.08	7.13	7.19	7.24	7.30	7.35	7.41	7.46
26.0	6.35	6.40	6.46	6.51	6.57	6.62	6.68	6.73	6.79	6.84	6.90	6.95	7.01	7.07	7.12	7.18	7.23	7.29	7.34	7.40
26.5	6.29	6.34	6.40	6.45	6.51	6.56	6.62	6.67	6.73	6.78	6.84	6.89	6.95	7.00	7.06	7.11	7.16	7.22	7.27	7.33
27.0	6.23	6.28	6.34	6.39	6.45	6.50	6.56	6.61	6.67	6.72	6.77	6.83	6.88	6.94	6.99	7.05	7.10	7.15	7.21	7.26
27.5	6.17	6.23	6.28	6.33	6.39	6.44	6.50	6.55	6.60	6.66	6.71	6.77	6.82	6.87	6.93	6.98	7.04	7.09	7.14	7.20
28.0	6.12	6.17	6.22	6.28	6.33	6.38	6.44	6.49	6.54	6.60	6.65	6.70	6.76	6.81	6.87	6.92	6.97	7.03	7.08	7.13
28.5	6.06	6.11	6.17	6.22	6.27	6.33	6.38	6.43	6.49	6.54	6.59	6.64	6.70	6.75	6.80	6.86	6.91	6.96	7.02	7.07

Table 6.2-6. Solubility of oxygen in freshwater at various temperatures and pressures.—Continued

[Solubility shown in milligrams per liter. Values based on published equations by Benson and Krause (1980 and 1984). Temp. deg C, temperature in degrees Celsius]

Temp. (deg C)	Atmospheric pressure, in millimeters of mercury																			
	600	605	610	615	620	625	630	635	640	645	650	655	660	665	670	675	680	685	690	695
29.0	6.01	6.06	6.11	6.16	6.22	6.27	6.32	6.37	6.43	6.48	6.53	6.59	6.64	6.69	6.74	6.80	6.85	6.90	6.95	7.01
29.5	5.95	6.00	6.06	6.11	6.16	6.21	6.27	6.32	6.37	6.42	6.47	6.53	6.58	6.63	6.68	6.74	6.79	6.84	6.89	6.95
30.0	5.90	5.95	6.00	6.05	6.11	6.16	6.21	6.26	6.31	6.37	6.42	6.47	6.52	6.57	6.63	6.68	6.73	6.78	6.83	6.88
30.5	5.85	5.90	5.95	6.00	6.05	6.10	6.16	6.21	6.26	6.31	6.36	6.41	6.46	6.52	6.57	6.62	6.67	6.72	6.77	6.82
31.0	5.79	5.85	5.90	5.95	6.00	6.05	6.10	6.15	6.20	6.25	6.31	6.36	6.41	6.46	6.51	6.56	6.61	6.66	6.71	6.77
31.5	5.74	5.79	5.84	5.90	5.95	6.00	6.05	6.10	6.15	6.20	6.25	6.30	6.35	6.40	6.45	6.50	6.55	6.61	6.66	6.71
32.0	5.69	5.74	5.79	5.84	5.89	5.94	5.99	6.04	6.10	6.15	6.20	6.25	6.30	6.35	6.40	6.45	6.50	6.55	6.60	6.65
32.5	5.64	5.69	5.74	5.79	5.84	5.89	5.94	5.99	6.04	6.09	6.14	6.19	6.24	6.29	6.34	6.39	6.44	6.49	6.54	6.59
33.0	5.59	5.64	5.69	5.74	5.79	5.84	5.89	5.94	5.99	6.04	6.09	6.14	6.19	6.24	6.29	6.34	6.39	6.44	6.49	6.54
33.5	5.54	5.59	5.64	5.69	5.74	5.79	5.84	5.89	5.94	5.99	6.04	6.09	6.14	6.19	6.24	6.28	6.33	6.38	6.43	6.48
34.0	5.50	5.54	5.59	5.64	5.69	5.74	5.79	5.84	5.89	5.94	5.99	6.04	6.08	6.13	6.18	6.23	6.28	6.33	6.38	6.43
34.5	5.45	5.50	5.55	5.59	5.64	5.69	5.74	5.79	5.84	5.89	5.94	5.98	6.03	6.08	6.13	6.18	6.23	6.28	6.32	6.37
35.0	5.40	5.45	5.50	5.55	5.59	5.64	5.69	5.74	5.79	5.84	5.88	5.93	5.98	6.03	6.08	6.13	6.18	6.22	6.27	6.32
35.5	5.35	5.40	5.45	5.50	5.55	5.59	5.64	5.69	5.74	5.79	5.84	5.88	5.93	5.98	6.03	6.08	6.12	6.17	6.22	6.27
36.0	5.31	5.36	5.40	5.45	5.50	5.55	5.60	5.64	5.69	5.74	5.79	5.83	5.88	5.93	5.98	6.02	6.07	6.12	6.17	6.22
36.5	5.26	5.31	5.36	5.41	5.45	5.50	5.55	5.60	5.64	5.69	5.74	5.78	5.83	5.88	5.93	5.97	6.02	6.07	6.12	6.16
37.0	5.22	5.27	5.31	5.36	5.41	5.45	5.50	5.55	5.60	5.64	5.69	5.74	5.78	5.83	5.88	5.93	5.97	6.02	6.07	6.11
37.5	5.17	5.22	5.27	5.31	5.36	5.41	5.45	5.50	5.55	5.60	5.64	5.69	5.74	5.78	5.83	5.88	5.92	5.97	6.02	6.06
38.0	5.13	5.18	5.22	5.27	5.32	5.36	5.41	5.46	5.50	5.55	5.60	5.64	5.69	5.73	5.78	5.83	5.87	5.92	5.97	6.01
38.5	5.09	5.13	5.18	5.22	5.27	5.32	5.36	5.41	5.46	5.50	5.55	5.59	5.64	5.69	5.73	5.78	5.83	5.87	5.92	5.97
39.0	5.04	5.09	5.13	5.18	5.23	5.27	5.32	5.36	5.41	5.46	5.50	5.55	5.59	5.64	5.69	5.73	5.78	5.82	5.87	5.92
39.5	5.00	5.05	5.09	5.14	5.18	5.23	5.27	5.32	5.37	5.41	5.46	5.50	5.55	5.59	5.64	5.69	5.73	5.78	5.82	5.87
40.0	4.96	5.00	5.05	5.09	5.14	5.18	5.23	5.28	5.32	5.37	5.41	5.46	5.50	5.55	5.59	5.64	5.69	5.73	5.78	5.82

