Chapter 13
Automated High-frequency Monitoring and Research

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Abstract High-frequency sensor measurements provide new opportunities to better understand and manage water resources. Recent advances in sensor and information technologies have enabled autonomous measurement and analysis of the aquatic environment at ever-increasing spatial and temporal resolution. Here, we describe the fundamentals of automated high-frequency lake monitoring, including hardware and telemetry design, sensor types and measurement principles, maintenance requirements, and quality assurance/quality control of datasets. These aspects require careful consideration to collect data that are suitably robust for monitoring and research needs. Examples are provided of the value of high-frequency measurements and derived data products for analysing short- and long-term lake processes. When applied with rigor, automated sensor measurements can improve programmes of management, monitoring, and research by providing baseline data, enabling rapid response to disturbance events, reducing some long-term costs, and opening new windows of opportunity to better understand the present era of declining water quality and environmental change.

Keywords High-frequency monitoring · Water quality sensors · Fluorometry · Data management

13.1 Introduction

Advances in technology can be leveraged in numerous ways to generate new insights into processes and characteristics of ecosystems. Whereas the foundations of modern limnology were laid with manual labour—field observations and laboratory analyses—more recently, sensor and information technologies have enabled

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autonomous measurement and analysis of the aquatic environment at ever-increasing spatial and temporal resolution. These technologies can be used to ‘fill the gaps’ inherent in traditional sampling designs both in time and space, detect rapid environmental change, and analyse short-term processes that can have cascading impacts through time and space. Perhaps most importantly, these technologies open the door to investigations and analyses previously unthinkable, or at least impractical, using more traditional methods.

High-frequency in situ monitoring of lakes entails the application of water quality and meteorological sensors with autonomous data collection platforms for continuous measurement of sub-daily physical, chemical, and biological dynamics. Sensors and instrumentation are typically mounted to a floating platform with on-board power and data acquisition systems (Fig. 13.1), and data are often transmitted in near-real-time to a database with a user interface enabling querying and visualisation. Platforms are usually solar-powered, providing capability for deployments in remote locales and enabling rapid collection of vast datasets with relatively little labour. Hence, it may be tempting to consider this approach as a short cut to data collection or as a substitute for routine monitoring and research. However, high-frequency lake measurements are often complementary to many aspects of traditional monitoring and research and are most valuable within the context of a broader programme of data collection.

Water quality research and monitoring require highly dependable measurements. Myriad factors must be considered in order to collect robust, accurate, and continuous high-frequency data, as well as for its useful interpretation. This chapter seeks

Fig. 13.1 Monitoring buoy on Lake Waikaremoana (Image: M. Osborne)

to provide an overview of many important considerations when undertaking automated measurements of lake water quality using sensor technologies. Continuous, high-quality data can be critical to understanding lake dynamics and have proven a very valuable asset to programmes of lake management and restoration globally.

13.2 Why Monitor at High Frequency?

Autonomous monitoring and in situ sensor technologies enable more comprehensive understanding of lake processes through space and time and are a growth area in aquatic monitoring and research (Meinson et al. 2015). Continuous, near-real-time ('streaming') data provides a range of benefits over and above pure research. High-frequency data can facilitate adaptive and/or reactive management as in early warning detection of harmful algal blooms at recreational sites in lakes, selective off-take withdrawal from reservoirs, or prediction of impending regime shifts. For example, dissolved oxygen depletion in the hypolimnion of lakes during periods of thermal stratification is a key regulator and important indicator of lake 'health'. However, oxygen depletion in some conditions (e.g. polymixis) can be near-impossible to accurately characterise using a sampling protocol of infrequent (e.g. weekly to monthly) measurement. High-frequency monitoring enables a more thorough understanding of important processes by enabling accurate estimation of hypolimnetic oxygen depletion during stratification events often lasting a matter of just days.

Buoy data can provide a basis for hypothesis generation and context for more detailed or targeted experiments and investigations. A continuous record of environmental conditions and lake water quality is often very useful when conducting in-lake field experiments, for example, mesocosm studies or bioassays. Furthermore, the continuous nature of such monitoring records can ensure that 'ground-truth' data are always available, for example, during major storm events that can rapidly change water quality conditions or periods spanning discrete satellite observations of lake water quality. Importantly, long-term datasets of continuous measurements can be used in the calibration, validation, and refinement of water quality models. A continuous record of key state variables enables much better assessment of model performance than might be achieved with irregular and/or infrequent manual monitoring. Additionally, because some short-term processes have temporal legacies, high-frequency data can produce more accurate model forecasts by better representing transient conditions.

Streaming data can find important utility in education and public outreach if made available over the web. For example, anglers might utilise buoy data feeds to assess on-lake conditions for safety or to find the depth of optimum temperature for a temperature-selective target species (e.g. rainbow trout), and sailors may use wind speed and direction data to better chart their course. Publicly available data feeds can also be an effective tool for improving awareness of water quality issues as well as a valuable teaching resource. There are a range of approaches to sharing high-frequency sensor data. Increasingly, many organisations have policies whereby data are made publicly available to the maximum extent possible. It is generally encouraged to make data freely available to all those interested, notwithstanding some important limitations. Users often need to be made aware that near-real-time data is provided raw, without post-processing as necessary and often without important contextual metadata. This limits the immediate utility of the data, but provides for rapid dissemination. Frequently, multiple data releases are issued, with later versions providing calibrated, contextualised data.

In summary, buoy systems are flexible and adaptable to meet a broad range of monitoring and research needs. When data are collected and processed carefully, they can provide a comprehensive baseline water quality monitoring record and support a wide range of applications.

13.3 Types of Monitoring Platform

A typical high-frequency lake research and monitoring station consists of hardware including a buoy platform, data logger, solar power (batteries, panels and controller), communications, moorings, sensors, and/or multi-probes. By optimising the form and features of a buoy platform, an ideal system can be created to match specific needs, applications, and budget. Common buoy designs include both fixed depth and 'profiling' (variable depth) sensors. The specific design and configuration will depend on multiple factors, many of which are described herein. While we make an attempt to provide a discussion on many of the most critical design and configuration elements, there are several other resources available that complement this chapter and provide additional information on high frequency aquatic research and monitoring practices. Examples are the European Cooperation in Science and Technology (COST) Action NETLAKE (Networking Lake Observatories in Europe) series of 'toolbox' technical reports, which are available online (netlake.org).

13.3.1 Fixed Depth Sensor Buoys

Water quality sensors are suspended in the water column at fixed depths. Most commonly, sensors are hung from a surface-mounted buoy and thus sensor depth is relative to surface. Figure 13.1 shows such a fixed-sensor buoy deployed in Lake Waikaremoana, New Zealand. Occasionally, sensors are suspended from a sediment-mounted platform by a cable connected to a buoyant object and, thus, sensor depth is relative to the lake bottom (Fig. 13.2). For either configuration, the most common sensors include a temperature 'string' of multiple water temperature sensors located at varying depths on a single cable and arrays of additional sensors near-surface, near-bottom, and sometimes at specific depths in between. Although this is the most common type of sensor system, the cost of sensor replication and

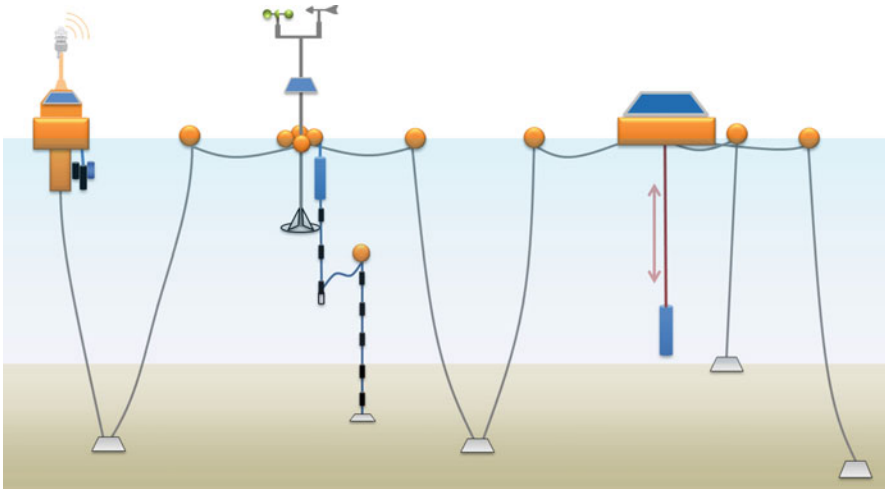

Fig. 13.2 Schematic diagram of three alternative buoy and mooring configurations. (Left) Single point mooring with surface buoy, water quality sensors, and a compact weather station. (Middle) Vertical 'spar' buoy with two-point mooring, multi-probe (sonde), dual bottom- and surface-referenced temperature sensor string, and component weather station. (Right) 'Profiling' system on three-point mooring with arrows indicating vertical control of a sonde

burden of sensor maintenance (including cross-calibration of replicated sensors) mean that measuring multiple variables at even moderate vertical resolution is often impractical. Accordingly, most variables are measured at a single near-surface depth (commonly about 1 m), assumed to be representative of the surface mixed layer. This design is sufficient to characterise overall water quality in well-mixed systems where temperature stratification is of lesser importance, but is often inadequate for capturing vertical gradients in chemical and biological processes. For example, in lakes that exhibit strong seasonal stratification, sensors deployed near the surface do not readily respond to processes occurring nearby or below the thermocline (e.g. deep chlorophyll maxima). However, because temperature readings are usually collected throughout the water column and simultaneously, these systems are ideal for measuring physical processes in lakes, for example, heat flux, internal waves, and seiches.

13.3.2 *Profiling Sensor Buoys*

A water quality sensor package is attached to an automated winch and is raised and lowered through the water column on a pre-determined (user-adjustable) sampling routine (e.g. 12 profiles per day measuring at 1 m vertical resolution through a 20-m water column). These systems enable detailed vertical measurement resolution whilst eliminating the need for replication and cross-calibration of sensors at multiple depths. Relative to fixed depth sensor systems, control equipment is more complicated and has moving parts and must, therefore, be well-designed and robust, with error-handling capabilities and a programme of regular maintenance. Depending on the depth of the water column and the necessary sensor equilibration time at each sample depth, profiling sensor buoys may only return to a specific depth every hour or longer, whereas single depth sensors can record at frequencies in the order of seconds to minutes. However, because profilers can sample all variables throughout the water column, they are much more powerful than fixed depth sensor systems for understanding chemical and biological processes both vertically and temporally, for example, bottom water oxygen consumption, pH variability, and estimated phytoplankton distribution.

13.3.3 Towed or Autonomous Probes

Although outside the scope of this chapter, many of the sensor technologies discussed within are also used on towed or autonomous underwater vehicles. While data buoys are generally used to provide a continuous record of water quality at a single geo-coordinate, towed and autonomous probes are most often used to investigate vertical and horizontal variation in water quality during short-term surveys (see Feature Box 13.1). Towed platforms complement buoys and can provide better characterisation of spatial variability in water quality, at the expense of temporal coverage. In contrast, fixed and profiling platforms characterise water quality through time at a point or depth gradient. Surveys using towed probes can be useful to ground-truth data for remote sensing studies.

