Lakes and Reservoirs: Guidelines for Study Design and Sampling

Chapter 10 of
Section A, National Field Manual for the Collection of Water-Quality Data
Book 9, Handbooks for Water-Resources Investigations

Techniques and Methods 9–A10
Supersedes USGS Techniques of Water-Resources Investigations
Book 9, Chapter A10, version 1.0

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph of the *Annie*, "First Boat Ever Launched on Yellowstone Lake." Reported to first be used on June 29, 1871. James Stevenson and H.W. Elliott, 5th annual report, page 96. William Henry Jackson, photographer (Yellowstone National Park). U.S. Geological and Geographical Survey of the Territories, Yellowstone Series, 1871, Vol. III (Hayden Survey). Image file: *http://library.usgs.gov/photo/#/item/51dca2c7e4b097e4d383aebd*.

Lakes and Reservoirs: Guidelines for Study Design and Sampling

By U.S. Geological Survey

Chapter 10 of
Section A, National Field Manual for the Collection of Water-Quality Data
Book 9, Handbooks for Water-Resources Investigations

Techniques and Methods 9–A10
Supersedes USGS Techniques of Water-Resources Investigations,
Book 9, Chapter A10, version 1.0

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia:
First release: 2015, online as Techniques of Water-Resources Investigations, book 9, chapter A10, version 1.0
Revised: May 2018, online as Techniques and Methods, book 9, chapter A10

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov.

Suggested citation:
U.S. Geological Survey, 2018, Lakes and reservoirs—Guidelines for study design and sampling: U.S. Geological Survey Techniques and Methods, book 9, chap. A10, 48 p., https://doi.org/10.3133/tm9a10. [Supersedes USGS Techniques of Water-Resources Investigations, book 9, chap. A10, version 1.0]

ISSN 2328-7055 (online)

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
nanometer (nm)	3.937×10^{-8}	inch (in.)
micrometer (µm)	3.937×10^{-5}	inch (in.)
micrometer (µm)	3.281×10^{-6}	foot (ft)
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
	Volume	
milliliter (mL)	0.0338	ounce, fluid (fl. oz)
liter (L)	0.2642	gallon (gal)
	Mass	
microgram (µg)	3.527×10^{-8}	ounce, avoirdupois (oz)
milligram (mg)	3.527×10^{-5}	ounce, avoirdupois (oz)
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature: Water and air temperatures are reported in degrees Celsius (°C).

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8.$$

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8x°C) + 32.$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988.

Specific electrical conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or in micrograms per liter (µg/L).

Selected Symbols

>	greater than
<	less than
µm	micrometer
µg/L	microgram per liter (equivalent to part per billion)
mg/L	milligram per liter (equivalent to part per million)
mm^3/L	cubic millimeter per liter
$µm^3$/L	cubic micrometer per liter

Chapter A10. Lakes and Reservoirs: Guidelines for Study Design and Sampling

By U.S. Geological Survey

Abstract

The "National Field Manual for the Collection of Water-Quality Data" (NFM) is an online report with separately published chapters that provides the protocols and guidelines by which U.S. Geological Survey personnel obtain the data used to assess the quality of the Nation's surface-water and groundwater resources. Chapter A10 reviews limnological principles, describes the characteristics that distinguish lakes from reservoirs, and provides guidance for developing temporal and spatial sampling strategies and data-collection approaches to be used in lake and reservoir environmental investigations.

Within this chapter are references to other chapters of the NFM that provide more detailed guidelines related to specific topics and more detailed protocols for the quality assurance and assessment of the lake and reservoir data. Protocols and procedures to address and document the quality of lake and reservoir investigations are adapted from, or referenced to, the protocols and standard operating procedures contained in related chapters of this NFM.

Before 2017, the U.S. Geological Survey (USGS) "National Field Manual for the Collection of Water-Quality Data" (NFM) chapters were released in the USGS Techniques of Water-Resources Investigations series. Effective in 2018, new and revised NFM chapters are being released in the USGS Techniques and Methods series; this series change does not affect the content and format of the NFM. More information is in the general introduction to the NFM (USGS Techniques and Methods, book 9, chapter A0, 2018) at https://doi.org/10.3133/tm9A0. The authoritative current versions of NFM chapters are available in the USGS Publications Warehouse at https://pubs.er.usgs.gov. Comments, questions, and suggestions related to the NFM can be addressed to nfm-owq@usgs.gov.

1.0 Introduction

Lakes and reservoirs constitute the largest source of the usable freshwater on Earth. With approximately 97 percent of the water on Earth being saline and stored primarily in the oceans, only 3 percent of Earth's remaining water resource exists as freshwater (http://water.usgs.gov/edu/watercyclefreshstorage.html; accessed 02/03/2015). An estimated 68.7 percent of that freshwater is contained in glaciers and ice caps and thus is not readily or practicably available for human use, 30.1 percent resides in groundwater, and about 0.3 percent is surface water. Of that 0.3 percent surface water, about 2 percent is found in rivers, 11 percent in swamps, and about 87 percent is contained in lakes and reservoirs.

Limnology is the study of all inland waters, including streams and rivers. In this chapter, however, the term **limnology**[1] refers only to the study of lakes and reservoirs. Limnological studies are typically conducted by the U.S. Geological Survey (USGS) to gain an understanding of ecosystem dynamics in order to develop effective strategies to monitor, assess, and prevent deterioration of lake and reservoir structure and function. Commonly collected data for limnological studies include field characteristics and other observational data, general conditions of the water body, water chemistry, aquatic biology, and living and nonliving bottom material (tables 10–1 and 10–2). The specific set of data collected depends on objectives of the study.

Before 2017, the U.S. Geological Survey (USGS) "National Field Manual for the Collection of Water-Quality Data" (NFM) chapters were released in the USGS Techniques of Water-Resources Investigations series. Effective in 2018, new and revised NFM chapters are being released in the USGS Techniques and Methods series; this series change does not affect the content and format of the NFM. More information is in the general introduction to the NFM (USGS Techniques and Methods, book 9, chapter A0, 2018) at https://doi.org/10.3133/tm9A0. The authoritative current versions of NFM chapters are available in the USGS Publications Warehouse at https://pubs.er.usgs.gov. Comments, questions, and suggestions related to the NFM can be addressed to nfm-owq@usgs.gov.

[1]Terms in bold are among the terms defined in the glossary at the end of this chapter.

Table 10–1. Primary references for commonly collected data for limnological studies.

[NFM, "National Field Manual for the Collection of Water-Quality Data"; GPS, global positioning system; USGS, U.S. Geological Survey]

Data group	Description[1]	Primary references[2] consulted
Field characteristics and observational data.	General field observations, such as water color and clarity, current meteorological conditions, presence of visible algae, presence of surface accumulations or scums of cyanobacteria.	NFM 1. NFM 4. NFM 7.4. Wetzel and Likens, 2000. Wetzel, 2001.
	Quality-assurance procedures and policies GPS coordinates Photographs of current conditions Meteorological conditions several days before sampling. Occurrence of recent inflow events Water residence time Lake or reservoir pool elevation	
General conditions and properties of the water body.	Light attenuation Secchi disk Solar radiation	NFM 7.4. NFM 7.4.1.B.
	Standard field measurements, such as water temperature, specific conductance, pH, dissolved oxygen, and **turbidity**.	NFM 6. Wetzel and Likens, 2000. Wetzel, 2001. Wagner and others, 2006.
Water chemistry: Inorganic constituents and organic compounds.	Nutrients, such as phosphorus and nitrogen	NFM 4. NFM 5. Hem, 1989. Wetzel, 2001.
	Alkalinity and acid neutralizing capacity (ANC)	NFM 6.6.
	Suspended sediment (solids)	NFM 4. NFM 5.
	Major ions	NFM 2. NFM 4. NFM 5. Hem, 1989.
	Carbon	NFM 2. NFM 4. NFM 5. Hem, 1989.
	Trace elements	NFM 2. NFM 4. NFM 5. Hem, 1989.
	Trace organic compounds	NFM 2. NFM 4. NFM 5.
Aquatic biology, including **benthic fauna.**	Fecal indicator bacteria	NFM 7.1.
	Chlorophyll	NFM 7.4.
	Phytoplankton	NFM 7.4. NFM 7.5. Britton and Greeson, 1987. Wetzel and Likens, 2000. Wetzel, 2001. American Public Health Association, 2005.

Table 10–1. Primary references for commonly collected data for limnological studies.—Continued

[NFM, "National Field Manual for the Collection of Water-Quality Data"; GPS, global positioning system; USGS, U.S. Geological Survey]

Data group	Description[1]	Primary references[2] consulted
Aquatic biology, including **benthic fauna**.—Continued	Periphyton	NFM 7.4. Britton and Greeson, 1987. Wetzel and Likens, 2000. Wetzel, 2001. American Public Health Association, 2005.
	Zooplankton	Britton and Greeson, 1987. Wetzel and Likens, 2000. Wetzel, 2001. American Public Health Association, 2005.
	Fish	Britton and Greeson, 1987. Wetzel and Likens, 2000. Wetzel, 2001.
	Macrophytes	Britton and Greeson, 1987. Wetzel and Likens, 2000. Wetzel, 2001.
	Actinomycetes bacteria density	NFM 7.5.
	Cyanobacteria	NFM 7.5.
Nonliving material	Bottom-material sampling strategies and procedures	NFM 8. Britton and Greeson, 1987. Wetzel and Liken, 2000. Wetzel, 2001. American Public Health Association, 2005.

[1]Terms in bold are among the terms defined in the glossary at the end of this chapter.

[2]For description of and guidance for specific USGS protocols and methods for collecting selected types of data, refer to references, including NFM chapters (NFM 4) or chapter sections (NFM 7.4.1.B). The chapters are available from http://water.usgs.gov/owq/FieldManual/.

1.1 Purpose and Scope

This chapter of the "National Field Manual for the Collection of Water-Quality Data" (NFM) is designed to provide the general information, considerations, preparations, and USGS-specific sampling guidelines needed to design and implement studies in which lake or reservoir environmental quality can be reliably monitored and evaluated. To this end, this chapter includes a review of the basic principles of limnological (lake and reservoir) science, provides an explanation of the distinguishing characteristics of lakes and reservoirs, and places special emphasis on the appropriate temporal and spatial sampling strategies and approaches needed to account for differing data requirements (depending on characteristics of the water body under investigation). The discussion of study design in section 4.0 refers to standard USGS methods and quality-assurance protocols in the sampling and collection of water, bottom material, and biological components that are more fully described in other sections of the NFM (table 10–1).

Topics related to stream and groundwater systems and their interactions with lakes or reservoirs are not addressed in this report. Also beyond the scope of this chapter are guidelines specific to sampling saline lakes or seas, the Great Lakes, ponds and stormwater detention or retention basins, and subsurface water bodies (such as those found in karst environments).

2.0 Basic Limnology

Limnology is the study of the physical, chemical, and biological interactions within inland waters. Limnological studies include the movements and biogeochemical changes that occur as water moves through drainage basins and within lakes and reservoirs. Relatively static lake and reservoir waters (collectively referred to as **lentic** waters) are functionally linked with the surrounding landscape, including the flowing waters in streams (collectively referred to as **lotic** waters) (Wetzel, 2001). The term "lakes" commonly is used to encompass both natural water bodies and manmade impoundments (reservoirs) of inland waters that are relatively stable (standing or still waters), open to the atmosphere, and nonflowing or low-flowing (relative to free-flowing rivers and streams). In the context of conceptualizing and designing studies for

Table 10–2. Comparative characteristics and properties between reservoirs and natural lake ecosystems (modified from Wetzel, 1990).

Properties[1]	Natural lakes	Reservoirs
Geographical distribution	In the United States, predominantly in the northern glaciated regions.	In the United States, predominantly in the southern nonglaciated regions.
Climate	Precipitation commonly close to or exceeds evaporative losses.	Precipitation often low and evaporation high or greater than precipitation.
Drainage basins	Generally circular, lake basin usually central; usually small in comparison to lake area (around 10:1).	Usually narrow, elongated lake basin in base or drainage basin; area large in comparison to lake area (around 100:1 to 300:1).
Shoreline development	Relatively low; stable	High, astatic
Water level fluctuations	Small, stable	Large, irregular
Thermal stratification	Natural regime; often dimictic or monomictic	Variable, irregular; often too shallow to stratify in riverine and **transitional zones**; often can temporarily stratify in lacustrine zones.
Inflow	Runoff to lake via small tributaries (low stream orders) and diffuse sources; penetration into stratified waters small and dispersive.	Most runoff to lake via river tributaries (high stream orders); penetration into stratified strata complex (over-, inter-, underflows); often flow is directed along an old riverbed valley.
Outflow (withdrawal)	Relatively stable; surface water	Highly irregular with water use; withdrawal from surface layers or from hypolimnion.
Flushing rates	Long, relatively constant (one to many years)	Short, variable (days to several weeks); increase with surface withdrawal, disruption of stratification with hypolimnetic withdrawal.
Sediment loading	Low, limited dispersal; relatively constant rates seasonally.	High with large drainage basin area; flood plains large; deltas large, channelized, gradation rapid.
Deposition of sediments	Low, limited dispersal; relatively constant rates seasonally.	High in riverine zone, decreasing exponentially down reservoir; greatest in old river valley; highly variable rates seasonally.
Suspended sediment in water	Low to very low; turbidity low	High, variable; high percentage clay and silt particles; turbidity high.
Allochthonous particulate organic matter (POM).	Low to very low	Moderate, especially fine POM during spates and inundation of flood plains.
Water temperature	Generally lower (because lakes are concentrated in more northern climate regions).	Somewhat higher (because reservoirs are concentrated in more southern climate regions).
Dissolved oxygen	Somewhat higher solubilities (lower temperatures); small horizontal variability; metalimnetic oxygen maxima more common than minima.	Somewhat lower solubilities (higher temperatures); greater horizontal variability with inflow, withdrawal, and **particulate organic matter** loading patterns; metalimnetic oxygen minima more common than maxima.

Table 10–2. Comparative characteristics and properties between reservoirs and natural lake ecosystems (modified from Wetzel, 1990).—Continued

Properties[1]	Natural lakes	Reservoirs
Light extinction	Vertical light gradients predominate over the scale of meters; variable but relatively low extinction from dissolved organic compounds and biogenic particulate matter.	Horizontal gradients predominate over the scale of kilometers; light extinction irregular and often very high, particularly in riverine and transitional zones from abiogenic particulate matter; euphotic zone commonly increases in lacustrine zones.
External nutrient loadings	Variable but relatively predictable; loadings often moderated by biogeochemical influences of wetland/**littoral** interface zones.	Generally higher than in natural lakes (larger drainage basin, more human activity, greater water-level fluctuations); variable, often unpredictable.
Nutrient dynamics	Vertical gradients dominate; often low internal loading, particularly in lakes without severe culturally induced eutrophication.	Horizontal gradients predominate; dependent upon sedimentation rates, **residence times**, and flow regimes; concentrations in water decrease with distance from headwaters; irregular internal loading.
Dissolved organic matter (DOM).	Allochthonous and littoral/wetland sources predominate; relatively constant, often high; refractory DOM predominates.	Allochthonous and benthic sources predominate; irregular, often high; refractory DOM predominates.
Littoral zone/wetland	Dominates primary production in most lakes; important to regulation of nutrient and dissolved particulate organic matter loadings.	Irregular and limited by severe water-level fluctuations.
Phytoplankton	Vertical and seasonal gradients predominate; small horizontal gradients; light and inorganic nutrient limitations predominate.	Marked horizontal gradients; volumetric primary productivity (or P_{max}) decreases from headwaters to dam; areal primary productivity relatively constant horizontally; light and inorganic nutrient limitations predominate.
Bacterial heterotrophy	Benthic and littoral/wetland bacterial hetero-trophy predominates in most lakes.	**Pelagic**, particle-associated, and benthic bacterial heterotrophy predominates in riverine zones.
Zooplankton	Vertical and seasonal gradients predominate; horizontal patchiness moderate; phytoplankton is a predominate food source.	Maximal development common in transition zone; horizontal patchiness high; particulate **detritus** (including adsorbed DOM) variably augments phytoplankton as food source.
Benthic fauna	Moderate to high diversity; productivity moderate to high.	Low diversity with minimal and irregular littoral zone; productivity low to moderate; initially high with inundated terrestrial vegetation.
Fish	Warm- and coldwater species composition; spawning success good, egg mortality lower, larval success good; moderate productivity.	Predominantly warmwater species composition; differences often related to initial stocking; spawning success variable (low with low water levels), egg mortality increases with siltation, larval success reduced with less **refugia**; productivity initially (5 to 20 years) high, then decreasing.

Table 10–2. Comparative characteristics and properties between reservoirs and natural lake ecosystems (modified from Wetzel, 1990).—Continued

Properties[1]	Natural lakes	Reservoirs
Biotic community relationships.	Diversity high; niche specialization moderately narrow; growth selection variable, relatively homeostatic; immigration-extinction processes slow; production low to moderate, relatively constant.	Diversity low; niche specialization broad; growth selection rapid; immigration extinction processes rapid; net production high soon after inundation, then decreasing.
Ecosystem succession rates	Similar to reservoirs but greatly protracted	Similar to lakes but greatly accelerated; greatly stressed by human manipulations of basin and drainage basin.

[1]Terms in bold are among the terms defined in the glossary at the end of this chapter.

environmental assessments, however, reservoirs are distinguished from lakes by differences in structural, as well as functional, characteristics. To serve the purpose of this guidance, therefore, the terms "**lake**" and "**reservoir**" are defined as shown below.

Some natural lakes have been engineered with elevated modified spillways to increase or decrease pool elevation and storage; in this respect, they function as a reservoir but have many hydrologic, geologic, and physical characteristics/features in common with lakes. A continuum exists from lakes to reservoirs, from the basic seepage lake (no inlets or outlets), to a natural drainage lake (with inlets and outlets), to a slightly impounded system, to a full-blown drinking water supply or flood-risk reduction reservoir. Typical characteristics and properties along this continuum between lake and reservoir are listed in table 10–2.

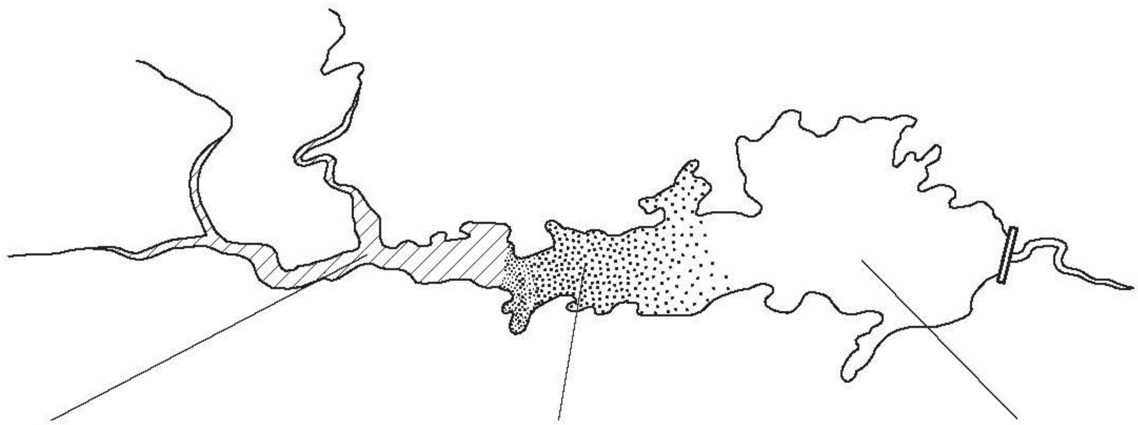
The residence time of water in reservoirs is usually considerably less than in lakes (Wetzel, 2001). Compared to natural lakes, reservoirs generally exhibit a larger degree of spatial heterogeneity with respect to water quality. This heterogeneity results from longitudinal gradients in basin morphology, flow velocity, flushing rate, and the loading rates of sediment, nutrients, and other constituents that usually enter at the upstream end of the reservoir. Typically, three zones occur in reservoirs along the downstream gradient, which differs from natural lakes (fig. 10–1; from Kimmel and others, 1990).

- An upstream **riverine zone** is characterized by higher flow velocity, shorter residence time, high concentrations of bioavailable nutrients and suspended solids (higher turbidity), and greater light extinction relative to the downstream portions of the reservoir.
    - Inorganic (silt and clay) turbidity often limits the depth to which light can penetrate, which is referred to as the photic zone.
    - Often the depth of the **mixed layer** exceeds the depth of the photic zone; consequently, primary production (algal photosynthesis) is often light-limited.
- A **transitional zone** is characterized by increasing phytoplankton productivity and biomass occurring in conjunction with increasing basin width, decreasing flow velocity, increasing residence time, increasing sedimentation of fine silt and clay particles near the surface (lower turbidity), and increasing light penetration. Because both light and nutrients are more available in the transition zone, this area can be the most productive and fertile region in a reservoir.
- A **lacustrine zone** occurs nearest the dam.
    - This zone usually has the lowest flow velocity, longer residence time, lower nutrient and suspended sediment concentrations, higher water transparency, and a deeper photic zone than the transition zone.
    - Primary production in the lacustrine zone is often nutrient-limited during most of the growing season and often supported by internal nutrient cycling rather than nutrients transported from upstream.

The riverine, transition, and lacustrine zones in a reservoir are not discrete, invariable entities, but result from the combined effects of a number of overlapping gradients. These zones are transient and usually dynamic and expand and contract in response to inflow volumes, density flow characteristics, and reservoir operating schedules. In general, the principles of limnology apply equally to lakes and reservoirs, although the physical and chemical structure and biological processing of reservoirs are temporally and spatially more variable than those of lakes. Reservoirs, therefore, can behave differently than lakes.

2.1 Physical and Chemical Limnology

Fluctuations in light penetration, temperature, pH, and concentrations of dissolved oxygen and nutrients, such as phosphorus and nitrogen, interact to exert important influences on the chemical composition and quality of lake water and the lacustrine ecosystem. An understanding of these properties



Riverine Zone	Transitional Zone	Lacustrine Zone
• Narrow, channelized basin	• Broader, deeper basin	• Broad, deep, lake-like basin
• Relatively high flow velocities	• Reduced flow velocities	• Little flow velocities
• High suspended solids, turbidity, low light availability, photic zone less than mixing zone	• Reduced suspended solids, less turbidity, light availability increased	• Relatively clear, light more available at depth, photic zone greater than mixing zone
• Nutrient supply by advection, relatively high nutrients	• Adjective nutrient supply reduced	• Nutrient supply by internal recycling, relatively low nutrients
• Light-limited primary production	• Primary production relatively high	• Nutrient-limited primary production
• Cell losses primarily by sedimentation	• Cell losses by sedimentation and grazing	• Cell losses primarily by grazing
• Organic matter supply primarily allochthonous	• Intermediate between allochthonous and **autochthonous** organic matter sources	• Organic matter supply primarily autochthonous
• More eutrophic	• Intermediate	• More oligotrophic

Figure 10–1. Diagram of an idealized reservoir showing longitudinal zonation and environmental factors controlling light and nutrient availability for phytoplankton production, algal productivity and standing crop, organic matter supply, and trophic status in an idealized reservoir (modified from Kimmel and others, 1990, figure 6.1).

and their short- and long-term effects on lake systems is briefly covered below. This understanding is necessary for developing a sound lake-monitoring strategy and for interpreting the data collected. Comprehensive explanations of water-quality data and lake processes are provided in Hem (1985) and Wetzel (2001). Techniques to measure physical and chemical properties are described in sections 6.0 and 7.0 below.