Table 6.2-7. Salinity correction factors for dissolved oxygen in water (based on specific conductance).

[Factors are dimensionless. Values based on published equations by Benson and Krause (1984). Temp. deg C, temperature in degrees Celsius; salinity correction factors for 30 to 35 degrees Celsius begin several pages forward]

Temp. (deg C)	Specific conductance, in microsiemens per centimeter at 25 degrees Celsius														
	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000	13000	14000
0.0	1.0000	0.9961	0.9922	0.9882	0.9843	0.9804	0.9764	0.9724	0.9684	0.9644	0.9604	0.9564	0.9524	0.9483	0.9443
1.0	1.0000	0.9961	0.9923	0.9884	0.9845	0.9805	0.9766	0.9727	0.9687	0.9648	0.9608	0.9568	0.9528	0.9488	0.9448
2.0	1.0000	0.9962	0.9923	0.9885	0.9846	0.9807	0.9768	0.9729	0.9690	0.9651	0.9611	0.9572	0.9532	0.9493	0.9453
3.0	1.0000	0.9962	0.9924	0.9886	0.9847	0.9809	0.9770	0.9732	0.9693	0.9654	0.9615	0.9576	0.9536	0.9497	0.9458
4.0	1.0000	0.9962	0.9925	0.9887	0.9849	0.9811	0.9772	0.9734	0.9696	0.9657	0.9618	0.9579	0.9541	0.9502	0.9462
5.0	1.0000	0.9963	0.9925	0.9888	0.9850	0.9812	0.9774	0.9736	0.9698	0.9660	0.9622	0.9583	0.9545	0.9506	0.9467
6.0	1.0000	0.9963	0.9926	0.9889	0.9851	0.9814	0.9776	0.9739	0.9701	0.9663	0.9625	0.9587	0.9549	0.9510	0.9472
7.0	1.0000	0.9963	0.9927	0.9890	0.9853	0.9816	0.9778	0.9741	0.9703	0.9666	0.9628	0.9590	0.9552	0.9514	0.9476
8.0	1.0000	0.9964	0.9927	0.9891	0.9854	0.9817	0.9780	0.9743	0.9706	0.9669	0.9631	0.9594	0.9556	0.9519	0.9481
9.0	1.0000	0.9964	0.9928	0.9892	0.9855	0.9819	0.9782	0.9745	0.9708	0.9672	0.9634	0.9597	0.9560	0.9523	0.9485
10.0	1.0000	0.9964	0.9928	0.9893	0.9856	0.9820	0.9784	0.9747	0.9711	0.9674	0.9637	0.9601	0.9564	0.9527	0.9489
11.0	1.0000	0.9965	0.9929	0.9893	0.9858	0.9822	0.9786	0.9750	0.9713	0.9677	0.9640	0.9604	0.9567	0.9530	0.9494
12.0	1.0000	0.9965	0.9930	0.9894	0.9859	0.9823	0.9787	0.9752	0.9716	0.9680	0.9643	0.9607	0.9571	0.9534	0.9498
13.0	1.0000	0.9965	0.9930	0.9895	0.9860	0.9825	0.9789	0.9754	0.9718	0.9682	0.9646	0.9610	0.9574	0.9538	0.9502
