Algae: Source to Treatment

AWWA MANUAL M57
First Edition

American Water Works Association

Contents

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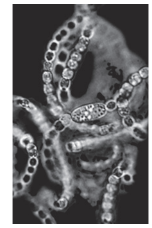
Methods



Chapter 1

Recent Developments in Online Monitoring Technology for Surveillance of Algal Blooms, Potential Toxicity, and Physical–Chemical Structure in Rivers, Reservoirs, and Lakes

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SUMMARY

Disclaimer: The vendors, manufacturers, and equipment described in this work were chosen as representative examples of the types of instrumentation currently commercially available for use in the water-quality monitoring field. The inclusion of these examples does not constitute an endorsement by the Center for Applied Aquatic Ecology, North Carolina State, or AWWA. Sensor development and the area of online monitoring is changing rapidly, therefore individuals interested in specific monitoring areas or equipment types are encouraged to use an Internet Web search to determine all possibilities.

Previous AWWA manuals and review papers have discussed the application of many online monitoring tools (e.g., Grayman et al. 2001, Knappe et al. 2004, Glasgow

et al. 2004), but in the last ca. five years significant advances have been made in communication technology and instrument development, resulting in the introduction of many new products that are useful in monitoring algae and associated water quality parameters. The main objective of this chapter is to introduce the reader to new developments in online monitoring using Web-based technologies and real-time or near-real-time sensors useful in the detection and monitoring of algae. Specific instruments and their limitations will be described, as well as case studies of monitoring programs that are currently operational. Suggestions are included of an appropriate strategy for managing a program with the ultimate goal to track algal blooms and associated physical–chemical conditions in surface freshwater sources.

A successful online monitoring program requires appropriate planning in the installation and deployment of online monitoring equipment, and in choosing methods for the acquisition and postprocessing of the data for efficient operational and management decisions. Large amounts of data are acquired by this type of program due to the short-time-scale sampling that is possible with presently available equipment. Moreover, efficient communication systems enable rapid uploads of data to the data acquisition computer (DAC) and Web site. The rapid development in this technology has led to availability of dedicated hardware and software through many commercial vendors. It is also possible for a water treatment plant or municipality to create custom-designed systems for specific problems using commercially available hardware and in-house information technology personnel. Initial investment in planning will yield an online system with functional, valuable data products to assist operators and managers.

Recent important developments in pigment sensor technology have enabled improved tracking of algal blooms in real time and provide an early warning system for water treatment plant operators and managers. Various manufacturers have integrated both chlorophyll (indicator of total phytoplankton biomass) and phycocyanin pigment sensors (the latter, a major pigment in cyanobacteria) into multiparameter water quality sondes, allowing remote assessments of relative fluorescence. These remote data inform interested parties of impending or existing changes in algal biomass in real time or near-real time. With this early warning, dedicated field samples can be taken to quantitatively assess biomass, species composition, cyanotoxins, taste and odor compounds, and other parameters of interest. Remotely acquired online data for algal pigments are in relative fluorescence units, however, and should be calibrated for each bloom event by dedicated discrete field sampling for chlorophyll *a* and phycocyanin concentrations, and through analysis by standardized laboratory methods.

Many options for instrumentation and modes of deployment are available for establishing a Web-based online monitoring system. Laboratory-based instruments include various flow-through devices that can be installed in-line with source water to give an accurate real-time assessment of algal blooms. In addition to standard packages for environmental conditions, these instruments include the above-mentioned pigment sensors. Recently, a quantitative biosensor also became commercially available, which uses bluegill sunfish as "sentinels" for toxic conditions in source waters. This technology senses not only the presence of harmful algal toxins, but also other substances that are toxic to fish. Instruments and systems available for field deployment include fixed-structure and buoy-based water-column profilers and autonomous underwater vehicles (AUVs) that can be programmed to assess water quality in large reservoirs.

The data acquired by profilers and in-line source water instruments are limited spatially since they are fixed site deployments, whereas data from AUV technology are limited temporally because of the high cost and effort involved to continually run AUVs. Online real-time monitoring systems need to be supported by both regularly scheduled and event-driven field sampling efforts to calibrate the instruments. In addition, remotely sensed pigment data require calibration with samples analyzed using standard laboratory methods. Overall, the online monitoring programs built around this equipment, in concert with standard Web-based information technology, can provide operators and managers with valuable early warning system capability for detecting and tracking harmful algal blooms in real or near-real time.

INTRODUCTION

Potable water treatment plants need to monitor source water conditions on a timescale as close to real time as possible. Such data provide managers and operators the capability to detect changing conditions, such as developing algal blooms or turbidity/pollutant spikes, that require immediate action for efficient, cost-effective water treatment. Increases in the nutrient pollution (cultural eutrophication) of surface waters can lead to algal blooms, the occurrence of taste and odor causing organisms, and potentially toxic algal species (here including cyanobacteria; e.g., Wetzel 2001, Touchette et al. 2007, Burkholder et al. 2010, Botana 2007). Anthropogenic impacts on reservoirs will continue to intensify in the future due to increases in population growth and watershed development. Algal blooms can develop rapidly at distant sites and can then be transported to municipal source water intakes by increased precipitation/flow, by changes in wind magnitude and direction, or from controlled water release from dams as examples. In order to sample and monitor the dynamic nature of algal blooms, source waters should be monitored, insofar as economically feasible, at both high temporal and small spatial scales.

The need for drinking water is on the rise due to urban development and population growth in many parts of the United States. At the same time, water shortages and usage restrictions are becoming more frequent due to shortages caused by climatic events, such as long-term droughts (Arnell 1999, Lettenmaier et al. 2004, Milley et al. 2005). The lower flushing rates imposed by droughts often promote algal blooms in nutrient-enriched (eutrophic) surface waters (Wetzel 2001). Many water plant operators and managers often do not have the lead time to sample small-scale events or the early warning notification to control problems such as increases in potentially toxic algal blooms. Thus, commonly warning of impending, in-progress, or recent increases in algal biomass is captured during field-based sampling of a water source by water plant personnel or following complaints from recreational users and other concerned citizens.

Traditional field efforts for water quality monitoring are cost and labor intensive due to the requirement of personnel, vehicles, and sampling gear, and can be augmented and strengthened using online and real-time-accessible equipment. Instruments such as multiparameter sondes are underutilized when monitoring programs depend on field sampling efforts exclusively. Infrequent sampling is conducted in most standard field monitoring programs, and this frequency misses many pollutant-loading events that occur on smaller timescales. New Web-based technologies and developments in real-time monitoring equipment, with hourly or more frequent sampling capability 24/7, can be valuable in the assessment of algal blooms and the deleterious changes in coupled physical–chemical conditions (e.g., increases in nutrients, turbidity, pH, and dissolved oxygen). The information gained from the detection of developing algal blooms and pollutant spikes in real or near-real time can be a powerful tool in guiding day-to-day decisions in water treatment protocols.