Box 13.1 Remote Sensing Techniques for Lake Assessments: The Lake Biwa Example

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Phytoplankton blooms associated with eutrophication can be detected at the lake water surface with satellite or airborne sensors, and spatial distributions can, therefore, be monitored remotely. High concentrations of suspended sediments can also be readily detected from space (Fig. 13.3). On the other hand, lake water constituents can sometimes change dramatically as a result of interactions between the water column and the bottom sediments. These deep-water processes are essentially invisible to airborne detection systems. In order to overcome this difficulty, we have applied advanced in situ sensing

(continued)

Box 13.1 (continued)
technologies including autonomous underwater vehicles (AUV), remotely operated vehicles (ROV), side scan sonar (SSS), and multi-beam sonar (MBS). These optical or acoustic sensing technologies enable observations of changes in deep-water conditions. Such approaches were first developed for ocean monitoring, but they are highly applicable to large deep lakes and gaining popularity. One example is the deep water exploration and monitoring of Lake Biwa, the largest and oldest lake in Japan. Hydrothermal vents were first discovered in 2009 using a high definition video camera mounted on the AUV ‘Tantan’. Since then, vent activities have been observed continuously by AUV and it has been found that the number of vents is increasing. Gas bubbles from bottom sediments were also detected by ROV, SSS, and MBS.

Figure 13.3 shows the stereoscopic view of gas bubbles taken by MBS around the submerged mountain in Lake Biwa. The dark red colour indicates the shallower area (around 20 m depth) and the dark blue colour corresponds to the deepest area (around 100 m depth). The horizontal and vertical scales are about 1.5 km. Several series of gas bubbles can be clearly seen around the mountain, and the positions of those gas bubbles were able to be compared with the vent positions observed by AUV. In large deep lakes like Lake Biwa, it is not easy to take samples at a specific position within a small area. The target area has to be narrowed down and defined as accurately as possible. Acoustic remote sensing provides a powerful approach to identify key locations. On the other hand, optical remote sensing in water is sensitive to sediment disturbance and turbidity, which impairs the ability to obtain clear images. The AUV ‘Tantan’ is, therefore, maintained at a depth that is always 1 m above the bottom sediments in Lake Biwa, and transects are run at that precise depth over distances of 1–2 km. The best approach to investigate the bottom waters and sediments of lakes is to apply a combination of methods based on optical and acoustic sensing techniques. Each of these techniques has strengths and limitations, but the array of information allows much greater understanding that complements the highly resolved surface-water information obtained from satellites and airborne sensors.

13.4 System Design

For in situ buoy applications, a large disc or square float typically serves as the physical platform, providing buoyancy and stability for a waterproof housing of data logging, solar power production, and communications equipment. Platforms must be of appropriate size and buoyancy to support the necessary sensor, control, and power equipment and stable enough to collect accurate meteorological data (if required). Deep-set ballast weight can help to improve platform stability. Vertical ‘spar’ buoys are an excellent design to cope with strong winds and large waves, because buoys

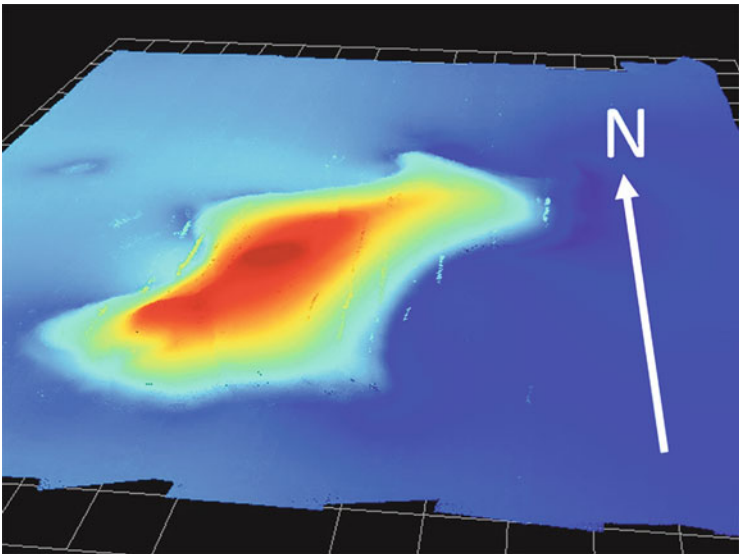


Fig. 13.3 The stereoscopic image of bottom and gas bubbles in Lake Biwa measured by MBS. Dark red colour indicates shallow area (20 m depth) and dark blue colour indicates deep area (100 m depth)

with larger bases will tip to angles concurrent with wave motion unless the platform is bigger than the wave period.

Floatation platforms should be solid (e.g. ionomer foam) or foam-filled to prevent sinking if damaged (e.g. boat strike), able to be easily accessed and maintained using available vessels, and resilient to all environmental conditions. For example, if vandalism of equipment is a concern, then exposed wires and visible sensors might be undesirable; however, sensors should also be easily retrievable for necessary calibrations and maintenance. Care should be taken to ensure that sensitive electronics are effectively sealed against water ingress, particularly around points of cable entry. Multiple barriers to ingress (i.e. double enclosures) can increase reliability. There are a number of manufacturers of buoys, and platforms can often be purchased without any sensors or other hardware, providing users with the ability to construct fully customised packages.

13.4.1 Mooring

Buoys must be properly moored to ensure they remain securely located and sensors remain undamaged. Buoys are usually deployed at or near the deepest location of the lake to ensure that measurements can be made throughout the water column and are representative of whole lake characteristics. Moorings should be resistant to abrasion and corrosion (mating of dissimilar metals in aquatic environments is generally to be avoided due to the potential for galvanic corrosion) and should help absorb the impact of wave and wind action whilst also allowing enough ‘travel’ to cope with water level variation. Where surface level changes dramatically, it can be challenging to achieve a mooring design that can adjust between levels without leaving too much slack at low levels such that potential damage to hanging sensors could be caused by drifting to undesirable locations or entanglement of sensor and mooring lines. In shallow lakes with variable water level, a fixed pole or platform can be an effective alternative to a moored floating platform.

Floating buoys can be moored with single, two-, or three-point mooring depending on the location, depth, and types of sensors used (Fig. 13.2). Single point moorings are used when buoy-based sensors are deployed on or immediately below the buoy flotation and do not hang far into the water column. Surface sensors are protected and less vulnerable to damage caused by subsurface debris, high currents, and entanglement from anchor lines. Sensors hung deeper (e.g. temperature strings) can become damaged as the buoy spins around the central axis of a single mooring line. Single point moorings are uncommon because many buoy systems include sensors deep in the water column, and because a single mooring may result in loss of the whole system should the mooring line become damaged.

Two-point moorings are commonly used when sensors are deployed in the water column below the buoy. The mooring lines are often held taut and away from the buoy by two smaller surface or subsurface floats which are connected to parent mooring lines that run to the lakebed and connect via a bottom chain to anchors. These surface-mounted buoys pull double duty by reducing the likelihood that passing boaters will pull up directly alongside, potentially damaging the main buoy. This design allows sensors to hang freely in the water column beneath the buoy and be retrieved independently of mooring lines.

Three-point moorings are commonly used in deep systems which can experience high winds and large waves. Reinforced connection points and routine checks can be necessary in exposed locations. For example, a single season of large waves and high winds is sufficient to cause wear through a 10-mm diameter stainless steel D-shackle connection. Meteorological sensors can benefit from three-point mooring to reduce listing and turning of the buoy, which can affect wind speed and direction measurements (although some wind sensors have an internal compass to correct for buoy rotation). Three-point moorings also provide additional security, reducing the risk of excessive drifting and sensor entanglement should one mooring line become damaged.

13.4.2 Ice Cover

Many lakes experience seasonal ice cover. Ice presents serious challenges and threats to deployed buoys. Frequently, buoys are removed just before predicted ice-in and re-deployed after the last ice melts. This avoids potential damage to the buoy and sensors, but limits the water quality monitoring duration. There are several other solutions to maintaining high-frequency sampling in lakes that form ice. One option is to redeploy sensors below ice cover using a subsurface mooring buoy below the maximum predicted ice cover depth. In this approach, sensors are deployed relative to the bottom rather than relative to the surface. Another option is to leave the buoy deployed but remove mooring lines, which can get twisted and broken if left in place. This approach risks damage to the buoy structure. Furthermore, the buoy can drift with the ice and in the spring and may move great distances. If the monitoring buoy is removed from the lake during the ice cover periods, management of the existing moorings must be considered. It can be very difficult to pull up mooring lines that have buried deeply into sediment. An approach is to again use subsurface buoys below the depth of maximum ice cover and retrieve the mooring lines after ice-off using divers.

13.4.3 Visibility

Local regulations often require that sensor platforms be clearly marked and visible both night and day, particularly where powered craft operate. Relevant authorities should be consulted to gain consent for the installation, decide on location, and determine the correct colouring of the platform as well as requirements for lighting and flash patterns. Solar-powered marine LED navigation beacons are a convenient way to mark buoy installations. It is often worthwhile (or required) to install placards at nearby boat ramps explaining the design of the platform and its purpose, as well as marking the buoy itself with contact information. These can be great tools to engage with the public about what is being measured, how data are being used, and how those interested might be able to access the data.

13.4.4 Power Requirements

Before designing or choosing a system, it is important to consider the cumulative power consumption of chosen sensors and communications, as well as seasonal patterns in power production. A detailed power audit may be needed to determine necessary power generation and reserve supply, including an understanding of solar collection efficiency and local climate variability (sunlight hours). Too much power is usually better than not enough; however, multiple high-capacity sealed lead-acid batteries and large solar panels can quickly make for a cumbersome platform. Because of their heavy weight, batteries are often stored deep within a buoy to act as extra ballast. Most commonly used batteries (typically sealed lead-acid) ‘off-gas’ hydrogen and should not be charged within hermetically sealed enclosures.

13.4.5 Circuit Protection

Proper grounding of sensors and equipment is essential to ensure proper operation and to prevent damage from lightning-induced voltage surges or electrostatic discharge. Grounding and circuit protection are complex subjects, and a detailed description is beyond scope here. Nevertheless, the general principal of lightning and surge protection is to provide a lowest-resistance path to ground which bypasses sensitive components of the system. Many pieces of equipment commonly used in data buoys (data loggers, solar regulators, etc.,) have some degree of in-built circuit protection, be it resettable fuses or gas discharge tubes. Proper grounding of all equipment is necessary to ensure the functionality of in-built protection, usually requiring connection to a 'ground plane' which in terrestrial systems is commonly provided by a copper rod driven into the earth. In the aquatic environment, achieving an adequate connection to ground can be more challenging, particularly where conductivity is low (i.e. in most lakes). Additional measures are usually required, and this is an area of system design where careful consultation of equipment manufacturer's recommendations and advice or assistance from qualified personnel is strongly advised.

13.4.6 Data Collection (Logging and Telemetry)

Cellular, radio, or satellite telemetry enable near-real-time transmission of water quality data over the lifetime of a monitoring buoy. Cellular modems require a network subscription and adequate wireless signal at the lake's surface, bearing in mind that data can usually be somewhat reliably transmitted well below the threshold of reception needed for a tolerable voice call. Radio systems require a radio base established within range of the transmitter and, where feasible, can be an attractive alternative to the ongoing cost of cellular communications subscriptions. In the rare instance that neither cellular nor radio signals are sufficient, a satellite modem can be used to remotely access data, although this can be an expensive option. Alternatively, buoys can log data internally to then be retrieved at user-specified intervals. Due to the low cost of large-capacity memory chips, buoy visits can often be in the order of months without running out of available memory.