14.0	1.0000	0.9965	0.9931	0.9896	0.9861	0.9826	0.9791	0.9756	0.9720	0.9685	0.9649	0.9613	0.9578	0.9542	0.9506
15.0	1.0000	0.9966	0.9931	0.9897	0.9862	0.9827	0.9793	0.9758	0.9723	0.9687	0.9652	0.9617	0.9581	0.9545	0.9510
16.0	1.0000	0.9966	0.9932	0.9898	0.9863	0.9829	0.9794	0.9760	0.9725	0.9690	0.9655	0.9620	0.9584	0.9549	0.9513
17.0	1.0000	0.9966	0.9932	0.9898	0.9864	0.9830	0.9796	0.9761	0.9727	0.9692	0.9657	0.9622	0.9587	0.9552	0.9517
18.0	1.0000	0.9967	0.9933	0.9899	0.9865	0.9831	0.9797	0.9763	0.9729	0.9695	0.9660	0.9625	0.9591	0.9556	0.9521
19.0	1.0000	0.9967	0.9933	0.9900	0.9866	0.9833	0.9799	0.9765	0.9731	0.9697	0.9663	0.9628	0.9594	0.9559	0.9524
20.0	1.0000	0.9967	0.9934	0.9901	0.9867	0.9834	0.9800	0.9767	0.9733	0.9699	0.9665	0.9631	0.9597	0.9562	0.9528
21.0	1.0000	0.9967	0.9934	0.9902	0.9868	0.9835	0.9802	0.9769	0.9735	0.9701	0.9668	0.9634	0.9600	0.9566	0.9531
22.0	1.0000	0.9968	0.9935	0.9902	0.9869	0.9836	0.9803	0.9770	0.9737	0.9704	0.9670	0.9636	0.9603	0.9569	0.9535
23.0	1.0000	0.9968	0.9935	0.9903	0.9870	0.9838	0.9805	0.9772	0.9739	0.9706	0.9672	0.9639	0.9605	0.9572	0.9538
24.0	1.0000	0.9968	0.9936	0.9904	0.9871	0.9839	0.9806	0.9774	0.9741	0.9708	0.9675	0.9642	0.9608	0.9575	0.9541
25.0	1.0000	0.9968	0.9936	0.9904	0.9872	0.9840	0.9808	0.9775	0.9743	0.9710	0.9677	0.9644	0.9611	0.9578	0.9545
26.0	1.0000	0.9968	0.9937	0.9905	0.9873	0.9841	0.9809	0.9777	0.9744	0.9712	0.9679	0.9647	0.9614	0.9581	0.9548
27.0	1.0000	0.9969	0.9937	0.9906	0.9874	0.9842	0.9810	0.9778	0.9746	0.9714	0.9681	0.9649	0.9616	0.9584	0.9551
28.0	1.0000	0.9969	0.9938	0.9906	0.9875	0.9843	0.9812	0.9780	0.9748	0.9716	0.9684	0.9651	0.9619	0.9586	0.9554
29.0	1.0000	0.9969	0.9938	0.9907	0.9876	0.9844	0.9813	0.9781	0.9750	0.9718	0.9686	0.9654	0.9621	0.9589	0.9557

Table 6.2-7. Salinity correction factors for dissolved oxygen in water (based on specific conductance).—Continued

[Factors are dimensionless. Values based on published equations by Benson and Krause (1984). Temp. deg C, temperature in degrees Celsius; salinity correction factors for 30 to 35 degrees Celsius begin several pages forward]