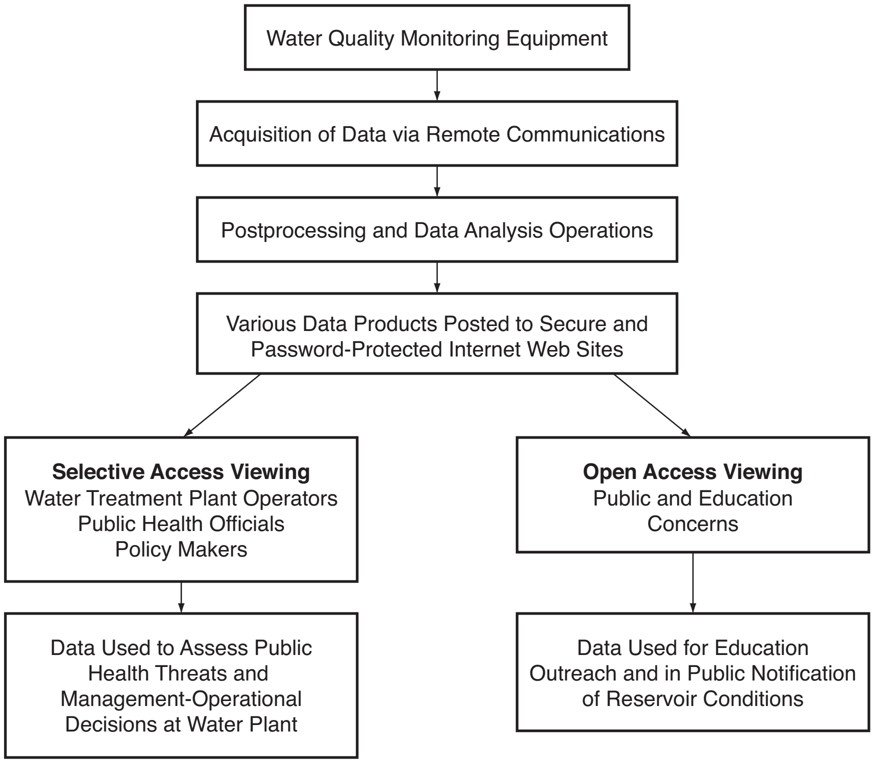
Recent introductions of commercial water quality monitoring equipment have included buoy- and piling-mounted water-column profilers useful in monitoring biological and physical–chemical parameters throughout the entire water column. Extended deployment water quality instruments equipped with antibiofouling measures have pigment-specific sensors that allow real-time monitoring of algal biomass as relative chlorophyll or phycocyanin fluorescence. AUV technology recently has been designed to assess water quality in entire reservoirs, providing three-dimensional representations of the reservoir environment. In addition, the recent application of biomonitoring technology using fish as biosensors has resulted in a commercially available system to monitor a wide range of chemicals and environmental stressors, including emerging and unknown toxicants in source waters. These significant new hardware developments have been accompanied by new water quality software management tools. The large amounts of data acquired by these technologies require user-friendly postprocessing and visualization software packages for rapid, accurate management decisions and public notification.

DEPLOYMENT AND OPERATIONAL CONSIDERATIONS IN ONLINE MONITORING PROGRAMS

The development of a sound strategy that considers the data of interest, the site or sites of interest, and the amount of funds dedicated to the effort is necessary for maximum success before initiating an online monitoring program. Depending on the number of monitoring units that are economically feasible for a given real-time program, the primary sensor should be placed at or near the intake to drinking water treatment plants to afford depth profiles in real-time assessment of physical–chemical conditions and algal abundance. Instruments can also be placed in-line with raw water intake pipes between the reservoir and the water treatment plant. Secondary sensors that are deployed should be located at sites distant from the intake where the majority of the upstream or incoming flow and pollutants can be assessed; for example, sensors mounted upstream from the intake on bridge pilings, situated in an area where the reservoir narrows and large volumes of water flow past. If a suitable hard structure such as on a bridge piling or channel marker is not available for mounting instruments, a floating platform or buoy system can be used. However, floating systems are often logistically hard to maintain and there are potential difficulties related to liability and in obtaining the proper permits for deployment. Problem areas in a reservoir known to have recurrent algal blooms or water quality problems are also candidates for real-time monitoring, such as where algal blooms historically occur or where there are extended water residence times or low flushing rates. The acquisition of online and real-/near-real-time field data can be programmed to occur at varied timescales depending on the user's requirements. Due to the stand-alone nature of the equipment, timescales of minutes to hours can be achieved, giving maximum temporal resolution in the data.

Large amounts of data can be acquired quickly in an online monitoring program, which can overwhelm a facility that has limited data acquisition, management, and decision-making power. It is important to acquire high-quality, properly calibrated data that can be viewed by managers and other users with short lead-time. It is also vital that programs with numerous field sites have the ability to manage, process, and present the large amounts of data in an easily interpretable format. To this end, a necessary feature of online monitoring programs is a robust data acquisition and postprocessing software package. Web-based technologies and software packages (e.g., MATLAB, LabView, Campbell Scientific RTMCPRO) are available that can seamlessly integrate data acquired in real time with user-specific programming based on individual needs. These software packages can be specifically configured for data acquisition, visualization, and dissemination via the Internet.

The construction of a user-friendly Web site consisting of graphics that are easily understood is also essential in online monitoring programs. Multilevel,



Note: After data acquisition and postprocessing, water quality data managers can post various data products to Web sites based on final use. Products used in water plant and public health management and operational uses can also be password-protected to allow access only by authorized personnel. The acquisition of high temporal- and spatial-scale data allows more confidence for managers and policy makers in decisions about appropriate water treatment protocols during algal blooms. Educational organizations and the general public can access the data for use in instructional and recreational activities, respectively.

Figure 1-1 A generalized flow diagram of data acquisition and product dissemination illustrating how water quality monitoring products can be distributed to both public and private concerns (Courtesy of the NC State University Center for Applied Aquatic Ecology)

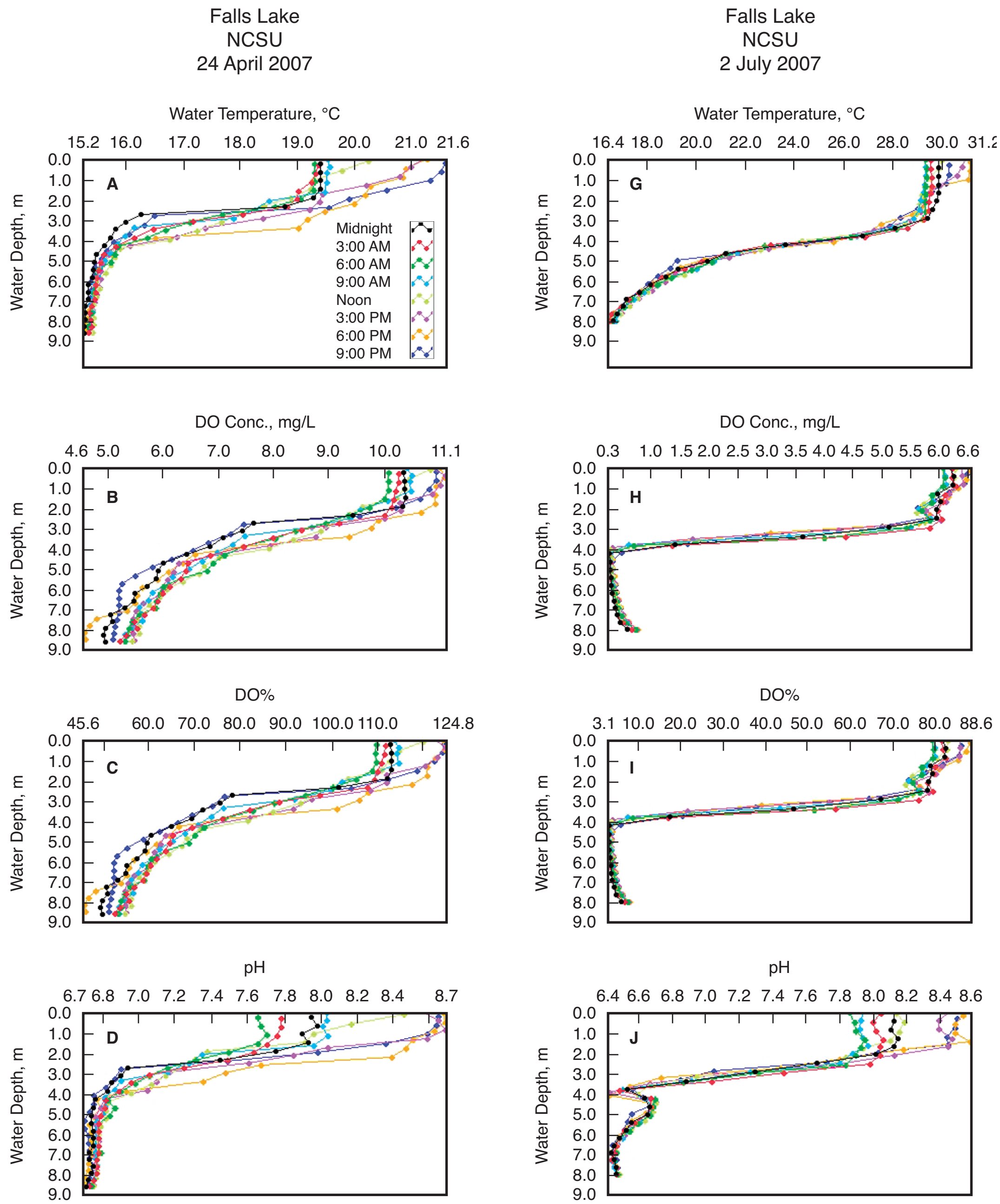
password-protected sites on the same Web site are a popular method of providing data to various user groups. Web pages can be constructed to provide the public with information concerning water quality conditions and the presence of algal blooms or unusual physical–chemical conditions. More detailed Web pages, accessible via a password, can be constructed for a specific audience (Figure 1-1). Graphics and data sets addressing specific geographical locations or water plant operations can be made available to local utility managers and operators to assist in decision making. For instance, the presence of large numbers of taste and odor causing algal species can be communicated through a secure Web site, and appropriate actions can be taken by personnel responsible for water plant operations. Other important considerations in the acquisition and dissemination of algal and physical–chemical data are the duration between data acquisition and posting and in the validation and calibration of online/real-time data. Developers of online monitoring systems must decide the minimum timescale that is acceptable and then build the system accordingly. This decision will have bearing, as well, on the type of offsite communication technology selected for use. If the timescale of interest is minutes to hours, for example, RF modems (spread spectrum radio) or satellite methods of communication would provide appropriate support. If the timescale of interest is multiple hours or even days, then cell phone modems can be used. Also, depending on the length of a program and the data acquisition timescale, a large archive of data can be obtained that can then be mined at a later date for information such as seasonal changes and the response of the source water (e.g., reservoir) to event-driven inputs (e.g., turbidity spikes from rain events, algal blooms, other physical–chemical events). The long-time-series data provided by these monitoring efforts can be valuable in assessing trends in water quality parameters in concert with changing land use and climatic events, and the efficacy of management strategies to reduce loadings of nutrients and other pollutants of concern.