2.1.1 Light and Water Clarity

The attenuation of light through a water column provides an estimate of the extent of the photic zone; that is, the depth of water that is exposed to sufficient sunlight to allow photosynthesis to occur. The thickness of the photic zone is typically measured from the water surface down to where light intensity decreases to 1 percent of that at the surface. Measurement of light attenuation is a routine part of data collection for most USGS lake and reservoir investigations (NFM A7.4). Light attenuation is commonly determined by using one of two methods: (1) direct measurement of surface and underwater solar radiation, or (2) measuring water clarity, generally with a Secchi disk (section 6.0).

The amount of direct solar radiation that reaches the water surface varies with the angular height of the sun and, therefore, with time of day, season, and latitude (Wetzel, 2001). The quantity and quality of light also vary with the transparency of the atmosphere and the distance the light must travel through it; therefore, it varies with altitude and meteorological conditions (Wetzel and Likens, 2000). Much of the light is reflected from the water surface and is, therefore, unavailable to the aquatic system, although some can be backscattered to the water surface indirectly.

Water clarity or transparency is also used to estimate the light extinction coefficient, which is a measure of how quickly light is attenuated (Wetzel and Likens, 2000; NFM 7.4.1.B). Water clarity commonly is measured using a Secchi disk (section 6.0) and is referred to as the "Secchi depth." A simple rule of thumb is that the photic zone is approximately 2.5 times the Secchi depth.

Many factors influence water clarity, such as water color and the abundance of **algae**, zooplankton, and suspended sediment. Diminished clarity in lakes often occurs with an increase in phytoplankton abundance in summer. In reservoirs, inorganic turbidity composed of suspended solids, such as silts and clays, typically affect water clarity, especially at the upper end of the reservoir. At the lower end of the reservoir, however, phytoplankton generally exerts the most dominant influence on water clarity.

2.1.2 Temperature and Stratification

In freshwater lakes and reservoirs, water density is primarily a function of water temperature. This relation is highly nonlinear; water is most dense at approximately 4 degrees Celsius (~4 °C) and becomes less dense with either warming or cooling. In addition, small changes in water temperature further from 4 °C have greater changes in density than small changes near 4 °C (fig. 10–2). This nonlinear relation results in wind being inadequate to completely mix the water column as water temperatures increase or decrease from 4 °C, and, therefore, lakes often stratify or freeze. During the annual cycle, many lakes and reservoirs thermally stratify for extended periods and later destratify either once (during winter if there is no ice cover), referred to as **monomictic**, or twice (during the spring and fall and restratify under the ice), referred to as **dimictic**.

During winter months, water temperatures in lentic waters often decrease to near or below 4 °C. If ice cover does not occur, the density differences between different temperatures around 4 °C are small, allowing complete (wind) mixing of the water column. During warm, calm days, however, as air temperatures and daylight hours increase during spring, the water at the surface (in deeper lakes) heats more quickly than it can be mixed by the wind with the deep, cooler (denser) waters below. As water near the surface warms, the density difference between two successive warm water temperatures, for example 29 and 30 °C, is greater than cooler water, for example 4 and 5 °C (fig. 10–2). The density difference between 29 and 30 °C is 37.25 times greater than the density difference between 4 and 5 °C. The wind energy needed to mix 29 and 30 °C water would be proportionally greater than the energy needed to mix 4 and 5 °C water. Relative thermal resistance to mixing (Wetzel, 2001) is the phenomenon that allows a **thermocline** to set up and the water body to stratify. At warmer water temperatures, a difference of only a few degrees is sufficient to prevent complete mixing.

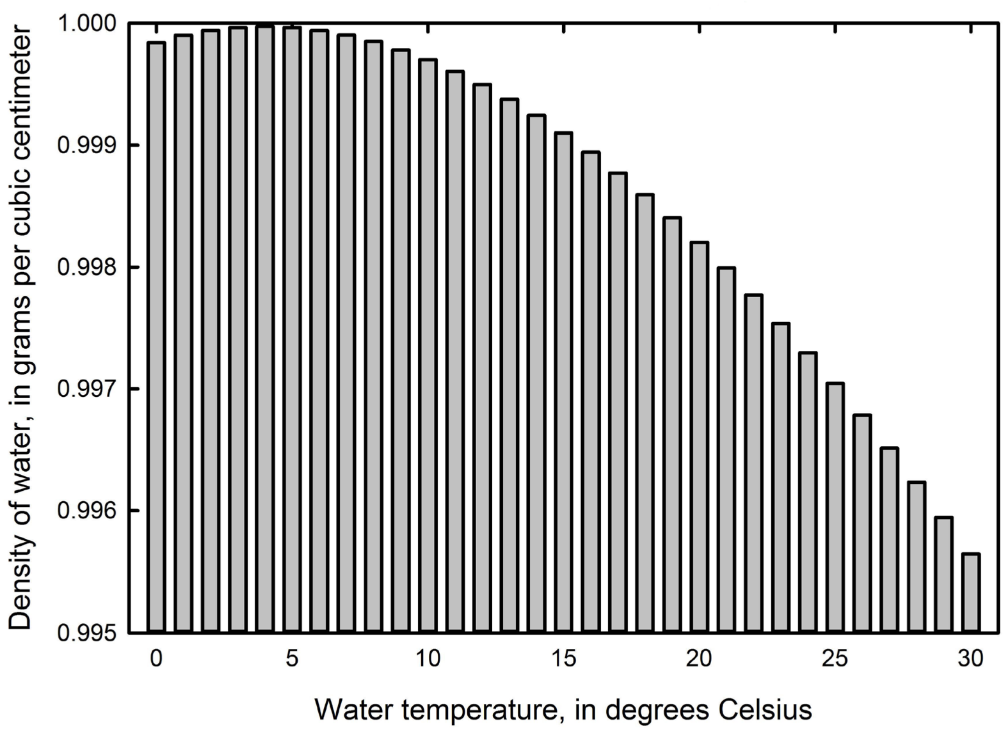


Figure 10–2. Graph showing density of water distribution by water temperature.

Over time, the water column in deeper lakes and reservoirs, typically greater than 6 meters (m), will be divided into three layers (fig. 10–3): the **epilimnion**—the warmer, more buoyant water near the lake surface; the **hypolimnion**—the cooler, more dense water near the lake bottom (having the temperatures close to the final spring temperature before stratification); and the **metalimnion** (middle layer)—where the thermocline (the plane of maximum rate of temperature change with depth) exists. The metalimnion ranges from warm to cold between the epilimnion and hypolimnion.

Annually, a lake or reservoir will cycle from being **isothermal** in the spring to being thermally stratified at variable thermocline depths in the summer (fig. 10–4). Shallow lakes, defined as having a maximum depth less than about 6 m (Osgood and others, 2002), typically experience only short periods of thermal stratification—when the cooler, more dense bottom water (hypolimnion) does not mix with the warmer, less dense surface water (epilimnion)—rather than a single extended period of stratification from early summer through early fall. This difference in the extent of mixing results in three types of lakes:

- Polymictic lakes: Lakes in which water frequently mixes to the bottom in the deepest areas throughout the open-water period.
- Dimictic lakes: Lakes in which water mixes to the bottom in the deepest areas only during the spring and again in the fall (autumn), referred to as spring and fall turnover. These lakes have extended periods of stratification in summer and are under ice in winter.

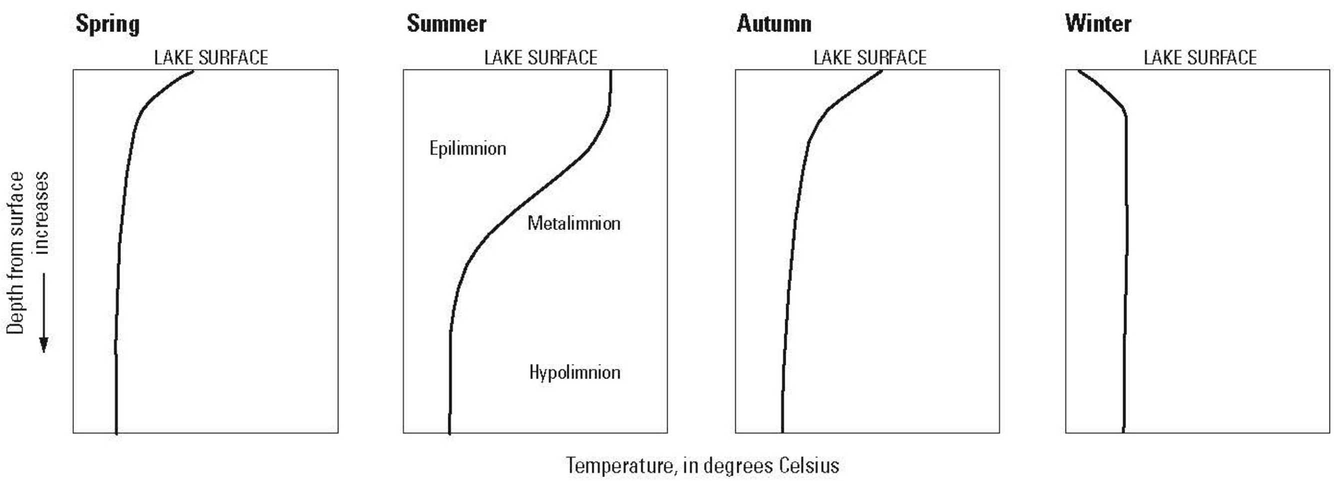


Figure 10–3. Water-temperature profiles for a classical deep, temperate-zone lake by seasons of the year (from Averett and Schroder, 1994, fig. 12).

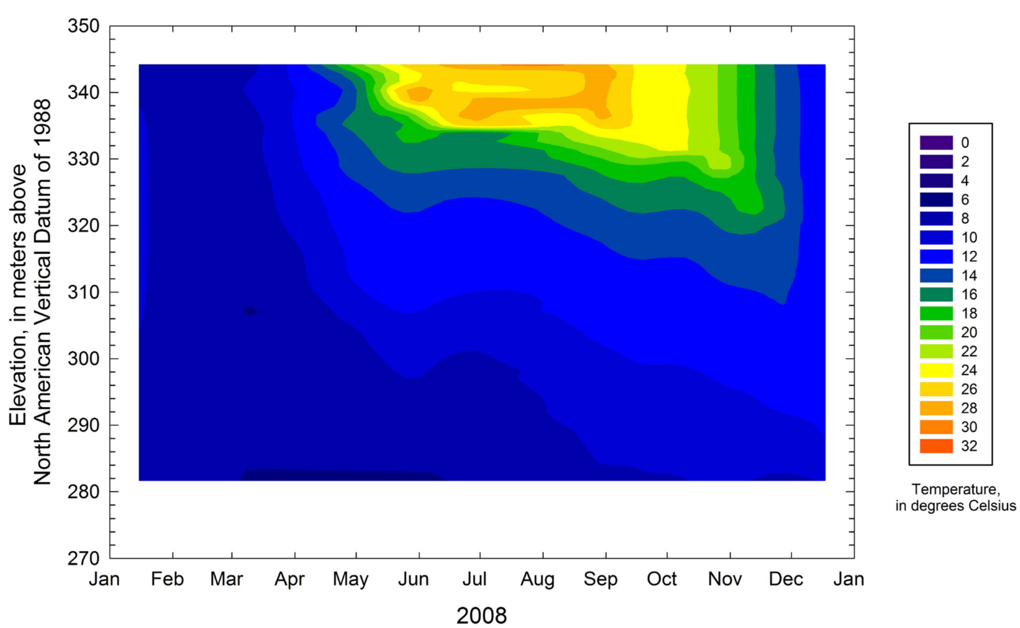


Figure 10–4. Depth and time plot of water-temperature contours from Beaver Lake, a deep reservoir in Arkansas (De Lanois and Green, 2011, appendix).

- Monomictic lakes: Lakes in which water mixes to the bottom in the deepest areas over one extended period throughout late fall and winter. These are deeper lakes that typically do not freeze.

2.1.3 pH

The pH is a measure of the acidity of water. The pH is defined as the negative logarithm of a hydrogen-ion (H+) concentration and varies, generally, over a 14-unit log scale (refer to NFM A6.4) with a pH value of 7 being defined as neutral. Values less than 7 indicate acidic conditions; the lower the value the stronger the acidity. Values greater than 7 indicate alkaline conditions. The pH of water is important because it affects the solubility of many chemical constituents, and because aquatic organisms have limited pH tolerances.

Lake pH is influenced in part by photosynthesis and respiration of planktonic algae and aquatic plants. Phytoplankton and aquatic plants produce oxygen and consume carbon dioxide through photosynthesis during the daytime, causing pH to increase. These plants consume oxygen and produce carbon dioxide through respiration, which is the dominant metabolic process during nighttime when photosynthesis is not occurring. Carbon dioxide combines with water molecules to form carbonic acid; therefore, nighttime respiration causes a decrease in pH. The result is a daily cycle in the pH of a lake. Because phytoplankton are generally more concentrated near the water's surface, changes in pH in the epilimnion, where photosynthesis usually occurs, are more extreme than in the hypolimnion. Productive lakes with high algae and fish populations generally have a pH between 6.7 and 8.2. Values of pH greater than about 8.5 have been shown to cause the release of phosphorus from lake sediments (James and Barko, 1991), often triggering additional phytoplankton growth.

2.1.4 Dissolved Oxygen

Dissolved-oxygen concentration is one of the most critical factors affecting lake and reservoir ecosystems because oxygen is an essential element for most aquatic life, and it is involved in many chemical reactions (see section 5.0 for information on the measurement of dissolved oxygen). Very low dissolved-oxygen concentrations can control some types of chemical reactions. The solubility of oxygen in water is inversely related to temperature. That is, oxygen solubility decreases as water temperature increases. This relation is important because at warmer temperatures the metabolic rate of an organism increases but less oxygen is available for respiration. The primary sources of dissolved oxygen are from the air and photosynthesis. The minimum dissolved-oxygen concentration specified in national water-quality criteria for early life stages of warm-water aquatic life is 5.0 milligrams per liter (mg/L) (U.S. Environmental Protection Agency, 1986).

In early summer, if thermal stratification develops, the metalimnion restricts the surface supply of dissolved oxygen to the hypolimnion (fig. 10–5). The hypolimnion can become isolated from the atmosphere. Thus, as summer progresses, the dissolved-oxygen concentration can decrease in response to decomposition of dead algae that settle from the epilimnion and in response to the biological and chemical oxygen demand of the sediments. The oxygen demand from these processes may completely deplete the oxygen in the water near the lake bottom, creating a condition of anoxia. Oxygen depletion then progresses upward but usually is confined to the hypolimnion (fig. 10–6).

Anoxia in the hypolimnion is common in stratified (nutrient rich, eutrophic; described below) lakes and reservoirs. During anoxic conditions, many aquatic organisms cannot survive, but many other species (primarily bacteria) can only function in such conditions. Therefore, a shift from oxic to

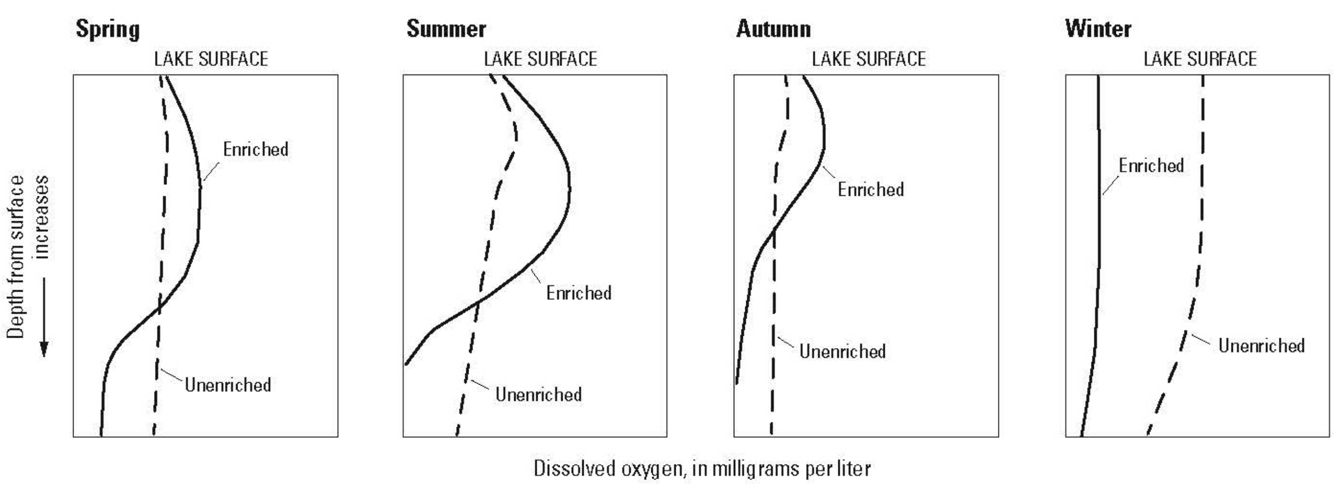


Figure 10–5. Dissolved-oxygen profiles for classical deep (stratified) temperate-zone lakes by seasons of the year and nutrient enrichment (from Averett and Schroder, 1994, fig. 13).

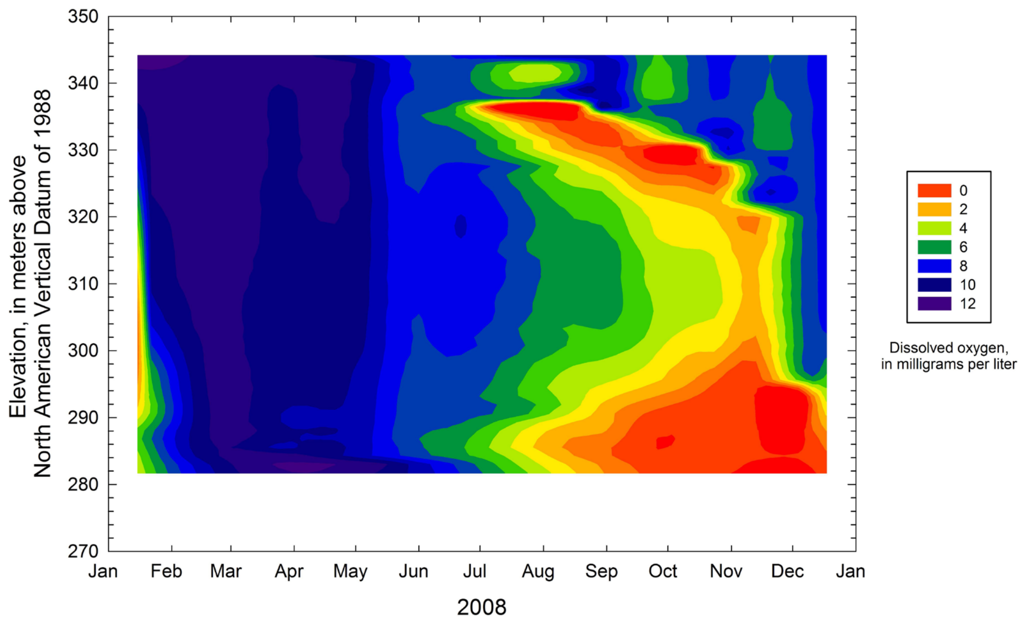


Figure 10–6. Depth and time plot of dissolved-oxygen contours (in milligrams per liter) from Beaver Lake, Arkansas (De Lanois and Green, 2011, appendix).

anoxic conditions produces a rapid and dramatic change in the biological community and chemical environment. Anoxia also can increase the release of phosphorus from the bottom sediments. This phosphorus then mixes throughout the water column during spring and fall turnover.

2.1.5 Phosphorus and Nitrogen

Phosphorus is one of the essential nutrients for plant growth. High phosphorus concentrations, however, can cause dense algal populations (**blooms**) and, therefore, can be a major cause of increased lake productivity, referred to as **eutrophication**. When phosphorus concentrations exceed about 0.025 mg/L at the time of spring overturn in lakes and reservoirs, these water bodies may occasionally experience excess or nuisance growth of algae or other aquatic plants (U.S. Environmental Protection Agency, 1986). In many regions of the country other nutrients, particularly nitrogen, can lead to eutrophication. Phosphorus is often the nutrient in shortest supply, therefore, limiting or controlling plant growth. In water, dissolved orthophosphate is that part of total phosphorus that is most readily available for use by algae.

Internal phosphorus recycling occurs in many lakes. Phosphorus used by algae, aquatic plants, fish, and zooplankton is stored within these organisms. As these organisms die and decompose, this phosphorus is returned to the lake water and sediment. Anoxia in the hypolimnion makes phosphorus more soluble, adding further to the release of phosphorus from the falling particulate matter and lake sediments. During spring and fall mixing/turnover events, the phosphorus that was released from decomposing matter and the bottom sediments into the hypolimnion during anoxia mixes throughout the lake. As mentioned earlier, pH values of 8.5 and greater can also cause the release of phosphorus from lake sediments even if anoxia is not present. These phenomena are part of the internal-recycling processes of lakes. The phosphorus is then available for algal growth.

Nitrogen, like phosphorus, is an essential nutrient for plant and algal growth; however, nitrogen is often in abundant supply from the atmosphere and other sources. If phosphorus is abundant relative to algal needs, nitrogen can become the limiting nutrient. In that case, algal blooms are more likely to be triggered by increases in nitrogen than by increases in phosphorus. Some blue-green algal species (**cyanobacteria**) can fix nitrogen from the atmosphere (Wetzel, 2001). Therefore, in situations where other types of algae are excluded because of a shortage of nitrogen, the nitrogen-fixing cyanobacteria algae have a competitive advantage and may be present in abundance.

Lakes and reservoirs with total nitrogen-to-phosphorus ratios larger than 15 to 1 near the surface may generally be considered phosphorus limited; a ratio from 10 to 1 to 15 to 1 indicates a transition situation, and a ratio smaller than 10 to 1 generally indicates nitrogen limitation. Total nitrogen is the sum of ammonia, organic nitrogen, and nitrate-plus-nitrite nitrogen. Near-surface concentrations are commonly used to compute the total nitrogen-to-phosphorus ratio because most algal species grow near the lake surface.

2.1.6 Chlorophyll *a*

Chlorophyll a is a photosynthetic pigment found in algae (Wetzel, 2001) and other green plants. The concentration of chlorophyll a, therefore, is commonly used as a measure of the density (biomass) of the algal population in a lake or reservoir. Chlorophyll a concentrations are generally highest during summer when algal populations are highest. Moderate populations of desirable algae are important in the food chain; however, excessive populations or algal blooms are undesirable. Algal blooms can cause taste and odor problems and limit light penetration needed to support the growth of submerged aquatic plants. Certain species of blue-green algae (cyanobacteria) can produce toxins.

2.2 Trophic Classification

One method of classifying the water quality of a lake is with trophic state index (TSI) values based on near-surface concentrations of total phosphorus, chlorophyll *a*, and Secchi depths, as developed by Carlson (1977) (table 10–3). The indices were developed to place these three characteristics on similar scales to allow comparison of different lakes. TSI values based on total phosphorus concentrations (TSI_P), chlorophyll *a* concentrations (TSI_C), and Secchi depths (TSI_{SD}) are computed for each open-water sampling by use of equations 1 through 3. The individual index values can be averaged monthly, and the monthly average values can then be used to compute summer (May through September) average TSI values:

$$TSI_P = 4.15 + 14.42 \text{ [ln total phosphorus (in micrograms per liter)]} \tag{1}$$

$$TSI_C = 30.6 + 9.81 \text{ [ln chlorophyll a (in micrograms per liter)]} \tag{2}$$

$$TSI_{SD} = 60.0 - 14.41 \text{ [ln Secchi depth (in meters)]} \tag{3}$$

The TSI approach to lake classification developed by Carlson (1997) assigns numerical ranges to the three or four trophic conditions that are generally used to describe the wide range of lake and reservoir water-quality conditions. **Oligotrophic** lakes have TSI values less than 40; have a limited supply of nutrients; typically have low phosphorus concentrations, low algal populations, and high water clarity; and contain oxygen throughout the year in their deepest zones (Wisconsin Department of Natural Resources, 1992). **Mesotrophic** lakes have TSI values between 40 and 50, a moderate supply of nutrients, a tendency

Table 10–3. Trophic state index values (Chl, SD, TP), trophic state attributes, and possible changes to the water supply that might be expected in a temperate lake as the amount of algae changes along the trophic state gradient.