Temp. (deg C)	Specific conductance, in microsiemens per centimeter at 25 degrees Celsius														
	15000	16000	17000	18000	19000	20000	21000	22000	23000	24000	25000	26000	27000	28000	29000
0.0	0.9402	0.9361	0.9321	0.9280	0.9239	0.9198	0.9157	0.9116	0.9074	0.9033	0.8992	0.8950	0.8909	0.8867	0.8826
1.0	0.9408	0.9367	0.9327	0.9286	0.9246	0.9205	0.9164	0.9124	0.9083	0.9042	0.9001	0.8960	0.8918	0.8877	0.8836
2.0	0.9413	0.9373	0.9333	0.9293	0.9252	0.9212	0.9172	0.9131	0.9091	0.9050	0.9009	0.8969	0.8928	0.8887	0.8846
3.0	0.9418	0.9378	0.9339	0.9299	0.9259	0.9219	0.9179	0.9139	0.9099	0.9058	0.9018	0.8978	0.8937	0.8897	0.8856
4.0	0.9423	0.9384	0.9345	0.9305	0.9266	0.9226	0.9186	0.9146	0.9107	0.9067	0.9027	0.8986	0.8946	0.8906	0.8866
5.0	0.9428	0.9389	0.9350	0.9311	0.9272	0.9233	0.9193	0.9154	0.9114	0.9075	0.9035	0.8995	0.8955	0.8915	0.8875
6.0	0.9433	0.9395	0.9356	0.9317	0.9278	0.9239	0.9200	0.9161	0.9122	0.9082	0.9043	0.9004	0.8964	0.8924	0.8885
7.0	0.9438	0.9400	0.9361	0.9323	0.9284	0.9246	0.9207	0.9168	0.9129	0.9090	0.9051	0.9012	0.8973	0.8933	0.8894
8.0	0.9443	0.9405	0.9367	0.9329	0.9290	0.9252	0.9213	0.9175	0.9136	0.9098	0.9059	0.9020	0.8981	0.8942	0.8903
9.0	0.9447	0.9410	0.9372	0.9334	0.9296	0.9258	0.9220	0.9182	0.9143	0.9105	0.9067	0.9028	0.8989	0.8951	0.8912
10.0	0.9452	0.9415	0.9377	0.9340	0.9302	0.9264	0.9226	0.9188	0.9150	0.9112	0.9074	0.9036	0.8998	0.8959	0.8921
11.0	0.9457	0.9419	0.9382	0.9345	0.9308	0.9270	0.9233	0.9195	0.9157	0.9119	0.9082	0.9044	0.9006	0.8968	0.8929
12.0	0.9461	0.9424	0.9387	0.9350	0.9313	0.9276	0.9239	0.9201	0.9164	0.9126	0.9089	0.9051	0.9014	0.8976	0.8938
13.0	0.9465	0.9429	0.9392	0.9355	0.9319	0.9282	0.9245	0.9208	0.9171	0.9133	0.9096	0.9059	0.9021	0.8984	0.8946
14.0	0.9470	0.9433	0.9397	0.9361	0.9324	0.9287	0.9251	0.9214	0.9177	0.9140	0.9103	0.9066	0.9029	0.8992	0.8954
15.0	0.9474	0.9438	0.9402	0.9366	0.9329	0.9293	0.9257	0.9220	0.9183	0.9147	0.9110	0.9073	0.9036	0.8999	0.8962
16.0	0.9478	0.9442	0.9406	0.9370	0.9334	0.9298	0.9262	0.9226	0.9190	0.9153	0.9117	0.9080	0.9044	0.9007	0.8970
17.0	0.9482	0.9446	0.9411	0.9375	0.9340	0.9304	0.9268	0.9232	0.9196	0.9160	0.9123	0.9087	0.9051	0.9014	0.8978
18.0	0.9486	0.9451	0.9415	0.9380	0.9345	0.9309	0.9273	0.9238	0.9202	0.9166	0.9130	0.9094	0.9058	0.9022	0.8985
19.0	0.9490	0.9455	0.9420	0.9385	0.9349	0.9314	0.9279	0.9243	0.9208	0.9172	0.9136	0.9101	0.9065	0.9029	0.8993
20.0	0.9493	0.9459	0.9424	0.9389	0.9354	0.9319	0.9284	0.9249	0.9214	0.9178	0.9143	0.9107	0.9071	0.9036	0.9000
21.0	0.9497	0.9463	0.9428	0.9394	0.9359	0.9324	0.9289	0.9254	0.9219	0.9184	0.9149	0.9114	0.9078	0.9043	0.9007
22.0	0.9501	0.9467	0.9432	0.9398	0.9363	0.9329	0.9294	0.9260	0.9225	0.9190	0.9155	0.9120	0.9085	0.9049	0.9014
23.0	0.9504	0.9470	0.9436	0.9402	0.9368	0.9334	0.9299	0.9265	0.9230	0.9196	0.9161	0.9126	0.9091	0.9056	0.9021
24.0	0.9508	0.9474	0.9440	0.9406	0.9372	0.9338	0.9304	0.9270	0.9236	0.9201	0.9167	0.9132	0.9097	0.9063	0.9028
25.0	0.9511	0.9478	0.9444	0.9411	0.9377	0.9343	0.9309	0.9275	0.9241	0.9207	0.9172	0.9138	0.9104	0.9069	0.9034
26.0	0.9515	0.9481	0.9448	0.9415	0.9381	0.9347	0.9314	0.9280	0.9246	0.9212	0.9178	0.9144	0.9110	0.9075	0.9041
27.0	0.9518	0.9485	0.9452	0.9419	0.9385	0.9352	0.9318	0.9285	0.9251	0.9217	0.9183	0.9149	0.9115	0.9081	0.9047
28.0	0.9521	0.9488	0.9455	0.9422	0.9389	0.9356	0.9323	0.9289	0.9256	0.9222	0.9189	0.9155	0.9121	0.9087	0.9053
29.0	0.9524	0.9492	0.9459	0.9426	0.9393	0.9360	0.9327	0.9294	0.9261	0.9228	0.9194	0.9161	0.9127	0.9093	0.9060