An example of an online field monitoring program that uses currently available commercial technology for real-time collection and rapid dissemination of algal and physical–chemical water column structure in a reservoir is the North Carolina State University (NCSU) Center for Applied Aquatic Ecology North Carolina Reservoirs Cyanobacteria Project, originally funded by the North Carolina Department of Health and Human Services and the US Centers for Disease Control and Prevention. Using data acquired from water quality sondes, profiler technology, and custom LabView programming, investigators can monitor the water column from depth profiles for six parameters taken in both local and distant reservoirs. The parameters are user-selectable and can be chosen based on need. Data are acquired from each station's sonde by a data logger and then communicated via cell phone modem to a central DAC where the information is automatically posted to a Web site (www.ncsu.edu/wq and www.ncsu.edu/wq/RTRM/dp14/ index.html) for viewing. Depth profiles of these data (e.g., Figure 1-2) at 3-hour intervals show hydrological conditions during spring and summer. The first set of profiles (Figure 1-2A–F), taken 24 April 2007, shows a spring phytoplankton bloom and the associated water-column conditions. The second set (Figure 1-2G–L) document the water-column structure during well-stratified summer conditions on 2 July 2007. These data are being used by local water plant managers to assess changes in source water quality in near-real time for modifying treatment protocols.

Commercial enterprises have recently developed data management services that include the acquisition of the data and/or data postprocessing and delivery of final data summaries including graphic visualizations. For example, EcoNet® (YSI Inc.) is an Internet-enabled data management system designed to collect and analyze water quality and hydro-meteorological data. This Web-enabled remote monitoring and control system is designed to acquire and postprocess large amounts of data that are then available via the Internet for user accessibility and management decisions. An example of such an operational system is the Mecklenburg County, N.C., Continuous Monitoring and Alert Notification Network (CMANN). This system includes 24 continuously sampling multiparameter water quality sondes linked to the Internet via EcoNet. The purpose of the CMANN program is to provide real-time water quality information to public works officials and other end users via specific Web sites when environmental changes occur on a short timescale.

PIGMENT SENSORS: FIELD MEASUREMENTS VERSUS LABORATORY METHODS

Fluorescence-based sensors are powerful tools for monitoring relative algal biomass, but care is needed in interpreting the fluorescence measurements with actual algal numbers or chlorophyll concentration data (Kirk 1994). These sensors can provide both discrete and continuous data concerning the presence of algae but are relative in comparison to



NOTE: The graphs illustrate two selected days, which include three hourly casts resulting in eight complete profiles per day. The first series (panels A–F) show water temperature, DO, pH, turbidity, and chlorophyll relative concentration on 24 April 2007. These plots reveal interesting structure concerning the thermocline, high pH values, turbidity structure, and chlorophyll structure due to a spring bloom. The second series (panels G–L) show the same parameters on 2 July 2007, revealing a strong thermocline, anoxic conditions below 4 m, and peaks in turbidity and chlorophyll structure just below the thermocline.

Figure 1-2 Whole water column structure of site located at a municipal water plant reservoir intake using profiler technology (Courtesy of NC State University Center for Applied Aquatic Ecology)

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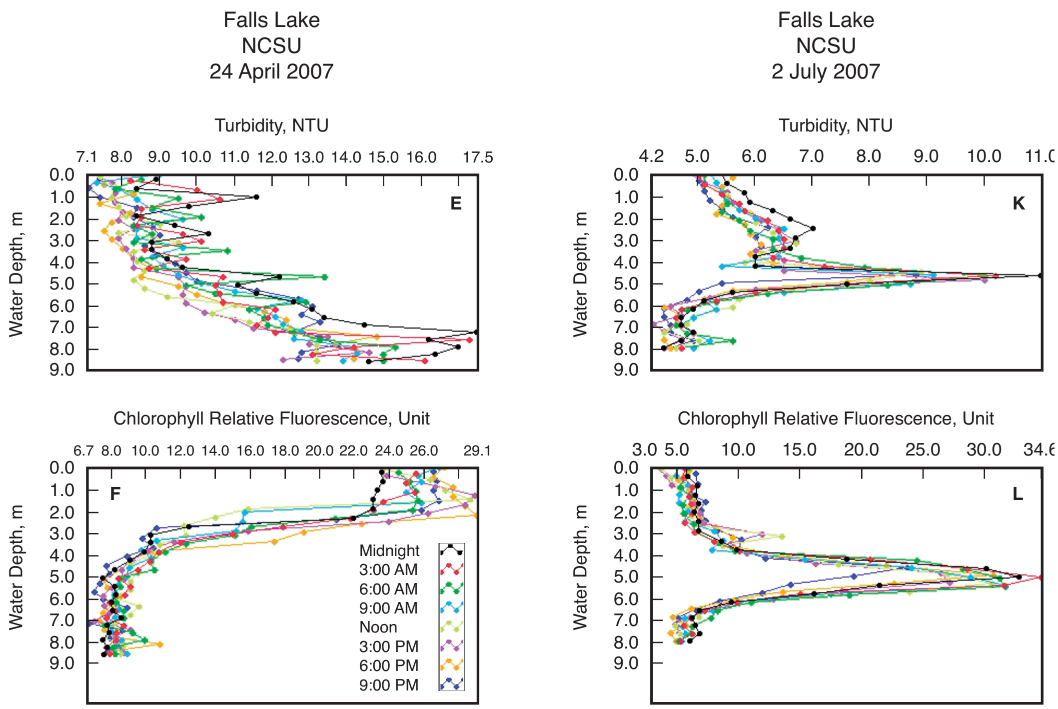

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Figure 1-2 Whole water column structure of site located at a municipal water plant reservoir intake using profiler technology (continued)

standard laboratory methods, and thus the data are reported as relative fluorescence units. Many phytoplankton have a pronounced diurnal signal in fluorescence (Geider and Osborne 1987). The fluorescence yield measured by the sensor provides "snapshot" information on the photoadaptive state of the algal cells, and the specific light regime, at the time of measurement. For example, if an algal cell is adapted to high irradiance, the fluorescent yield will be less than the same cell adapted to lower irradiance (Falkowski and La Roche 1991). Fluorescence yield is also temperature dependent. Therefore, the sondes provide information about relative phytoplankton abundance but not quantitative data on algal biomass or chlorophyll concentrations. For specific blooms of interest, quantitative data on algal biomass (biovolume) can be obtained for comparison using standard light microscopy techniques (e.g., Lund et al. 1958, Burkholder 1992, Wetzel and Likens 2000). Chlorophyll concentration data can be obtained using standard laboratory instruments (fluorometers, spectrophotometers, high-performance liquid chromatography [HPLC]) after extraction in organic solvents (USEPA 1997, method 445.0; APHA et al. 2005, standard method 10200 H; Schlüter et al. 2006).