Data loggers are commonly used to store and transmit data from sensors as well as control sampling frequency and power supply. Data loggers are generally highly robust and programmed with relative ease. Important considerations include compatibility with preferred options for telemetry and sensor communications. For example, some data loggers will support a limited number of serial devices (e.g. RS232, RS485) and so may not be an ideal choice where multiple sensors are required and use such communications. Many systems allow the data logger to be controlled remotely, for example, allowing for adaptive sampling by modulation of sensor sampling frequency, from anywhere in the world.

13.4.7 Open-Source, Low Cost Hardware

Commercial data loggers are perhaps the most common ‘brain’ for automated water quality monitoring. However, open-source microcontrollers and miniature computers are low-cost and flexible alternatives that are gaining increasing use with sensor technologies. Platforms such as Raspberry Pi (www.raspberrypi.org), Arduino (www.arduino.cc), and BeagleBoard (www.beagleboard.org) provide the opportunity to replace data loggers with low-cost open technology that can be in many ways more analytically powerful than traditional data loggers. For example, these technologies can be used to push analytics onto the sensor platform itself thereby enabling a buoy to perform its own diagnostics and some degree of quality assurance and control. This approach can be used to assess sensor stability and the likelihood of unwanted sensor drift, connect sensors to cue one another, or otherwise develop an ‘internet of things’ approach to environmental sampling. Nevertheless, in many cases, care and expertise is required in order to collect research quality data using certain technologies. For example, collecting precise and accurate readings from analog sensors can require additional hardware if the microcontroller does not natively include an appropriate precision reference voltage against which to measure the signal from the sensor.

13.4.8 Software and Data Access

During set up, users will generally define intervals for sensor measurement and data transmission. A typical system might log data from sensors every 15 min with an integration time of 30 s and transmit data to a central server every hour or every day. Limitations on logging and communications frequency are often at the discretion of the operator; however, power consumption during logging and communications may sometimes limit very high frequencies of logging and transmittance. Some sensors require a relatively long equilibration period to adjust to water quality gradients. For example, some optical dissolved oxygen sensors can take over 5 min to equilibrate to accurately measure a drastic change in dissolved oxygen concentration. It should be noted that many dissolved oxygen sensor manufacturers claim a short equilibration period (e.g. <30 s), but often quote accuracy to 60 or 90% over this period. Further accuracy (e.g. to 99%) can take several additional minutes.

13.4.9 Alarms and Notifications

A key component of buoy-based monitoring and research is the ability for end users to respond rapidly to sensor readings that exceed pre-defined thresholds. For example, dredgers using turbidity sensors may have to respond quickly to high suspension levels to reduce sediment loads and deterioration of downstream water quality. Most databases can be configured to send automated alarm notifications via SMS or e-mail that provide immediate alerts when sensor readings exceed pre-defined thresholds. This technology can also facilitate adaptive sampling of water quality. Abnormally, high or low values may signal sensor failure, calibration drift, or biofouling; thus, buoy operators can be automatically notified of the need to check sensor function and fidelity. As described above, microcontrollers and miniature computers also increase the capability of sensors to cue other measurements. For example, stream and lake sensors can be set to sample more frequently based on meteorological sensors detecting passing storm fronts, or sensors can be cued in order to sample based on a running-averaged-mean or deviation from a particular distribution.

13.5 Sensors

There are literally thousands of possible sensors for buoy-based applications. Sensors are usually classified either by parameter type (e.g. physical, chemical, or biological sensors) or by the technology or measurement principle that they use (e.g. electrochemical, optical). The measurement principle employed has implications for sensor cost, measurement stability, susceptibility to fouling, calibration, and maintenance requirements. Sensor technologies are constantly advancing. One such example is optical dissolved oxygen sensors, which have largely replaced electrochemical sensors in common use despite a somewhat higher cost, due to increased long-term stability and lower maintenance and calibration requirements.

13.5.1 Sensor Communications

Sensors use a variety of methods to transmit measurements to data collection platforms (e.g. data loggers). It is worthwhile remembering that most sensors are measuring some sort of electrical signal, which must then be amplified and/or interpreted into a meaningful value. Such interpretation can be performed within the sensor, by the data logger, at the database, or during post-processing. Accurate record keeping of data transformations, scaling factors, and unit conversions is an essential component of metadata collection.

Analog sensors output a raw electrical signal, which may be a single-ended voltage (e.g. 0–5 V), differential voltage (e.g. ±250 mV), or current loop (e.g. 4–20 mA).

Digital sensors generally contain an on-board analog to digital converter (ADC) and may or may not also have on-board data logging. These sensors output digital information using a variety of protocols such as RS232 or RS485. Another popular serial data standard, SDI-12, allows connection of multiple sensors using three wires (power supply, ground, and data) and communicates with sensors individually via allocated sensor addresses.

13.5.2 Meteorological Sensors

Understanding the response of lake processes in response meteorological changes is an essential component of lake research and monitoring. Therefore, many lake buoys include meteorological sensors. Typical meteorology measurements include wind speed, wind direction, precipitation (multiple forms, e.g. rain, hail and snow), barometric pressure, air temperature, and relative humidity. Compact weather stations such as the Vaisala WXT520 or Lufft WS-series instruments are popular choices. These multi-sensors provide several key variables in a single package and may contain no moving parts due to the use of ultrasonic anemometers (wind speed sensors). For higher demands with regard to sensor accuracy, component meteorological sensors can also be used. Regardless of the technology employed, platform stability, overall height, and deterrence of birds (usually by installation of spikes) are important considerations.

13.5.3 Temperature Sensors

Water temperature is one of the most commonly reported lake measurements because it is extremely important to a number of aquatic processes and is relatively inexpensive and easy to measure. Fisheries management, hydroelectric plants, selective withdrawal dams, and numerous aspects of aquatic and sediment research often depend on having water temperature data from throughout the water column. Temperature in many lakes is measured continuously using strings of temperature sensors that span the water column, with sensors located at fixed depths. Commercially available temperature sensors range greatly in accuracy (c. $\pm 0.5^\circ$C to $\pm 0.001^\circ$C) and corresponding cost (a few cents to hundreds of dollars per sensor). Temperature sensors are commonly put close to one another near the surface or epilimnion of the lake (often up to every 0.25 m), so that high-spatial-resolution temperature data is collected in this zone, where temperatures can vary over short spatial and temporal scales. Below the metalimnion, sensors may be relatively sparsely located because temperature gradients are smaller and more predictable deeper in the water column.

13.5.4 Light Sensors

Light and water transparency are two fundamental properties of aquatic ecosystems. Transparency regulates a number of in-lake processes, including the maximum depth of photosynthesis and oxygen production as well as changes in temperature throughout the water column. Above surface atmospheric sensors can measure incident (downward) light or reflected light (albedo) by pointing a sensor at the lake surface. Below water, light sensors can be used to measure transparency. Underwater measurements typically include two or more sensors deployed at different depths. The difference in light between the sensors is used to estimate the diffuse attenuation coefficient for light. Underwater light sensors are typically located on an arm away from the buoy to reduce or eliminate potential shading effects from the buoy above, and regular or automated cleaning of light sensors is essential. Many different sensors exist depending on the wavelengths of interest. Examples include visible light (400–750 nm), PAR (photosynthetically active radiation, 400–700 nm), ultraviolet light UVA and UVB (280–400 nm), infrared (700–3000 nm), total short-wave radiation, total long-wave radiation, and total global radiation. PAR sensors are the most commonly used light sensors underwater because PAR wavelengths are used by photosynthesising algae.

13.5.5 Other Sensors

Table 13.1 summarises a range of common sensors and measurement technologies. When designing a system and choosing sensors, it is worth spending time carefully evaluating research and monitoring questions, and how this relates to requirements for sensor accuracy, available resources for maintenance, and the need for spatial sensor replication. These aspects strongly influence the total cost of the system, and cost may ultimately determine the final configuration. All sensor-based measurements must be collected and interpreted carefully in order to draw robust conclusions from data (see case study on fluorescence, below).

13.5.6 Multi-probes (Sondes)

A sonde (French for probe) is used to house, protect, and connect many underwater sensors within a single, integrated package. Sondes provide common power and communications for a range of sensors and usually store sensor calibration information. Typically, sondes have on-board power and data logging but can also be easily configured for communications with external power and data loggers. Sondes can be expensive compared to component sensors, but the convenience of a common interface saves much time and effort in cabling, calibration, and system

Table 13.1 Overview of common measurement variables, sensor technologies, advantages/disadvantages and example manufacturers and instruments

Variable	Units	Sensor type	Description	Pros	Cons	E.g. *manufacturer*: model
Physical						
Water temperature	°C	NTC thermistor	Temperature-dependent resistor with negative temperature coefficient	• Fast response time with calibration • Long-term stability • Accurate and precise	• Non-linear calibration • Commercial options can be relatively expensive	*PME*: T-Chain
		IC temperature sensor	Integrated circuit with analog or digital output	• Pre-processed output (e.g. linear analog, digital) • Inexpensive	• Lower accuracy from factory calibration	*Dallas Instruments*: DS18B20
Photosynthetically active radiation (PAR)	μE m^{-2} s^{-1}	Silicon photodetector	Silicon photodetector with optical bandpass filter (400–700 nm) and diffuser	• Inexpensive • Multiple sensors can be used to estimate light attenuation (K_d)	• Requires careful mounting underwater. Sensitive to shading and rotation	*Li-Cor*: LI192 quantum sensor
Turbidity	FTU, FNU	Nephelometric, non-ratio	Light source and photodetector at 90° to one another	• Accurate at low turbidity	• Non-linearity at high turbidity	*Turner Designs*: cyclops C7 'T'
	FNRU	Nephelometric, ratio	Light source and 90° primary photodetector with additional detectors at other angles	• Improved accuracy at very low turbidity • Reduced interference from colour	• Non-linearity at high turbidity	*Hydrolab*: 4-beam GLI-2
	NTU, BU	Backscatter	Light source and photodetector at <90° to one another	• Wide measurement range • Improved accuracy at high turbidity	• Less accurate at low turbidity	*Campbell Scientific*: OBS-3+

Transmission	%, m^{-1}	Beam transmission and attenuation	Reduction in light intensity over a fixed path length	• Accounts for both scattering and absorption	• Can be limited in dynamic range	*Wet Labs*: C-Star
Water level	m	Echo sounder	Time delay between emission and return of sound pulse determines water column depth	• Buoy mounted	• Interference (e.g. sensors, moorings)	*Airmar*: DT800
		Pressure sensor (absolute)	Hydrostatic pressure on sensing diaphragm	• No vent tube required	• Must be bottom-mounted	*INW*: PT12
		Pressure sensor (differential)	Hydrostatic and atmospheric pressure on sensing diaphragms	• Inherent atmospheric compensation	• Must be bottom mounted • Vent tube to atmosphere required	In-situ: level TROLL 500
Chemical						
Dissolved oxygen	% sat, mg L^{-1}	Polarographic	Silver anode and noble metal cathode in a potassium chloride solution	• Lower cost	• Consumptive, requires stirring • Warm up period required • Measurement drift	*Sea-Bird Electronics*: SBE43
		Polarographic pulsed	Polarographic but with third (silver) electrode to enable pulsing of measurement	• Reduces need for solution stirring	• Warm up period required • Measurement drift	*YSI*: 6562
		Galvanic	Anode and cathode of dissimilar metals (zinc or lead anode, silver or nickel cathode)	• Possible to achieve fast response time	• Shorter lifetime • Sensitive, e.g. to H_2S	*AMT*: galvanic micro-sensor
		Optical: intensity	Quenching of fluorescent response by dye to blue light excitation, dependent on dissolved oxygen concentration	• More stable than electrode sensors	• Slow response time • Susceptible to photobleaching • Moderate cost	*InSite IG*: Model 10
		Optical: lifetime luminescence	Lifetime (phase shift) of quenching response, dependent	• Better long-term stability than fluorescence intensity	• Slow response time • Moderate cost	*ONSET*: HOBO DO data logger