[TSI, trophic state index; Chl, chlorophyll; SD, Secchi depth; TP, total phosphorus; µg/L, microgram per liter; m, meter; <, less than; >, greater than; NA, not applicable. (See http://www.secchidipin.org, accessed February 3, 2015.)]

TSI	Chl (µg/L)	SD (m)	TP (µg/L)	Trophic state attributes[1]	Water supply
<30	<0.95	>8	<6	**Oligotrophy:** Clear water, oxygen throughout the year in the hypolimnion, often referred to as ultraoligotrophic.	Water may be suitable for an unfiltered water supply.
30–40	0.95–2.6	8–4	6–12	**Hypolimnia** of shallower lakes may become anoxic.	NA
40–50	2.6–7.3	4–2	12–24	**Mesotrophy:** Water moderately clear; increasing probability of hypolimnetic anoxia during summer.	Iron, manganese, taste, and odor problems worsen. Raw water turbidity requires filtration.
50–60	7.3–20	2–1	24–48	**Eutrophy:** Anoxic hypolimnia, macrophyte problems possible.	NA
60–70	20–56	0.5–1	48–96	Blue-green algae dominate, algal scums and macrophyte problems.	Episodes of severe taste and odor problems possible.
70–80	56–155	0.25–0.5	96–192	**Hypereutrophy** (light-limited productivity)**:** Dense algae and macrophytes.	NA
>80	>155	<0.25	192–384	Algal scums, few macrophytes	NA

[1]Terms in bold are among the terms defined in the glossary at the end of this chapter.

to produce moderate algal blooms and have moderate clarity, and occasionally have oxygen depletions in the deepest zones of the lake. **Eutrophic** lakes have TSI values greater than 50; a large supply of nutrients; severe water-quality problems, such as frequent seasonal algal blooms and poor clarity; and oxygen depletion being common throughout the deeper zones of the lake. Eutrophic lakes with TSI values greater than 60-70 are often further classified as **hypereutrophic** lakes, and they typically have even more severe water-quality problems, including frequent and extensive algal blooms.

The transition of lakes from being classified as oligotrophic to hypereutrophic is a natural process as lakes age as a result of the addition of nutrients and organic materials, including the loading of silt and organic matter from their watersheds. This process is referred to as eutrophication. Lakes and reservoirs enriched by human activities are said to be culturally eutrophic. Mesotrophy is a term often used to position a lake or reservoir in between the low, oligotrophic, and high eutrophic status.

2.3 Biological Limnology

Lakes and reservoirs have three distinct and interacting biological communities or zones: (1) littoral zone (shallow areas) and its sediments, (2) open-water pelagic zone—deep areas with sufficient light penetration to support photosynthesis (photic zone), and (3) **profundal zone**—deep areas below effective light penetration and its sediments (Cooke and others, 2005; fig. 10–7). Eutrophication and other ecological processes that occur in one zone directly or indirectly affect processes in other zones. For example, nutrients that cause algal blooms may come from lake sediments and decomposition of littoral zone plants, as well as from external loading (Cooke and others, 2005). When setting up a water-quality monitoring strategy, it may be necessary to collect data from all nutrient sources in each of the zones (fig. 10–7) in order to determine and understand the major processes that are occurring in the water body.

The bottom sediments of a lake or reservoir can be divided into littoral and profundal sediments (fig. 10–7). The littoral zone encompasses that shoreline region commonly influenced by the disturbances of breaking waves (Wetzel, 2001). Below the littoral zone is a transitional zone, the littoriprofundal zone, occupied by scattered photosynthetic algae and bacteria. The littoriprofundal zone is often adjacent to the metalimnion of stratified lakes and reservoirs. The remainder of the sediments, free of vegetation, is referred to as the profundal zone (Wetzel, 2001).

Macrophytes (emergent, floating, and submersed vascular plants) and their attached flora and fauna dominate the wetland-littoral zone (Cooke and others, 2005). In very productive systems, the macrophytes may often have large masses of filamentous algae attached to them as thick mats. Shallow, lighted sediments often have highly productive epilithic, epipelic, and epiphytic flora (algae growing on surfaces of rocks, sediments, and vascular plants) (Cooke and others, 2005). These plants are distinctly different from the microscopic, floating (planktonic) cells and colonies of algae.

2.3.1 Littoral Zone

The littoral zone often has high species diversity and is commonly the area of a water body where fish reproduction and development occur (Cooke and others, 2005). This area is also usually important waterfowl habitat. Plant biomass in the littoral zone typically replaces itself two or more times per summer in productive lakes and reservoirs, leading to inputs of nonliving dissolved and particulate organic matter termed “detritus” to the water column and sediments. Detritus, whether from the watershed or from in-lake productivity, is a stable source of energy and nutrients for lake and reservoir **autotrophic** and **heterotrophic** production.

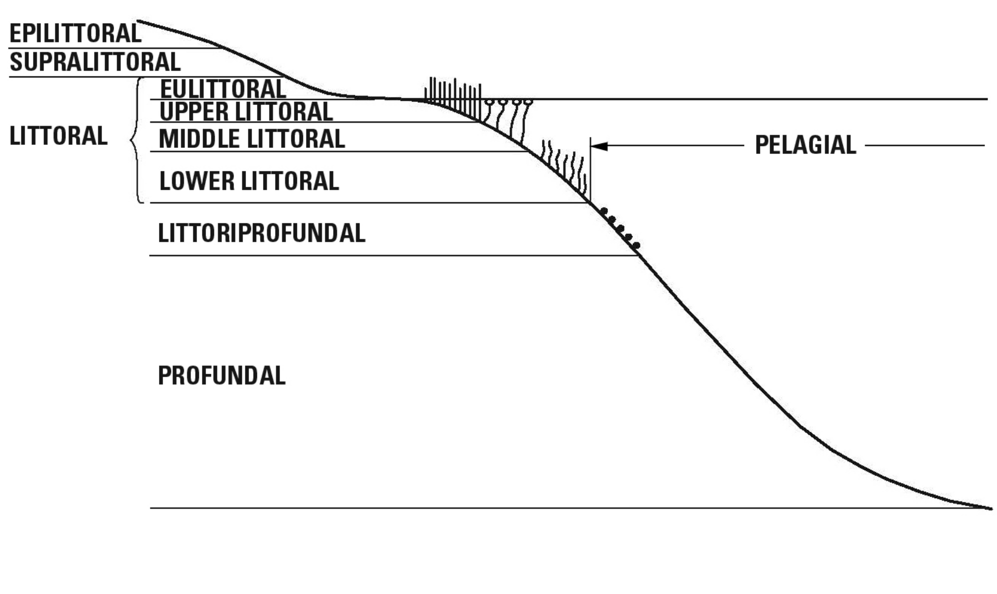


Figure 10–7. Diagram showing lateral zonation in lakes and reservoirs (from Wetzel [2001] modified from Hutchinson [1967]).

2.3.2 Pelagic Zone

Plankton (phyto- and zooplankton), and the fish grazing on them, dominate the pelagic zone (Cooke and others, 2005). The phytoplankton includes algae that can produce unsightly "blooms" and low water clarity. The pelagic community obtains energy from sunlight and from detritus transported to it from stream inflows and the littoral zone. The phytoplankton of most enriched lakes and reservoirs is often dominated by one or a few species of highly adapted algae and bacteria (for example, green algae and the nuisance blue-green algae (cyanobacteria)). Zooplankton include the primary grazers of detritus, bacteria, and algae, though their abundance may be regulated by complex interactions with the algal community and predators, such as fish and insects (Cooke and others, 2005).

2.3.3 Profundal Zone

The profundal community receives nutrients and energy from organic matter loaded to or produced in the lake or reservoir (Cooke and others, 2005). Inorganic forms of nutrients can settle from the water column to the profundal zone and its bed sediments. In enriched lakes and reservoirs, large areas of the produndal sediments are continuously anoxic during thermal stratification due to intense microbial respiration from the decay of deposited detritus. Anoxic conditions can cause high rates of nutrient release from the bed sediments to the water column—referred to as internal loading (Cooke and others, 2005). In lakes and reservoirs that are not impacted by nutrient enrichment, anoxic conditions in the profundal sediments have less of an impact. Internal nutrient loading in oligotrophic lakes and reservoirs is less than in enriched, eutrophic lakes and reservoirs.

3.0 Comparative Properties of Lakes and Reservoirs

When designing a lake or reservoir monitoring study, it is important to first gather as much historical, morphometric, hydrologic, and water-quality information as possible related to the water body and its watershed. Examination of the existing information is often useful for describing current conditions, determining the existence and extent of a problem, and identifying appropriate techniques and approaches for assessment. The types of study-design considerations and preliminary information-gathering processes should reflect the structural and functional differences that distinguish lakes from reservoirs.

- Common to all lake and reservoir studies is the need to assemble currently available data to help describe the following information:
- Morphometry – basin length, width, perimeter (shoreline length) and bottom shape
- Drainage area
- Hydrologic data network (for example, locations of stream gages)
- Land use and land cover
- Topography and land slope
- Soil type(s) and erosion potential
- Climactic data (for example, seasonal precipitation patterns; annual maximum, minimum, and average air temperature; and wind speed and direction)
- Annual runoff
- National Pollutant Discharge Elimination System-permitted discharges
- Hydraulic residence time and (or) flushing rate
- Morphometric characteristics that are useful for planning a study include:
    - Surface area
    - Volume
    - Mean and maximum depth
    - Maximum effective length and width (distance wind can blow across the water body without landscape obstructions)
    - **Shoreline development ratio** (ratio of shoreline length to that of a circle with the same surface area)

Areas of potential lake or reservoir sediment erosion or accumulation and other such hydromorphometric characteristics are important to identify in the context of study objectives. When developing the approach for either a lake or a reservoir study, it is important to identify areas of sediment deposition, as these are areas of potential chemical enrichment and influence. Distinct biological zones should be identified as well: the littoral zone is the most biologically productive area in the water body; the epilimnion and metalimnion are the most productive phytoplankton zones. Chemical qualities in these zones are influenced by biological activity. For example, in many eutrophic lakes and reservoirs, the hypolimnion is isolated from the atmosphere and reaeration. Bacterial respiration can remove all the dissolved oxygen over time and anaerobic conditions can develop, causing the dissolution of phosphorus, iron, manganese, and other elements. Also, decomposition of settling organic matter is reduced under these anaerobic conditions. Of course, other lake and reservoir conditions can be important depending on study objectives. What is important in one study may not be that important in another.

For reservoirs, the study approach should consider factors such as demands on the reservoir for flood-risk reduction, potable and industrial water supply, irrigation, hydroelectric power supply, navigation, fish and wildlife habitat, recreation, and aesthetics.

- These considerations can affect the proposed methods of data collection and interpretation that also may rely on determining an expanded set of physical characteristics, including:
  - Length and slope of the main channel
  - Sinuosity ratio
  - Normal pool elevation
  - Spillway elevation
  - Shoreline length
  - Ratio of drainage to surface area
  - Volume contained in the normal pool and flood pool
  - The length and mean, maximum, and relative depth to bottom (normal pool)
  - Outlet elevation(s)

Consequently, depending on whether a lake or reservoir is to be studied, differing considerations and guidelines should be considered when designing the approach and selecting the methods to be used for collecting samples and data for water, sediment, and biological analyses, such as spatial and temporal heterogeneities in the water body and long-term changes in the system.

Basin characteristics such as drainage area, annual runoff, topography and slope, land use/land cover, soil types, and erosion potential are all characteristics that influence discharge and constituent loading into lakes and reservoirs.

3.1 Spatial and Temporal Heterogeneity

Reservoirs typically have larger and more elongated drainage basins than natural lakes and are usually located at the mouth of a relatively large drainage basin (Thornton, 1990). Reservoirs may receive only a small proportion of their total inflow as direct runoff from the adjacent watershed, with the majority of water, nutrient, and sediment load entering from one or two major tributaries located a considerable distance from the dam. Most of the variability in physical conditions and water quality in natural lakes occurs in the vertical dimension, such as light, temperature (stratification), dissolved substances, productivity, and decomposition (Hutchinson, 1957; Wetzel, 1983; Kimmel and others, 1990). This vertical heterogeneity results from density gradients that are set up because of differences in water temperature and possibly salinity/specific electrical conductance. In winter, if a lake is not ice covered, the water column is typically mixed from top to bottom; the wind is usually capable of mixing the entire water column because of the low resistance to mixing resulting from the density similarities. If a lake freezes, the water column typically stratifies with slightly warmer, denser water near the bottom and cooler less dense water near the surface.

In reservoirs, similar vertical heterogeneities exist, but downstream (horizontal) gradients in water quality also occur, typically resulting in reservoirs being divided into the riverine, transition, and lacustrine zones described earlier in figure 10–1. The relative productivity of the mixed, near-surface water generally decreases down-reservoir as the advected nutrient supply is reduced with increasing distance from tributary inflows and as phytoplankton production becomes more dependent on internal nutrient regeneration (Kimmel and others, 1990; fig. 10–8). The **trophic state** (as reflected by clarity, phosphorus supply, algal content, phytoplankton productivity, dissolved oxygen depletion, or indices based on these physical and chemical properties) usually shifts from conditions that are more eutrophic to more oligotrophic along the riverine-transition-lacustrine gradient. Temporal variation in lakes and reservoirs also occurs due to seasonal climatic events and related tributary inflows (fig. 10–9).

Depending on the relative importance of inputs from the watershed, inflow characteristics, and flushing rates, the three zones may not always be distinguishable within a particular reservoir (fig. 10–10). For example, in a rapidly flushed, run-of-the-river reservoir receiving turbid inflow, conditions characteristic of the riverine zone may persist throughout most of the reservoir. On the other hand, in a long-residence-time storage reservoir, both the riverine and transition zones may be compressed into a small up-reservoir portion of the basin.

Inflow into lakes and reservoirs can vary dramatically. In natural lakes with small tributaries, inflow generally flows through diffuse sources, and flow into stratified waters is small and dispersive. In reservoirs and lakes with large tributary inputs, inflows into the stratified waters can occur as over-, inter-, or underflow (fig. 10–11), based on density differences between tributary and reservoir waters, which are primarily driven by differences in water temperatures. When flows are high, inflows may pass through the reservoir in a few days to weeks as a plunging inter- or underflow, carrying the suspended sediment and other constituents with it. If flows are very high, inflows may completely push the water in the reservoir downstream, resulting in the reservoir acting as a slow-moving river.

Other sources of horizontal spatial heterogeneity are often related to the dendritic nature (shoreline) of lake and reservoir basins and to tributaries of differing water quality. This spatial heterogeneity due to dendritic shorelines can result in embayments having limnological characteristics unique from adjacent main channel areas (Kimmel and others, 1990). These embayments may be quite important to game-fish and forage-fish populations as food sources and nursery areas. Differences in primary and secondary productivity between embayments and the main basin areas may be further enhanced if extensive areas of macrophytes occur in the embayments.

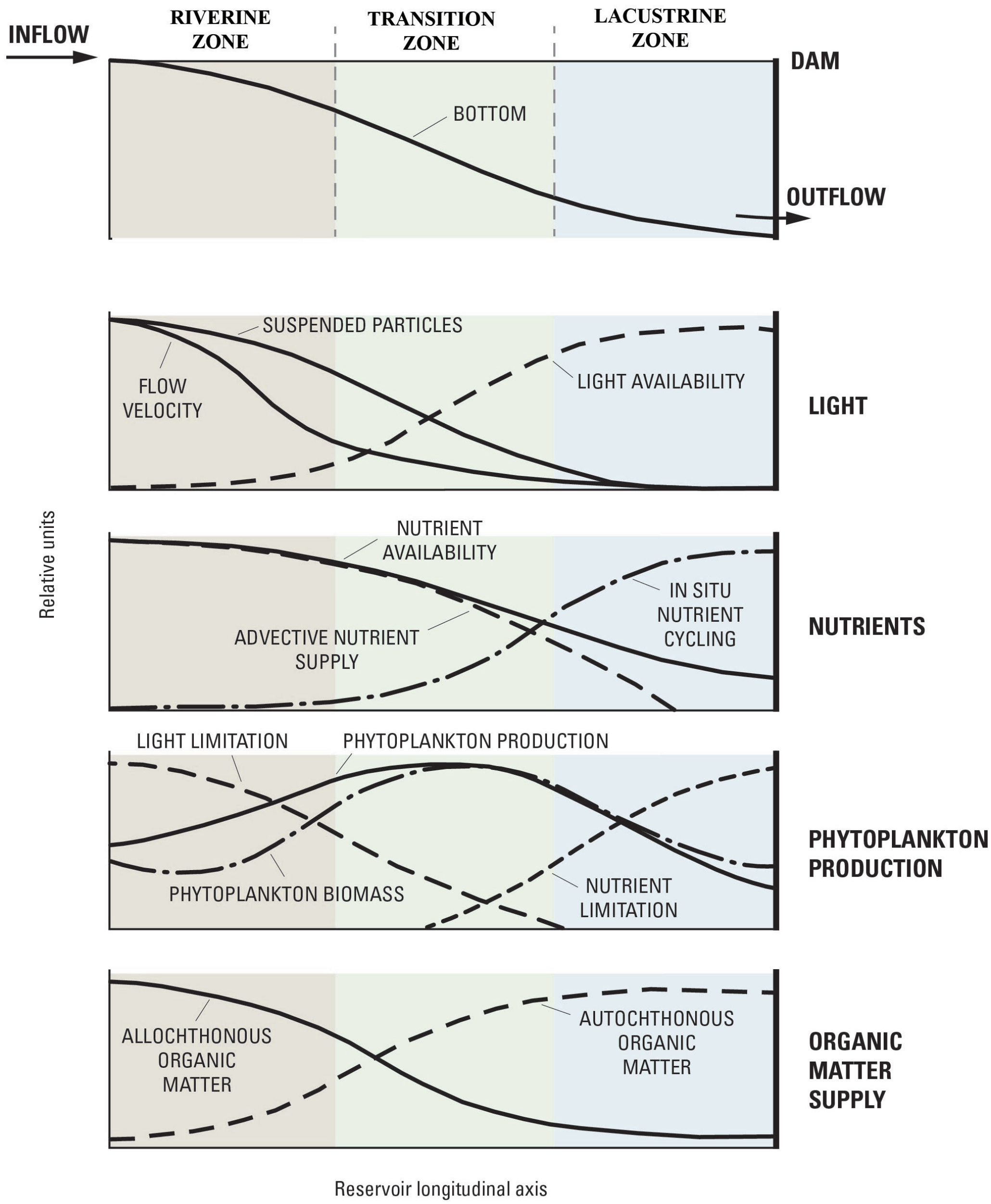


Figure 10–8. Cross-sectional view of gradients showing environmental factors that affect phytoplankton productivity and biomass, and the relative importance of allochthonous organic matter along the longitudinal axis of an idealized reservoir (from Kimmel and others, 1990, fig. 6.2).

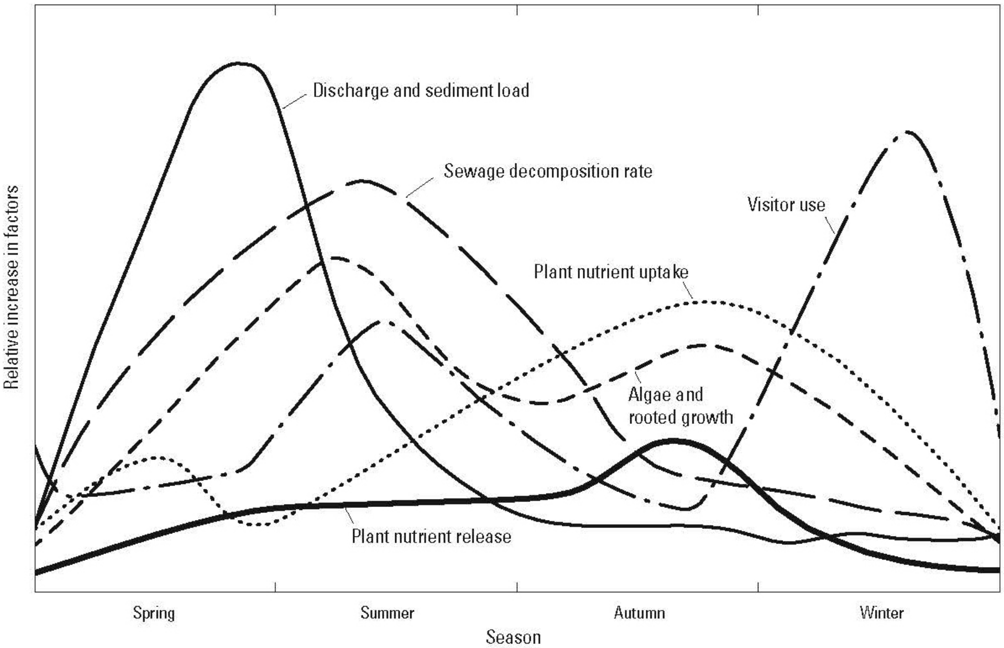


Figure 10–9. Graph showing an example of different combined impact factor curves by seasons of the year (from Averett and Schroder, 1994, fig. 11).

In summary, there are many functional similarities between natural lakes and reservoirs. Nevertheless, because of their differences in size, shape, drainage basin, quantity, and quality of inflow and outflow, the physical and chemical structure and biological processing in reservoirs are generally more variable in both space and time than they are in natural lakes. This variability should be considered when designing a program to collect water, sediment, and biological samples. Lake and reservoir systems vary widely in their complexity and similarity to each other. Shallow reservoirs can often be considered a slow-moving river and have longitudinal, as well as lateral, gradients resulting from tributaries entering along the main downstream axis. Vertical gradients also can occur as a result of thermal stratification and density-driven inflows.

3.2 Reservoir Aging

Reservoirs naturally age (natural eutrophication) and the aging process can be accelerated depending on the level of human-derived development in the drainage basin (cultural eutrophication). It is important to know what position the reservoir being investigated is in within the aging process in order to better interpret the results of the study. Reservoirs typically experience a highly productive period, termed the "trophic upsurge," shortly after construction (Baranov, 1961; Kimmel and Groeger, 1986). This trophic upsurge is the result of a combination of several factors: (1) a large influx of organic detritus and inorganic nutrients from the recently inundated reservoir basin, (2) an abundance of high-quality habitat and food for benthic organisms, and (3) a rapidly expanding lacustrine environment (Baxter, 1977; Ploske, 1981; Benson, 1982). The trophic upsurge is followed by a trophic depression, which is, in fact, the initial approach of the reservoir ecosystem toward its natural equilibrium level (Kimmel and Groeger, 1986; fig. 10–12).

The magnitude and duration of each of these phases (fig. 10–12) is quite variable among reservoirs because of differing basin inundation rates, internal and external nutrient loading rates, flushing rates, the quantity and quality of new habitat, the fish assemblages present, and reservoir operations (Ploskey, 1981; Kimmel and Groeger, 1986). The brief initial periods of trophic upsurge and depression result from changes in internal nutrient loading (see 1 in fig. 10–12).