Recommendations from researchers and sensor manufacturers are to calibrate the relative fluorescence measured by the instrument to a known biological entity for each specific bloom of interest; for example, a unialgal culture can be used in the case of monospecific blooms, or a known concentration of an extracted pigment (e.g., chlorophyll *a* or phycocyanin) can be used for mixed blooms. Highly purified algal pigments can be purchased from various chemical suppliers and used to standardize sensor readings to a known pigment concentration. The same calibration factor should not be relied upon from bloom to bloom because of the factors previously mentioned. The best comparative approach for a specific bloom of interest is to collect several grab samples in the field concomitantly with fluorescent sensor measurements and then determine the pigment concentration of the grab samples using standard laboratory extractive methods. The pigment concentration measurements can then be used to "normalize" the field fluorescence sensor data.

MULTIPARAMETER WATER QUALITY SONDES AND PIGMENT-SPECIFIC SENSORS

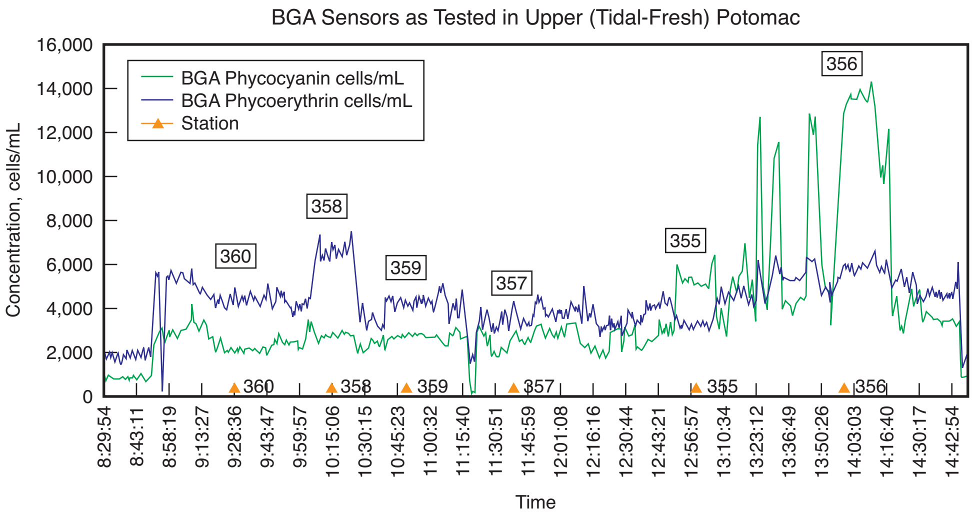
If one type of instrument is to be recommended as the standard instrument for water quality monitoring in both field and water treatment plant monitoring efforts, it is the multiparameter water quality sonde (the most common form factor is shown in Figure 1-3). These instruments are manufactured by many companies, for example, YSI, Hach-Hydrolab Inc., Turner Designs Inc., Greenspan Inc., In Situ Inc., and Eureka Environmental Engineering. The first three of these vendors manufacture multiparameter sondes that are equipped with pigment-specific sensors (i.e., for freshwaters, chlorophyll *a*, and phycocyanin) along with standard sensors such as temperature, dissolved oxygen (DO), pH, and oxidation reduction potential. These instruments are equipped with a sensor head area and a body that contains the microprocessor, which is responsible for data acquisition and computational functions necessary for calibration and communication. It should be noted that various vendors specialize in optical measurements of ocean water, including devices to measure chlorophyll, phycocyanin, and phycoerythrin (two common cyanobacterial pigments), but these companies are not active in equipment manufacture for water plant operations so they are not considered here.

Recent developments in sensor technology and other mechanical improvements have increased the utility of the multiparameter sonde, hereafter referred to only as "sonde." Two primary improvements are the use of luminescent detection technology to design improved pigment-specific sensors and the use of DO sensors. Chlorophyll *a*- and phycocyanin-specific sensors are presently available from YSI, Hach-Hydrolab, and Turner Designs; luminescence-based DO sensors are available from YSI and Hach-Hydrolab. This new technology replaces the standard Clark type and pulsed electrodes that were previously used on sondes to measure DO. Increases in DO and pH values are often indicative of an algal bloom; therefore, the data can often be used as a proxy for the occurrence of algal blooms when a fluorescence-based sensor is not available. The distinct advantages in use of luminescent DO sensors are (1) no membrane or electrode solution to replace and (2) longer deployments between calibrations. Another development in sonde technology is the use of automated wipers to clean biofouling organisms that grow on sensor surfaces. These wipers can be programmed to clean the sensor on a regular basis, thereby allowing greater accuracy in field measurements and longer intervals between maintenance.

A primary advantage in using sondes is that they can be set up for automatic data acquisition using industry standard data loggers and can also be deployed unattended where data is logged to an internal memory. Most sondes are configured to communicate with data loggers using standard SDI-12 and RS-232 protocols. A program resident in the data logger queries the sonde for data, which is then logged to a data logger. The data can be accessed via various communication methods such as cell phone,

Figure 1-3 Close-up photographs of six commercially available water quality sondes equipped with multiple sensors and antifouling wipers: (A) YSI 6600V2 (Courtesy of R. Ellison, YSI, with permission); (B) Turner Designs C6 (Courtesy of Turner Designs, with permission); (C) Troll (Courtesy of In Situ); (D) CS304 sonde (Courtesy of Greenspan); (E) Hach-Hydrolab DS5x (Courtesy of R. Reed); (F) Manta (Courtesy of Eureka Environmental). These instruments can be controlled using standard industry data loggers in either the SDI-12 or RS232 modes, for data acquisition, postprocessing, and posting to Internet sites for user viewing.

satellite, and spread spectrum RF radio modems after the data have been recorded, postprocessed, and posted to a Web site for viewing. These multiparameter systems can be deployed in reservoirs distant from a water treatment plant (e.g., upstream) to provide warning of incoming algal blooms. They can also be configured to acquire data automatically at a specific time interval while sampling water pumped onboard or towed behind a boat, resulting in high resolution data. A detailed time series of test



Station	Cells/mL
360	7,519
358	10,127
359	5,473
357	8,893
355	300,541
356	552,667

NOTE: The white-boxed numbers indicate the station numbers. The sensors were compared to evaluate whether the PC or the PE sensor was more effective in this estuarine area, which is known for extensive *Microcystis* blooms. The PC sensor provided better response to cyanobacterial biomass. Cell count data (via light microscopy) from samples taken at each station are indicated on the right side of the chart. The PC data correlate well with the cell counts. This time series illustrates the patchy nature of cyanobacteria biomass along the transect.

Figure 1-4 A time series of data acquired in the upper Potomac (brackish waters) using YSI phycocyanin (PC) and phycoerythrin (PE) sensors (Note: PE detectors are not available for freshwaters). (Courtesy of R. Ellison, YSI, with permission.)

data acquired in the upper Potomac (Figure 1-4) illustrates the variability in cyanobacteria biomass over long distances. This information is useful in assessing the present condition of source water in reference to the occurrence and location of algal blooms. These instruments can also be deployed at water intake structures. They are small and can be moved to other areas on short notice if deemed necessary. Readers are encouraged to check sonde manufacturers' Web sites for new technological developments and products regarding these instruments.