(continued)

Table 13.1 (continued)

Variable	Units	Sensor type	Description	Pros	Cons	E.g. *manufacturer*: model
			on dissolved oxygen concentration	• Insensitive to interference by ambient light		
		Optical: fast response	Lifetime luminescence but without permeable light barrier	• Very fast response time	• Higher cost	*JFE Advantek*: RINKO series
Dissolved carbon dioxide		Non-dispersive infrared	Diffusion of gas through an oil resistant matrix interface, concentration-dependent absorption of IR electromagnetic radiation	• Relatively low cost and maintenance	• Slow response time (minutes)	*Pro-Oceanus*: Mini-Pro CO2
Methane	g m^{-3}	Spectroscopy	E.g. cavity enhanced absorption	• Measure all GHGs simultaneously • Accuracy, sensitivity	• Cost, size • Requires surface/ pumped chamber	*LGR*: GHG Analyzer
		Tunable diode laser absorption spectroscopy	Membrane diffusion with concentration-dependent laser light intensity	• Accuracy, sensitivity • Long-term stability	• Cost, size	*Contros*: HydroC CH_4
		Non-dispersive infrared	Diffusion of gas from liquid through an oil-resistant matrix interface	• Relatively low cost and maintenance	• Slow response time (minutes)	*Pro-Oceanus*: Mini-Pro Methane
Conductivity	μS cm^{-1}	Contacting: 2, 3 or 4 electrode	Conductivity-dependent current produced when voltage is applied to immersed electrodes	• Low-cost • Accurate	• Cell constant must be appropriate to intended range of measurement • Sensitive to fouling and corrosion	*Ponsel*: digisens-4-electrode

		Inductive	AC drive coil voltage induces current in a receive coil, proportional to the conductivity of the solution	• More robust than electrode sensors • Insensitive to fouling and interference by suspended solids	• Less accurate at low conductivity • Relatively higher cost	*Stevens Greenspan*: EC300
pH	Unitless	Combination electrode	Electric potential created between a glass electrode and reference electrode is a function of pH	• Lower cost	• Can't be stored dry • Require regular cleaning and calibration	*Ponsel*: Digisens pH/ORP
		ISFET (solid state)	Silicon chip in contact with solution measures voltage potential between its surface and underlying semiconductor	• Robust (no glass), can be stored dry • Easily cleaned • On-board temperature compensation	• Often greater sensor drift than for glass bulb sensors • Higher cost	*Campbell Scientific*: CS526L
Oxidation/reduction potential	mV	Combination electrode	Voltage between inert metal electrode and reference electrode	• Often shares reference electrode with pH sensor	• Drift	*INW*: TempHion pH/ORP
Nitrate	g m^{-3}	Ultraviolet spectrometry (optical)	Spectral absorption c. 200–400 nm. Stable UV light source, fibre optic sensing probe, and precision spectrometer. Nitrate determined by least squares fitting algorithm	• Long-term stability • Real-time nitrate measurements	• Very high cost	*Satlantic*: SUNA v2
Phosphate, ammonium, nitrate	g m^{-3}	Ion-selective electrode	As for pH, but with membrane and reference electrode specific to other ions	• Low cost	• Poor sensitivity • Drift	*INW*: TempHion ISE
		Automated wet chemistry	Multi-beam fibre optic colorimeter with silicon detector and fluorimetric measurement. Automated wet chemistry with reagent reservoirs	• Laboratory-style analysis, in-situ • Sensitive and accurate	• Labour intensive • High cost • Consumables (reagents)	*Systea*: WIZ probe

(continued)

Table 13.1 (continued)

Variable	Units	Sensor type	Description	Pros	Cons	E.g. *manufacturer*: model
Dissolved organic matter	fDOM	Fluorometry	Fluorescence using LED excitation and optical detection at wavelengths targeted for dissolved organic matter	• Long-term stability • Moderate cost	• Temperature-dependence	*Wet Labs*: ECO FL CDOM
Biological						
Pigment fluorescence	RFU	Fluorometry	Fluorescence using LED excitation and optical detection at wavelengths targeted for chlorophyll and or accessory pigments including phycocyanin	• Long-term stability • Moderate cost	See case study	See Table 13.2

configuration. Popular manufacturers include YSI, Eureka Environmental, Hydrolab, and In-Situ. Sensors typically integrated by sondes include pressure (depth), temperature, conductivity (salinity), pH/ORP, dissolved oxygen, turbidity, chlorophyll, and cyanobacteria (phycocyanin/phycoerythrin).

13.5.7 Acoustic Sensors

Although infrequently deployed directly on buoys, acoustic sensors are an important class of water quality sensors. Acoustic sensors are occasionally deployed concurrently with buoys to understand a wide range of lake characteristics. Acoustic Doppler Current Profilers (ADCPs) are most commonly deployed on lake bottoms with upward facing sensors, but can also be surface mounted. The sensors can identify the location and movement of particles by using the Doppler effect of sound waves scattered back from particles in the water column. The frequency of the emitting sensor dictates in part the particle size measured. The sensors can be used to study characteristics such as flow and circulation, waves, gas flux, bottom tracking (depth), zooplankton movement (e.g. diel vertical migration), and fish movement.

13.6 Photosynthetic Pigment Fluorometers: Measurement Principle, Pitfalls, and Interpretation

Phytoplankton biomass is usually quantified by either manual counting with biovolume measurements or estimated by determining sample concentration of extracted photosynthetic pigment (chlorophyll *a*). All phytoplankton contain chlorophyll *a*, and many also contain accessory pigments which harvest light energy for transfer to the photosynthetic reaction centre. Photosynthetic pigments are ‘fluorescent’ compounds. Fluorescence is the absorption of energy as light with instantaneous emission of light at longer wavelengths (lower energy), and each fluorescent compound has signature peak absorbance and emission wavelengths. Laboratory measurement of chlorophyll *a* requires extraction of pigment from the cells by acetone/ethanol/methanol digestion, followed by in vitro measurement of the fluorescence intensity of the extracted pigment using a benchtop fluorometer. By contrast, in vivo fluorometers measure the fluorescent response of living phytoplankton cells and as such can be used for high-frequency unattended monitoring and integration with real-time data collection systems. In vivo fluorescence is typically less precise and more error-and interference-prone than extracted in vitro fluorescence; therefore, instrumentation and data need to be managed meticulously in order to maximise the utility of these measurements.

13.6.1 Measurement Principle

The primary pigments analysed for freshwater phytoplankton are chlorophyll and phycocyanin. Chlorophyll pigments can be measured separately (e.g. *a*, *b*, *c*) or as total chlorophyll. Each pigment has slightly different excitation and emission spectra. Chlorophyll *a* absorbs light predominantly from the blue wavelengths (maximum excitation at 440 nm) and has a fluorescence peak at 675–685 nm (Lee et al. 1995; Gregor and Maršálek 2005). Phycocyanin is a dominant accessory pigment in freshwater cyanobacteria (the analogue in marine cyanobacteria is phycoerythrin) and absorbs light in the orange and red wavelengths (550–630 nm) with maximum excitation at 620 nm and emission at around 650–660 nm (Fig. 13.4) (Lee et al. 1995; Gregor and Maršálek 2005; Bastien et al. 2011).

In vivo fluorometers typically use an LED light source to excite a 'sensing volume' of water in front of the optical window and measure emitted fluorescence via detection filter located at a 90° angle to the excitation source. Single pigment instruments utilise excitation and detection wavelengths specific to the pigment being measured. Different manufacturers use slightly varying excitation and emission wavelengths, and this should be considered when comparing instruments or using different sensors at different sites (Table 13.2). The different excitation and emission wavelengths of the various manufacturers are in part controlled by the optical quality of the glass and filters used in the sensors. High quality materials

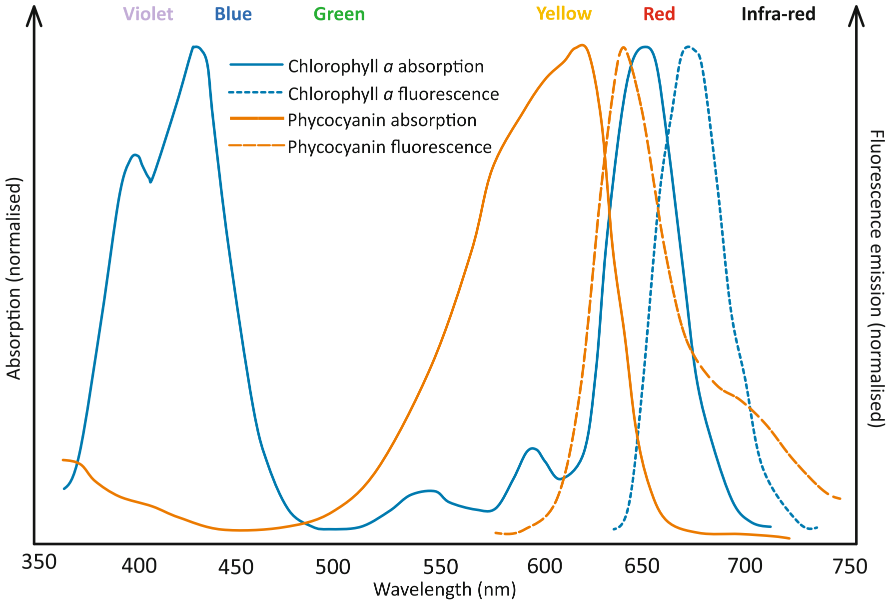


Fig. 13.4 Normalised absorption and emission (fluorescence) spectra of chlorophyll *a* and phycocyanin, the photosynthetic pigments most often measured in vivo for fluorometric sensing of phytoplankton. Spectra adapted from Taiz and Zeiger (2010)

Table 13.2 Excitation and detection wavelengths for several commonly used chlorophyll and phycocyanin fluorometers

		Chlorophyll		Phycocyanin	
Manufacturer	Instrument	Excitation (nm)	Detection (nm)	Excitation (nm)	Detection (nm)
Turner designs	Cyclops-7	460	696/44	595	≥630
Yellow Springs Instruments (YSI)	6600 series	470	650–700	595	650
	EXO series[a]	470 ± 15	685 ± 20	590 ± 15	685 ± 20
Chelsea technologies	TriLux[a]	470	685	610	685
Trios GmBH	Micro-Flu	470	685	620	655
Seapoint Ltd	Chlorophyll	470 ± 15	685 ± 15	Na	Na
Wet Labs	ECO series	470	695	630	680
BBE	Fluoroprobe[a]	450	680	610	680

[a] Combination sensor with multiple excitation/single detection. BBE probe has three additional excitation wavelengths not given above

typically have a smaller wavelength range of excitation and emission but are also more expensive. Narrow bandwidths are required to separate different types of chlorophyll, hence why many sensors measure ‘total chlorophyll’. ‘Combination’ fluorometers have multiple excitation LEDs but use a single detection filter. This method operates on the principle that light energy captured by accessory pigments is rapidly transferred to chlorophyll *a* where it is used for photosynthesis. As such these instruments aim to measure the proportion of pigments in the phytoplankton sample. An example of this approach is the BBE FluoroProbe which utilises six excitation wavelengths (370, 470, 525, 570, 590, and 610 nm) and detects the fluorescent response of chlorophyll *a* at 680 nm.