Following the trophic depression, the magnitude and variability in biological production within the maturing reservoir become dependent on external inputs of nutrients and organic matter from the watershed, as in natural lakes (Kimmel and Groeger, 1986). Because the drainage-basin area relative to surface area and volume is large, fluvial inputs are usually the most important sources of nutrients for most reservoir ecosystems (Gloss and others, 1980; Kimmel and Groeger, 1986; Kimmel and others, 1990). Nutrients in the tributaries result from a combination of nonpoint sources (runoff from many diffuse sources within the watershed) and point sources (municipality and commercial and industrial facilities). The amount of nutrients in runoff typically depends on land use within the watershed (Likens, 1972; Hutchinson, 1973). Undisturbed terrestrial ecosystems usually are characterized by runoff that is low in dissolved and particulate substances, while, pastures, croplands, and urban areas contribute much greater nutrient loads to aquatic systems (Likens, 1975). Therefore, land-use patterns in the watershed have long-term effects on reservoir productivity and water quality (Kimmel and Groeger, 1986).

If lakes or reservoirs are permitted to age without the water body or watershed being otherwise disturbed, one would expect (based on present understanding of the relations

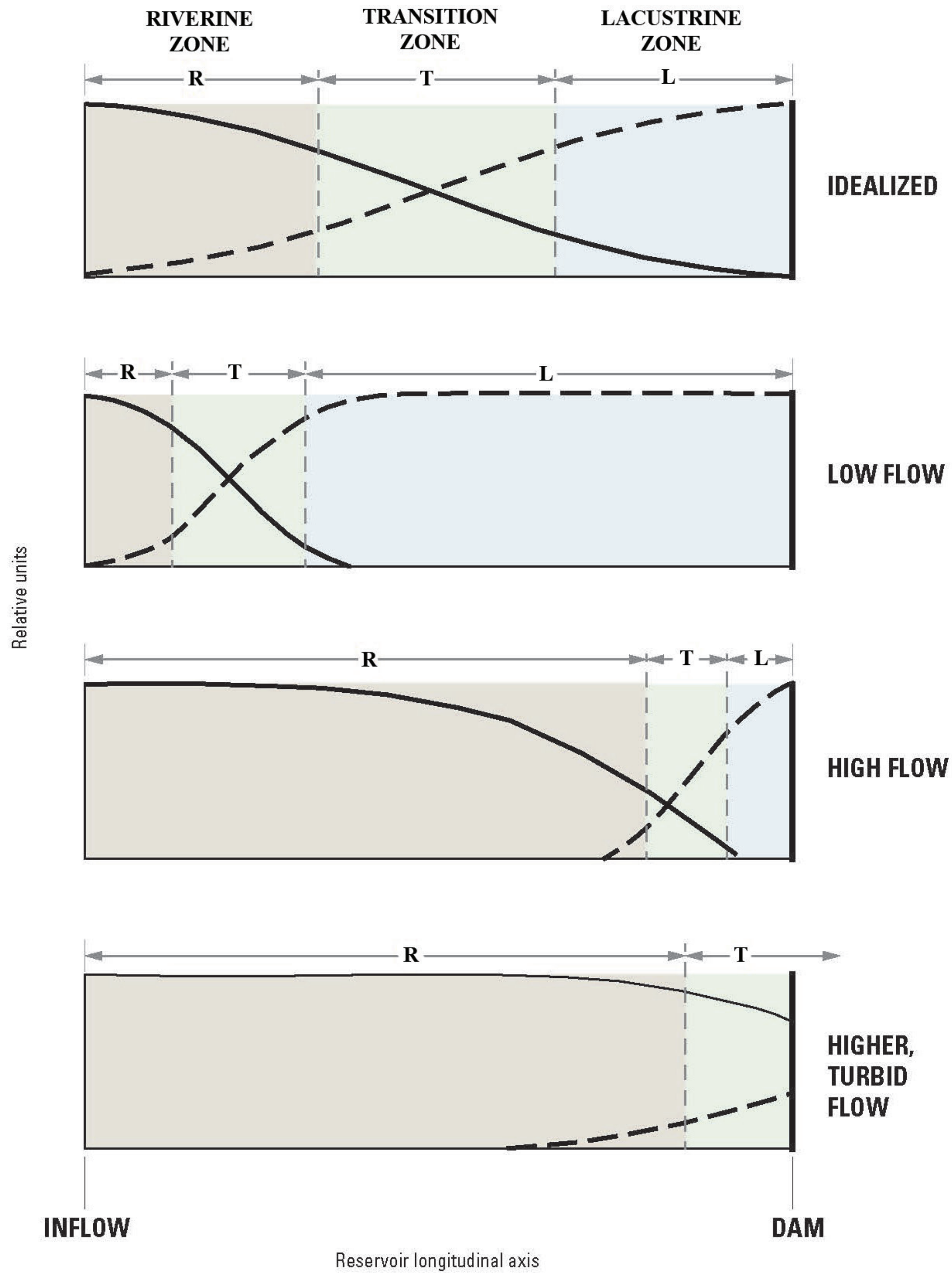


Figure 10–10. Diagram showing variation in the longitudinal zonation of environmental conditions within reservoirs. Solid and dashed lines represent the prevalence of riverine and lacustrine conditions, respectively. The longitudinal zonation is dynamic spatially and temporally and fluctuates in response to watershed runoff, inflow characteristics, density-flow behavior, and reservoir operations. R, riverine; T, transition; and L, lacustrine (from Kimmel and others, 1990, fig. 6.3.)

between basin morphology, nutrient loading rates, and lacustrine productivity) that biological productivity would either remain relatively constant over time or gradually increase (Kimmel and Groeger, 1986). Because the construction of reservoirs often promotes additional land-use changes and technological development within the watershed, water-quality and productivity changes attributable to “natural” reservoir aging are usually small compared to the effects of human-induced changes to watershed-reservoir interactions.

4.0 General Considerations for Study Design

Eight distinct steps are involved in the design, implementation, and analysis of any lake or reservoir sampling program: (1) problem identification (purpose of the study), (2) statement of scope and objective(s), (3) formulation of the approach (sampling strategy and design), (4) implementation of the sampling design (data and sample collection), and (5) data management, (6) analysis, (7) interpretation, and (8) dissemination of the results. Following this structure helps ensure

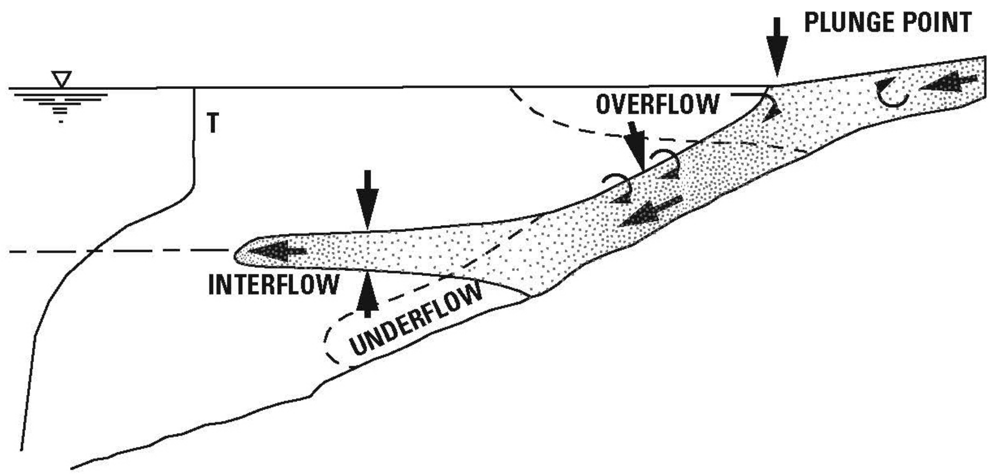


Figure 10–11. Diagram showing density inflows (over-, inter-, and underflow) into lakes and reservoirs. T, water temperature (from Ford, 1990, fig. 2.10).

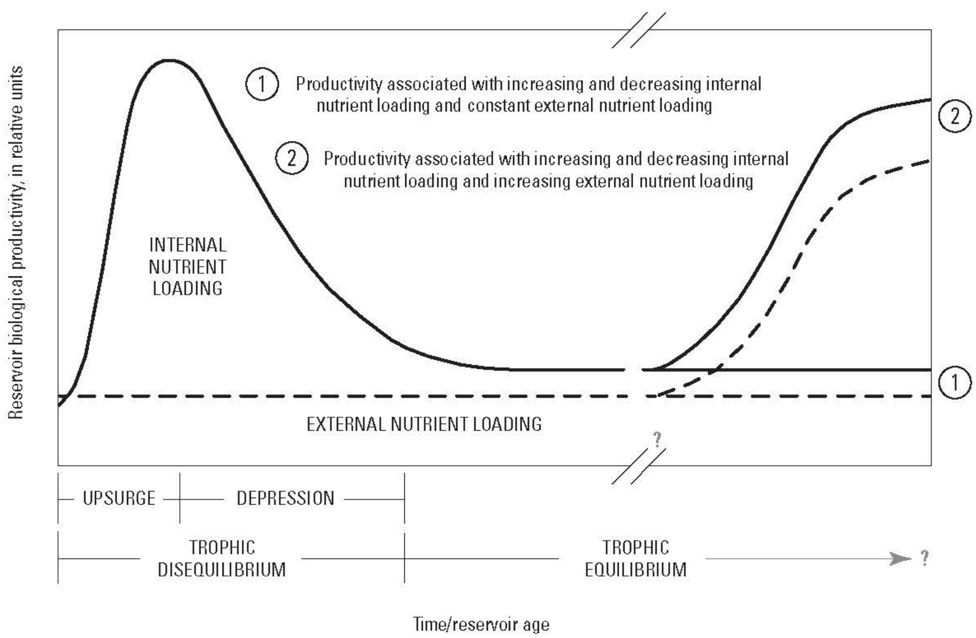


Figure 10–12. Conceptual model showing changes in factors influencing reservoir water quality and biological productivity as a reservoir matures and ages (modified from Kimmel and Groeger, 1986, fig. 2).

that data collection, results, and conclusions will be clearly presented.

Defining the study (project) objectives involves identifying the water-quality issues of concern and developing an approach to differentiate the potential factors or causes of the symptoms or concerns. The U.S. Army Corps of Engineers (1987) provides a useful table of water-quality concerns and possible contributing factors used in establishing objectives (table 10–4). Once the study objectives have been defined, the scientific approach and specific methods for the study can be identified and an implementation plan can be developed. As data and information are collected and water-quality processes and concerns become better understood, the water-quality objectives can be refined and the sampling program can be modified to better identify the areas of uncertainty and concern.

4.1 Common Study Types

The design of lake and reservoir water-quality studies varies depending on the purpose, scope, and objectives of each study. Most studies can be broadly categorized into one of three common types: reconnaissance, diagnostic (also commonly referred to as monitoring), or interpretive (Averett and Schroder, 1994).

- In many cases, little data and information are available for a given lake or reservoir and a **reconnaissance or pilot study** may be required to gather baseline information to determine the need for, or objectives and scope of, a future environmental investigation or assessment.

- A **diagnostic study** is appropriate when the water quality within a lake or reservoir has already reached

Table 10–4. Water-quality concerns and the possible contributing factors or causes in lakes and reservoirs (modified from U.S. Army Corps of Engineers, 1987).

[Fe, iron; Mn, manganese; NH_3, ammonia; H_2S, hydrogen sulfide; N_2, nitrogen gas; X, indicates water-quality concern can be present]

	Water-Quality Concerns																							
Possible Contributing Factors	Large flow variations	Scour	Erosion	Mudflats	Cold release temperatures	Unnatural release temperature	Low release dissolved oxygen	High release metals (Fe, Mn, and others)	High release NH_3 and H_2S	N_2 supersaturating	High turbidity	High suspended solids	Total dissolved solids/salinity	High nutrient concentrations	High pH	Low pH	Contaminants	Organics	Taste and odor compounds	Disinfection byproduct precursors	Algae blooms	Aquatic weeds	Pathogenic bacteria	Fish stress
Bottom withdrawal					X		X	X	X								X	X	X	X				X
Plunging spillway flow		X								X														X
Hydropower operation	X	X			X		X	X	X	X							X	X	X	X				X
Fluctuating water level			X	X							X	X												X
Stable water level																					X	X		
Large fetch/waves		X	X								X	X												
Limited mixing														X							X	X	X	
Extensive littoral sreas																					X	X		
Watershed land use (Agri/Urban)							X				X	X	X	X		X	X	X	X	X	X		X	X
High sediment inflow							X				X	X		X			X	X				X		X
High nutirent inflow							X							X							X			
High total organic carbon inflow							X										X	X	X	X				
Point source discharges											X	X		X	X	X	X	X	X	X	X		X	X
Stratification					X	X	X																	
Ice cover							X																	
High evaporation													X	X										
Sediment oxygen demand							X																	X
Organic decomposition							X	X	X					X			X	X	X	X	X			
Hypolimnetic anoxia							X	X	X					X			X	X	X	X				X
Reduced chemical species								X	X								X	X	X	X				X
Internal nutrient loading									X					X							X			
High algal production							X				X				X			X	X	X	X			
High macrophyte production							X							X	X			X						

the problem state and specific data and analyses are needed to describe or explain its condition. If regulatory compliance information is needed, a diagnostic study can be designed to gather data and information that specifically relate to the regulated constituents.

- An **interpretive study** typically has an expanded scope that can include, for example, identifying and developing an understanding of biogeochemical processes or causes of a specified problem, determining trends in the water-quality data collected or the problem that was identified, and performing simulations to help diagnose and forecast future water-quality conditions based on various potential solutions to the problem.

4.1.1 Reconnaissance Studies

Reconnaissance studies are common for a lake or reservoir for which either very little to no relevant data or information have been collected, or for which data are needed to establish the boundaries and scope of a more in-depth investigation. A common purpose for reconnaissance studies is to gather baseline information that can be used to determine current water-quality conditions (such as the trophic status), or provide water-resource managers the information needed for developing resource-management strategies.

Reconnaissance studies often are limited in resources and time, which constrains the objectives, scope, and approach of the investigation to target only the immediate questions of concern so as to provide a foundation or rationale for future investigations. The information gathered should be sufficient to fill in where historical data or other data essential to addressing the purpose of the investigation are absent (table 10–5). The data collected should provide, depending on the purpose, scope, and objectives, a basis on which to describe the physical, chemical, and biological conditions and variability of the water body. Care should be taken to determine what specifically needs to be sampled (water, bed material, and biological components), the onsite data to be collected, the number and location of possible sampling sites, and the constituents for which samples will be analyzed. Multiparameter instruments can be used to determine vertical and horizontal physical and limited chemical variations among different areas in the lake or reservoir (table 10–5). In addition to the environmental properties that are determined routinely, these instruments can be equipped to measure such properties as pigment fluorescence and photosynthetic active radiation.

- Depending on the size of the lake or reservoir, longitudinal and cross-sectional transects can be made with the multiparameter instruments to determine the spatial variability associated with physical and basic chemical and biological characteristics to identify discrete locations or sampling sites for further water-quality sampling and assessment.

Table 10–5. Typical physical, chemical, and biological components and their priority in a reconnaissance study.

[In assessing general water-quality and water-quality changes, priority 1 variables have maximum utility, priority 2 variables have moderate utility, and priority 3 variables have some utility]

Variable	Priority
Physical	
• Water depth	1
• Water temperature profile	1
• Secchi disk transparency	1
• pH profile	2
• Specific conductance profile	2
• Turbidity profile	3
Chemical	
• Dissolved-oxygen profile	1
• Nutrients (phosphorus and nitrogen species)	1
• Total and dissolved organic carbon	2
• Major ions	3
• Trace elements	3
Biological	
• Chlorophyll	1
• Pathogenic indicators (*Escherichia coli*, fecal coliform).	2
• Phytoplankton: diversity, abundance, and biovolume.	3
• Macrophytes	3
• Zooplankton	3
• Littoral macroinvertebrate fauna	3
• Profundal macroinvertebrate fauna	3
• Fish diversity and abundance	3

- After the lake or reservoir is divided into one or more sections for water-quality sampling and assessment, specific locations within each section should be identified and marked by buoys or recorded using a global positioning system so one can return to the same location for additional sampling, as needed.
- Common water (and bed-sediment) components typically include chemical-constituent analyses of nutrients (nitrogen and phosphorus components), major ions, trace elements, organic matter, and targeted contaminants (table 10–5). Common biological components typically include chlorophyll, phytoplankton, macrophytes, and benthic fauna.

The design of a water-quality reconnaissance study should document which media (water, bed sediment, and biological components) and chemical and physical properties and constituents should be measured or analyzed, and the rationale for sampling site locations, so as to provide future study teams a context in which to understand the historical data record and use that insight to inform future study plans.

4.1.2 Diagnostic Studies

Diagnostic studies often are conducted to provide water-resource managers with the information needed to develop or evaluate the feasibility of specific cost-effective protection and restoration strategies for vulnerable or impaired lakes/reservoirs. For example, building on information gathered from reconnaissance, a diagnostic water-quality assessment could be developed to determine the sources, causes, and extent of a lake or reservoir being threatened or affected by sediment/nutrient loading, sedimentation, and (or) nutrient enrichment. A diagnostic study could be designed to evaluate the efficacy of potential or in-place controls on water-quality impairment. For these and other study scenarios, a diagnostic assessment often requires an interdisciplinary approach in which the study team includes the expertise of multiple disciplines, such as biology, geology, chemistry, physics, and engineering.

Diagnostic studies often extend beyond the boundary of the water body into the drainage basin. Major tributaries to the lake or reservoir commonly are monitored or otherwise included in the data-collection effort in order to quantify the water quality of the inflow water. Results from diagnostic studies may also be used in interpretive studies that use statistical or mathematical models to simulate and interpret functions and processes in the lake or reservoir and forecast future conditions based on various management options.

In diagnostic studies, it is usually important to determine both the concentrations and the quantity of constituents entering and leaving the lake or reservoir. To accomplish this, continuous stream gages can be installed on the major tributaries to provide the volumetric discharge needed to calculate constituent loads entering the lake or reservoir. It is good to have as much of the watershed gaged as possible to reduce or eliminate assumptions for ungaged flow. Water-quality samples should be collected frequently enough over the entire hydrologic regime in order to calculate constituent loads and quantify the amount of material entering the lake or reservoir.

- A few computer programs that estimate constituent loads and yields include:
    - EGRET (Hirsch and DeCicco, 2014, http://pubs.usgs.gov/tm/04/a10/)
    - LOADEST (Runkel and others, 2004, http://water.usgs.gov/software/loadest/)
    - Fluxmaster (Hoos and others, 2008, http://pubs.usgs.gov/of/2008/1163)
    - FLUX (Walker, 1999; also U.S. Army Corps of Engineers, http://el.erdc.usace.army.mil/elmodels/emiinfo.html)
    - GCLAS (Koltun and others, 2006, http://water.usgs.gov/software/GCLAS/)
- When developing diagnostic studies, sampling design should:
    - Collect data to describe seasonal variability at specific sites at specific times consistently throughout the year. This allows changes to be identified and verified and trends in annual average conditions to be recognized and validated. In addition to describing variability in vertical conditions in both lakes and reservoirs, horizontal variability, both across and upstream and downstream in a reservoir, should be captured whenever possible.
    - Consistently measure water temperature, pH, specific conductance, dissolved oxygen, and Secchi-disk transparency during each site visit.
    - Use consistent sampling protocols. Physical and chemical data can be augmented with analysis of biological indicators, such as chlorophyll, phytoplankton, macrophytes, and benthic fauna.

Diagnostic studies generally provide results in summary tables, graphic displays, and statistical analyses rather than provide detailed interpretation of the processes causing the changes in water quality. See Helsel and Hirsch (2002) for parametric and nonparametric statistical analyses that are appropriate for various study objectives and sampling strategies.

4.1.3 Interpretive Studies

Interpretive studies typically have an expanded scope compared to other studies. An example of an interpretive study is one for which the effects of watershed point- and nonpoint-source nutrient enrichment are examined and the changes in extent of lake/reservoir eutrophication after implementation of best-management practices to reduce nonpoint source loading are being forecast. An interpretive study generally is best carried out after completion of a reconnaissance study of the system (Averett and Schroder, 1994). Interpretive studies typically require additional and more detailed data and information to examine processes, assess conditions, interpret trends, and possibly forecast future conditions and resource-management scenarios. Statistical and mathematical simulation tools commonly are used to assess or diagnose current conditions and forecast future conditions, based on changes in watershed management and resultant changes in loading.

Depending on the objectives, interpretive studies may require several years of data collection from various media (water, bed sediment, and biological components) at multiple sites, including inflowing tributaries, in-lake or in-reservoir sites, and sites downstream of the lake/reservoir. On the basis of results from a reconnaissance or diagnostic study (in which the spatial and temporal variability within the system is defined), a monitoring plan can be developed to include collection of water, bed sediment, and biological samples at specific longitudinal, horizontal, and vertical locations (including tributaries) at a specified frequency. The resulting data can then be used in statistical or mathematical models to describe and better understand the physical, chemical, and biological functions and processes within the system.

Some of the statistical, descriptive, and mathematical tools typically used in interpretive studies are briefly described below.

- Trends in water quality can be examined using various statistical methods and software. The statistical methods that are typically used are those designed to overcome common statistical problems encountered by conventional statistical trend techniques in the analysis of water-quality data, including data that are non-normal and seasonally varying, and water-quality records with missing values, "less-than" (censored) values, and outliers. The type of data collected will determine whether parametric or nonparametric statistical trend tests should be used.

- Many data analysis and statistical (empirical) tools are available for describing and interpreting water-quality conditions and forecasting future conditions. Many of the empirical tools are described in detail in Reckhow and Chapra (1983a), as well as in the sources shown below:

  - Phosphorus Loading Models (Vollenweider, 1968, 1976; Vollenweider and Dillon, 1974; Vollenweider and others, 1980; Panuska and Kreider, 2003)

  - USEPA–NES Trophic State Delineation (U.S. Environmental Protection Agency, 1974)

  - Carlson's Trophic State Index (Carlson, 1977)

  - Nutrient Loading and Lake Response (Rast and Lee, 1978)

  - Simplified Procedures for Eutrophication Assessment and Prediction (Walker, 1985; http://el.erdc.usace.army.mil/elmodels/emiinfo.html, accessed 2/4/2015)

  - Phosphorus Loading Concept and the OECD Eutrophication Programme (Rast and Thornton, 2005)

  - Eutrophication Classification According to Trophic Criteria (Klapper, 2005)

- Many mathematical modeling tools are available to help describe and interpret lake and reservoir water-quality conditions and for forecasting future conditions. Many of these models and techniques are described in Reckhow and Chapra (1983b) and more recently in Mooij and others (2010). Some of the most widely used include (accessed between 1/28/2015 and 2/4/2015):

  - BATHTUB, http://el.erdc.usace.army.mil/elmodels/emiinfo.html

  - CE-QUAL-W2, http://www.cee.pdx.edu/w2/

  - EFDC, http://www.epa.gov/athens/wwqtsc/html/efdc.html

  - DYRESM--CAEDYM, http://tools.envirolink.govt.nz/dsss/dynamic-reservoir-simulation-model-computational-aquatic-ecosystem-dynamics-model/

  - ELCOM, http://www.ce.utexas.edu/prof/hodges/site2006/elcom.htm

  - GLM, http://aed.see.uwa.edu.au/research/models/GLM/

4.2 Sampling Strategies and Approaches

The purpose of defining a specific sampling strategy is to make data collection more efficient and so that the obtained information is sufficient to meet study objectives. The sampling strategy and design should be as cost effective as possible. Since the purpose of the sampling design is to describe specific water-quality characteristics, a sampling design should consider the variability in the system, such as vertical and longitudinal gradients, and seasonal variability. Study design should consider:

- Vertical and longitudinal gradients (Thornton and others, 1982), different sources and locations of tributary loading, and seasonal patterns that increase the variability in the data.