In order to ensure the acquisition of valid data that can be relied on for management, planning, and research efforts, a rigorous quality assurance/quality control protocol must be in place and documented with a quality assurance project plan. It is suggested that individuals involved in environmental monitoring and technology visit the USEPA Web site at www.epa.gov/quality for up-to-date information on quality management tools and other guidance specific to the proper acquisition of environmental data. One example of the need for detailed and accurate record keeping is in the case of sensors deployed under harsh field conditions where it is important to maintain individual calibration and maintenance logs for each sensor. For example, initial values of the sensors should be recorded before and after calibration to give a record of any sensor drift. This data is also useful as an early warning to sensor failure, allowing the technician to be proactive in the replacement of equipment. Manufacturer recommendations should be strictly adhered to at a minimum concerning calibration and maintenance; however, site-specific conditions will oftentimes require a more vigorous approach to equipment maintenance and calibration due to biofouling. Many manufacturers of water quality sondes have introduced self-cleaning features that remove biofouling films with wipers (e.g., YSI, Turner Designs, Hach-Hydrolab). Systems using older equipment or equipment not equipped with self-cleaning features must be rigorous in calibration and maintenance to avoid erroneous data due to biofouling, especially in highly eutrophic systems and during the warm seasons.

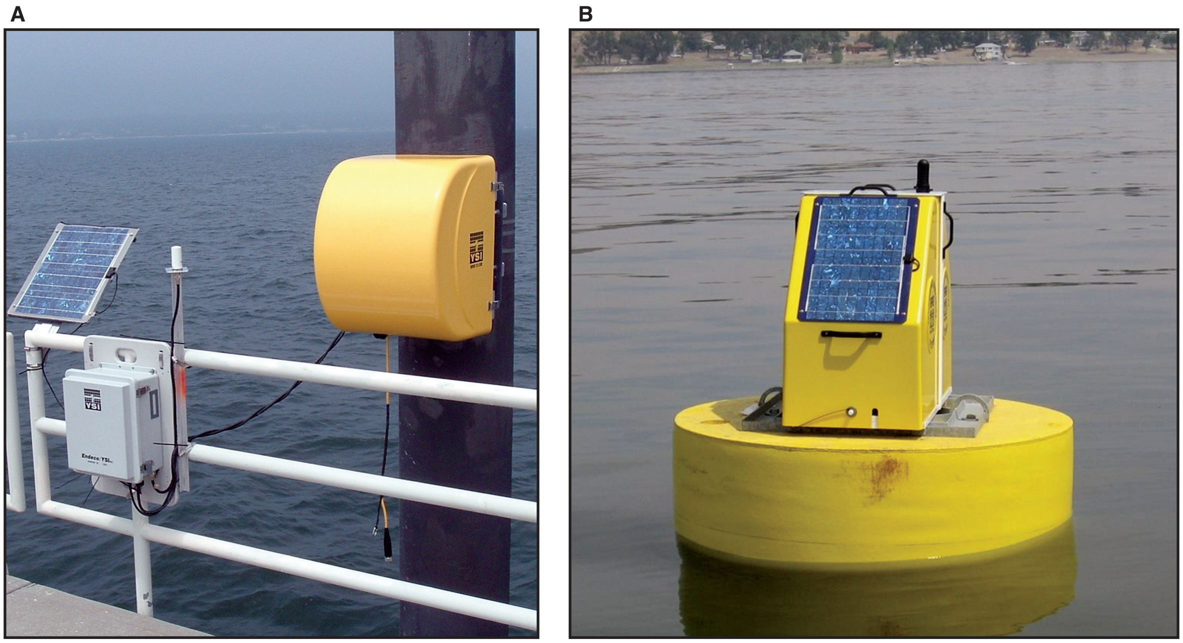


Figure 1-5 Two commercially available water-column profilers. (A) The fixed structure-mounted version is designed to be mounted on hard structures such as water intakes, piers, or bridge pilings. (B) The buoy-mounted profiler version is deployable in open water using two-point mooring. Both units are accessible via commercially available communications devices such as RF modem, cell phone, and satellite. The fixed structure-mounted instrument is also accessible via landline phone. (Courtesy of R. Ellison, YSI, with permission.)

Flow-through systems installed in-line to raw water intake pipes should also be inspected and cleaned regularly to remove any biofouling or foreign material.

EXAMPLES OF WATER-COLUMN MONITORING: PROFILING PLATFORMS, AUV TECHNOLOGY, AND BUOY-BASED SYSTEMS

Buoy and fixed-structure water quality profiling systems, which monitor the entire water column, recently have become commercially available. These systems can monitor depth-dependent structures for issues including turbidity spikes, chlorophyll spikes, high and low DO, pH variability, and phycocyanin spikes, providing valuable information for water plant operators in selecting appropriate filtration and other treatment protocols. If the water plant has a raw-water intake structure that allows water to be pulled from various depths, the data can inform plant operators of undesirable, depth-dependent changes in water quality that can then be avoided by taking water from a different depth. Examples of currently available commercial equipment are the YSI model 6952 buoy-based vertical profiling system and the model 6950 fixed system (Figure 1-5). The latter system is based on technology developed by scientists at the NCSU Center for Applied Aquatic Ecology (US Patent 7,040,157). A water quality sonde along with a computer-controlled winch allow acquisition of water-column biological and physical–chemical data at user-selected intervals. The data are communicated from the remote site to the water treatment facility using various commercially available devices (cell phone modems, spread spectrum RF modems, satellite, and so forth). A pontoon-mounted system (model 6951), similar to the buoy-mounted form factor, is also available for use in quiescent waters.

Examples of water-column data acquired by a fixed mount system are shown in Figure 1-2 (also see Deployment and Operational Considerations in Online Monitoring Programs). Contour plots of all water-column profiles acquired for a complete year at a municipal water plant reservoir intake using profiler technology illustrate the detailed biological, physical, and chemical structure that can be documented (Figure 1-6). Both longer-term (seasonal) and small-time-scale events can be recognized with multiyear or continuous profiler deployments, allowing managers the ability to be proactive in decision making, especially regarding problems that arise on a seasonal basis. The massive database acquired can also be useful in modeling efforts to improve predictive capability.

The advantages and disadvantages should be considered when selecting which system to deploy, especially site-specific characteristics of the reservoir. The fixed system can be mounted on water intake structures, piers, and bridge pilings and will be more stable from high wave action due to wind events. Moreover, if the system is mounted on a readily accessible water intake structure, operators will be able to maintain and calibrate the system easily. Buoy-mounted systems are less stable in high wind and wave conditions, but can be relocated to areas of interest by towing with a boat. On the other hand, a boat is required for maintenance and calibration of this system.

Monitoring large areas in a source water, or the entire source water, has been problematic because of the amount of man-hours and equipment that are required. The recent advent of commercially available AUV technology enables source water quality monitoring in three dimensions, permitting an assessment to be performed on the entire water body with limited personnel. The YSI EcoMapper AUV (Figure 1-7) is designed to be launched by one person; it autonomously surveys a water body using preprogrammed course and depth values. The AUV is fitted with standard sensors to allow the same multiparameter data to be acquired as with water quality sondes. The vehicle can measure a maximum of 10 water quality parameters at one-second intervals during missions up to 12 hours in length. Examples of turbidity and depth data acquired with this system are shown in Figures 1-7C and 1-7D, respectively. The high variability in the data, captured by the AUV, demonstrates the need for such high temporal and spatial sampling to provide operators and managers an overall assessment of depth-dependent water quality conditions, for example, near a potable water treatment plant, over small timescales. This system would be especially valuable in source waters where motorized boat traffic is not allowed, such as many restricted-access municipal reservoirs and recreational lakes. On the other hand, autonomous deployment of this equipment in source waters with high recreational use could be deleterious both to the equipment and to the general public, due to the probability of encounter with boat traffic.