Fluorometers amplify detected fluorescent light energy and convert to output either as analog (typically 0–5 V) or digital (serial) signals. Uncalibrated sensor output is typically reported as ‘relative fluorescence units’ (RFU), or if the zero value for the instrument has been set using deionised water, measurements may be reported as ‘raw fluorescence units blanked’ (RFUB). Raw measurements can provide insight into short- to medium-term phytoplankton dynamics. However, the relationship between phytoplankton biomass and fluorescence is complex and can be influenced variously by species assemblage, sample concentration, ambient light interference, non-photochemical quenching, bio-fouling, and temperature. Non-photochemical quenching in particular can have large effects on the accuracy of chlorophyll fluorescence sensors and, therefore, many sensors provide poor characterisations of chlorophyll under bright light conditions. Interpretation of fluorescence data should carefully consider these multiple influences.

13.6.2 Gain, Signal Linearity, and Quenching

Most in vivo fluorometers have adjustable gain in order to provide appropriate measurement resolution across a broad range of phytoplankton concentrations. If fixed, the sensor range needs to be sufficient to cover all conditions through time and, if it is to be controlled dynamically, it may be desirable to perform calibrations across multiple ranges or record range for each measurement for analysis during post-processing because measurement ranges provided by manufacturers for different gain settings on their instruments are often nominal only.

High absorbance in the water column can ‘quench’ fluorescence and result in erroneously low values. At high chlorophyll concentrations, fluorescence can be quenched via absorption of emitted light by the phytoplankton themselves. This means that detected fluorescence at very high concentrations may actually be *lower* than at moderate concentrations (Fig. 13.5). High absorbance by dissolved organic matter can also quench fluorescence. To account for this, some pigment sensors have fluorescence dissolved organic matter sensors (e.g. BBE FluoroProbe). Quenching can be avoided by dilution of highly concentrated samples, although this approach may be impractical for continuous and/or remote measurement. Thresholds for quenching may be determined by analysing a dilution series; however, the relationship between quenching and phytoplankton concentration may differ with phytoplankton physiology (e.g. filamentous vs. colonial). High turbidity from non-algal sources can also adversely affect signal linearity, by either increasing detected fluorescence at low phytoplankton abundances due to increased scattering or decreasing detected fluorescence at high phytoplankton abundance due to increased absorption.

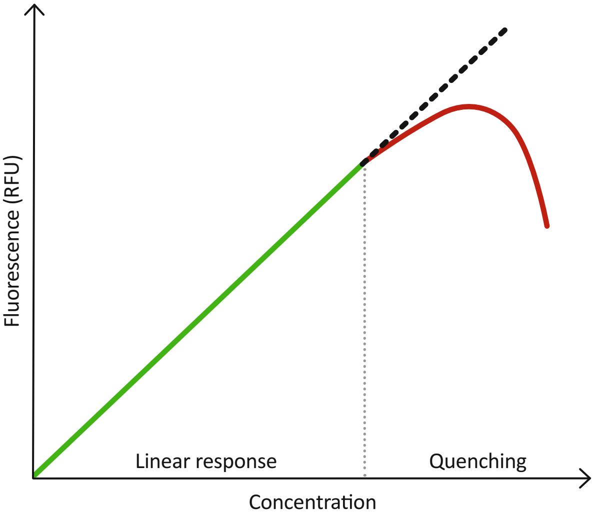


Fig. 13.5 Linear and ‘quenching’ regions of a generalised fluorometer response to increasing sample concentration

13.6.3 Ambient Light Interference

In some cases, ambient light can interfere with the detection optics of fluorometers, compromising data quality during brightly lit daylight hours. Advanced fluorescence sensors minimise this source of error by modulation of the LED light source, and measuring continuously whereby differences in fluorescence when the excitation LED is on and off are used to remove ambient light effects. Sensitivity to ambient light varies between manufacturers and models; therefore, it can be important to understand the instrument used, the light climate of the water, and any protection or shading offered by the buoy platform itself, in order to determine if any additional measures are needed to combat the effect of ambient light, e.g. shade caps or flow-through cells.

13.6.4 Temperature Effects

Fluorescence measurements are inherently temperature dependent. Algal fluorescence decreases as temperature increases, and a commonly used equation for temperature correction of chlorophyll fluorescence is

$$Fr = Fs^{[n(Ts-Tr)]}$$

where n is a temperature coefficient, Tr is the reference temperature, Fr is the calculated fluorescence reading at the reference temperature, and Fs is the observed fluorescence reading of the sample at the time of reading the sample temperature, Ts.

A common temperature coefficient for in vivo chlorophyll fluorescence is 1.4 (as recommended by Turner Designs Ltd).

13.6.5 Non-photochemical Quenching

Non-photochemical quenching (NPQ) is a mechanism used by phytoplankton to prevent damage to photochemical reaction centres during exposure to high intensity light. Absorption of excess light stimulates NPQ whereby excess energy is emitted mostly as heat, thus reducing emission of energy as photons (fluorescence). In practice, NPQ results in lower observed chlorophyll fluorescence than would be observed from identical biomass in low-light conditions. This photo-protective response can occur rapidly and is substantial; it can reduce estimated chlorophyll concentrations by nearly an order of magnitude (Fig. 13.6). Therefore, care must be taken when interpreting daytime fluorescence measurements particularly where sensor readings are being related to extractive chlorophyll measurements from grab samples collected during daytime for the purpose of calibration (Fig. 13.7).

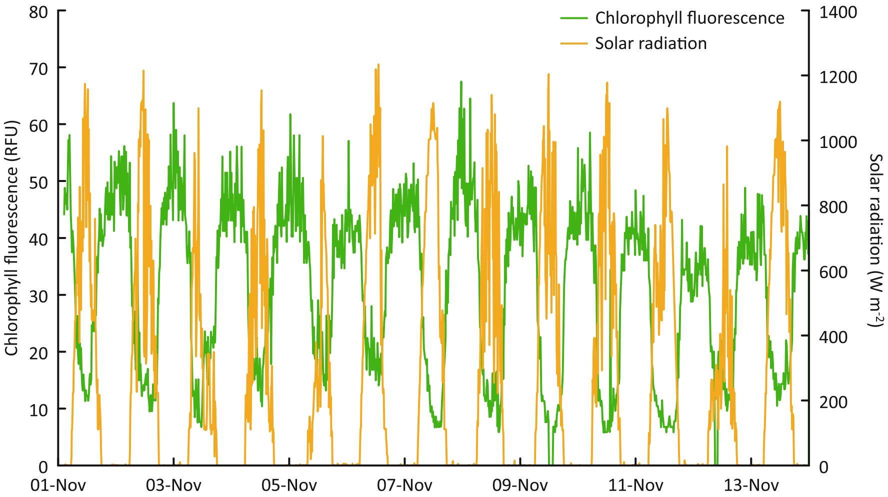


Fig. 13.6 Chlorophyll fluorescence (1 m depth) and short-wave radiation at Lake Rotorua. Fluorescence readings (green) demonstrate the effect on measured fluorescence of non-photochemical quenching (NPQ) in response to solar radiation (yellow)

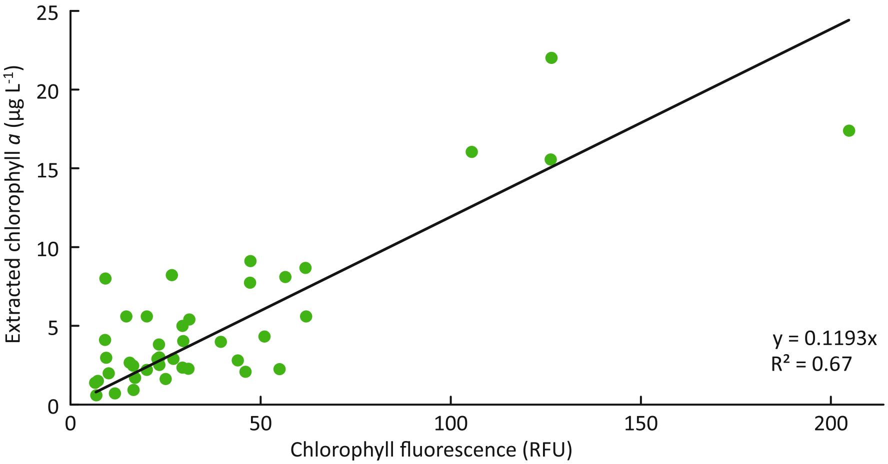


Fig. 13.7 Relationship between extracted chlorophyll and corresponding daily average pre-dawn-post-dusk chlorophyll fluorescence measurements, from Lake Tutira New Zealand, 2009–2012

Modelling and adjusting for the effects of NPQ can be difficult because it can vary day-to-day due to drivers including mixing depth, mixing rate, surface irradiance, light attenuation coefficient, as well as algal species, cell geometry, and cell nutrient status. A common approach is to disregard chlorophyll fluorescence measurements from dawn to slightly after dusk and focus on night-time measurements. While quick and easy, this approach has the disadvantage of removing a substantial portion of the data and preventing analyses of sub-daily dynamics (e.g. effects of diurnal stratification).

13.6.6 Fluorometer Calibration and Fluorescence Versus Biomass

When deploying in vivo fluorometers for long-term continuous measurement, a constant relationship between raw measurements and chlorophyll *a* concentration should not be assumed, due to multiple influences including temporal and spatial variation in species composition, light exposure, and sample temperature, as described above. Therefore, it is good practice to record measurements in raw units in the first instance, whereby raw fluorescence can be converted to chlorophyll or biomass equivalents during post-processing, if required. In situ sensors may also be sensitive to integration time and particle size effects. For example, if a sensor only operates for a 1-s integration time every occasion it turns on, and during its ‘on’ period a large colonial cell is in front of the optics, it may register erroneously high fluorescence. One way to minimise this effect is to use as large an integration time as the sensor and power system can enable, in order to average-out sources of variability.

Chlorophyll fluorescence often relates well to measurements of extracted chlorophyll *a* (Fig. 13.7); however, where species assemblages are complex and dynamic, and particularly where cyanobacteria are frequently dominant, fluorescence for multiple pigments is desirable, along with regular extractive measurements and species enumeration with biovolume estimates spanning seasonal and inter-annual variation. This represents considerable effort, and, as such, fluorescence can be a quick and easy method of measuring relative change in phytoplankton communities. However, due to the limitations described above, chlorophyll fluorescence sensors are often best considered as a tool to complement rather than replace traditional, lower-frequency monitoring strategies. In some cases, such as when buoyant cyanobacteria are present, there can be a substantial vertical gradient in chlorophyll and cell counts. Even profiling buoys, which better represent dynamics through the water column than fixed depth sensors, often cannot characterise cyanobacterial surface scums which can vary over spatial scales of millimetres.