Table 6.2-7. Salinity correction factors for dissolved oxygen in water (based on specific conductance).—Continued

[Factors are dimensionless. Values based on published equations by Benson and Krause (1984). Temp. deg C, temperature in degrees Celsius; salinity correction factors for 30 to 35 degrees Celsius begin several pages forward]

Temp. (deg C)	Specific conductance, in microsiemens per centimeter at 25 degrees Celsius																
	30000	31000	32000	33000	34000	35000	36000	37000	38000	39000	40000	41000	42000	43000	44000	45000	
0.0	0.8784	0.8742	0.8701	0.8659	0.8617	0.8575	0.8533	0.8491	0.8449	0.8407	0.8365	0.8323	0.8281	0.8239	0.8197		
1.0	0.8795	0.8753	0.8712	0.8670	0.8629	0.8587	0.8546	0.8504	0.8462	0.8421	0.8379	0.8337	0.8296	0.8254	0.8212		
2.0	0.8805	0.8764	0.8723	0.8682	0.8641	0.8599	0.8558	0.8517	0.8476	0.8434	0.8393	0.8351	0.8310	0.8268	0.8227		
3.0	0.8815	0.8775	0.8734	0.8693	0.8652	0.8611	0.8570	0.8529	0.8488	0.8447	0.8406	0.8365	0.8324	0.8283	0.8242		
4.0	0.8825	0.8785	0.8745	0.8704	0.8664	0.8623	0.8582	0.8542	0.8501	0.8460	0.8419	0.8379	0.8338	0.8297	0.8256		
5.0	0.8835	0.8795	0.8755	0.8715	0.8675	0.8635	0.8594	0.8554	0.8513	0.8473	0.8433	0.8392	0.8351	0.8311	0.8270		
6.0	0.8845	0.8805	0.8766	0.8726	0.8686	0.8646	0.8606	0.8566	0.8526	0.8485	0.8445	0.8405	0.8365	0.8325	0.8284		
7.0	0.8855	0.8815	0.8776	0.8736	0.8697	0.8657	0.8617	0.8577	0.8538	0.8498	0.8458	0.8418	0.8378	0.8338	0.8298		
8.0	0.8864	0.8825	0.8786	0.8746	0.8707	0.8668	0.8628	0.8589	0.8549	0.8510	0.8470	0.8431	0.8391	0.8351	0.8311		
9.0	0.8873	0.8834	0.8796	0.8757	0.8718	0.8678	0.8639	0.8600	0.8561	0.8522	0.8482	0.8443	0.8404	0.8364	0.8325		
10.0	0.8882	0.8844	0.8805	0.8766	0.8728	0.8689	0.8650	0.8611	0.8572	0.8533	0.8494	0.8455	0.8416	0.8377	0.8338		
11.0	0.8891	0.8853	0.8815	0.8776	0.8738	0.8699	0.8661	0.8622	0.8583	0.8545	0.8506	0.8467	0.8428	0.8389	0.8351		
12.0	0.8900	0.8862	0.8824	0.8786	0.8748	0.8709	0.8671	0.8633	0.8594	0.8556	0.8517	0.8479	0.8440	0.8402	0.8363		
13.0	0.8908	0.8871	0.8833	0.8795	0.8757	0.8719	0.8681	0.8643	0.8605	0.8567	0.8529	0.8490	0.8452	0.8414	0.8375		
14.0	0.8917	0.8879	0.8842	0.8804	0.8767	0.8729	0.8691	0.8654	0.8616	0.8578	0.8540	0.8502	0.8464	0.8426	0.8388		
15.0	0.8925	0.8888	0.8851	0.8813	0.8776	0.8739	0.8701	0.8664	0.8626	0.8588	0.8551	0.8513	0.8475	0.8437	0.8400		
16.0	0.8933	0.8896	0.8859	0.8822	0.8785	0.8748	0.8711	0.8674	0.8636	0.8599	0.8561	0.8524	0.8486	0.8449	0.8411		
17.0	0.8941	0.8905	0.8868	0.8831	0.8794	0.8757	0.8720	0.8683	0.8646	0.8609	0.8572	0.8535	0.8497	0.8460	0.8423		
18.0	0.8949	0.8913	0.8876	0.8840	0.8803	0.8766	0.8730	0.8693	0.8656	0.8619	0.8582	0.8545	0.8508	0.8471	0.8434		
19.0	0.8957	0.8921	0.8884	0.8848	0.8812	0.8775	0.8739	0.8702	0.8666	0.8629	0.8592	0.8556	0.8519	0.8482	0.8445		
20.0	0.8964	0.8928	0.8892	0.8856	0.8820	0.8784	0.8748	0.8711	0.8675	0.8639	0.8602	0.8566	0.8529	0.8493	0.8456		
21.0	0.8972	0.8936	0.8900	0.8864	0.8828	0.8793	0.8757	0.8720	0.8684	0.8648	0.8612	0.8576	0.8539	0.8503	0.8467		
22.0	0.8979	0.8943	0.8908	0.8872	0.8837	0.8801	0.8765	0.8729	0.8693	0.8658	0.8622	0.8585	0.8549	0.8513	0.8477		
23.0	0.8986	0.8951	0.8915	0.8880	0.8845	0.8809	0.8774	0.8738	0.8702	0.8667	0.8631	0.8595	0.8559	0.8523	0.8487		
24.0	0.8993	0.8958	0.8923	0.8888	0.8853	0.8817	0.8782	0.8747	0.8711	0.8676	0.8640	0.8605	0.8569	0.8533	0.8497		
25.0	0.9000	0.8965	0.8930	0.8895	0.8860	0.8825	0.8790	0.8755	0.8720	0.8685	0.8649	0.8614	0.8578	0.8543	0.8507		
26.0	0.9006	0.8972	0.8937	0.8903	0.8868	0.8833	0.8798	0.8763	0.8728	0.8693	0.8658	0.8623	0.8588	0.8552	0.8517		
27.0	0.9013	0.8979	0.8944	0.8910	0.8875	0.8841	0.8806	0.8771	0.8736	0.8702	0.8667	0.8632	0.8597	0.8562	0.8527		
28.0	0.9019	0.8985	0.8951	0.8917	0.8883	0.8848	0.8814	0.8779	0.8745	0.8710	0.8675	0.8641	0.8606	0.8571	0.8536		
29.0	0.9026	0.8992	0.8958	0.8924	0.8890	0.8856	0.8821	0.8787	0.8753	0.8718	0.8684	0.8649	0.8615	0.8580	0.8545		