Campbell Scientific Inc., Logan, Utah, markets a series of water quality monitoring buoys that can be used in freshwater ponds and small lakes with minimal wave action. These buoys are suitable for monitoring at a single fixed depth and do not have profiling capacity. The CSBUOY-DT and CSBUOY-NS buoys are self-contained packages that offer managers the ability to monitor water quality parameters via wireless technology. The effective range of these buoys is approximately ~1.6 km (1 mi) using a 7-A·h, 12-Vdc battery recharged with a 5-watt solar panel. Options are available to increase range to more than 16 km using a higher gain antenna with clear line of sight. After data acquisition and postprocessing with dedicated software, visualization software packages (e.g., LabView, MATLAB, Campbell RTMCPRO, or Vista Data Vision VDVSE) can be used to post the data from these platforms to Web sites.

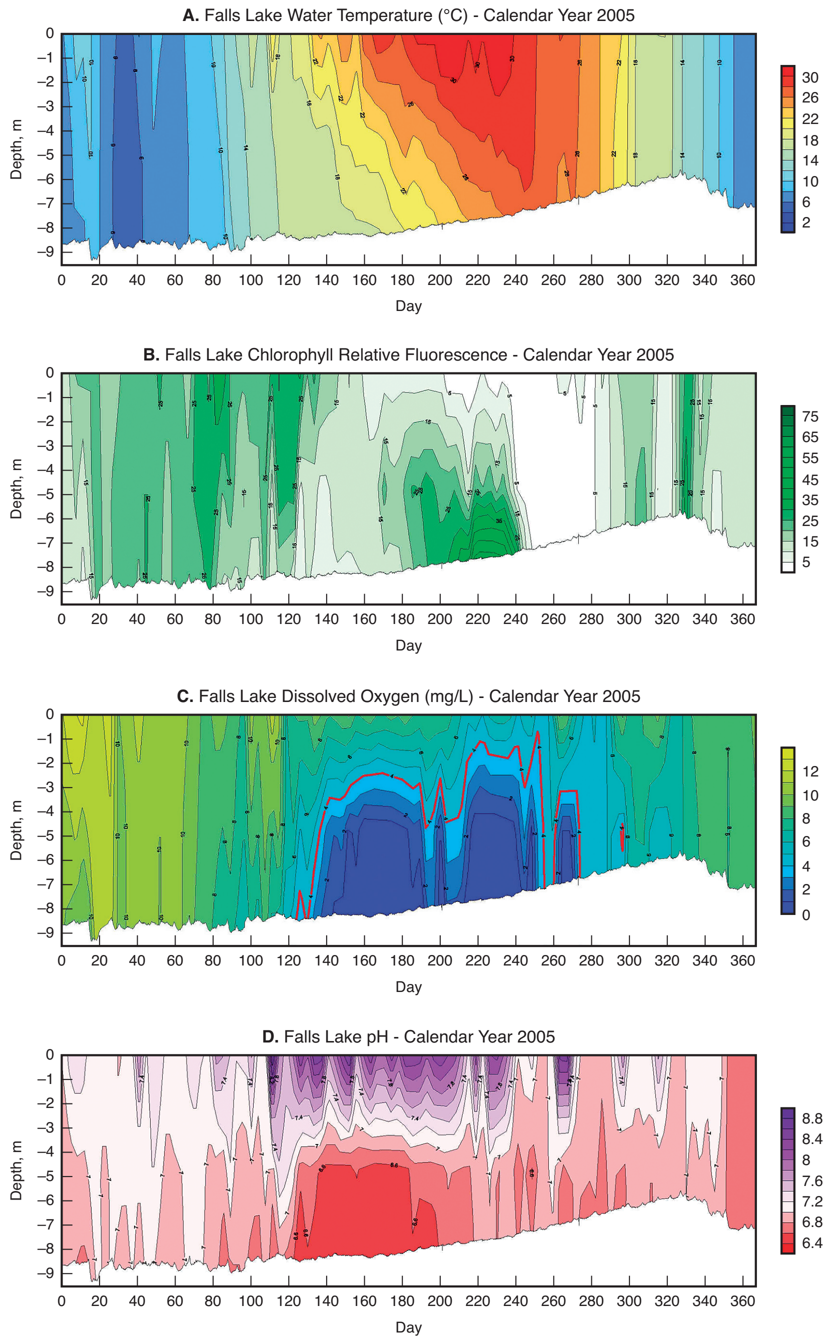


Figure 1-6 Contour plots, constructed using Surfer (version 7.0), of water-column profiles acquired at a municipal water plant reservoir intake using profiler technology during 2005, showing strong temporal and spatial resolution in all parameters: (A) Temperature. (B) Chlorophyll relative fluorescence; note spring phytoplankton blooms indicated at days ~80 and 120, and fall blooms at days ~320–330. (C) Dissolved oxygen, showing stratified DO conditions throughout the summer with low seasonal DO conditions from days 140 to ~260, followed by tropical storms that resulted in a well-mixed water column. (D) pH, again showing seasonally stratified conditions. Seasonal trends are clear in all parameters, as well as shorter-timescale signals in DO, pH, and chlorophyll relative fluorescence. These plots are useful to managers, water treatment plant operators, policy makers, and other end users in visualizing and presenting large amounts of data. (Courtesy of NC State University Center for Applied Aquatic Ecology.)

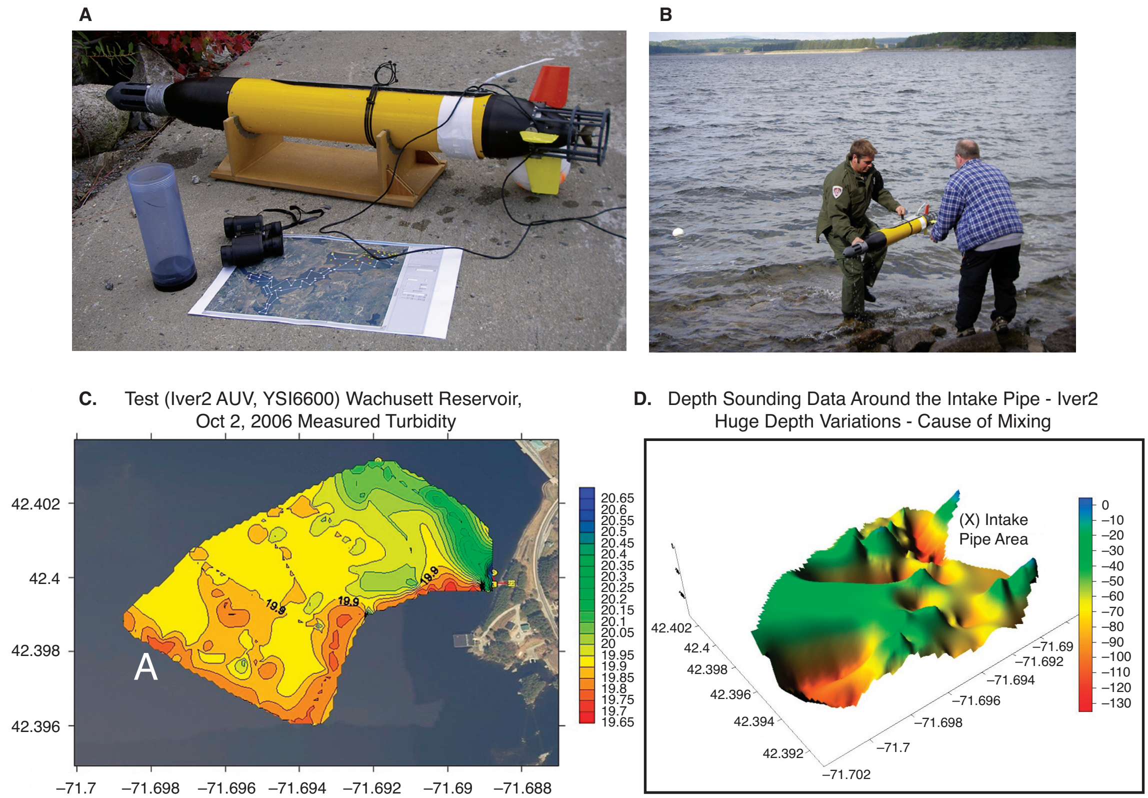


Figure 1-7 Illustration of YSI AUV available for monitoring reservoirs in three dimensions and associated data: (A, B) AUV is self-contained and is equipped with standard water quality sensors currently available, which can be seen at the tip of the AUV. The unit is small, which enables easy deployment and recovery. (C, D) Examples of turbidity and depth data acquired by AUV (Iver2, YSI6600) at the Wachusett Reservoir, illustrating the small-scale spatial variability of both parameters. (Courtesy of R. Ellison, YSI, with permission.)