13.6.7 Methods of Fluorometer Calibration

13.6.7.1 Pigment Laboratory Standard

Fluorometers typically come with a factory calibration and default dynamic range(s), often based on a primary standard of extracted pigment (e.g. phycocyanin pigment from prozyme diluted in deionised water, Turner Designs Cyclops C-7 phycocyanin). User-performed calibrations with primary standards are not always practical. For example, extracted chlorophyll must be suspended in acetone and, therefore, requires a specialised vessel or coupling to avoid damaging the optical window of the instrument, and phycocyanin standards can be expensive to procure and degrade quickly. It should be noted that chlorophyll in vivo may fluoresce differently to an equivalent concentration of extracted chlorophyll (e.g. due to variation within a colony of algal cells), and so calibrations based on extracted suspensions may not provide a precise conversion of in situ fluorescence to chlorophyll extracted from grab samples.

13.6.7.2 Secondary Synthetic Standard

Secondary synthetic standards are used to quantify long-term stability of field instrumentation, rather than to calibrate sensors in order to accurately estimate chlorophyll *a* concentrations. Standards can be a solid or liquid fluorescent material used to provide repeatable measurements in order to evaluate the consistency of instrument output. Some manufacturers supply standards made from a disc of solid fluorescent material mounted in a sleeve to ensure consistent orientation (e.g. Turner Designs' solid secondary standard range), whereas others recommend the use of a solution of fluorescent dye (frequently Rhodamine). Dye solutions are able to be easily reproduced, but are also subject to dilution error and batch variability. Solid materials are less prone to user error but are difficult to replicate exactly if the original is damaged or lost. Earp et al. (2011) provide an excellent review of multiple dyes and solid materials for chlorophyll fluorometers, recommending Plexiglass Satinice® 'Plum' for a solid standard and fluorescein dye for a liquid standard. When using a liquid standard, it is advisable to purchase a single batch of dye sufficient to perform multiple standard measurements, and all secondary standards should be kept in the dark to reduce degradation.

13.6.7.3 Cell Culture Dilution Series

The linear range of a sensor, as well as the relationship between biovolume and fluorescence, can be determined by lab experiments measuring a dilution series of cultured cells. The complexity of the relationship between phytoplankton biomass and fluorescence is highlighted by variability in the fluorescent responses of similar biovolumes among different species (Fig. 13.8). Therefore, a site-representative mixed assemblage may be the most appropriate method to relate fluorescence to biovolume.

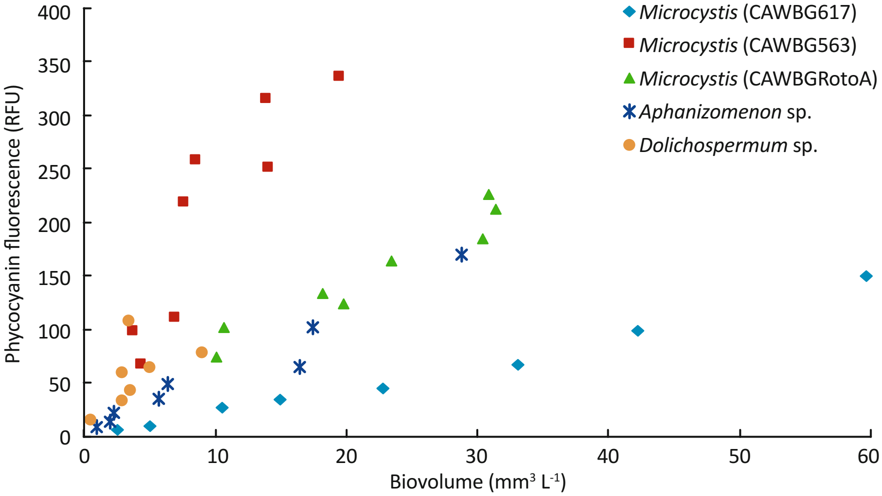


Fig. 13.8 Relationship between raw phycocyanin fluorescence and biovolume for five phytoplankton species, using a Chelsea Instruments ‘TriLux’ fluorometer. Data from Hodges (2016)

13.6.7.4 Grab Samples

A useful means of calibration is to relate sensor measurements through time with corresponding quantitative measurements of water samples collected at lower frequencies (Fig. 13.7). Relationships must be carefully constructed and not assumed to be universal across lakes or highly consistent through time due to the combined influences of species succession, quenching, temperature-dependence, ambient light interference, and NPQ described above.

13.7 System Maintenance and Calibration

Regardless of the platform and sensors used, periodic maintenance and calibration are required to ensure quality data collection. Maintenance intervals are largely dependent on sensor specifications, site location, water quality conditions, and other variables. Common maintenance intervals depend on water conditions, for example, waterways that are highly productive with high phytoplankton biomass are more susceptible to fouling and degradation of measurement quality (Fig. 13.9). Each sensor usually has a recommended calibration frequency; consult instrument-specific literature for more details.

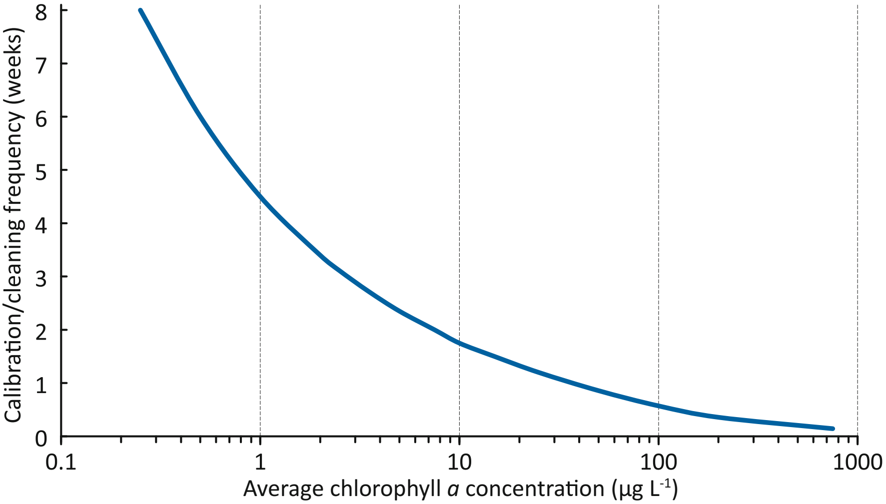


Fig. 13.9 Conceptual diagram of recommended cleaning frequency for near-surface-mounted sensors

13.7.1 Anti-fouling Technology

A common problem for in situ measurements of any kind, especially during extended sensor deployments, is fouling. Either biological (active) or non-biological (passive) fouling can occur. Active fouling refers to the growth of plants and animals over an instrument's measurement surfaces, whereas passive fouling results from substances such as silt, clay, and organic residue accumulation. Fouling can have substantial effects on sensor readings. For example, for many optical sensors such as dissolved oxygen, chlorophyll, CDOM, or turbidity sensors, fouling can block the passage of light from the source beam and to the detector. Biological fouling can increase measurements of dissolved oxygen and fluorescence as attached plants grow near the sensor window. In the interest of long-term deployments, particularly those in high-fouling waters, many in situ sensors now possess anti-fouling equipment to increase the accuracy and minimise the frequency of sensor maintenance. Many sensors have the option of in-built mechanical wiping devices that sweep fouling agents from the sensor surfaces prior to measurement (Fig. 13.10). For sensors that do not have the option of a mechanical wiper, an after-market third party wiper can sometimes be installed on the sensor. Other anti-fouling approaches include copper surfaces such as a ring around the sensor face, blasting of compressed air, ultrasonic disruption, automated pumping of biocides, and anti-fouling paint.

Fig. 13.10 An Apogee Instruments Quantum (PAR) sensor mounted in a Zebra-Tech 'Hydro-Wiper' automatic sensor wiper after 2 years deployed in oligotrophic Lake Waikaremoana, New Zealand. Although the wiper body and arm (pointing to 5 o'clock) were heavily grown over, the sensor's optical surface (centre) was clean and reading accurately (Image: M. Osborne)

13.8 Data: Quality Assurance and Quality Control

Automated monitoring platforms are capable of collecting vast quantities of data in short time. Quality assurance and quality control of sensor data are vital and can be challenging.

13.8.1 Data Collection: Quality Assurance

Assuring data quality begins before sensors are deployed. Sensors should ideally be calibrated according to manufacturer's recommendations and in consideration of the environment in which they will be submersed. Calibration consistency is important. For example, measurement temperature and/or atmospheric pressure (elevation) might affect calibration values for a host of sensors, including pH, dissolved oxygen, and fluorescence. Sensor performance should be carefully evaluated, being mindful of the age and lifespan of sensors, for instance, a three-point calibration may be more useful than two-point calibration, if sensor linearity is a concern. Sometimes, it is preferable to log raw values and apply calibration equations during post-processing of data. Regardless of the approach, accurate record keeping is always vital, including sensor calibrations, observed bio-fouling and timing of manual sensor cleaning, sensor gain changes or other wiring modifications, and any other factors which may later help explain sudden changes or unexpected values when processing data.

13.8.2 Data Processing: Quality Control

A single platform measuring 20 variables every 5 min will produce more than half a million individual observations per year. Because of the nature of sensor measurements, it is unlikely that such a dataset will proceed to analysis or publication without the need for error detection, correction, interpolation, and/or data transformations. Even meticulously collected (good quality assurance) datasets require thorough examination before graduating from raw streaming data to research, outreach, or other disseminated products. Erroneous data are sometimes glaringly obvious within the parent dataset. Often, automated protocols can be implemented to identify and remove these data. However, many sensor errors are more subtle and less easily detected by coarse 'filters'. There are various methods to quality control high-frequency datasets and most often a combined approach of automated and manual quality control is adopted.

Many data collection systems have capability for a range of automatic data processing, where observations must meet a set of criteria in order to avoid being quarantined or flagged for later investigation. Commercial time-series management platforms, including Kisters' 'WISKI' and Aquatic Informatics 'Aquarius', provide a range of native and customisable tools for detection of outliers or suspicious measurements. Organisations such as the USA's National Ecological Observatory Network (NEON) have invested extensively in establishing a range of tools and protocols for automated quality control of sensor network data (Taylor and Loescher 2013). Criteria by which data may be subjected to automated filters include unit checks, upper and lower limits, maximum expected rate of change, and missing or repeated (stalled) measurements. Once identified, erroneous measurements are not always straightforward to correct. For example, suppose one identifies negative light measurement values in a dataset. Clearly, these are erroneous. However, should they be removed or adjusted, and if they are adjusted, should all light measurements be similarly adjusted (i.e. are the negative values isolated incidents, or do they indicate a consistent negative bias for all measurements)? These questions are not trivial to answer as they can impact data patterns and results.

Ultimately, while automated quality control tools are a useful or necessary first step, many datasets benefit greatly from visual interrogation and expert user input. There is no substitute for knowing your waterbody, your sensors, and your data. Subtle sources of error may not be detected by pre-determined data editing limits, for example, where a slight measurement drift has affected the saturation reading of a dissolved oxygen sensor. Additional tools may be used to assist with post-processing of data following the 'coarse filter' of automated quality control. These tools may assist with retrospectively applying scaling factors to raw data (sensor calibration), back-correcting electronic sensor drift, or editing outliers not detected by pre-set thresholds. The user communities of software platforms such as MATLAB and R are useful resources, as is community-driven software (e.g. see Case Study 13.9).