Table 6.2-7. Salinity correction factors for dissolved oxygen in water (based on specific conductance).—Continued

[Factors are dimensionless. Values based on published equations by Benson and Krause (1984). Temp. deg C, temperature in degrees Celsius; salinity correction factors for 30 to 35 degrees Celsius begin several pages forward]

Temp. (deg C)	Specific conductance, in microsiemens per centimeter at 25 degrees Celsius																
	45000	46000	47000	48000	49000	50000	51000	52000	53000	54000	55000	56000	57000	58000	59000		
0.0	0.8155	0.8112	0.8070	0.8028	0.7986	0.7944	0.7901	0.7859	0.7817	0.7775	0.7733	0.7691	0.7648	0.7606	0.7564		
1.0	0.8170	0.8128	0.8086	0.8045	0.8003	0.7961	0.7919	0.7877	0.7835	0.7793	0.7751	0.7709	0.7668	0.7626	0.7584		
2.0	0.8185	0.8144	0.8102	0.8061	0.8019	0.7978	0.7936	0.7894	0.7853	0.7811	0.7770	0.7728	0.7686	0.7645	0.7603		
3.0	0.8200	0.8159	0.8118	0.8077	0.8035	0.7994	0.7953	0.7911	0.7870	0.7829	0.7788	0.7746	0.7705	0.7664	0.7623		
4.0	0.8215	0.8174	0.8133	0.8092	0.8051	0.8010	0.7969	0.7928	0.7887	0.7846	0.7805	0.7764	0.7723	0.7682	0.7641		
5.0	0.8230	0.8189	0.8148	0.8108	0.8067	0.8026	0.7986	0.7945	0.7904	0.7863	0.7823	0.7782	0.7741	0.7700	0.7660		
6.0	0.8244	0.8204	0.8163	0.8123	0.8082	0.8042	0.8002	0.7961	0.7921	0.7880	0.7840	0.7799	0.7759	0.7718	0.7678		
7.0	0.8258	0.8218	0.8178	0.8138	0.8098	0.8057	0.8017	0.7977	0.7937	0.7897	0.7857	0.7816	0.7776	0.7736	0.7696		
8.0	0.8272	0.8232	0.8192	0.8152	0.8112	0.8073	0.8033	0.7993	0.7953	0.7913	0.7873	0.7833	0.7793	0.7753	0.7713		
9.0	0.8285	0.8246	0.8206	0.8167	0.8127	0.8088	0.8048	0.8008	0.7969	0.7929	0.7889	0.7850	0.7810	0.7770	0.7731		
10.0	0.8299	0.8259	0.8220	0.8181	0.8141	0.8102	0.8063	0.8023	0.7984	0.7945	0.7905	0.7866	0.7826	0.7787	0.7748		
11.0	0.8312	0.8273	0.8234	0.8195	0.8156	0.8117	0.8077	0.8038	0.7999	0.7960	0.7921	0.7882	0.7843	0.7804	0.7764		
12.0	0.8324	0.8286	0.8247	0.8208	0.8170	0.8131	0.8092	0.8053	0.8014	0.7975	0.7936	0.7898	0.7859	0.7820	0.7781		
13.0	0.8337	0.8299	0.8260	0.8222	0.8183	0.8145	0.8106	0.8067	0.8029	0.7990	0.7952	0.7913	0.7874	0.7836	0.7797		
14.0	0.8349	0.8311	0.8273	0.8235	0.8197	0.8158	0.8120	0.8082	0.8043	0.8005	0.7966	0.7928	0.7890	0.7851	0.7813		
15.0	0.8362	0.8324	0.8286	0.8248	0.8210	0.8172	0.8134	0.8095	0.8057	0.8019	0.7981	0.7943	0.7905	0.7867	0.7828		
16.0	0.8374	0.8336	0.8298	0.8260	0.8223	0.8185	0.8147	0.8109	0.8071	0.8033	0.7995	0.7958	0.7920	0.7882	0.7844		
17.0	0.8385	0.8348	0.8310	0.8273	0.8235	0.8198	0.8160	0.8123	0.8085	0.8047	0.8010	0.7972	0.7934	0.7896	0.7859		