- Initial conditions - Spatial and seasonal variability at the beginning of the sampling program so that procedures can be incorporated to minimize their impact during the later data analysis and interpretation phases (U.S. Army Corps of Engineers, 1987).

Often a single station is not adequate to characterize lake or reservoir water quality; therefore, the required number and location of sampling stations must be determined. Depending on study objectives, one sample station may be sufficient in a small lake or when trying to characterize a specific location in a reservoir (for example, at the drinking-water intake) rather than collecting fewer samples at several stations. In other cases, many stations may be needed to describe the variability in the system.

4.2.1 What to Sample

The purpose, objective(s), and scientific approach of a study will determine what media (water, bed sediment, and biological components) should be sampled and what variables should be measured. It is important to keep in mind the various zones or strata in lakes and reservoirs: thermal, light, chemical, depth, littoral, pelagial, profundal, riverine, transition, and lacustrine. The following example provides an idea of what should be sampled in an eutrophication study.

> ***Example:*** On the basis of the water-quality concerns and possible contributing factors in lakes and reservoirs (table 10–4), data are often collected for many of the physical, chemical, and biological variables listed in table 10–5. Field measurements, including vertical profiles of water temperature, dissolved-oxygen concentrations, pH, specific electrical conductance, and photosynthetic pigments (chlorophyll and others), and Secchi disk transparency usually are collected onsite at the time of sampling. Common analytes measured in water samples typically include nutrients, dissolved solids, major ions, trace elements, organic carbon, and organic constituents (table 10–6). Biological samples in water and bed sediments are often collected as well. Biological analyses in water samples could include chlorophyll concentrations, pathogen indicator density (fecal coliform, *Escherichia coli*), and possibly phytoplankton and zooplankton diversity, abundance, and biomass/biovolume, aquatic macrophytes, and fish. Bed sediments often are analyzed for nutrients, trace metals, and organic carbon.

4.2.2 How Many Samples to Collect

The purpose and objectives of the study will determine how many and how often samples should be collected. The number of samples should be sufficient to represent the variability in water quality that exists at the location the site was chosen to represent and the time period the sample was chosen to represent. In addition to the typical samples that will be used for water-quality analysis, quality-assurance samples should also be collected to identify, quantify, and document bias and variability in the data. Statistical tools and guidance are available to help design a statistical strategy for sample collection (Thornton and others, 1982; Gaugush, 1987; Averett and Schroder, 1994).

If the project is a reconnaissance study as discussed above, sampling sites are typically located across the lake or reservoir in areas that represent different zones or strata. If the lake or reservoir is thermally stratified, samples are typically collected within each layer, especially the epilimnion and hypolimnion. The number of samples needs to be sufficient to achieve study and data-quality objectives and strengthen an understanding of the limnological system.

Table 10–6. List of selected water-quality constituents that are often measured in water-quality samples.

Sample group	Field-measured property or analytical constituent
Ambient conditions at time of sampling.	Temperature
	Dissolved oxygen
	Specific conductance
	pH
	Alkalinity
	Color
	Suspended sediment (suspended solids).
Major ions	Calcium
	Chloride
	Dissolved solids
	Fluoride
	Iron
	Magnesium
	Manganese
	Potassium
	Silica
	Sodium
	Sulfate
Nutrients	Orthophosphate
	Total phosphorus
	Nitrite plus nitrate nitrogen
	Ammonia nitrogen
	Ammonia plus organic nitrogen
	Total nitrogen
Organic carbon	Total organic carbon
	Dissolved organic carbon
Trace elements	Aluminum
	Antimony
	Arsenic
	Barium
	Beryllium
	Cadmium
	Chromium
	Cobalt
	Copper
	Lead
	Manganese
	Molybdenum
	Nickel
	Silver
	Uranium, natural
	Zinc

4.2.3 Where to Sample: Systematic, Random, and Stratified Approaches

A sample is a single representation of a particular aspect of a system; a substantial amount of data and information can be gained from a sample or a measurement (Averett and Schroder, 1994; NFM 8). Therefore, it is important that care be taken when selecting the location(s) where samples will be collected and measurements will be made. A single sample may not represent the whole or even define the average condition of the whole system. Therefore, samples typically need to be collected at a variety of locations to define the average and the extremes, as well as other attributes of the system. In some instances, more samples are collected and more measurements are made than are necessary to meet study objectives. Oversampling may provide security, but this is an expensive and poorly designed study approach (Averett and Schroder, 1994). Oversampling at the beginning of a study, however, is often required to understand the variability in the system and to enable a more optimal study design to be established.

Lakes and reservoirs can be complex systems in regard to selecting sampling sites (Averett and Schroder, 1994). In the formation of reservoirs, stream valleys are drowned, and each area may become a miniature reservoir with its own hydrologic patterns. Therefore, keep in mind the different zones in a reservoir described above: riverine, transition, and lacustrine or lake-like. Also consider the biological, light, and thermal zones. There is no single quantitative method for sampling-site selection. Sites should be selected in accordance with the scientific approach that will be used for the analysis and interpretation of the data, as described below, and considering what the data will represent.

In small lakes, sampling is usually conducted at only one location that is near the deepest location in the lake, or near the deepest location in each of the basins of a multibasin lake. Sampling at the deepest location will often provide the best description of the vertical variability in water quality. It is preferred that this location is near the center of each basin to minimize internal mixing processes. In larger lakes and in reservoirs, more than one location is often needed to describe the spatial variability in water quality. Of the various methods used to determine where to sample these more complex systems, the three most common approaches are systematic, random, and stratified approaches; each approach is described, in brief, below. (See also the discussion in NFM 8 on applications and limitations of statistical methods for the selection of bottom-material sampling sites).

- Systematic Approach

  Systematic sampling consists of selecting the first sampling site at random, and then selecting the remaining sampling sites at some predetermined space (Averett and Schroder, 1994). This technique can easily be used in most lake and reservoir studies, but the samples may provide biased results. Systematic sampling is a common sampling method, particularly in a sampling program designed to sample large water bodies (Gaugush, 1987).

- Random Approach

  A random sampling approach requires that the samples be collected without bias and be representative of the entire lake or reservoir (Averett and Schroder, 1994). The basic concept is to estimate the mean and measurement uncertainties, which requires that every sampling unit or other discrete unit that is selected for sampling has an equal chance of being chosen. For example, when planning to collect samples at three sites, select the three sites using an unbiased procedure. This approach applies to the selection of dates for sample collection as well as sampling locations (see section 4.2.4). In other words, if you plan on collecting 12 samples in a year, choose the 12 sample collection dates in an unbiased manner. Gaugush (1987) describes in detail the statistical procedure for designing a simple random sampling program.

- Stratified Approach

  Stratified random sampling is useful when the strata are distinct; that is, they have known sizes and boundaries (Averett and Schroder, 1994). In this situation, the reservoir could be divided into specific strata (zones). If a simple random sample is drawn from each stratum, then the sampling design is referred to as stratified random sampling (Gaugush, 1987). Strata in lakes and reservoirs can also be vertical zones, such as epilimnion, metalimnion, and hypolimnion. Likewise, in a reservoir, the strata of interest might also be the riverine, transition, and lacustrine zones along the downstream gradient.

  Stratified random sampling has two important advantages over simple random sampling. First, it can be advantageous to obtain data on separate subsets of the target population. Second, stratified sampling may produce an increase in the precision (error reduction) of the estimate for the entire population. The estimates for the strata can then be combined into a precise estimate for the target population. The total number of samples used in such a design will often be less than would be required using a simple random sample design (Gaugush, 1987).

4.2.4 When to Sample: Seasonal and Diurnal Considerations

Just as spatial patterns in lake and reservoir water quality are ultimately determined by flow regime, wind, and the vertical and longitudinal changes in light penetration and temperature, temporal patterns are determined by the dynamics of the flow regime, wind, and seasonal changes in temperature and solar radiation (Gaugush, 1987). Some of the temporal variability may be quite random, such as variability associated with changes in flow, whereas other variability may be quite consistent from one year to the next, such as variability associated with water temperatures. The annual cycle of changes in thermal stratification is well documented in limnology texts, such as Wetzel (2001) and Thornton and others (1990).

- Seasonal

  In warm monomictic lakes and reservoirs, the summer stratified period is preceded and followed by a period of fall/winter circulation. In such a case, stratification of the temporal variability into only two seasons may be sufficient to adequately account for the temporal component of variability in the lake or reservoir water quality. In dimictic lakes and reservoirs, the periods of mixing occur during the spring and fall turnover and are preceded and followed by periods of stratification. The duration and extent of these seasonal events can be used to stratify a sampling program temporally (Gaugush, 1987). Typically, monthly sampling is adequate to capture and describe the seasonal variability in water quality of lakes and reservoirs. It is preferable to collect monthly samples at about the same time of month each year to better enable long-term analyses.

- **Diurnal**

  Environmental conditions affecting lakes and reservoirs can change over a 24-hour period. Solar radiation varies from high intensity during midday to darkness throughout the night. As a result, surface temperatures may fluctuate between the extremes of day and night, especially in the shallow littoral areas. In addition, light affects productivity, which leads to diurnal patterns in dissolved oxygen, pH, and phytoplankton production. Organisms like phytoplankton and zooplankton often move vertically and (or) horizontally to relocate themselves in response to these environmental changes. These movements are usually associated with light, food availability, and predation pressures (Wetzel and Likens, 2000).

  When sampling a site multiple times during the year or season, most sampling is conducted at a consistent time of day to eliminate much of the **diurnal** variability in water quality. A dissolved oxygen profile at 0500 hours may be quite different from one collected at 1700 hours on the same day. This variability is true also for measurements of pH and chlorophyll measured by **in vivo** fluorescence. The primary causes of diurnal variations in these measures are photosynthesis and aerobic respiration. Photosynthesis is driven by sunlight and produces oxygen, which causes an increase in dissolved oxygen during the day. Large differences in 24-hour dissolved-oxygen minima and maxima can occur. In addition, phytoplankton and zooplankton can migrate up and down in the water column to acquire a position for optimum light intensity or food. Typically, routine sampling should be done at about the same time of day, preferably between 1000 and 1500 hours, when the sun is relatively high in the sky.

- Flow

  In reservoirs, temporal changes in flow regime can also provide a means to temporally stratify sample collection (Gaugush, 1987). Flow regimes can be divided into a high-flow stratum (for example, during the spring season high flows) and a low or base-flow stratum (during the summer and fall low flows).

  Including a combination of thermal and flow stratification considerations can improve a sampling design that will account for a greater proportion of the temporal variability; for example, winter circulation, high flow (March–May), thermally stratified (June–September), and fall/winter mixing low flow (October–February).

5.0 Preparations for Data Collection: Data Management and Safety Precautions

Prior to data collection, specific protocols should be established for setting up site files and for data management. Checklists help ensure that equipment and supplies will be ordered on time, that data-collection activities will be completed appropriately, and that data-quality requirements will be met (see NFM 1.1.1, fig. 1–1).

It is important that field personnel understand the purpose for which the various types of data are being collected and what the samples are meant to represent. This better enables field personnel to make more informed changes when field conditions are different than expected. Field crews should:

- Review the project sampling-and-analysis, quality-assurance, and work-schedule plans and be trained in how to collect the types of measurements and samples needed.

- Understand the physical and chemical limitations and utility of each piece of equipment to be used with respect to meeting project data-collection objectives and data-quality requirements. The operational range of the sampling equipment to be used should be verified and tested.

- Document conditions that could affect sampling operations (for example, site access, commercial traffic, recreation activities, and potential safety hazards) and the training needed.

- Follow all safety procedures.

  - Review the safety plan.

- Ensure that personnel have the current Occupational Safety and Health Administration Hazardous Waste Operations and Emergency Response (HAZWOPER) certification, which is required when working at sites designated as hazardous.
- Personnel operating a motorized vessel must have completed the USGS Motorboat Operator Certification Course (**MOCC**) and maintain current certification (USGS-SAF-MOCC-S1657-UDT).
- Evaluate potential sources of contamination at the site, based on the target analytes to be collected.

5.1 Site Files

USGS field personnel are responsible for establishing site files in the National Water Information System (NWIS)[2] for each station or site that is to be sampled (table 10–7) and for creating field folders for each location (detailed information is given in NFM 4.1). It is the responsibility of project personnel to ensure the functionality of the NWIS files, make updates promptly, and check that the information contained is correct.

A field (or site) folder for each data-collection site should be created and taken on each trip to the site. The field folder should contain information about the site that can be referenced and updated by field personnel to help locate and safely access sites, collect and process water samples and data, and record observations that could be useful for future site visits. Recommended contents for the field folder are listed in NFM 4.1 (see fig. 4–2), but the folder should be customized according to project needs.

Field notes for lake and reservoir samples are recorded on paper and (or) in electronic field forms. The field form typically includes the station identifiers and descriptions; field personnel involved in collecting the sample; information for the laboratory; date, time, record number, and associated water-quality data related to a given water-quality sample; alkalinity titration numbers; meter calibration and field measurements; quality-control information; and the NWIS database information that is required for storage of laboratory and other analytical results.

5.2 Safety Precautions

The USGS, as a Bureau of the U.S. Department of the Interior (DOI), structures its safety program using DOI safety guidelines. These guidelines are described in the Departmental Manual Part 485 titled “Safety and Occupational Health Program” (http://elips.doi.gov/elips/Browse.aspx?startid=1594&dbid=0), which is updated periodically to reflect current DOI policies. USGS safety policies and regulations are found in USGS Handbook 445–3–H, “Safety and Health for Field Operations” (http://www.usgs.gov/usgs-manual/handbook/hb/445-3-h.pdf). Additional safety requirements are described in “A Guide to Safe Field Operations” (U.S. Geological Survey, 1995) and in numbered memorandums from the Water Mission Area. A safety officer is designated in each Water Science Center of the USGS to provide additional information and guidance.

The NFM chapter 9, “Safety in Field Activities” (http://water.usgs.gov/owq/FieldManual/Chap9/content.html), describes hazards commonly encountered when engaged in field activities related to the collection of water-quality data. Each field site is unique and could have special safety requirements that need to be identified. Chapter 9 is meant to be used in conjunction with the DOI manuals, and handbooks cited above. It is the responsibility of the Water Science Center Safety Officer and Project Chief to ensure that the safety courses needed are taken by all field personnel and safety policies and procedures are implemented (table 10–8).

Personnel using sampling equipment should become familiar with the hazards involved and establish appropriate safety practices before using the equipment. Personnel should:

- Make sure all equipment is in safe working condition. All electrical equipment must bear the approval seal of Underwriters Laboratories and must be properly grounded to protect against electrical shock.
- Consider and prepare for hazards associated with the operation of motor vehicles, boats, winches, tools, and other incidental equipment.
    - Boat operators must be up-to-date with their motorboat operator training and certification (MOCC).
    - All boats must bez equipped with fire extinguishers, boat horns, throw rope and life ring, extra float cushions and personal floatation devices (PFDs), and flares or other emergency communication devices.
    - Field personnel working on or near water should be able to swim.
- Prepare a job hazard assessment (JHA) and communication plans.
    - All field personnel need to be fully aware of all lines of communication.
    - Field personnel should have a daily check-in safety procedure.
    - An emergency communications plan should be readily accessible that includes up-to-date contacts for police, ambulance, fire departments, hospitals, and search and rescue personnel.

All surface waters and sediments should be considered possible health hazards and potential sources of human or animal wastes and other types of toxic or pathogenic substances. Infectious agents and toxic substances can be inhaled

[2]NWIS is the hydrologic database of the U.S. Geological Survey and is updated periodically.

Table 10–7. Minimum information required for electronic storage of site and lake water-quality data in the U.S. Geological Survey National Water Information System (NWIS).

[GWSI, Ground-Water Site Inventory; USGS, U.S. Geological Survey; QWDATA, Quality of Water Data; WRD, Water Resources Division]

Required information for creation of a surface-water site in NWIS[1, 2]		
Data description	**Component (C) number for data entry into GWSI**	**Example (Description of code)**
Agency code	C4	USGS.
Station identification number	C1	0209799150.
Station name	C12	B.E. Jordan Lake AB US Hwy 64 at Wilsonville, NC.
Latitude	C9	354430.
Longitude	C10	0790109.
Coordinate accuracy	C11	S (nearest second).
Coordinate method	C35	R (reported).
Coordinate datum	C36	NAD83.
USGS Water Science Center	C66	37 (North Carolina).
Country	C41	US (United States).
State	C7	37 (North Carolina).
County	C8	037 (Chatham).
Time-zone code	C813	EST.
Daylight-savings flag	C814	Y (yes).
Agency use[3]	C803	A (Active).
Station type	C802	LK.
Required information for storage of sample analyses in the water-quality file of NWIS (QWDATA)[1]		
Data description	**Alpha parameter code**	**Example data (Description of code)**
Agency code	AGENCY	USGS.
Station identification number	STAID	0209799150.
Date (year/month/day)	DATES	20140716.
Time (standard 24-hour clock)	TIMES	1530.
Sample medium	MEDIM	WS (surface water).
Sample type	STYPE	9 (regular sample).
Analysis status hydrologic	ASTAT	U (unrestricted).
Hydrologic ("Hydro") condition.	HSTAT	9 (stable, normal stage).
Hydrologic event	EVENT	9 (routine sample).

[1]Numerous additional data fields are available in NWIS that can be useful for data analysis or mandatory for meeting study objectives (for example, indicating whether a non-USGS agency collected the data).

[2]Modified from Groundwater Site Inventory Schedule Form 9–1904–A, Revised June 2004, NWIS 4.4.

[3]See WRD Policy Memorandum 2009.02/Administrative Policy and Services Instructional Memorandum No. 2009-09 (see wrdpolicy09.02 at http://water.usgs.gov/admin/memo/policy/policy.html).

Table 10–8. Standard health and safety practices for U.S. Geological Survey personnel.

Recommended Training
• First aid
• Cardiopulmonary resuscitation (CPR)
• Vehicle safety
• Boating and water safety
• Field safety (weather, personal safety, orienteering, and site reconnaissance prior to sampling)
• Equipment design, operation, and maintenance
• Handling of chemicals, fuel spills, and other hazardous materials
Communications
• Check-in schedule
• Sampling itinerary (vehicle used and description, time of departure and return, and travel route)
• Contacts for police, ambulance, hospitals, fire departments, and search and rescue personnel
• Emergency services available near each sampling site and base location
• Cell (or satellite) phone. Mobile telephones and or satellite communication services for remote areas where cellular service is not available should be accessible at all times.
Personal Safety
• Protect the health and safety of all personnel. Always err on the side of personal safety.
• Field clothing and other protective gear including personal flotation devices (PFDs) for all field personnel. PFDs are required to be worn at all times when over, in, or near a water body, including when in a boat or on a boat dock.
• Medical and personal information (allergies and personal health conditions)
• Personal contacts (family, telephone numbers, and other)
• Physical exams and immunizations
• At least two persons should be present (in a boat) during all sample-collection activities and no one should be left alone while in the field.
• Exposure to lake water and sediments should be minimized as much as possible. Use gloves and clean exposed body parts as soon as possible after contact. Wear heavy gloves when hands are used to agitate the substrate during collection of benthic macroinvertebrate samples.
• Use appropriate protective equipment (gloves and safety glasses) when handling and using hazardous chemicals.
• Be familiar with the symptoms of heat/sun stroke and be prepared to move a suffering individual into cooler surroundings and hydrate immediately.
• Be familiar with the symptoms of hypothermia and know what to do in case symptoms occur.

or absorbed through the skin (NFM 9). It is advisable for field personnel to be immunized against tetanus, hepatitis, typhoid fever, and polio. Toxin-producing algae may be present in eutrophic or hypereutrophic waters, and gloves should be worn when coming in contact with such waters (NFM 7.5.8). Many hazards lie out of sight in the bottoms of lakes and reservoirs. Broken glass or sharp pieces of metal embedded in the substrate can cause serious injury if care is not exercised when walking or working with hands.

6.0 Field-Measured Properties

In situ measurements (water properties directly measured within the water body) that describe the general physical, chemical, and biological conditions in a water body are usually referred to as field-measured properties. Understanding the distribution in these properties ensures that the other samples being collected accurately represent the conditions, zones, or strata in the water body for which the sample is supposed to represent. Chapter 6 of the NFM establishes USGS protocols, requirements, and recommended practices for collecting field measurements, including sensor calibration, technical specifications of instruments, quality control of the measurement process, and criteria for data reporting (table 10–9). Field-measurement protocols and the required and recommended methods needed to preserve the integrity of the water data being collected are described in other chapters of this field manual and in the USGS Techniques and Methods reports referenced below (table 10–9).

USGS personnel should refer to the NFM for instructions relating to calibration, maintenance, measurement criteria, possible measurement interferences, and quality-control procedures that pertain to each of the water properties covered in chapter 6 (NFM A6.0 through A6.7) and in Techniques and Methods 1–D3 and 1–D5. The NFM chapters A6.0 through A6.7 provide required and recommended procedures for measurements made when using the same single- or dual-parameter instruments at multiple field sites or stations, while NFM A6.8 provides that information for use of sensors bundled in multiparameter instruments. "Guidelines and Standard Procedures for Continuous Water-Quality Monitors" (Wagner and others, 2006) provides the basic USGS guidelines and procedures for field-site and water-quality monitor selection, field procedures and compliance with sampling protocols given in the NFM, continuous-monitor calibrations, and record computation, review, and data reporting. Common multiparameter instruments have sondes that typically include sensors for the

Table 10–9. U.S. Geological Survey protocols and guidance documents for in situ or onsite measurements of water-quality properties.

[NFM, "National Field Manual for the Collection of Water-Quality Data"; USGS, U.S. Geological Survey]

Title	Description
NFM, chapter 6, Field Measurements	
A6.0, Guidelines for Field-Measured Water-Quality Properties	Chapters A6.0 through A6.7 provide general information about the water property and specific protocols, procedures, and recommendations for field-measurement practices, with a primary focus on making discrete measurements using single or dual-parameter instruments.
A6.1, Temperature	
A6.2, Dissolved Oxygen (DO)	
A6.3, Specific Electrical Conductance (SC)	
A6.4, pH	
A6.5, Reduction-Oxidation Potential – Electrode Method (ORP or Redox).	
A6.6, Alkalinity and Acid Neutralizing Capacity (ANC)	
A6.7, Turbidity	
A6.8, Use of Multiparameter Instruments for Routine Field Measurements.	Chapter A6.8 provides guidance for measuring the properties listed above (chapters A6.1–A6.4 and A6.7) specific to using a multiparameter sonde.
NFM, chapter 7, Biological Indicators	
A7.4, Algal Biomass Indicators A7.4.1, Pre-sampling considerations	Section 7.4.1.B includes information on measuring light attenuation by Secchi disk, turbidimeter, and light meter.
A7.4.2, In vivo measurement of chlorophyll and phycocyanin	Section 7.4.2 describes use of fluorescence-based sensors.
Techniques and Methods 1–D3[2]	
Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting.	Guidelines for site- and monitor-selection considerations; sensor inspection and calibration methods; field procedures; data evaluation, correction, and computation.
Techniques and Methods 1–D5[3]	
Optical Techniques for the Determination of Nitrate in Environmental Waters: Guidelines for Instrument Selection, Operation, Deployment, Maintenance, Quality Assurance, and Data Reporting.	Information for USGS field operations regarding the selection and use of ultra-violet (UV) nitrate sensors, including instrument types and maintenance of sensor performance, sensor design, sensor characterization techniques and typical interferences, and approaches for sensor deployment.