ONLINE INSTRUMENTS FOR CHARACTERIZING SOURCE WATERS

The advent of online fluorescent monitoring equipment in recent years has provided early warning of the onset of blooms of taste and odor causing and/or toxic algae. It also enables background monitoring of algal biomass through daily and seasonal changes. Two variants of similar technology are offered by Turner Designs (Sunnyvale, Calif.) to monitor chlorophyll *a* and phycocyanin in source water. The AlgaeWatch™ and CyanoWatch™ instruments are based on fluorescence detection systems (relative fluorescence units), which Turner Designs has engineered and manufactured since 1972. AlgaeWatch monitors chlorophyll *a*, and CyanoWatch is designed to monitor phycocyanin, which can be used, along with simple confirmation by light microscopy, to detect cyanobacteria (Figure 1-8). Both instruments are designed to be installed in-line with source water pipes. The use of these sensors can assist management decisions on the need for various filtration and other treatment processes. These systems can be remotely accessed via a 4–20 mA output to a data logger, with dedicated software that allows 24-hour access to data via a Web-based computer.

Figure 1-8 The Turner Designs AlgaeWatch online fluorometer. This instrument was installed by a municipal potable water treatment plant to sample source water for algal blooms. (Courtesy of Turner Designs, with permission.)

The use of fish as biomonitors for water quality is widespread in various parts of the world where water treatment plants use fish “sentinels” in tanks and other devices to assess changes in behavior due to stress from toxic substances and low water quality (Grayman et al. 2001). Concerns over water security have risen in recent years and have led to an increased interest in technology that is amenable to rapid toxic detection for water supplies (van der Schalie et al. 2001a, 2006). Research by investigators at the US Army Center for Environmental Health and Research has resulted in a commercially available product (US Patent 6,058,763) that monitors specific fish behavior parameters directly related to stress and toxicity. The device, called the intelligent Aquatic BioMonitoring System®, or iABS (Figure 1-9A), is currently marketed by Intelligent Automation Corporation (www.iac-online.com). This innovative aquatic biomonitoring system uses fish to assess toxicity of water supplies and source waters in a controlled and quantitative manner (Mikol et al. 2007, Shedd et al. 2001). The system is automated and includes exposure chambers that each hold a bluegill sunfish (*Lepomis macrochirus* Rafinesque). Body movements and ventilatory behavior (Figure 1-9B) are sensed by electrodes, recorded, postprocessed using the dedicated software Biomonitor Expert for visualization, and posted to a Web site. These data are easily viewed via the Web, and the software system can be configured to issue alarms triggered

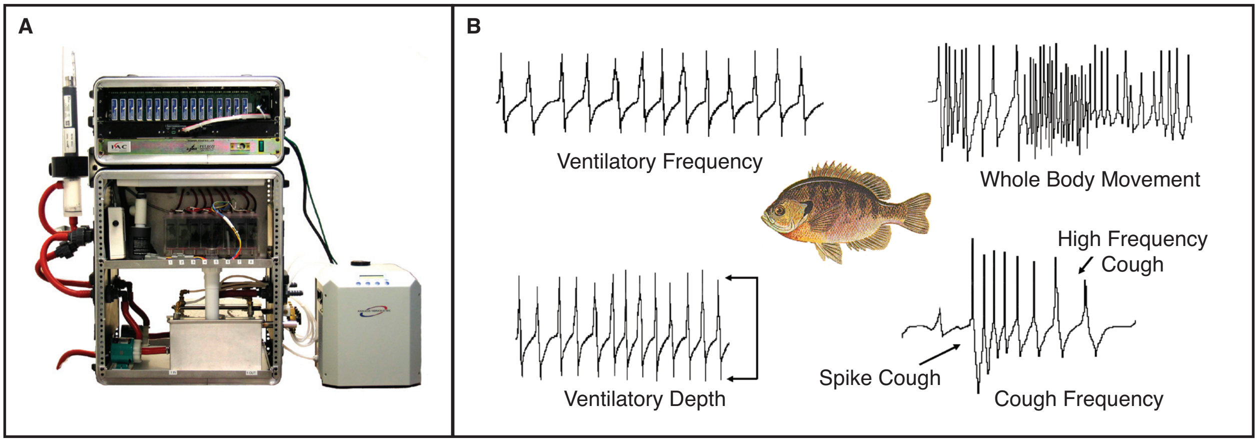


Figure 1-9 Fish ventilatory and behavior patterns monitored using the (A) IAC 1090 Fish Biomonitor system and Expert Software, which evaluates (B) ventilatory frequency, whole body movement, ventilatory depth, and cough frequency to determine the health and stress state of the fish. Deviations from baseline values result in an alarm and notification to water plant managers for further evaluation. (Courtesy of B. Lawler, Intelligent Automation Corporation Inc., with permission.)

by fish stress from toxic substances. This system has been tested successfully with some harmful algal species (van der Schalie et al. 2001b), illustrating its potential to provide early warning of toxic substances such as cyanotoxins in source water protection.

Other commercially available online biomonitoring equipment that uses biological entities to serve as sensors for water quality problems includes the Daphnia Toximeter, Fish Toximeter, and Algae Toximeter manufactured by bbe Moldaenke (www.bbe-moldaenke.de). These instruments are engineered such that the organism is exposed to a sample water stream and is monitored by motion analysis software in the case of the Fish and Daphnia Toximeters or software that records changes in fluorescence, in the case of the Algae Toximeter. Changes in organism response is recorded and interpreted by the dedicated software to trigger alarms or indicate changes caused by toxic or deleterious conditions, providing water system operators early warning to potentially hazardous events. The AlgaeOnlineAnalyser, also from bbe Moldaenke, continuously measures in real time chlorophyll fluorescence, algae class, and photosynthetic activity of natural algal assemblages in sample stream water. This instrument is useful in monitoring changes in algal communities and physiology that may occur over long periods of time due to various environmental impacts.

It should also be noted that existing instrumentation in water treatment plants can be integrated into an online monitoring program to assess changes in water quality due to algal blooms. For example, turbidimeters and particle counters from various vendors (e.g., HF Scientific Inc. [www.hfscientific.com] and Hach Inc. [www.hach.com]—turbidimeters; Hach—particle counters) use a variety of communication protocols (RS232, RS484, modbus, etc.), that allow maximum flexibility in online system integration. Increasing trends and spikes in turbidity and particle numbers are valuable information that can warn water plant operators as to changing conditions in raw water supply.

LIMITATIONS OF ONLINE AND REAL-TIME MONITORING EQUIPMENT

There are specific limitations to all monitoring technologies due to basic design features that can affect the spatial and temporal scale of data acquisition. Instruments that are designed to be mobile, for example an AUV, may be limited due to deployment-recovery considerations such as the duration of deployment in the source water and the amount of effort that can be invested for maintenance, calibration, and troubleshooting. An AUV gives excellent temporal and spatial resolution in characterizing the biological and physical–chemical environment of a reservoir, but long-term assessment of the environment can be limited if the instrument is not deployed to provide a continuous database. The timescale of dedicated AUV deployments will constrain the characterization of rapidly changing conditions, such as initiation of algal blooms or event-driven changes in water quality, unless the system is operated on short timescales that allow maximum resolution.

Data acquired by sondes deployed at a single fixed depth, and profiling devices that are located at a single site obviously will be limited to characterization of that site and will miss environmental changes at distant sites. In the case of sondes deployed at a fixed depth, the user will not gain information on water-column conditions above or below the sonde. Another limitation in acquiring chlorophyll or phycocyanin fluorescent data using sondes and profilers occurs when trying to assess the abundance of algae that form benthic or floating mats, for example the potentially toxic cyanobacterium *Plectonema wollei* Farlow ex Goment (previously known as *Lyngbya wollei*).