13.8.3 Metadata

Metadata is information that describes important aspects of data. The creation and maintenance of metadata is an important component of quality data stewardship. In general, it is advised to develop or adopt a 'controlled vocabulary' both for data itself and associated metadata. Several organisations have developed controlled vocabulary applicable to high-frequency water quality measurements, including the Global Lake Ecological Observatory Network (GLEON) and the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI). Common metadata that are generated for high-frequency sensor measurements include:

> *What are the characteristics of the system in which the measurement was made?* When comparing across sites, it is frequently beneficial to have summary information on the lake, for example, mean and maximum depth, surface area, and long-term average water quality conditions (e.g. nutrient concentrations, chlorophyll *a* concentration, DOC concentration, and water clarity).
>
> *Where was the observation made?* Depth, latitude, longitude, as well as more local information such as if the sensor was hung on a shaded side of a buoy and if the sensor depth is relative to the surface or bottom. This also includes information on the location relative to its position in the lake. For example, most buoys are deployed at or near the deepest location in a lake.
>
> *What generated the observation?* Make and model of the sensor as well as an instrument-specific identifier.
>
> *How was the observation generated?* Aspects such as the frequency of sampling, sensor integration time, and sensor dwell time (for profiling applications) can impact measurements and their interpretation.
>
> *When was the data created?* Time stamps are nearly always associated with all high-frequency data, but given the diversity of date-time formats around the world as well as time changes (e.g. 'daylight savings time'), care should be taken to ensure proper interpretation of data-associated time stamps.
>
> *To what level of quality assurance and control were the sensor and observation subjected?* This includes information such as the most recent date of calibration (and observed drift between calibrations), how the sensor was calibrated (including the calibration standard(s) used), whether the sensor had accessory components to minimise instrument error (e.g. shade caps, anti-fouling paints or materials, wipers, etc.,), and the degree of fouling observed during routine maintenance and calibration. Information on replaceable sensor components should also be maintained. For example, many optical dissolved oxygen sensors have membranes that are recommended to be replaced regularly (e.g. yearly). The date the sensor cap was replaced and the calibration specifications of the membrane should be maintained.
>
> *What post-collection processing was used on the data?* Information such as automated or manual data quality control protocols and data versioning is important to record. In general,

it is advised that raw data are always maintained alongside any processed data derivatives. Often, it is advisable that users conduct quality assurance and quality control within a scientific workflow environment such as Kepler (https://kepler-project.org/). Scientific workflows provide a process for designing, executing, archiving, and sharing data, processing steps, and provenance information.

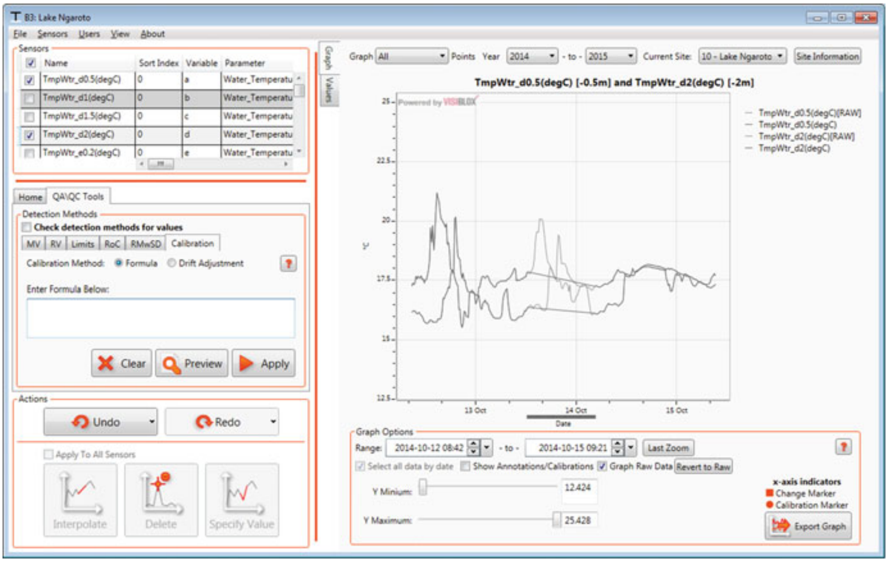
Metadata specific to multiple measurements (e.g. site and sensor information) may need to be stored differently to metadata relating to each individual measurement (e.g. post-processing data transformations). Storage of metadata can take various forms, from informal field notes, standalone software tools (see case studies below), or within a formalised database or time-series data management software. The objective is to make the metadata standardised, repeatable, and accessible.

13.9 Case Study: Quality Control of High-Frequency Monitoring Data Using Community-Driven Freeware

High-frequency environmental datasets often utilise a range of sensing technologies, each with myriad factors that may compromise measurement accuracy and precision. Comprehensive quality assurance and quality control are vital for effective and appropriate use of these data, yet rigorous error detection, data editing, and metadata management can be challenging, particularly where the user does not have access to established cyberinfrastructure tailored to these tasks.

'B3' is a freeware, standalone application designed specifically to assist with quality assurance and quality control of environmental sensor datasets. Its aim is to provide an intuitive working environment based on a visual interface for semi-automated editing of outlying data and erroneous measurements (Fig. 13.11). A range of sensor-specific thresholds can be specified, and a variety of methods is provided for rapid error detection. Subsets of data can be selected from an interactive plot and subsequently mathematically transformed or deleted. B3 encourages collection of a comprehensive set of site and sensor metadata, including sensor calibration records which can be used to quickly and easily post-correct electronic drift common to many sensors. Furthermore, B3 records a detailed log of data modifications, including provision for a user to input reasons for any changes. Raw data are then stored as a separate layer so that the original data (or earlier modified data) can be re-created at any time.

The development of B3 was inspired by a need within the Global Lake Ecological Observatory Network (GLEON) research community for an accessible tool for data management (for information about GLEON see Feature Box 13.2 and for similar emerging networks see Feature Box 13.3). The software was developed at the University of Waikato, New Zealand, and has attained broad uptake by lake researchers and managers globally, with user feedback driving ongoing development of its capabilities.



☑	Name	Sort Index	Variable	Parameter
☑	TmpWtr_d0.5(degC)	0	a	Water_Temperatu
☐	TmpWtr_d1(degC)	0	b	Water_Temperatu
☐	TmpWtr_d1.5(degC)	0	c	Water_Temperatu
☑	TmpWtr_d2(degC)	0	d	Water_Temperatu
☐	TmpWtr_e0.2(degC)	0	e	Water_Temperatu

☐ Check detection methods for values

Calibration Method: ● Formula ○ Drift Adjustment

☐ Apply To All Sensors

Graph: All Points Year: 2014 - to - 2015 Current Site: 10 - Lake Ngaroto

Range: 2014-10-12 08:42 - to - 2014-10-15 09:21

☑ Select all data by date ☐ Show Annotations/Calibrations ☑ Graph Raw Data

Y Minium: 12.424

Y Maximum: 25.428

Fig. 13.11 Screenshot from the assisted data quality control freeware 'B3' (https:/www.lernz.co.nz/tools-and-resources/b3)

Box 13.2 Global Lake Ecological Observatory Network

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The Global Lake Ecological Observatory Network (GLEON), a grassroots network founded in 2005, conducts innovative science by sharing and interpreting high-resolution sensor data to understand, predict, and communicate how lakes respond to a changing global environment. GLEON is primarily a network of people, with more than 500 members (150 students) in 50 countries and growing rapidly. GLEON is also a network of lakes, with 60 lake observatories across 6 continents and in 34 countries (see examples in Fig. 13.12). Finally, GLEON is a network of data, including high-frequency data gathered from sensors mounted on buoys (see figure below). While the lakes and data aspects of the network underpin the scientific products and analyses that GLEON members produce, explicit attention to the people network has served both GLEON science and its members exceedingly well (Weathers et al. 2013). Formed in 2005, GLEON serves as a model of bottom-up international research collaboration. GLEON members are committed to

(continued)

Box 13.2 (continued)

using a ‘network science’ approach that brings together the networks of people, ecosystems, and data to study lakes worldwide. This approach enables researchers to analyse data from a broad spectrum of lakes and conduct cross-site comparisons and experiments, advancing research on topics such as metabolism and carbon cycling in lakes, the role of wind and advection in lake physics, the development of lake models, and response and recovery of lakes to extreme events. GLEON advances lake science through in-person meetings, including at annual meetings of the network held around the world, and by using a variety of cyber-enabled technologies and working group formats. GLEON engages with lake management organisations, stakeholders and citizen scientists through co-developed research and monitoring programmes. For more information, visit www.gleon.org.

Fig. 13.12 A selection of GLEON lake monitoring platforms, clockwise from top left: L. Vanajanselkä, Finland (Image: L. Arvola), L. Sunapee, USA (M. Eliassen), L. Waikaremoana (M. Osborne), Laguna La Salada, Argentina (L. Borre), L. Mendota, USA (T. Bier), Yang Yuan L., Taiwan (D. Liao), L. Winnebago, USA (M. Felix), and Trout Bog, USA (T. Meinke)

Box 13.3 Networking Lake Observations in Europe (NETLAKE)

Eleanor Jennings
Centre for Freshwater and Environmental Studies, Dundalk Institute of Technology, Dundalk, Ireland

The NETLAKE (Networking Lake Observatories in Europe) COST Action (www.netlake.org) (2012–2016) was set up by European GLEON members, together with other scientists who had been active in automated high frequency monitoring (AHFM) in European lakes. Its members came from 26 - European countries, with additional participants in Australia, New Zealand, and the USA. The outputs included practical guidance, as downloadable factsheets, on station deployment and on data analysis, collaborative research papers, a citizen science project, and a review of the use of AHFM across Europe. The information on AHFM in Europe was captured in both a critical review (Marcé et al. 2016) and in a metadatabase of sites. The latter included data on where lakes were being monitored, details on the frequency and duration of monitoring, and the sensors used. Taken together, these two sources provided a unique snapshot of lake AHFM in Europe in 2015–2016. In total, metadata for stations on 67 European lakes were captured. Twenty-nine of these were Swiss lakes, many at higher altitudes, where only water temperature was measured. However, all other sites had stations measuring multiple parameters. It was of note that only ten sites had data archives that spanned over a decade, seven of which (Muggelsee (Germany), Feeagh (Ireland), Windermere (UK), Estwaithe (UK), Balaton (Hungary), Erken (Sweden)) were stations that had originally been deployed in the EU-funded REFLECT and CLIME projects of the late 1990s and early 2000s. In general, monitoring stations for the metadatabase sites were being used for research purposes: only seven lakes were drinking water sources, while one was a very large Czech fish pond (2.38 km^2, and 6 m in depth). However, Marcé et al. (2016) gave case study examples where AHFM was also being used to provide data on water quality at recreational beaches at lakes, inform salmonid fish management. Of particular note was a complex network of AHFM systems deployed in 18 water supply reservoirs in Sardinia (Italy) by the Ente Acque della Sardegna (ENAS), not included in the NETLAKE database. NETLAKE has provided a foundation for installation, maintenance, and networking of AHFM systems in lakes across Europe and will be a rich resource for researchers as AHFM becomes increasingly mainstream for monitoring of, and research on, lakes globally.