[1]NFM chapters and chapter sections are available at https://water.usgs.gov/owq/FieldManual.

[2]Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting (https://pubs.usgs.gov/tm/2006/tm1D3/).

[3]Optical Techniques for the Determination of Nitrate in Environmental Waters (https://ca.water.usgs.gov/pubs/2013/tm1d5.html).

collection of temperature, specific electrical conductance, dissolved oxygen, and pH data, but can be configured to measure other properties, such as turbidity and fluorescence. Sampling and measuring indicators of algal biomass are described in NFM A7.4, which includes sections on the use of sensors for making direct (in situ) measurements of light availability, chlorophyll, and phycocyanin. When creating a vertical water-quality profile by deploying a multiparameter sonde through a water column, follow the instructions given below under “Multiparameter Instrument Sondes” (section 6.2).

6.1 Light Attenuation

Measurement methods for estimating the thickness of the upper layer of water that light penetrates (referred to as the photic or euphotic zone) require either use of a Secchi disk or an instrument by which solar radiation is determined directly.

- Secchi Disk Method. The Secchi disk is a weighted disk with alternating black and white quadrants, 20 centimeters (cm; 8 inches) in diameter, and attached to a line with distance marked in meters or feet. The disk is slowly lowered in the water column until it is no longer visible. The depth at which the disk is no longer visible is referred to as the Secchi depth. Secchi depths should be measured on the shady side of the boat. The thickness of the photic zone is measured by multiplying Secchi disk depth by a factor of approximately 2.5 (Welch, 1948; Horne and Goldman, 1994; Wetzel and Likens, 2000). Light penetration, as measured with a Secchi disk, can vary considerably when the sun is at extreme angles. Therefore, if only one sample is to be collected in a day, the Secchi measurement generally is made between the hours of 1000 and 1500 hours. The NFM A7.4 describes how to measure water transparency using a Secchi disk.

- Surface and Underwater Solar Radiation. Measurements of surface and underwater irradiance (light availability) include shortwave (100 to 400 nanometers (nm)), reflected longwave (infrared radiation; 700 to 3.5x105 nm), and **photosynthetic active radiation** (**PAR**; 400 to 700 nm) and are measured using a pyrheliometer, pyranometer, net radiometer, or quantum sensor (see fig. 10–13 in section 6.3.2). Refer to NFM A7.4 for detailed information about measurements of solar radiation.

Light attenuation can be measured using the surface (terrestrial) radiation sensor along with the underwater radiation sensor. The depth where the underwater sensor reaches 1 percent of the surface intensity identifies the bottom or thickness of the photic zone. The extinction coefficient is the absolute value of the slope of the natural log of solar radiation with depth. Refer to NFM A7.4, Technical Notes and Tips-2, to calculate the portion of the water body in which light is sufficient for photosynthesis (the euphotic depth).

6.2 Multiparameter Instrument Sondes

Multiparameter instruments, in which various types of sensors are bundled in a **data sonde**, provide concurrent measurement of various water-quality related properties (sometimes referred to as “parameters” in the industry literature) that should or must be measured onsite, such as water temperature, dissolved oxygen, specific electrical conductance, pH, and turbidity (NFM A6.8; Wagner and others, 2006). Additional sensors could be added to the data sonde to measure light attenuation, chlorophyll, phycocyanin and **phycoerythrin** (cyanobacteria pigments) (NFM A7.4; NFM A7.5), nitrate, and colored fluorescent **dissolved organic matter**. An advantage of multiparameter sondes is that they can be activated manually or be programmed for data collection and storage at defined time steps.

Prior to using a multiparameter instrument, the sensors should be properly calibrated or the calibration checked following the protocols and guidance given in NFM A6.8 (see table 10–9 for relevant sections), and NFM A7.4 and A7.5 (for chlorophyll, phycocyanin, phycoerythrin, and cyanobacteria).

6.2.1 Temperature, Dissolved Oxygen, pH, Specific Electrical Conductance, and Turbidity

- Temperature. Water temperature is important when determining the various strata and zones in a water body. The proper calibration and maintenance of the thermistor or temperature sensor is extremely important for water-quality studies. Refer to NFM A6.1 and A6.8 for USGS guidelines and procedures related to selection, calibration, maintenance, and measurement criteria for thermistor thermometers. The accuracy of measurements of dissolved oxygen, specific electrical conductance, pH, oxidation-reduction potential,[3] the rate and equilibria of chemical reactions, biological activity, and fluid properties depend on the accuracy of the temperature measurement.

- Dissolved Oxygen. Data that accurately describe dissolved-oxygen concentrations are essential for documenting changes in the water quality of lakes and reservoirs and determining whether or not the changes observed were caused by natural phenomena or human activities. The NFM chapters A6.2 and A6.8 provide guidelines and procedures related to equipment selection, calibration, maintenance, and deployment of either optical (luminescence-based technology) or the amperometric (Clark cell) sensors. Optical sensors are recommended for long-term deployment and are replacing the amperometric sensors as the measurement method of choice for most USGS field studies. As is the case of other gases, oxygen solubility often exhibits an inverse relation to temperature.

[3]See NFM 6.5 “Reduction-Oxidation Potential.”

- pH. The pH, or activity (effective concentration) of hydrogen ions (H^+), in a lake or other aqueous system, is a measure of the acidity of the water. Water with a pH value of 7 is defined as "neutral" at a temperature of 25 °C, when the H^+ concentration is equal to that of the hydroxide (OH^-) concentration. Remember that the chemical equilibrium of hydrogen ions in solution is temperature dependent. Refer to NFM A6.4 for a more detailed definition and informative explanation of pH and how it is measured in accordance with USGS protocols and requirements. Several methods are described in the NFM that can be applied to the measurement of pH in standing waters. The NFM chapters A6.4 and A6.8 provide guidelines and procedures related to pH equipment maintenance, calibration, and measurement.

- Specific Electrical Conductance (SC). Electrical conductance is a measure of the capacity of a substance to transmit an electrical current. The SC of water is a function of the types and quantities of dissolved substances it contains, normalized to a unit length and unit cross section at a specified temperature (NFM A6.3). The presence of charged ionic species in a simple solution makes it conductive; that is, as ion concentrations increase, the electrical conductance of the solution increases. SC, therefore, provides a rough indication of the total number of ions present in a solution and thus is related to total dissolved solids (TDS) and ionic strength. Temperature affects the SC value at the time of measuring and must be factored into the measurement. Most instruments report SC adjusted to a common water temperature (25 °C). The NFM A6.3 and A6.8 describe USGS calibration and measurement procedures for SC in standing water, using either a contacting-type sensor (dip cell, cup cell, or flow cell) or electrodeless-type sensors.

- Turbidity. Many instruments are available for measuring turbidity, each of which is assigned a USGS parameter and method code (see "Turbidity parameter and methods codes" on the index page for "6.7 Turbidity" at http://water.usgs.gov/owq/FieldManual/Chapter6/6.7_contents.html). The specific calibration instructions and the calibrants needed depend on the instrument being used. The NFM A6.7 and A6.8 provide guidance on equipment and sensor types, calibration procedures, reference and turbidity standards, and quality-assurance practices in the measurement of turbidity.

6.2.2 Algal Biomass: Photosynthetic Pigments

- Depending on the sensor and instrument capability, fluorescence-based sensors can be connected to a multiparameter data-sonde profiler or used individually to measure pigment fluorescence (NFM A7.4, section 7.4.2). Follow the instructions for profiling under "Methods of Sonde Deployment" (section 6.3.1) for collecting a measurement profile.

- **Chlorophyll**. Fluorescence-based sensors can be deployed in situ to provide a discrete or continuous measure of total chlorophyll. The chlorophyll sensor produces a relative measure of total chlorophyll and can be adjusted to chlorophyll a concentrations by relating fluorescence values with analytical concentrations extracted from water samples collected at the same site.

- **Cyanobacteria**. **Phycocyanin** and **phycoerythrin** (pigments in cyanobacteria) concentrations also can be estimated by in vivo fluorescence to provide a continuous record. Refer to NFM A7.4 for pros and cons and guidance on equipment use, calibration, and measurement of in vivo fluorescence measurements.

6.2.3 Ultraviolet Nitrate Sensors

Ultraviolet (UV) photometers for in situ determination (discrete or continuous measurements) of nitrate concentrations have been tested and are being employed at selected sampling stations (primarily at USGS stream and river sites). Guidance and detailed information about types and use of UV nitrate sensors is given in Pellerin and others (2013), Techniques and Methods 1–D5 (see table 10–9).

6.3 Methods of Sonde Deployment

Multiparameter instruments can be lowered through the water column during sampling (profiling) or they can be installed and configured to provide data continuously at a single station or on a data platform (section 6.3.2). For additional information, see Wagner and others (2006), NFM A6.8, and table 10–9).

6.3.1 Profiling

Prior to lowering the sonde through the water column, the sonde and (or) transducer must be calibrated and weighted properly so that it sinks properly. Consult the manufacturer before adding weight to the instrument.

To manually collect profile data, use the following procedure:

1. Record (automatically or manually) each depth at which a measurement(s) is made.
    a. Some multiparameter instruments may include or can be custom ordered with a pressure transducer that estimates water depth.
    b. For instruments without pressure transducers, the approximate depth of the sonde as it is lowered through the water column can be followed by placing incremental marks along the instrument cable. Alternatively, a single-instrument pressure transducer can be deployed attached to the sonde.
2. Deploy the sonde and record, at the selected depth intervals, the values given from the field-measurement sensors for which the sonde was outfitted (usually temperature, pH, SC, and DO).
    a. Lower the sonde to just under the surface of the water.
    b. Wait for the sensors to stabilize before recording the set of field measurements, in accordance with the USGS field-measurement protocols described in NFM A6. (Note that some instruments and sensors require a longer equilibration time: check the manufacturer's recommendations.)
    c. Based on the total depth of the water body and vertical variability within the water column, lower the sonde in 0.5- to 1-m-depth increments (or other depth interval, in accordance with study objectives and requirements).
        - Record each depth interval; then wait for all the sensors to stabilize to the new depth conditions before recording the set of field-measurement values for that depth.
        - It is usually best for long-term evaluations to lower and record field measurements at consistent depth intervals.
3. Continue to lower the sonde and record depth and field-measurement values until the sonde reaches bottom (avoid stirring bottom sediments).

6.3.2 Water-Quality Monitoring Platforms with Continuous Sensors or Multiparameter Sondes

Water quality can change frequently in lakes and reservoirs, requiring frequent, repeated measurements to characterize the temporal variations in quality (Wagner and others, 2006). Operation of a water-quality monitoring platform with multiparamter sondes can provide a nearly continuous record of specific water-quality constituents. The data being collected can be recorded on site or distributed directly by telemetry to the Internet. Continuous water-quality monitoring systems can be mounted or moored on fixed structures (such as piers and dam walls), mounted on an anchored barge (fig. 10–13), or suspended from an anchored buoy (fig. 10–14). These systems can operate a single sensor at a fixed depth, multiparameter sondes with multiple sets of sensors at fixed depths (fig. 10–15), or sensors or sondes can be raised or lowered using a mechanical wench or ballast system (fig. 10–16).

- As part of water-quality lake/reservoir studies, temperature and dissolved oxygen are the two properties most often measured. Other field-measured properties can include SC, pH, turbidity, pigment fluorescence, ammonia, nitrate, chloride, and solar radiation (most often PAR).
- Meteorologic stations also often are associated with the continuous water-quality monitoring platforms in order to provide information critical to the interpretation of the water-quality data collected.

Lake and reservoir water quality ranges from clear, pristine, oligotrophic systems to highly productive eutrophic or hypereutrophic systems. Continuous monitoring in highly productive environments can be challenging because of relatively rapid biofouling. In addition, corrosion of electronic components can occur in high humidity areas. The choice and placement of instrumentation in a lake or reservoir is based on the data objectives of the project.

The number of vertical depths at which measurements are made should depend on the extent of vertical mixing, similar to collecting other water-quality samples (Wagner and others, 2006). Measurements can be made at evenly spaced intervals or at points relative to where changes in field-measured properties, such as temperature or salinity gradients, typically occur. If vertical stratification is usually sharply defined, the locations for measurements can be chosen across the transition zone and more closely spaced to adequately represent the position and degree of stratification.

The frequency at which measurements are made is based on the data objectives of the project and should depend on the temporal variation of change in the system. In a stable, stillwater system, hourly data may be adequate to capture the temporal variation. In more dynamic, frequently mixed (polymictic) systems or in rapidly flushed systems, more frequent

Figure 10–13. Photograph of barge-mounted continuous water-quality monitoring system on Lake Houston, Texas, station 2295554095093401 (photograph by T.D. Oden, U.S. Geological Survey).

Figure 10–14. Photograph of buoyed continuous water-quality monitoring system on Lake Maumelle, Arkansas, station 072623995 (photograph by W.R. Green).

data collection may be needed. In the former, a single mulit-parameter data sonde mechanically positioned at the various depths may be sufficient. In the latter, a string of sensors positioned at different depths, all recording at the same time, may be needed.

Figure 10–17 shows changes in the dissolved-oxygen concentrations in Lake Maumelle, Arkansas, a shallow drinking-water reservoir. The changes in concentration were based on data measured at a 5-minute frequency over a 7-day period using 12 vertically spaced sensors. This figure demonstrates wind-induced upwellings of hypolimnetic water and downwellings of epilimnetic surface water. The upwellings can move hypolimnetic water, rich in reduced iron and manganese, up to a depth where drinking water is withdrawn. The drinking-water treatment facility uses these data to adjust the treatment process in order to reduce the increased concentrations of elements that produce taste and odor problems and clog filters.

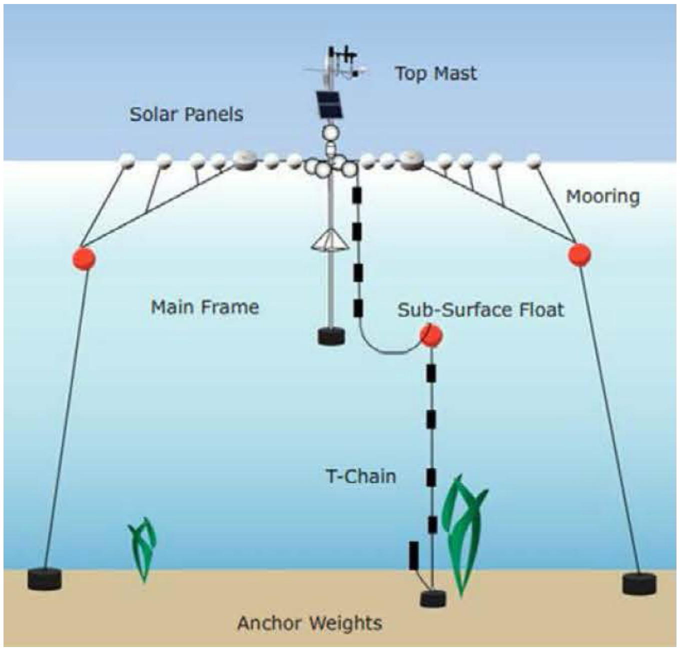


Figure 10–15. Diagram of a continuous water-quality monitoring system with multiple sensors. (Diagram courtesy of Precision Measurement Engineering, Inc., Vista, California.) The submerged buoys above each anchor allow the buoyed station to rise and fall with the changing pool elevations, keeping a tight mooring all the while.

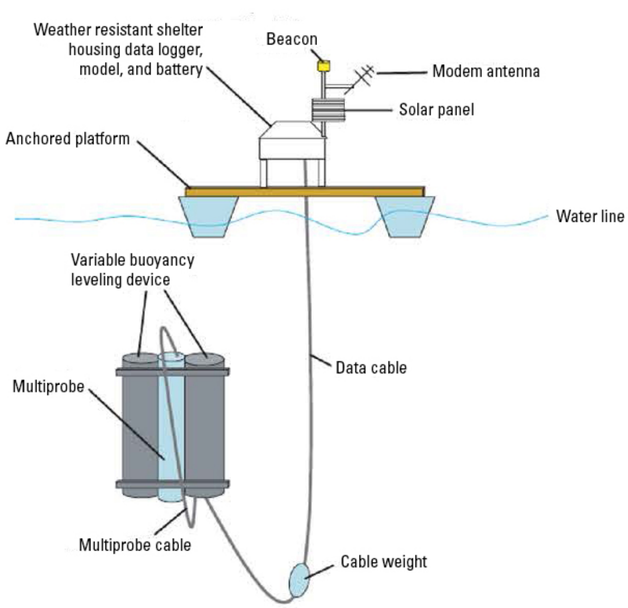


Figure 10–16. Diagram of a continuous water-quality monitoring system with a single set of sensors that is moved to various depths by use of a variable-buoyancy system (from Rowland and others, 2006, fig. 4).

7.0 Sampling in the Water Column

Chapters A4 and A5 of the NFM describe standard USGS methods (sampling and quality-control strategies, techniques, requirements, and recommendations) for the routine collection and processing of stream and groundwater samples.[4] Analogous sampling strategies, techniques, requirements, and recommendations also apply to USGS studies of lakes and reservoirs, as described in NFM A7.4 and A7.5. The NFM A7.5 provides specific guidance for sampling cyanobacterial community composition, toxins, and taste and odor compounds, and the use of equipment for various sample types, which are generally applicable for collecting all types of lake and reservoir samples. Studies of cyanobacteria require Teflon-coated samplers but other types of analyses do not necessarily need to use Teflon.

Before sample collection begins, field personnel should take steps to ensure that the samples collected will be representative of the aqueous system being investigated. A representative sample is one that typifies (represents) in time and space that part of the aqueous system to be studied and is delineated by the objectives and scope of the study. Obtaining representative samples is of primary importance for a relevant description of the lake or reservoir condition.

The types of sampling devices (samplers) commonly used to collect surface (NFM A2), discrete-depth (NFM A7.5), and depth-integrated samples (NFM A7.5) in lakes and reservoirs are listed in NFM A7.5, table 7.5–6. Detailed descriptions of the samplers and proper uses of these samplers are presented in Britton and Greeson (1987), NFM A2 and A4, and U.S. Environmental Protection Agency Standard Methods Sections 1060 and 10200 (American Public Health Association, 2005). The advantages and disadvantages of each sampler type are presented in NFM A7.4, tables 7.4–7 and 7.4–8. The two most common types of instruments used to collect water samples in lakes and reservoirs are the Van Dorn and Kemmerer samplers, each of which consists of a cylindrical tube attached to a depth-labeled rope or wire used to lower the sampler to a specific depth. The Van Dorn sampler has a horizontal cylinder with rubber covers on each end that are kept open until the sampler is lowered to the desired depth. The Kemmerer sampler has a vertical cylinder with stoppers on each end that are held open as the sampler is lowered by a line to a desired depth. These rubber covers or stoppers are triggered to close the ends of the tube using a messenger that is dropped down the line that is holding the sampler.

[4] NFM chapters 1, 2, and 3 provide information and guidance regarding field preparations, equipment selection, and equipment decontamination for water-quality studies, respectively, that can be applied to or adapted for lake and reservoir water-quality studies.

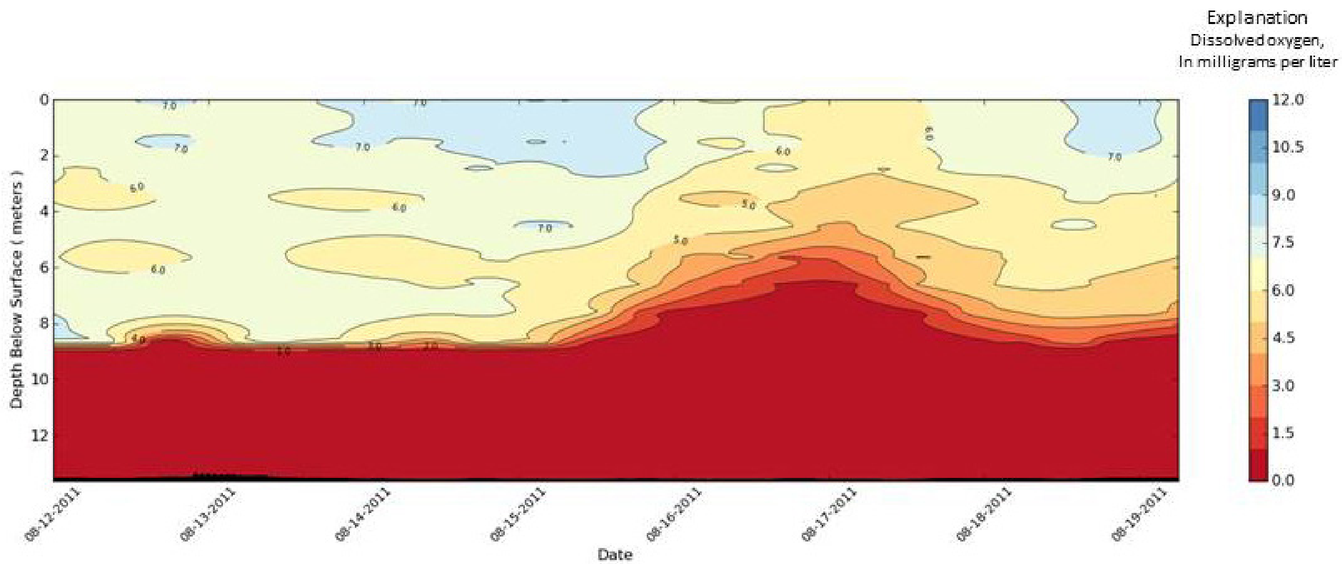


Figure 10–17. Time and depth contour plot of dissolved-oxygen concentrations measured every 5 minutes from a 12-sensor continuous water-quality monitoring platform in Lake Maumelle, Arkansas, station 072632995, August 16–23, 2011. Sensor depths are every 1 meter from 0.5 meter below the surface to 1 meter above the bottom.

8.0 Sampling Bottom Material

Bottom material in a lake or reservoir consists of living and nonliving, organic and inorganic material of varying physical, chemical, and biological composition that has been transported from the watershed or produced within the water body. Chemical and biological analysis of bottom materials can address a broad spectrum of objectives in lake and reservoir water-quality studies, such as surveillance monitoring, mass-transport loading, remediation effectiveness, presence or absence of contaminants, and spatial extent and temporal change of chemical constituents. The NFM A8 provides information and guidance for selecting sampling site locations, selecting equipment, quality-control samples, and procedures and protocols for the collection, processing, and shipping of bottom-material samples.

Analysis of bottom-material samples can include chemical analysis of the bulk sediment (Braun and others, 2012; Lower Granite Reservoir in eastern Washington; Robertson and others, 2012; Mercer Lake, Wisconsin); chemical (phosphorus) release studies (Robertson and Rose, 2008; Butternut Lake, Wisconsin); and sediment accumulation and reconstruction of past water quality using diatom community analyses (Juckem and Robertson, 2013; Shell Lake, Wisconsin). Field observations are typically recorded to document sample color, texture, odor, benthic organisms, detritus, and other visible characteristics.

Surface grab and core samples in lakes and reservoirs can be collected by wading in the shallow littoral zones. In deeper water bodies, bed-material samples are most often collected by dropping or dragging a sampler from a boat. Sometimes bed material is collected by scuba divers. Grab samples are commonly collected using Ekman, Peterson, or Ponar grab samplers (Lewis and others, 1982). Sediment cores are commonly collected using box, gravity, or piston corers (Van Metre and others, 2004; Juracek, 2011).

9.0 Sampling Biological Components

The ecology of a lake or reservoir system is driven by the ambient physical and chemical conditions, but is often assessed by investigating its biological components. Britton and Greeson (1987); Wetzel and Likens (2000); Moulton and others (2002); American Public Health Association (2005); NFM chapters A7.1 through A7.5; and the other references cited throughout this chapter provide detailed methods for the collection and processing of aquatic biological and microbiological samples.