18.0	0.8397	0.8360	0.8322	0.8285	0.8248	0.8210	0.8173	0.8136	0.8098	0.8061	0.8023	0.7986	0.7948	0.7911	0.7873		
19.0	0.8408	0.8371	0.8334	0.8297	0.8260	0.8223	0.8186	0.8149	0.8112	0.8074	0.8037	0.8000	0.7963	0.7925	0.7888		
20.0	0.8419	0.8383	0.8346	0.8309	0.8272	0.8235	0.8198	0.8161	0.8124	0.8087	0.8050	0.8013	0.7976	0.7939	0.7902		
21.0	0.8430	0.8394	0.8357	0.8321	0.8284	0.8247	0.8211	0.8174	0.8137	0.8100	0.8064	0.8027	0.7990	0.7953	0.7916		
22.0	0.8441	0.8405	0.8368	0.8332	0.8296	0.8259	0.8223	0.8186	0.8150	0.8113	0.8076	0.8040	0.8003	0.7967	0.7930		
23.0	0.8451	0.8415	0.8379	0.8343	0.8307	0.8271	0.8234	0.8198	0.8162	0.8126	0.8089	0.8053	0.8016	0.7980	0.7943		
24.0	0.8462	0.8426	0.8390	0.8354	0.8318	0.8282	0.8246	0.8210	0.8174	0.8138	0.8102	0.8065	0.8029	0.7993	0.7957		
25.0	0.8472	0.8436	0.8400	0.8365	0.8329	0.8293	0.8257	0.8222	0.8186	0.8150	0.8114	0.8078	0.8042	0.8006	0.7970		
26.0	0.8482	0.8446	0.8411	0.8375	0.8340	0.8304	0.8269	0.8233	0.8197	0.8162	0.8126	0.8090	0.8054	0.8018	0.7983		
27.0	0.8491	0.8456	0.8421	0.8386	0.8350	0.8315	0.8280	0.8244	0.8209	0.8173	0.8138	0.8102	0.8066	0.8031	0.7995		
28.0	0.8501	0.8466	0.8431	0.8396	0.8361	0.8326	0.8290	0.8255	0.8220	0.8184	0.8149	0.8114	0.8078	0.8043	0.8007		
29.0	0.8510	0.8476	0.8441	0.8406	0.8371	0.8336	0.8301	0.8266	0.8231	0.8196	0.8160	0.8125	0.8090	0.8055	0.8019		

Table 6.2-7. Salinity correction factors for dissolved oxygen in water (based on specific conductance).—Continued

[Factors are dimensionless. Values based on published equations by Benson and Krause (1984). Temp. deg C, temperature in degrees Celsius]

Temp. (deg C)	Specific conductance, in microsiemens per centimeter at 25 degrees Celsius														
	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000	13000	14000
30.0	1.0000	0.9969	0.9939	0.9908	0.9877	0.9845	0.9814	0.9783	0.9751	0.9720	0.9688	0.9656	0.9624	0.9592	0.9560
31.0	1.0000	0.9970	0.9939	0.9908	0.9877	0.9846	0.9815	0.9784	0.9753	0.9721	0.9690	0.9658	0.9626	0.9595	0.9563
32.0	1.0000	0.9970	0.9939	0.9909	0.9878	0.9847	0.9817	0.9785	0.9754	0.9723	0.9692	0.9660	0.9629	0.9597	0.9565
33.0	1.0000	0.9970	0.9940	0.9909	0.9879	0.9848	0.9818	0.9787	0.9756	0.9725	0.9694	0.9662	0.9631	0.9600	0.9568
34.0	1.0000	0.9970	0.9940	0.9910	0.9880	0.9849	0.9819	0.9788	0.9757	0.9727	0.9696	0.9665	0.9633	0.9602	0.9571
35.0	1.0000	0.9970	0.9940	0.9911	0.9880	0.9850	0.9820	0.9790	0.9759	0.9728	0.9698	0.9667	0.9636	0.9605	0.9573