13.9.1 Data Analysis: Derived Variables

Quality controlled high-frequency data can be used to estimate higher level derived products. These derived products characterise aspects of lakes in ways that their source measurements do not provide directly. Some of the most common derived products relate to lake physics/thermodynamics and carbon processing (lake metabolism). Repeatable calculation of derived products depends on using consistent algorithms. Accurate calculation of derived products can be ensured by accessible tools with transparent code. Fortunately, many developers subscribe to a culture of open data, code, and standards. Here, we highlight three software tools used to calculate a number of derived characteristics (Table 13.3). All of those packages are freely available with documented code and use methods and algorithms consistent with established literature, thereby facilitating comparisons of derived products among sites around the world.

13.9.2 Lake Analyzer

Lake Analyzer (Read et al. 2011) is a set of Matlab and R scripts that enable rapid calculation of indices of water column mixing and stratification, using high-frequency data collected from instrumented lake buoys. Derived products (Table 13.3) depend on inputs of bathymetry (hypsographic curve), water temperature, wind speed, water level, and salinity, but not all inputs are required for every product. Lake physical stability indices, surface mixing depth, and thermocline depth are calculated according to established literature definitions and output as a time series. Lake Analyzer also enables the visualisation of derived products and quality checking of data through multiple selectable mechanical screening procedures. The software provides a means to compare mixing and stratification indices in lakes across gradients of climate, hydrophysiography, and time, providing context for resulting biogeochemical processes at different spatial and temporal scales. LakeAnalyzer was produced through collaboration between Lake Ecosystem Restoration New Zealand (LERNZ), GLEON, and other research institutes.

13.9.3 Lake Heat Flux Analyzer

Lake Heat Flux Analyzer (Woolway et al. 2015) is a MATLAB package for ingestion of high-frequency buoy data to calculate energy fluxes. Lake surface energy fluxes regulate many physical processes between lakes and the atmosphere. The strength of energy fluxes regulates the degree of coupling between lake and atmosphere and can have major impacts on lake ecology. However, direct measurement of many fluxes at the water surface can be expensive and difficult. The Lake

Table 13.3 Community-developed software tools for calculating derived products from high-frequency lake water quality datasets

Programme	Derived products	Minimum high-frequency data inputs	Programme source	References
Lake Analyzer	Metalimnion extent Thermocline depth Friction velocity Lake number Wedderburn Number Schmidt stability Mode-1 vertical seiche period Brunt–Väisälä buoyancy frequency	Bathymetry Water temperature Wind speed	http://lakeanalyzer.gleon.org/ or https://cran.r-project.org/web/packages/rLakeAnalyzer/rLakeAnalyzer.pdf	Read et al. (2011)
Lake Heat Flux Analyzer	Surface fluxes of momentum Sensible heat Latent heat Heat transfer coefficients Incoming long-wave radiation Outgoing long-wave radiation	Air temperature Water temperature Relative humidity Wind speed Short-wave radiation	http://heatfluxanalyzer.gleon.org/ or https://github.com/GLEON/HeatFluxAnalyzer	Woolway et al. (2015)
Lake Metabolizer	Gross primary production Ecosystem respiration Net ecosystem production	Dissolved oxygen Water temperature Light Wind speed	https://github.com/GLEON/LakeMetabolizer or https://cran.r-project.org/web/packages/LakeMetabolizer/index.html	Winslow et al. (2016)

Heat Flux Analyzer programme requires time-series inputs of air and water temperature, relative humidity, wind speed, and short-wave radiation. Available outputs include surface fluxes of momentum, sensible and latent heat and their transfer coefficients, and the flux of long-wave radiation.

13.9.4 Lake Metabolizer

Lake Metabolizer (Winslow et al. 2016) is an R package for estimating gross primary production, ecosystem respiration, and the balance between the two (net ecosystem production). Together, these derived products characterise lake metabolism, which is a measure of the biologically mediated flux of carbon dioxide. Lakes are globally important hotspots of carbon cycling. In recent years, research and monitoring of lake gas fluxes has become increasingly common, especially with the increasing use of high-frequency optical dissolved oxygen sensors. Lake Metabolizer addresses this research and management priority by providing tools for consistent comparison of metabolism across sites and through time. Derived products depend on time-series inputs of dissolved oxygen, water temperature, light (commonly PAR), and wind speed.

Because there are multiple methods to calculate metabolism parameters, Lake Metabolizer implements up to five different metabolism models that can be linked with one of several gas flux models in order to provide a broad choice of conceptual assumptions and statistical techniques. However, some models require additional data inputs and parameterisation. Lake Metabolizer also contains an array of functions to manipulate data for related outputs, such as calculations of oxygen saturation and optical conversion.

13.10 Case Study: Monitoring Long-Term Changes in Hypolimnetic Dissolved Oxygen Depletion Rate Using High-frequency Monitoring

Lake Rotorua was the first lake monitoring buoy installation by the University of Waikato, New Zealand, in 2007. Rotorua is a lake of national significance and cultural importance that has suffered eutrophication since the 1960s with increasing pressure (nutrient loads) from pastoral intensification and urbanisation. An important aspect of high-frequency monitoring in the lake has been the tracking of bottom water oxygen depletion during periods of stratification in the polymictic lake. Oxygen depletion can range from a few days to several weeks in duration (Fig. 13.13). Several management strategies have been employed for Lake Rotorua, including land management, improved wastewater treatment, and alum dosing of two major inflows to the lake commencing in 2007. Water quality and the incidence of algae blooms improved substantially between 2003 and 2015.

High-frequency dissolved oxygen data were interrogated to investigate the rate of bottom water oxygen consumption (hypolimnetic oxygen demand) over the duration of the buoy installation. Tens of periods of stratification were captured, for which a selection of daily averaged dissolved oxygen concentrations are presented in Fig. 13.14, where day 1 is defined as the day most recent to the oxygen minimum where oxygen saturation was >85%. It can be seen that whereas in the mid- to late-2000s time to anoxia was generally 15 days, it took up to 27 days to reach anoxia

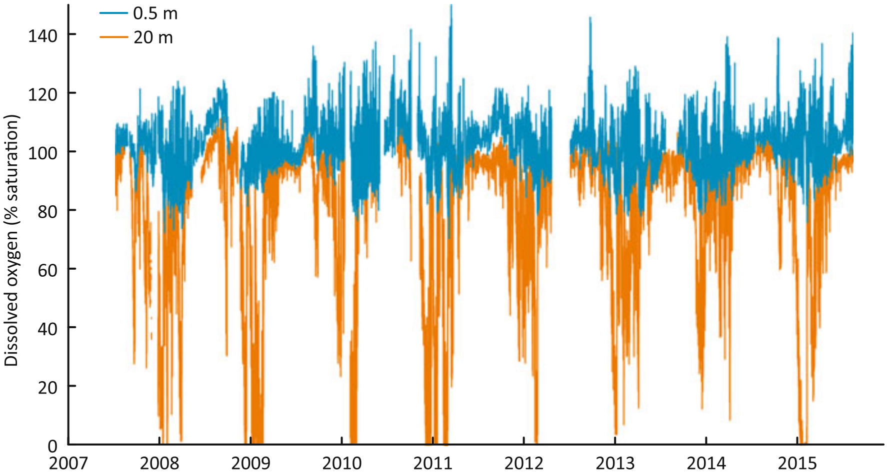

Fig. 13.13 Dissolved oxygen in near-surface (0.5 m) and near-bottom (20 m) waters of Lake Rotorua New Zealand. Data collected at 15 min intervals nearly continuously from mid-2007 to mid-2015

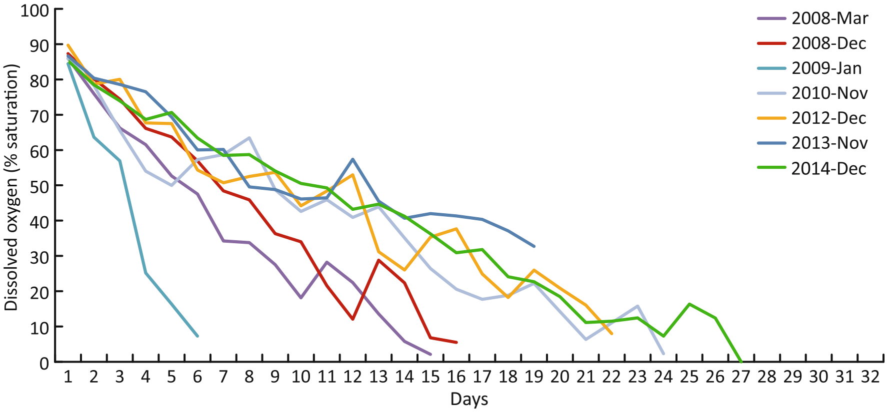

Fig. 13.14 Dissolved oxygen in bottom waters of Lake Rotorua, New Zealand, demonstrating long-term change in the duration taken to reach hypoxia in bottom waters during seven distinct periods of thermal stratification

post-2010. Because nutrients (particularly phosphorus) are released to the water column during hypoxic conditions in many lakes, stratification events have been an important driver of poor water quality in Rotorua (Burger et al. 2007). Understanding change in transient stratification and hypoxia/anoxia is vital for lake management in order to understand and attempt to disrupt the self-reinforcing feedback loop of internal nutrient loading.

13.11 Conclusions and Future Prospects

High-frequency water quality measurements represent an important and growing component of lake monitoring, research, and overall water resource management. High-frequency sensing leverage advances in sensor technologies, cyber-infrastructure, and associated hardware and software. However, sensors are not a panacea to water quality monitoring and research challenges. There are limitations to many types of sensors that should guide the application and interpretation of generated data. Furthermore, high-frequency sensor measurements do not always directly correspond to traditionally measured variables, meaning that users should not expect similar patterns or characteristics. These challenges have slowed the evolution and uptake of high-frequency sensors in some domains. However, despite these limitations, high-frequency sensor measurements open new windows of opportunity to understand phenomena that operate across multiple temporal and spatial scales. Use of high-frequency sensors can improve monitoring and management programmes by enabling rapid responses, reducing some long-term costs, and better characterising transient phenomena that can have legacies across space and time.

High-frequency buoy-based sensor measurements are poised to change in several important ways in the years ahead. First, the increasing development and application of data analysis capabilities has the potential to move buoy-based technologies beyond simply logging data to an environment where buoys and associated cyber-infrastructure can natively conduct many aspects of analytics, including quality control, adaptive sampling, and hypothesis generation, based on automated detection of thresholds, trends, and impending change. Secondly, sensor technologies are continually evolving and changing. While it is difficult to predict what new sensors will come to market in coming years, new technologies and methods for analysing existing data will no doubt provide opportunity to directly or indirectly infer additional water quality characteristics. Furthermore, miniaturisation, open hardware and software, and economies of scale will likely improve the accessibility of sensor technologies, while Moore's Law and software development should ensure the feasibility of measurement, storage, and processing of data at ever-finer spatial and temporal scales.

Sub-daily measurements are immensely useful. Nevertheless, the value of such datasets increases dramatically when their total duration extends to years or even decades. Therefore, future research and monitoring will inevitably benefit greatly from the existence of long-term high-frequency sensor data. Presently available technologies are mature to the point where they are applicable to a wide range of uses, and in an era of declining water quality and rapid environmental change, high-frequency sensors provide new opportunities to better understand and manage our global water resources.

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