- **Phytoplankton** composition and biomass (primary production) provides an integrated assessment water-quality conditions, an indication of eutrophication (nutrient enrichment), and the presence or absence of toxin and taste and odor producing organisms.

- Zooplankton composition and biomass (secondary production) supports both the water-quality and ecological assessment by providing insight to the quality of the food chain and the energy flow through the system.

- Microbial monitoring detects the presence or absence of fecal indicator bacteria and viruses (coliphage) and their pathogens (disease-causing organisms) and the potential contamination from human and animal (wildlife and livestock) waste.

- Benthic (bottom dwelling) invertebrate community composition and abundance, and aquatic macrophyte (native and introduced) distribution and biomass are integrators of past and present water-quality conditions.
- Fish community composition and abundance are integrators of past and present water-quality and ecological health, and they can provide insight into the quality of energy flow through the food chain.

9.1 Phytoplankton

Phytoplankton are unicellular photosynthetic organisms existing as single cells, colonies, chains, or filaments that generally are transported passively (some forms are active swimmers) by currents and other mixing processes (Britton and Greeson, 1987; NFM A7.4). Phytoplankton are photosynthetic microorganisms adapted to live partly or continuously in open water (Reynolds, 2006). Photoautotrophic plankton are the major **primary producer** of organic carbon in the pelagic zone of the seas and of inland waters. Phytoplankton blooms can severely affect water quality, either through algal blooms, the production of toxins that lead to fish kills or threats to human health, or through the decomposition of organic matter that can deplete oxygen when the algae die.

Integrated studies of aquatic ecosystems often include measurements of phytoplankton biomass and composition (Britton and Greeson, 1987; NFM A7.4). To maximize the use of phytoplankton data, the sampling sites and methods used for phytoplankton should correspond as closely as possible to those selected for other biological, microbiological, and chemical sampling. Measurements of biomass are described in part above and in the "General Guidelines—Photosynthetic Pigments" section of Britton and Greeson (1987, section 10.4.2.H). The most common measure of the overall amount of algae in a specific area or zone in a water body is a simple chlorophyll a concentration. However, phytoplankton identification and enumeration can provide much additional information. Phytoplankton can be identified and quantified using an optical microscope. This method can provide counts (density, number of counting units per milliliter) and the compositional makeup (diversity); it can also provide biomass based on the assumption that the volume of the organisms equals that of water based on displacement (1 mm3/L = 1 mg/L or 1 µm3 = 1 µg/L; Wetzel and Likens, 2000). Phytoplankton biomass can then be converted to carbon based on the assumption that the carbon content in different groups of phytoplankton (cyanobacteria, dinoflagellates, diatoms, green algae, and others) is a given portion of their total biomass (for example, carbon = biomass multiplied by 0.11).

- Knowledge of the average chlorophyll a concentration is an indication of the trophic state of a water body.
- Knowledge of species composition can indicate the causes of seasonal changes in biomass and indicate stresses imposed by contaminants that may not be evident from measurements of biomass (chlorophyll a) alone (Britton and Greeson, 1987).
- As bioindicators, phytoplankton and changes in phytoplankton populations can provide two main types of information about water quality (Bellinger and Sigee, 2010):
  - Long-term information—the status quo, and
  - Short-term information—environmental change.
- Changes in phytoplankton communities act as bioindicators and can serve as early warning signals that reflect the "health" status of an aquatic system.

9.1.1 Sample Collection

A chlorophyll a sample is collected by filtering a known amount of sample water (typically collected with a Van Dorn sampler) through a glass-fiber filter (typically 5 µm). The filter is then sealed in aluminum foil and immediately frozen or placed on ice. The filter paper itself is then used for the analysis. The filter is ground up in an acetone solution and either a fluorometer or spectrophotometer is used to quantify the light transmission at a given wavelength, which in turn is used to calculate the concentration of chlorophyll a.

Phytoplankton samples can be collected using any of the three general sampling methods described above under "Water Sampling" (section 7.0) and in NFM A7.5: surface samples, discrete-depth samples, or depth-integrated samples. For each sample type, a single grab sample may be collected or multiple grab samples may be composited. The types of sampling devices (samplers) commonly used to collect each type of sample are discussed and listed above in table 10–9. A detailed description of the samplers and their proper uses are presented in Britton and Greeson (1987), NFM chapters A2 and A4. Advantages and disadvantages of each sampler type are presented in NFM A7.4, table 7.4–8. Samples should be collected in a manner that does not rupture or deform phytoplankton cells, particularly when species composition is going to be quantified. Generally, sampling devices and **churn splitters** have minimal impact on phytoplankton cell integrity; exceptions are discussed in NFM A7.4, table 7.4–8. See NFM A7.5 for more detail on phytoplankton sample collection and processing.

9.1.2 Ancillary Data

Ancillary data collected as part of phytoplankton studies depend on the study objectives (NFM A7.5). Chlorophyll samples commonly are collected along with the phytoplankton sample. Other commonly measured variables are listed in table 10–1. Generally, all subsamples for laboratory analyses, including phytoplankton community composition, are collected from the same grab or composite sample. The volume of the grab or composite sample must be sufficient for all planned analyses.

9.2 Zooplankton

Zooplankton consist of small animals suspended in water that have limited powers of locomotion and that are generally subject to dispersal by the water movements and circulation (Wetzel, 2001). Zooplankton are dominated by four major groups: (1) protists that include **protozoa** and heterotrophic flagellates; (2) rotifers, and two subclasses of crustaceans; (3) cladocerans; and (4) copepods. Zooplankton are major herbivores as well as predators of other zooplankton in lakes and reservoirs (Wetzel and Likens, 2000). In order to better understand lake and reservoir metabolism, it is important to evaluate the composition, biomass, and role of zooplankton within the ecosystem.

9.2.1 Sample Collection

Britton and Greeson (1987) and Wetzel and Likens (2000) describe in detail collection and processing of zooplankton samples. Zooplankton can be collected with bottles, **bailers** or tubes, water pumps, and plankton nets, followed by filtering the water sample onsite or in the laboratory (Britton and Greeson, 1987; Wetzel and Likens, 2000). Plankton traps, such as tow nets or Schindler-Patalas traps, are often used to collect concentrated zooplankton samples. For more detail on zooplankton sample collection and processing, see Britton and Greeson (1987) and Wetzel and Likens (2000).

9.2.2 Ancillary Data

Ancillary data collected for zooplankton studies, like phytoplankton samples (above), depend on the study objectives. Commonly measured variables are listed in table 10–1.

9.3 Microorganisms

Three groups of potentially pathogenic microorganisms affect the public health acceptability of waters in the United States: fecal indicator bacteria, fecal indicator viruses, and protozoan pathogens. Detailed guidelines for sampling microorganisms that commonly are monitored for environmental assessments are found in NFM A7.1 through A7.5 and in other references cited in the respective sections below.

9.3.1 Fecal Indicator Bacteria

Fecal indicator bacteria are commonly used to assess the microbiological quality of water. Detailed guidelines for the collection and processing of fecal indicator bacteria are provided in NFM A7.1, which describes tests that can be completed in the field for identifying and enumerating five types of fecal indicator bacteria: total **coliform** bacteria, fecal coliform bacteria, ***Escherichia coli (E. coli)***, fecal **streptococci**, and ***Enterococci***. Also included in NFM A7.1 is guidance to collect samples to be analyzed for *Clostridium perfringes* (*C. perfringens*). Although these bacteria are not typically disease causing, they are usually associated with fecal contamination and the possible presence of waterborne pathogens.

The density of indicator bacteria is a measure of suitability of water for body-contact recreation or for consumption. Sterile techniques should be followed and their use documented in field notes when collecting and processing samples for fecal indicator bacteria. The equipment and supplies needed for sample collection, processing, and analysis (presence-absence or most-probable-number analysis) of fecal indicator bacteria in water and sediment are detailed in NFM A7.1.

The areal and temporal distribution of bacteria in the water and bottom sediments of lakes and reservoirs can be as variable as the distribution of suspended material because bacteria commonly are associated with solid particles. Because of this variability, it may be necessary to collect multiple samples throughout the lake to accomplish the data-quality objectives. At least three bottom-material samples should be collected from each site at the same depth and composited (NFM A7.1) due to the spatial heterogeneity of bacteria. Refer to NFM A7.1 for sampling methods and quality-control and quality-assurance procedures.

9.3.2 Fecal Indicator Viruses

Detailed guidelines for the collection and analysis of fecal indicator viruses (as indicated by **coliphage** estimates) are provided in NFM A7.2. Coliphages are viruses that are used as indicators of fecal contamination and of the microbiological quality of the water. Coliphages are not pathogenic to humans. Somatic coliphages and F-specific coliphages are used as viral indicators and are abundant in waters polluted with sewage contamination (International Association of Water Pollution Research and Control Study Group on Health Related Water Microbiology, 1991).

In lakes and reservoirs, the hand-dip, grab-sample, or sterile-point-sampler methods can be used to collect the sample (NFM A7.2). The specific equipment and supplies used to collect and analyze samples for fecal indicator viruses must be decontaminated and rendered sterile before and after sampling. Sterile conditions also must be maintained during collection, preservation, transport, and analysis of fecal indicator virus samples (NFM A7.2). Specific procedures have been developed that must be strictly followed (NFM A7.2). After collection, immediately chill samples in an ice chest or refrigerator at 1 to 4 °C, without freezing. To ship samples to the laboratory, double bag the sample containers before placing them into the bagged ice in a cooler. Seal the analytical services request form and, if required, the chain-of-custody form in doubled plastic bags and tape these forms to the inside lid of the cooler being shipped to the laboratory. Check that the sample identification and relevant information for use by the laboratory have been recorded correctly. The laboratory must begin the analysis of samples within 48 hours of sample collection.

9.3.3 Protozoan Pathogens

Cryptosporidium and ***Giardia*** are the principal protozoan pathogens that have been identified as the cause of several outbreaks of waterborne diseases and that have compromised the acceptability of public water supplies within the United States (Centers for Disease Control and Prevention, 2012; Xiao and others, 2013). The oocysts and cysts of protozoa survive longer in the environment and have greater resistance to disinfection than fecal indicator bacteria. Detailed guidelines for the collection and analysis of protozoan pathogens are provided in NFM A7.3.

Because there are cyclical and seasonal variations in their concentrations, a sampling program for *Cryptosporidium* oocysts and *Giardia* cysts needs to be conducted over an extended period of time (LeChevallier and Norton, 1995; Wilkes and others, 2009). A summary of requirements for sample-collection equipment, procedures for sample preservation, and holding-time requirements are given in NFM A7, section 7.3, table 7.3–2. In lakes and reservoirs, samples are collected using sterile equipment (see NFM A2) and adapting the sterile techniques described in NFM A7.1, A7.2, and A7.3.

The field and laboratory procedures for protozoan samples described in NFM A7 are specific to analysis by USEPA Method 1623: *Cryptosporidium* and *Giardia* in Water by Filtration/IMS/FA (U.S. Environmental Protection Agency, 2005). Method 1623 should be performed in a certified laboratory by a qualified analyst.

9.4 Benthic Fauna

Benthic fauna are animals living on and in the bed sediments and on plants in the littoral zone of lakes and reservoirs; the species are usually highly diverse (Wetzel and Likens, 2000). The segmented worms (oligochaetes and leaches), microcrustacea (ostracods), and macrocrustracea (mysids, isopods, decapods, and amphipods) are the major components of benthic fauna of freshwaters (Wetzel and Likens, 2000). As part of many lake and reservoir studies, reliable quantitative estimates of the amount and distributions of the benthic fauna are needed. The objective of many benthic fauna studies is focused on describing the abundance of insect larvae or other immature insect forms.

9.4.1 Sample Collection

Wetzel and Likens (2000) describe the collection and analysis techniques for benthic fauna in detail. Britton and Greeson (1987) describe in detail the collection and processing techniques used specifically for benthic invertebrates.

- Benthic invertebrates can be collected using:
  - Ekman, Ponar, VanVeen, and Petersen-type dredges or grabs
  - A smaller Ponar dredge (for example, the “Petite Ponar Grab”)
  - Core samplers, when an undisturbed sample is needed

9.4.2 Ancillary Data and Sample Processing

Ancillary data typically collected for benthic fauna studies, like other biological samples (above), depend on the study objectives. Some of the common measured variables collected in benthic fauna studies are listed in table 10–1.

9.5 Macrophytes

Macrophytes (typically referred to as aquatic plants) include vascular plants, bryophytes, and algae that can be seen without magnification. Characteristic forms of vascular plants found in aquatic habitats are (1) emergent rooted aquatics, (2) floating-leaved rooted aquatics, (3) submersed rooted aquatics, and (4) free-floating aquatics (Britton and Greeson, 1987). The growth of aquatic macrophytes is typically controlled by the availability of nutrients. Nutrient enrichment may result in excessive plant growth that can become a major nuisance, causing water-quality problems. Many nonnative submersed and emergent aquatic macrophytes invade and grow unchecked in many lakes and reservoirs. Some of these plants may form surface mats of vegetation.

The distribution and growth of aquatic macrophytes depend on depth of water, illumination, nutrient availability, water quality, water clarity, substrate, and water velocity (Britton and Greeson, 1987). Different species grow at different depths and light intensities. Sometimes the types of rooted vascular plants are arranged in zones corresponding to successively greater depths. The ability to grow in deeper water is impacted by turbidity. Free-floating aquatic plants may occur anywhere on the water surface, depending on wind direction and intensity and surface flow.

9.5.1 Sample Collection and Processing

- A quantitative description of the distribution of aquatic macrophytes may be obtained by careful sampling within defined quadrats (Wetzel and Likens, 2000).

Sampling sites can be selected using either a stratified random design or along a transect(s). Much of the biomass of rooted aquatic plants can occur below ground; therefore, it is essential to sample biomass from both above and below ground in any quantitative study. Replicate sediment core samples may be used to determine below-ground biomass.

- Aquatic macrophyte samples are typically collected by hand or with grappling hooks, rakes, oyster tongs, or dredges (Britton and Greeson, 1987).
- Entire plants should be collected, including the flowers, seeds, and if present, roots, and rhizomes or tubers, if possible.

For more detail on aquatic macrophyte collection and processing, see Britton and Greeson (1987) and Wetzel and Likens (2000).

9.5.2 Ancillary Data

Ancillary data typically collected as part of aquatic macrophyte studies, like other biological samples (above), depend on the study objectives. Some of the common variables measured as part of macrophyte surveys are listed in table 10–1.

9.6 Fish

Fish are the most common vertebrates in lakes and reservoirs. Their growth and survival depend, in part, on phytoplankton and zooplankton (food web) interactions and energy flow. Therefore, the amount and types of fish present are indicators of the ecological health of a lake or reservoir. Fish are often sampled to assess community structure, examine gut contents, and perform tissue-contaminant analysis. As top predators in the aquatic food chain, they tend to biomagnify and bioaccumulate toxins that move through the food chain, such as methylated mercury.

9.6.1 Sample Collection and Processing

Collecting fish in a quantitative manner requires knowledge of the selectivity, limitations, and efficiency of the different types of sampling gear (Britton and Greeson, 1987). Because of the nonrandom distribution of fish populations, the choice of sampling method, time of sampling, and frequency depend on the objectives of the particular study. The American Fisheries Society (Zale and others, 2013) recently updated its description of fish-sampling techniques to describe both passive and active capture techniques, as well as acoustical methods. In “Standard Methods for Sampling North American Freshwater Fishes” (Bonar and others, 2009), sections are dedicated to describing sampling of both warm- and coldwater fish in small and large standing waters. Warmwater fish typically occupy the littoral zones of lakes and reservoirs. Warmwater fish are typically of riverine origin and are oriented to the shoreline bottom (Miranda and Boxrucker, 2009). Few warmwater fish in the United States are strictly pelagic. Fish that do occupy the pelagic zone, like white, striped, and hybrid bass, originally were from fish families of marine origin. Coldwater fish typically occupy the hypolimnion of lakes and reservoirs and reservoirs, during stratified periods, but may be found throughout the water body when it is unstratified. Water bodies that support fish (such as trout and salmon) throughout the year are referred to as coldwater lakes and reservoirs (Beauchamp and others, 2009).

The most common active and passive gear used to sample fish in the littoral and pelagic zones include electroshocking boats, shoreline seines, purse seines, gill nets, fyke nets, trawls, and hydroacoustic devices. Miranda and Boxrucker (2009) report that each type of gear is particularly useful for sampling selected species, life stages, or species that occupy distinct habitats. Each type of gear and survey, however, provides only an approximate representation of the fish assemblage inhabiting the lake or reservoir. Miranda and Boxrucker (2009) found that electrofishing and fyke netting were the most useful tools for describing the fish community in the littoral zone, whereas, gill netting and hydroacoustic techniques were best suited to describe fish communities in the pelagic zone.

9.6.2 Ancillary Data

Ancillary data typically collected as part of fish studies, like other biological studies (described above), depend on the study objectives. Some of the variables commonly measured as part of fish surveys are listed in table 10–1. Some information that is especially useful includes specific electrical conductance to adjust the electrofishing settings, water temperature, turbidity (Secchi depth), and water depth (Miranda and Boxrucker, 2009). To help understand the results from fyke and gill nets, the dissolved-oxygen concentration at 1 m above the bottom and the average bottom slope should be measured. It is also important to document how long each type of gear was used.

Acknowledgments

The authors wish to acknowledge the dedication, expertise, and contributions of those U.S. Geological Survey (USGS) scientists who reviewed and improved the technical quality of this chapter of the “National Field Manual for the Collection of Water-Quality Data.” USGS reviewers and other contributors included Donna Francy, Jennifer Graham, Celeste Journey, James LaBaugh, Cassandra Pfeifle, Ryan Rasmussen, Chuck Schalk, Stan Skrobialowski, and Yvonne Stoker.

We thank the USGS Science Publishing Network team of Marilyn Billone, Iris Collies, Laura Coplin, Elizabeth Good, Cathy Knutson, and Angela Timms for their editorial, drafting, layout, and publication assistance.

References Cited

American Public Health Association, 2005, Standard methods for the examination of water and wastewater (21st ed.): Washington, D.C., American Public Health Association, American Water Works Association, and Water Environment Federation, sections 1060 and 10200.

Averett, R.C., and Schroder, L.J., 1994, A guide to the design of surface-water-quality studies: U.S. Geological Survey Open-File Report 93–105, 39 p., http://pubs.er.usgs.gov/publication/ofr93105.

Baranov, I.V., 1961, Biohydrochemical classification of reservoirs in European U.S.S.R., *in* Ti˘uˆrin, P.V., ed., 1966, The storage lakes of the U.S.S.R. and their importance for fishery: Jerusalem, Israel Program for Scientific Translations, p. 139–183.

Baxter, R.M., 1977, Environmental effects of dams and impoundments: Annual Review of Ecology and Systematics, v. 8, p. 255–283, http://www.annualreviews.org/doi/abs/10.1146%2Fannurev.es.08.110177.001351.

Beauchamp, D.A., Parrish, D.L., and Whaley, R.A., 2009, Coldwater fish in large standing waters, chap. 7 *of* Bonar, S.A., Hubert, W.A, and Willis, D.W., eds., Standard methods for sampling North American freshwater fishes: Bethesda, Md., American Fisheries Society, p. 97–117.

Bellinger, E.G., and Sigee, D.C., 2010, Freshwater algae—Identification and use as bioindicators: Hoboken, New Jersey, Wiley-Blackwell, 271 p.

Benson, N.G., 1982, Some observations on the ecology and fish management of reservoirs in the United States: Canadian Water Resources Journal, v. 7, p. 2–25, http://dx.doi.org/10.4296/cwrj0701002.

Bonar, S.A., Hubert, W.A, and Willis, D.W., eds., 2009, Standard methods for sampling North American freshwater fishes: Bethesda, Md., American Fisheries Society, 335 p.

Braun, C.L., Wilson, J.T., Van Metre, P.C., Weakland, R.J., Fosness, R.L., and Williams, M.L., 2012, Grain-size distribution and selected major and trace element concentrations in bed-sediment cores from the Lower Granite Reservoir and Snake and Clearwater Rivers, eastern Washington and northern Idaho, 2010: U.S. Geological Survey Scientific Investigations Report 2012–5219, 81 p., http://pubs.usgs.gov/sir/2012/5219/.

Britton, L.J., and Greeson, P.E., eds., 1987 [1989], Methods for collection and analysis of aquatic biological and microbiological samples: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A4, 363 p., http://pubs.er.usgs.gov/publication/twri05A4.

Carlson, R.E., 1977, A trophic state index for lakes: Limnology and Oceanography, v. 22, p. 361–369.

Centers for Disease Control and Prevention, 2012, Cryptosporidiosis surveillance—United States, 2009–2019 and Giardiasis surveillance—United States, 2009–2010: Surveillance Summaries, v. 61, no. 5, 23 p.

Clesceri, L.S., Greenburg, A.E., and Eaton, A.D., eds., 1998, Standard methods for the examination of water and wastewater (20th ed.): Alexandria, Va., American Public Health Association, American Water Works Association, Water Environment Federation, 1,325 p.

Cooke, G.D., Welch, E.B., Peterson, S.A., and Nichols, S.A., 2005, Restoration and management of lakes and reservoirs: New York, Taylor and Francis, 591 p.

De Lanois, J.L., and Green, W.R., 2011, Hypolimnetic dissolved-oxygen dynamics within selected White River reservoirs, northern Arkansas-southern Missouri, 1974–2008: U.S. Geological Survey Scientific Investigations Report 2011–5090, 15 p., http://pubs.usgs.gov/sir/2011/5090/.

Department of the Interior, Departmental Manual Part 485, Safety and Occupational Health Program, accessed February 13, 2015, at http://elips.doi.gov/elips/Browse.aspx?startid=1594&dbid=0.

Ford, D.E., 1990, Reservoir transport processes, *in* Thornton, K.W., Kimmel, B.L., and Payne, F.E., eds., Reservoir limnology—Ecological perspectives: New York, Wiley, p. 15–42.

Gaugush, R.F., 1987, Sampling design for reservoir water quality investigations: U.S. Army Corps of Engineers Instruction Report E–87–1, 86 p.

Gloss, S.P., Mayer, L.M., and Kidd, D.E., 1980, Advective control of nutrient dynamics in the epilimnion of a large reservoir: Limnology and Oceanography, v. 25, p. 219–228.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resource Investigations, book 4, chap. A3, 523 p., http://pubs.usgs.gov/twri/twri4a3/.

Hem, J.D., 1989, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263 p., http://pubs.usgs.gov/wsp/wsp2254/html/pdf.html.

Hirsch, R.M., and DeCicco, Laura, 2014, User guide to Exploration and Graphics for RivEr Trends (EGRET) and dataRetrieval—R packages for hydrologic data: U.S. Geological Survey Techniques and Methods, book 4, chap. A10, 94 p, http://dx.doi.org/10.3133/tm4A10.

Hoos, A.B., Terziotti, Silvia, McMahon, Gerard, Savvas, Katerina, Tighe, K.C., and Alkons-Wolinsky, Ruth, 2008, Data to support statistical modeling of instream nutrient load based on watershed attributes, southeastern United States, 2002: U.S. Geological Survey Open-File Report 2008–1163, 50 p., http://pubs.usgs.gov/of/2008/1163/.

Horne, A.J., and Goldman, C.R., 1994, Limnology (2d ed.): New York, McGraw-Hill, 576 p.

Hutchinson, G.E., 1957, A treatise on limnology. I. Geography, physics and chemistry: New York, Wiley, 1,015 p.