Temp. (deg C)	Specific conductance, in microsiemens per centimeter at 25 degrees Celsius														
	15000	16000	17000	18000	19000	20000	21000	22000	23000	24000	25000	26000	27000	28000	29000
30.0	0.9527	0.9495	0.9463	0.9430	0.9397	0.9364	0.9332	0.9299	0.9266	0.9232	0.9199	0.9166	0.9133	0.9099	0.9066
31.0	0.9530	0.9498	0.9466	0.9434	0.9401	0.9369	0.9336	0.9303	0.9270	0.9237	0.9204	0.9171	0.9138	0.9105	0.9071
32.0	0.9533	0.9501	0.9469	0.9437	0.9405	0.9373	0.9340	0.9308	0.9275	0.9242	0.9209	0.9176	0.9143	0.9110	0.9077
33.0	0.9536	0.9505	0.9473	0.9441	0.9409	0.9376	0.9344	0.9312	0.9279	0.9247	0.9214	0.9181	0.9149	0.9116	0.9083
34.0	0.9539	0.9508	0.9476	0.9444	0.9412	0.9380	0.9348	0.9316	0.9284	0.9251	0.9219	0.9186	0.9154	0.9121	0.9088
35.0	0.9542	0.9511	0.9479	0.9448	0.9416	0.9384	0.9352	0.9320	0.9288	0.9256	0.9224	0.9191	0.9159	0.9126	0.9094

Temp. (deg C)	Specific conductance, in microsiemens per centimeter at 25 degrees Celsius														
	30000	31000	32000	33000	34000	35000	36000	37000	38000	39000	40000	41000	42000	43000	44000
30.0	0.9032	0.8998	0.8964	0.8931	0.8897	0.8863	0.8829	0.8795	0.8760	0.8726	0.8692	0.8658	0.8623	0.8589	0.8554
31.0	0.9038	0.9005	0.8971	0.8937	0.8904	0.8870	0.8836	0.8802	0.8768	0.8734	0.8700	0.8666	0.8632	0.8597	0.8563
32.0	0.9044	0.9011	0.8977	0.8944	0.8910	0.8877	0.8843	0.8809	0.8776	0.8742	0.8708	0.8674	0.8640	0.8606	0.8572
33.0	0.9050	0.9017	0.8984	0.8950	0.8917	0.8884	0.8850	0.8817	0.8783	0.8749	0.8716	0.8682	0.8648	0.8614	0.8580
34.0	0.9056	0.9023	0.8990	0.8957	0.8923	0.8890	0.8857	0.8824	0.8790	0.8757	0.8723	0.8690	0.8656	0.8622	0.8588
35.0	0.9061	0.9028	0.8996	0.8963	0.8930	0.8897	0.8864	0.8830	0.8797	0.8764	0.8731	0.8697	0.8664	0.8630	0.8597

Table 6.2-7. Salinity correction factors for dissolved oxygen in water (based on specific conductance).—Continued
 [Factors are dimensionless. Values based on published equations by Benson and Krause (1984). Temp. deg C, temperature in degrees Celsius]

Temp. (deg C)	Specific conductance, in microsiemens per centimeter at 25 degrees Celsius														
	45000	46000	47000	48000	49000	50000	51000	52000	53000	54000	55000	56000	57000	58000	59000
30.0	0.8520	0.8485	0.8450	0.8416	0.8381	0.8346	0.8311	0.8276	0.8241	0.8207	0.8172	0.8137	0.8102	0.8066	0.8031
31.0	0.8529	0.8494	0.8460	0.8425	0.8391	0.8356	0.8321	0.8287	0.8252	0.8217	0.8182	0.8148	0.8113	0.8078	0.8043
32.0	0.8537	0.8503	0.8469	0.8435	0.8400	0.8366	0.8331	0.8297	0.8262	0.8228	0.8193	0.8159	0.8124	0.8089	0.8054
33.0	0.8546	0.8512	0.8478	0.8444	0.8410	0.8375	0.8341	0.8307	0.8272	0.8238	0.8204	0.8169	0.8135	0.8100	0.8066
34.0	0.8555	0.8521	0.8487	0.8453	0.8419	0.8385	0.8351	0.8317	0.8282	0.8248	0.8214	0.8180	0.8145	0.8111	0.8077
35.0	0.8563	0.8529	0.8496	0.8462	0.8428	0.8394	0.8360	0.8326	0.8292	0.8258	0.8224	0.8190	0.8156	0.8122	0.8087

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