Lakes and rivers are dynamic systems that can change rapidly because of variability in flow due to both anthropogenic and natural occurrences. Acoustic Doppler current profiler (ADCP or ADP) technology using either fixed and/or boat-mounted instruments can be used to monitor flow patterns important in tracking algal blooms and other water quality conditions (e.g., turbidity events and spills). Many commercial products are available and can be found with a general Web search using keywords such as ADCP, ADP, ADV, acoustic Doppler current profiler, or current meters.

FIELD METHODS USED IN CONJUNCTION WITH ONLINE MONITORING

There are many published manuals and textbooks with information and methods that describe basic considerations and methodologies for sampling source waters (e.g., APHA et al. 2005, Wetzel and Likens 2000). Field methods used for collecting algal samples and associated toxins must be adequate to enable further identification, molecular, and toxicity testing by water plant or supporting laboratories. In characterizing source waters, monitoring sites should be chosen to maximize the user's ability to characterize incoming pollutant sources, including known "hot spots" for algal blooms, fish kills, and DO deficits, as well as waters with the highest probability of human contact through recreational use (Meriluoto and Codd 2005). Real-time data should be groundtruthed by additional field sampling for parameters of interest such as phytoplankton biomass and dominant species, nutrients, and other pollutants.

Dedicated field sampling and associated analytical methods are useful in determining areas of high bloom activity and in identifying potentially harmful algae and their toxins. Commercially available toxin kits are available for some algal toxins and may be either quantitative or qualitative depending on the method and manufacturer (examples given in Table 1-1). Use of these kits can help water utilities assess the condition and toxin concentrations of source water and also the efficacy of filtration in the

Table 1-1 Selected commercially available kits for cyanotoxin detection/quantification

Toxin	Product Number	Vendor	Description of Product
Microcystin	EP 022	Envirologix	ELISA Microtiter® plate kit for quantitative detection of microcystins in surface waters. Limit of detection, 0.147 ppb microcystin-LR equivalents. Limit of detection for the high-sensitivity alternate protocol (potable water), 0.03 ppb assay range 0.16–2.5 ppb.
	ET 022	Envirologix	QualiTube kit for microcystin, ELISA tube field kit for qualitative determination of presence/absence of microcystin in surface waters (limit of detection 0.3 ppb); tubes read visually or with a photometer; assay range 0.5–3.0 ppb.
	520011	Abraxis, LLC	Microcystins/Nodularins (Adda), ELISA kit, Microtiter plate. Limit of detection 0.10 ppb (assay range 0.15–5 ppb).
	520012	Abraxis, LLC	Microcystin tube kit; quantitative, requires photometer.
	520012F	Abraxis, LLC	Microcystin tube kit; qualitative, requires photometer.
	CPP-023	Beacon Analytical Systems Inc.	ELISA Microcystin plate kit. Limit of detection ~0.05 ppb.
Cylindrospermopsin	522011	Abraxis, LLC	Cylindrospermopsin ELISA kit, Microtiter plate for quantitative detection; limit of detection 0.04 ppb, assay range 0.05–2.0 ppb.
Saxitoxin	52255B	Abraxis, LLC	Saxitoxin ELISA kit, Product No. 52255B: Microtiter plate, quantitative determination, limit of detection 0.015 ng/mL, assay range 0.02–0.4 ppb.

final product. It is important, however, to cross-confirm enzyme-linked immunosorbent assays (ELISAs) and protein phosphatase inhibition assays with standard HPLC, liquid chromatography/mass spectroscopy (LC/MS), and other methods as appropriate (Tillmanns et al. 2007). Advanced LC/MS/MS methods may be used for toxin variant determination (Meriluoto and Codd 2005).

All sampling devices and containers must be free of any biological or inorganic residue before sample collection. Standard washing and acid stripping of glassware is necessary, along with the use of a cleaner that removes DNA such as DNA Away by Molecular Bio-Products or DNase Displace from Fisher Scientific. These precautions are especially important in the collection of material for DNA, nutrient, and algal toxin analyses to eliminate the possibility of contamination. It is also recommended that all sampling devices be rinsed twice with source water from the site prior to collection.

Most standard methods for determining algal toxins describe collecting the algal material from water samples or surface scums and then extracting toxins from algal cells collected by filtration or lyophilized bloom material. Samples should be processed and analyzed as soon as possible within 24 hours after collection to minimize degradation of toxin and algal material and to maximize recovery. If samples are to be sent to commercial laboratories for toxin analysis, they should be prepared the same day of collection according to the receiving laboratory specifications and shipped under appropriate conditions (containers, temperature, light) within 24 hours.

Various commercially available sampling devices can be used to collect water samples at discrete depths or integrated samples collecting water from many depths. For example, water samplers are commercially available from Aquatic Ecosystems Inc. (www.aquaticeco.com) and Wildco (www.wildco.com). A Labline sampler can be used to take integrated water samples by lowering and raising the device at a constant rate between the depths of interest. The Labline sampler also allows discrete depth sampling, for example when physical parameters indicate fluorescence activity, elevated DO, or pH at a specific depth. A phytoplankton net tow is useful for collecting appreciable algal biomass from horizontal or vertical tows for qualitative determination of cell-bound toxin content. Net efficiency (depending on the mesh size and other features) needs to be considered in efforts to use these samples to estimate toxin content (Wetzel and Likens 2000). Water for toxin analysis should be collected in glass rather than plastic bottles to minimize toxin adsorption to the container walls. Toxin samples should be stored on ice during transport and filtered the same day of collection. The processed filtrate sample (soluble fraction) and the filter disc (cell-bound fraction) should be frozen separately at a minimum of –20°C to a maximum of –80°C (preferable; see appropriate references for further details, such as Chorus and Bartram 1999, Codd et al. 1999, and Meriluoto and Codd 2005).

FUTURE DIRECTIONS

The demand for drinking water will surely increase in the future due to population growth and the resulting development of municipal infrastructure. Watersheds will continue to be affected by a variety of anthropogenic and natural stressors, such as stormwater runoff due to increases in impervious surfaces, increases in harmful algal blooms, and extremes in climate. These synergistic stressors will increasingly challenge potable water treatment operations. The exceptional 2007 drought experienced by the southeastern United States (US Drought Monitor, www.drought.unl.edu/dm/monitor.html) provides a compelling example of how climate can quickly change the availability of water for the general public. The use of online monitoring and dedicated field techniques to assess source water for harmful algae will be a necessity to optimize management of decreasing water resources. Development of new online and field technologies is anticipated to grow in importance as a high priority for both government and private concerns.

The integration of molecular and analytical techniques with electronic sensors has great potential for future development and use in online monitoring programs. This emerging technology is based on analytical methods that detect specific toxic substances. Examples of these technologies include the electric cell-substrate impedance sensing system, which measures toxicant-induced changes in the electrical impedance of a cell monolayer (Keese et al. 1998), and the neuronal microelectrode array device, which evaluates changes in the action potential of a neuronal network via noninvasive extracellular recordings (Pancrazio et al. 2003). These sensors have been successfully employed in laboratory studies (van der Schalie et al. 2006), and future efforts are expected to include incorporation of this type of technology into online equipment and field deployment tests in source waters used for potable supplies.

It is also probable that additional municipalities will incorporate online monitoring into their water assessment programs in the future to assist managers and water treatment plant operators in planning for episodic events that negatively affect source water. The powerful information that can be gained from a robust online and field monitoring program will allow more accurate projections of costs related to water plant operations, such as the purchase of chemicals, filter material, and associated labor expenses. It is likely, as well, that manufacturing cost efficiency for online monitoring equipment will be realized by vendors. The resulting reduced initial monetary investment for the tools and associated software needed to implement this technology will make online monitoring an attractive addition to source water assessment programs for tracking harmful and noxious algal blooms that are expected to flourish in increasingly nutrient-enriched watersheds.

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