Hutchinson, G.E., 1967, A treatise on limnology. II. Introduction to lake biology and limnoplankton: New York, Wiley, 1,115 p.

Hutchinson, G.E., 1973, Eutrophication—The scientific background of a contemporary practical problem: American Scientist, v. 61, p. 269–279.

International Association of Water Pollution Research and Control Study Group on Health Related Water Microbiology, 1991, Bacteriophages as model viruses in water quality control: Water Research, v. 25, no. 5, p. 529–545.

James, W.F., and Barko, J.W., 1991, Littoral-pelagic phosphorus dynamics during nighttime convective circulation: Limnology and Oceanography, v. 36, no. 5, p. 949–960, http://www.aslo.org/lo/toc/vol_36/issue_5/.

Juckem, P.F., and Robertson, D.M., 2013, Hydrology and water quality of Shell Lake, Washburn County, Wisconsin, with special emphasis on the effects of diversions and changes in water level on the water quality of a shallow terminal lake: U.S. Geological Survey Scientific Investigations Report 2013–5181, 77 p., http://dx.doi.org/10.3133/sir20135181.

Juracek, K.E., 2011, Sedimentation and occurrence and trends of selected nutrients, other chemical constituents, and cyanobacteria in bottom sediment, Clinton Lake, northeast Kansas, 1977–2009: U.S. Geological Survey Scientific Investigations Report 2011–5037, 28 p., http://pubs.usgs.gov/sir/2011/5037/.

Kimmel, B.L., and Groeger, A.W., 1986, Limnological and ecological changes associated with reservoir aging, *in* Hall, G.E., and Van Den Avyle, M.J., eds., Reservoir fisheries management—Strategies for the 80's: Bethesda, Md., Southern Division American Fisheries Society, p. 103–109.

Kimmel, B.L., Lind, O.T., and Paulson, L.J., 1990, Reservoir primary production, *in* Thornton, K.W., Kimmel, B.L., and Payne, F.E., eds., Reservoir limnology—Ecological perspectives: New York, Wiley, p. 133–194.

Klapper, Helmut, 2005, The assessment, management and reversal of eutrophication, *in* O'Sullivan, P.E., and Reynolds, C.S., eds., The lakes handbook, V. 2, Lake restoration and rehabilitation: Malden, Mass., p. 438–461, http://dx.doi.org/10.1002/9780470750506.ch16.

LeChevallier, M.W., and Norton, W.D., 1995, Giardia and Cryptosporidium in raw and finished water: Journal of the American Water Works Association, v. 87, no. 9, p. 54–68.

Lewis, P.A., Mason, W.T., Jr., and Weber, C.I., 1982, Evaluation of three bottom grab samplers for collecting river benthos: Ohio Journal of Science, v. 82, p. 107–113.

Likens, G.E., 1972, Nutrient and eutrophication—The limiting nutrient controversy: Special Publication of the American Society of Limnology and Oceanography, v. 1, 328 p.

Likens G.E., 1975, Primary production of inland aquatic ecosystems, *in* Lieth, H., and Whittaker, R.W., eds., The primary productivity of the biosphere: New York, Springer-Verlag, p. 185–202.

Miranda, L.E., and Boxrucker, J., 2009, Warmwater fish in large standing waters, chap. 3 *of* Bonar, S.A., Hubert, W.A and Willis, D.W., eds., Standard methods for sampling North American freshwater fishes: Bethesda, Md., American Fisheries Society, p. 29–42.

Mooij, W.M., Trolle, D., Jeppesen, E., and others, 2010, Challenges and opportunities for integrating lake ecosystem modelling approaches: Aquatic Ecology, v. 44, p. 633–667, http://link.springer.com/article/10.1007%2Fs10452-010-9339-3.

Moulton, S.R., II, Kennen, J.G., Goldstein, R.M., and Hambrook, J.A., 2002, Revised protocols for sampling algal, invertebrate, and fish communities as part of the National Water-Quality Assessment program: U.S. Geological Survey Open-File Report 02–150, 75 p., http://pubs.usgs.gov/of/2002/ofr-02-150/.

Osgood, R.A., Brezonik, P.L., and Hatch, L., 2002, Methods for classifying lakes based on measures of development impacts: University of Minnesota Water Resource Center Technical Report 143, 32 p.

Panuska, J.C., and Kreider, J.C., 2003, Wisconsin lake modeling suite program documentation and user's manual, version 3.3 for Windows: Wisconsin Department of Natural Resources PUBL–WR–363–94, 32 p., accessed Dec. 12, 2011, at http://dnr.wi.gov/lakes/model/.

Pellerin, B.A., Bergamaschi, B.A., Downing, B.D., Saraceno, J.F., Garrett, J.D., and Olsen, L.D., 2013, Optical techniques for the determination of nitrate in environmental waters—Guidelines for instrument selection, operation, deployment, maintenance, quality assurance, and data reporting: U.S. Geological Survey Techniques and Methods, book 1, chap. D5, 37 p., http://pubs.usgs.gov/tm/01/d5/.

Ploskey, G.R., 1981, Factors affecting fish production and fishing quality in new reservoirs, with guidance on timber clearing, basin preparation, and filling: U.S. Army Corps of Engineers Waterways Experiment Station Technical Report E–81–11.

Preston, S.D., Alexander, R.B., Woodside, M.D., and Hamilton, P.A., 2009, SPARROW modeling—Enhancing understanding of the Nation's water quality: U.S. Geological Survey Fact Sheet 2009–3019, 6 p., http://pubs.usgs.gov/fs/2009/3019.

Rast, Walter, and Lee, G.F., 1978, Summary analysis of the North American (U.S. portion) OECD eutrophication project—Nutrient loading-lake response relationships and trophic state indices: U.S. Environmental Protection Agency Report EPA–600/3–78–008, 455 p.

Rast, Walter, and Thornton, J.A., 2005, The phosphorus loading concept and the OECD eutrophication programme—Origin, application, and capabilities, *in* O'Sullivan, P.E., and Reynolds, C.S., eds., The lakes handbook, v. 2, Lake restoration and rehabilitation: Malden, Mass., Wiley-Blackwell, p. 354–395, http://onlinelibrary.wiley.com/doi/10.1002/9780470750506.ch14/summary.

Reckhow, K.H., and Chapra, S.C., 1983a, Engineering approaches for lake management, v. 1—Data analysis and empirical modeling: Boston,, Mass., Butterworth Publishers, 340 p.

Reckhow, K.H., and Chapra, S.C., 1983b, Engineering approaches for lake management, v. 2—Mechanistic modeling: Boston, Mass., Butterworth Publishers, 200 p.

Reynolds, C.S., 2006, Ecology of phytoplankton: New York, Cambridge University Press, 535 p., http://dx.doi.org/10.1017/CBO9780511542145.

Robertson, D.M., and Rose, W.J., 2008, Water quality, hydrology and simulated response to changes in phosphorus loading of Butternut Lake, Price and Ashland Counties, Wisconsin, with special emphasis on the effects of internal phosphorus loading in a polymictic lake: U.S. Geological Survey Scientific Investigations Report 2008–5053, 46 p., http://pubs.usgs.gov/sir/2008/5053/.

Robertson, D.M., Garn, H.S., Rose, W.J, Juckem, P.F., and Reneau, P.C., 2012, Water quality, hydrology, and simulated response to changes in phosphorus loading of Mercer Lake, Iron County, Wisconsin, with special emphasis on the effects of wastewater discharges: U.S. Geological Survey Scientific Investigations Report 2012–5134, 58 p., http://pubs.usgs.gov/sir/2012/5134/.

Rowland, R.C., Westenburg, C.L., Veley, R.J., and Nylund, W.E., 2006, Physical and chemical water-quality data from automatic profiling systems, Boulder Basin, Lake Mead, Arizona and Nevada, water years 2001–04: U.S. Geological Survey Open-File Report 2006–1284, 17 p., http://pubs.usgs.gov/of/2006/1284/.

Runkel, R.L., Crawford, C.G., and Cohn, T.A., 2004, Load estimator (LOADEST)—A FORTRAN program for estimating constituent loads in streams and rivers: U.S. Geological Survey Techniques and Methods, book 4, chap. A5, 69 p., http://pubs.usgs.gov/tm/2005/tm4A5/.

Schwarz, G.E., Hoos, A.B., Alexander, R.B., and Smith, R.A., 2006, The SPARROW surface water-quality model—Theory, application and user documentation: U.S. Geological Survey Techniques and Methods, book 6, chap. B3, http://pubs.er.usgs.gov/usgspubs/tm/tm6B3/.

Thornton, K.W., 1990, Sedimentary processes, *in* Thornton, K.W., Kimmel, B.L., and Payne, F.E., eds., Reservoir limnology—Ecological perspectives: New York, Wiley, p. 43–70.

Thornton, K.W., Kennedy, R.H., Magoun, A.D., and Saul, G.E., 1982, Reservoir water quality sampling design: Journal of the American Water Resources Association, v. 18, p. 471–480, http://dx.doi.org/10.1111/j.1752-1688.1982.tb00014.x.

Thornton, K.W., Kimmel, B.L., and Payne, F.E., eds., 1990, Reservoir limnology—Ecological perspectives: New York, Wiley, 256 p., http://www.wiley.com/WileyCDA/WileyTitle/productCd-0471885010.html.

U.S. Army Corps of Engineers, 1987, Reservoir water quality analysis: U.S. Army Corps of Engineers Engineer Manual 1110–2–1201, 189 p.

U.S. Environmental Protection Agency, 1974, The relationship of nitrogen and phosphorus to the trophic state of northeast and northcentral lakes and reservoirs: National Eutrophication Survey Working Paper No. 23, 28 p.

U.S. Environmental Protection Agency, 1986, Quality criteria for water 1986: U.S. Environmental Protection Agency, EPA 440/5–86–001 [variously paged].

U.S. Environmental Protection Agency, 2005, Method 1623—Cryptosporidium and Giardia in water by filtration/IMS/FA: U.S. Environmental Protection Agency, EPA 815–R–05–002, 52 p.

U.S. Geological Survey, 1995, A guide to safe field operations: U.S. Geological Survey Open-File Report 95–777, 34 p., http://pubs.usgs.gov/of/1995/of95-777/.

U.S. Geological Survey, 2014, Safety and health for field operations: Handbook 445–3–H, accessed February 13, 2015, at https://www.usgs.gov/usgs-manual/handbook/hb/445-3-h.pdf.

U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1–A9, http://pubs.er.usgs.gov/publication/twri09.

Van Metre, P.C., Wilson, J.T., Fuller, C.C., Callender, Edward, and Mahler, B.J., 2004, Collection, analysis, and age dating of sediment cores from 56 U.S. lakes and reservoirs sampled by the U.S. Geological Survey, 1992–2001: U.S. Geological Survey Scientific Investigations Report 2004–5184, 180 p., http://pubs.usgs.gov/sir/2004/5184/.

Vollenweider, R.A., 1968, Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication: Paris, Organization for Economic Cooperation and Development Technical Report DAS/CSI/68.27, 159 p.

Vollenweider, R.A., 1976, Advances in defining critical loading levels for phosphorus in lake eutrophication: Memorie dell'Istituto Italiano di Idrobiologia, v. 33, p. 53–83.

Vollenweider, R.A., and Dillon, P.J., 1974, The application of the phosphorus loading concept to eutrophication research: Ottawa, Canada, National Research Council, NRCC Report No. 13690, 42 p.

Vollenweider, R.A., Rast, W., and Kerekes, J., 1980, The phosphorus loading concept and Great Lakes eutrophication, *in* Loehr, R.C., Martin, C.S., and Rast, W., eds., Phosphorus management strategies for lakes: Ann Arbor, Mich., Ann Arbor Science, p. 207–234.

Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A., 2006, Guidelines and standard procedures for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods, book 1, chap. D3, http://pubs.usgs.gov/tm/2006/tm1D3/.

Walker, W.W., 1985, Empirical methods for predicting eutrophication in impoundments, Report 3, Phase II—Model Refinements: U.S. Army Corps of Engineers Technical Report E–81–9, 310 p.

Walker, W.W., 1999, Simplified procedures for eutrophication assessment and prediction—User manual: U.S. Army Corps of Engineers Instruction Report W–96–2, 233 p.

Welch, P.S., 1948, Limnological methods: Philadelphia, Pa., McGraw-Hill, 381 p.

Wetzel, R.G., 1990, Reservoir ecosystems—Conclusions and speculations, *in* Thornton, K.W., Kimmel, B.L., and Payne, F.E., eds., Reservoir limnology—Ecological perspectives: New York, Wiley, p. 227–238.

Wetzel, R.G., 2001, Limnology—Lake and river ecosystems, 3d ed.: New York, Academic Press, 1,006 p.

Wetzel, R.G., and Likens, G.E., 2000, Limnological analyses, 3d ed.: New York, Springer, 429 p.

Wilkes, G., Edge, T., Gannon, V., Jokinen, C., Lyauety, E., Medeiros, D., Neumann, N., Ruecker, N., Topp, E., and Lapen, D.R., 2009, Seasonal relationships among indicator bacteria, pathogenic bacteria, *Cryptosporidium* oocysts, *Giardia* cysts, and hydrological indices for surface waters within an agricultural landscape: Water Research, v. 43, p. 2209–2223, http://dx.doi.org/10.1016/j.watres.2009.01.033.

Wisconsin Department of Natural Resources, 1992, Wisconsin water quality assessment—Report to Congress, 1992: Wisconsin Department of Natural Resources Publication WR254–92–REV, 220 p.

Xiao, G., Qiu, Z., Qi, J., Chen, J., Liu, F., Liu, W., Luo, J., and Shu, W., 2013, Occurrence and potential health risk of Cryptosporidium and Giardia in the Three Gorges Reservoir, China: Water Research, v. 47, p. 2431–2445, http://dx.doi.org/10.1016/j.watres.2013.02.019.

Zale, A.V., Parrish, D.L., and Sutton, T.M., eds., 2013, Fisheries techniques (3d ed.): Bethesda, Md., American Fisheries Society, 1,009 p., https://fisheries.org/shop/55067c.

Glossary

abiotic Denoting nonliving (physical or chemical) components of the environment.

algae Photosynthetic microscopic organisms that may occur as single cells, colonies, or filaments.

allochthonous Denoting material or energy stored in organic matter that was brought into a lake or reservoir.

allophycocyanin An accessory (blue) pigment to chlorophyll readily found in cyanobacteria (blue-green algae) and red algae.

autochthonous Denoting material or energy stored in photosynthetically formed organic matter synthesized within the lake or reservoir.

autotrophic Denoting an organism that is capable of synthesizing its own food from inorganic substances using light or chemical energy. Green plants, algae, and certain bacteria are autotrophs.

bailer A commonly used **thief sampler** consisting of a cylinder (of various diameters and lengths and types of construction material, such as stainless steel, polyvinyl chloride, or fluorocarbon polymer) with double check-valves (top and bottom), with a bottom emptying device.

benthic fauna The animal community associated with and living on the bottom of lakes and reservoirs.

benthic zone The area of a water body associated with the bottom of a lake or reservoir.

biotic Denoting the living (microbial, plant, and animal) components of the environment.

bloom Refers to a large population or extremely high cell densities of phytoplankton; a proliferation of phytoplankton dominated by a single or a few species; or a visible accumulation of phytoplankton at the water surface.

chlorophyll The green photosynthetic pigment found in cyanobacteria (blue-green algae) and in the chloroplasts of algae and plants.

churn splitter(s) A bucket or container (with lid and bottom spigot) used to mix and composite or subdivide a water sample. Churn splitters are of various volumes and types of construction material, such as polypropylene, polyethylene, or fluoropolymer plastic.

coliform A broad class of bacteria commonly used as an indicator of the sanitary quality of water.

coliphage (somatic and F-specific) A type of bacteriophage (bacteria-specific virus) that infects *Escherichia coli* and that is commonly used as a viral indicator.

Cryptosporidium Oocyst-producing unicellular microorganisms that can cause disease in humans and other animals.

cyanobacteria True bacteria with prokaryotic cell structure; however, cyanobacteria also have chlorophyll *a*, a photopigment characteristic of eukaryotic algae and higher plants. Structurally, the cyanobacteria are bacteria-like but functionally, the cyanobacteria are algae-like. Cyanobacteria are often called blue-green algae.

data sonde Multiparameter water-quality monitoring instrument used to measure key water-quality parameters (typically temperature, pH, specific electrical conductance, dissolved oxygen, and others) in the field.

destratification The development of vertical thermal convection or wind-induced circulation within a thermally stratified lake or reservoir that progressively erodes the metalimnion from above and continues until the water body becomes isothermal—often referred to as "lake turnover." *See also* thermal stratification.

detritus Nonliving particulate organic matter found in streams, lakes, and reservoirs.

diagnostic study A study that typically describes or explains the water quality of a lake or reservoir.

dimictic Lakes or reservoirs that have two extended mixing periods in a year, once after summer thermal stratification and the second after winter ice cover.

dissolved organic matter A broad classification of organic molecules defined as less than 0.5 µm in diameter.

diurnal Having a daily cycle, recurring every day.

Enterococcus Bacteria normally found in the feces.

epilimnion The warm, upper layer of a stratified lake or reservoir.

Escherichia coli (E. coli) Gram-negative, rod-shaped bacterium that is commonly found in the lower intestine of warm-blooded organisms, some strains of which are pathogenic.

euphotic zone *See* photic zone.

eutrophic A water body that has high nutrient content and levels of production.

eutrophication The process of nutrient enrichment (particularly nitrogen and phosphorus) in aquatic ecosystems leading to increased production.

flushing rate The rate at which the volume of water in a lake or reservoir is displaced—typically computed as the mean annual inflow or outflow divided by the volume (flushes per day or year).

Giardia Cyst-producing unicellular microorganisms that can cause disease in humans and other animals.

heterotrophic Denoting a type of organism that depends on previously formed organic compounds to provide energy for maintenance, growth, and replication. An organism that cannot synthesize its own food and is dependent on complex organic substances for nutrition is a heterotroph.

hypereutrophic Denoting a water body that has a very high nutrient content and levels of production.

hypolimnion The cold, dense bottom layer of a stratified lake or reservoir; the hypolimnion often becomes anoxic (little or no dissolved oxygen) in productive systems.

interpretive study A study that attempts to explain processes, outcomes, and results for a water body.

in vivo Refers to a measurement made within the natural environmental setting of the organism.

isothermal Uniform temperature. In lakes and reservoirs, isothermal refers to the entire water column being of constant temperature (density).

lacustrine zone The open water, lentic area in a water body. In reservoirs, the zone is at the downstream end, nearest the dam that resembles lake-like, lentic conditions. The lacustrine zone is characterized by a longer residence time, lower concentrations of dissolved nutrients and suspended sediment, clearer water, and a deeper euphotic zone.

lake A naturally formed inland water body of considerable size, localized in a basin that is surrounded by land and is apart from a river, stream, or other form of moving water that serves to feed or drain the lake.

lentic Denoting standing or relatively still water, relating to or living in still water, as opposed to **lotic** (moving water).

light extinction (attenuation) The reduction of light (radiant energy) with depth from both scattering and adsorption by suspended materials.

limnology The study of the physical, chemical, and biological interactions within inland water bodies.

littoral The region of the shore of and shallow bottom of a lake or reservoir where rooted vegetation can inhabit.

lotic Denoting flowing water, relating to or living in flow flowing water, as opposed to lentic (standing or still water).

mesotrophic Denoting a water body that has a moderate nutrient content and levels of production.

metalimnion The middle layer of a stratified lake or reservoir; the metalimnion is characterized by substantial decreases in temperature with depth.

mixed layer The surface layer of water in a lake or reservoir, stratified or not, that is relatively uniform in temperature and mixes as the result of wind and wave actions. This layer is often referred to as the epilimnion.

MOCC Motorboat Operator Certification Course (USGS–SAF–MOCC–S1657–UDT).

monomictic Denoting lakes or reservoirs that mix (destratify) for one prolonged period of the year, typically after summer thermal stratification.

oligotrophic Denoting a body of water with a low nutrient content and levels of production.

PAR (photosynthetic active radiation) Photosynthetic Active Radiation (PAR) measures irradiance or the amount of sunlight or ambient light that diffuses through water compared to surface light. PAR focuses on the dynamics of the photic zone, typically 1–5 meters below the surface (http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings/nldas-parameters/photo-active-radiation).

particulate organic matter Organic matter defined as greater than 0.5 micrometer (µm) in diameter.

pelagic Denoting the free open water area of a lake or reservoir.

photic (euphotic) zone Region of water column where there is enough light to support photosynthesis; typically defined as the region that extends from the surface to the depth where light is approximately 1 percent of that at the surface.

photosynthetic active radiation *See* PAR.

phycoerythrin An accessory (red) pigment to chlorophyll that is unique to the cyanobacteria.

phytoplankton The assemblage of small plants or photosynthetic bacteria suspended in the water having no or limited powers of locomotion.

primary producer Any green plant or any of various microorganisms like phytoplankton and cyanobacteria that can convert light energy (or chemical energy) into organic matter.

profundal zone The deeper area of a lake or reservoir that is free of vegetation.

protozoa A diverse group of unicellular eukaryotic organisms, many of which are motile.

reconnaissance study A study designed to provide a basic description of a water body and help provide information to scope future investigations.

refugia (plural of refugium) An area of a water body that has escaped ecological changes occurring elsewhere and so provides a suitable habitat for relict species.

reservoir Engineered systems (basically consisting of a dam constructed across a topographical constriction in a river valley) for the purpose of water management through planned releases of impounded water.

residence time The average time spent by a given water particle in a water body—water body volume divided by mean annual inflow or outflow (days or years).

riverine zone The up-reservoir lotic part of a reservoir characterized by higher flow, shorter residence time, and higher levels of nutrients and suspended solids. **Abiotic** turbidity often limits the thickness of the photic zone.

shoreline development ratio The ratio of the length of the shoreline to the length of the circumference of a circle whose area is equal to that of the lake or reservoir.

streptococci A group of gram-positive bacteria (genus *Streptococcus*), some strains of which can cause disease.

thermal stratification Refers to formation of layers with a vertical change in the temperature in lakes and reservoirs when water temperatures are above 4 °C (results in warmer water above colder water), or when temperatures are below 4 °C (results in colder water above warmer water).

thermocline The depth in lakes and reservoirs where the temperature gradient is greatest.

thief sampler A water-sample collection device used to collect instantaneous discrete water samples. The most commonly used thief samplers are the Kemmerer sampler, Van Dorn sampler, and double check-valve bailer with bottom emptying device. These samplers are available in various sizes and mechanical configurations and are constructed of various types of material (such as stainless steel, glass, polyvinyl chloride, and fluorocarbon polymer).

transitional zone The mid-reservoir zone between the up-reservoir riverine zone and the lacustrine zone at the lower end of the reservoir, typically characterized by higher phytoplankton productivity and biomass occurring in conjunction with increasing reservoir size (volume) and residence time, sedimentation of suspended inorganic materials, and increased light penetration.

trophic state The level of productivity in a lake or reservoir. The four main trophic states are oligotrophic, mesotrophic, eutrophic, and hypereutrophic.

turbidity The cloudiness or haziness of a fluid caused by the presence of suspended and dissolved matter, such as clay, silt, finely divided organic matter, plankton and other microscopic organisms, organic acids, and dyes.

zooplankton Small animals that feed on bacteria and phytoplankton, and that are suspended in water with limited powers of locomotion.

U.S. Geological Survey—**Lakes and Reservoirs: Guidelines for Study Design and Sampling**—Techniques and Methods 9–A10

ISSN 2328-7055 (online)
https://doi.org/10.3133/tm9-a10
Supersedes USGS Techniques of Water-Resources Investigations Book 9, Chapter A10, version 1.0