ALGAL FLUORESCENCE SENSOR SELECTION

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Front cover: Monitoring platform on Wainono Lagoon, Canterbury [Julie Grant, ECan].
Back cover: Deployment on a bridge pier, Kaiapoi River, Canterbury [Hamish Carrad, ECan].

CONTENTS

ABSTRACT

The growing commercial availability of fluorescence sensors creates opportunities to measure algal fluorescence, an indicator of biomass, at high frequencies. It can be challenging to select the "right" fluorescence sensor because sensors are built with different light sources, are sensitive to different wavelengths, and have different optical geometries.

This chapter provides information to help people select an algal fluorescence sensor for a high frequency or continuous deployment. It describes the sensors' basic operating principles and factors influencing their performance, compares sensor hardware and software, summarises key sensor selection questions, advises how to manage fouling, and showcases the variety of deployments undertaken across Aotearoa New Zealand. The chapter does not address field maintenance, data editing or data verification procedures in detail.

BACKGROUND

Obtaining information about water quality dynamics over short timescales (such as daily cycles, or during a storm or rain event lasting a few days) using conventional discrete samples or field measurements may be costly and logistically challenging to undertake frequently. Fortunately, high frequency water quality (HFWQ) can be measured using unattended sensors deployed on site to measure indicators (e.g., nitrate, algal fluorescence) and provide detailed insights into water quality dynamics at scales of interest (minutes to hours). However, these sensors can create different technical challenges, and unattended deployments can be resource hungry. Monitoring projects are more likely to succeed if they have (1) clearly defined objectives, (2) robust data collection systems, and (3) well thought-out methods for managing raw data and converting it into knowledge for decision-making.

This chapter provides detailed guidance on algal fluorescence sensors selection. It sits alongside guidance chapters on HFWQ Use Cases, Resourcing, Sensor Selection and Automated Anomaly Detection as part of the *High Frequency Water Quality Monitoring Guidance* project.

PURPOSE AND SCOPE

This chapter provides information on sensor selection for measuring algal fluorescence in-situ, at high frequency in rivers, lakes and estuaries. It will help regional council staff shorten the learning curve for new users, support them to select an appropriate sensor, and enable them to accelerate collection of baseline algal fluorescence data to guide more detailed sampling to characterise algal blooms.

RELATED RESOURCES

Useful reading that expands on the detail in this chapter can be found in the following documents:

- Overviews on the opportunities and challenges of measuring algal biomass with fluorescence sensors, including McBride and Rose (2018), Bertone et al. (2018) and Zamyadi et al. (2016).
- New Zealand examples of site-specific relationships between algal fluorescence sensor values and algal biomass, including Cotterill et al. (2019) and Stewart and Phillips (2018).
- Technical guidance on operating algal fluorescence sensors from the US Geological Survey and National Estuarine Research Reserve System (NERRS), including Foster et al. (2022), Hambrook Berkman and Canova (2007) and Dix et al. (2022).
- Lab evaluations of AF sensors, including Ma et al. (2022), Choo et al. (2018) and Levi et al. (2025).
- Field evaluations of AF sensors (sometimes combined with lab work), including Hodges et al. (2018), Johnston et al. (2022), Johnston et al. (2024) and Roesler et al. (2017). The Alliance for Coastal Technologies (ACT) recently evaluated multi-spectral fluorometers (see https://www.act-us.info).
- Research on San Francisco Estuary, including an inter-agency comparison that highlights many chlorophyll pigment sensor selection, calibration and sampling challenges (Stumpner et al. 2022b), and a spatial survey sensor comparison (Richardson et al. 2025).
- Overviews of phytoplankton early warning system methods and design, such as Almuhtaram et al. (2021) and Kraft et al. (2025).

SENSOR SELECTION STEPS

Sensor selection involves a sequence of steps (Figure 1). Figure 1 also links this chapter to other guidance chapters. Many factors must be considered when selecting an algal fluorescence sensor suitable to meet a user's monitoring objectives.

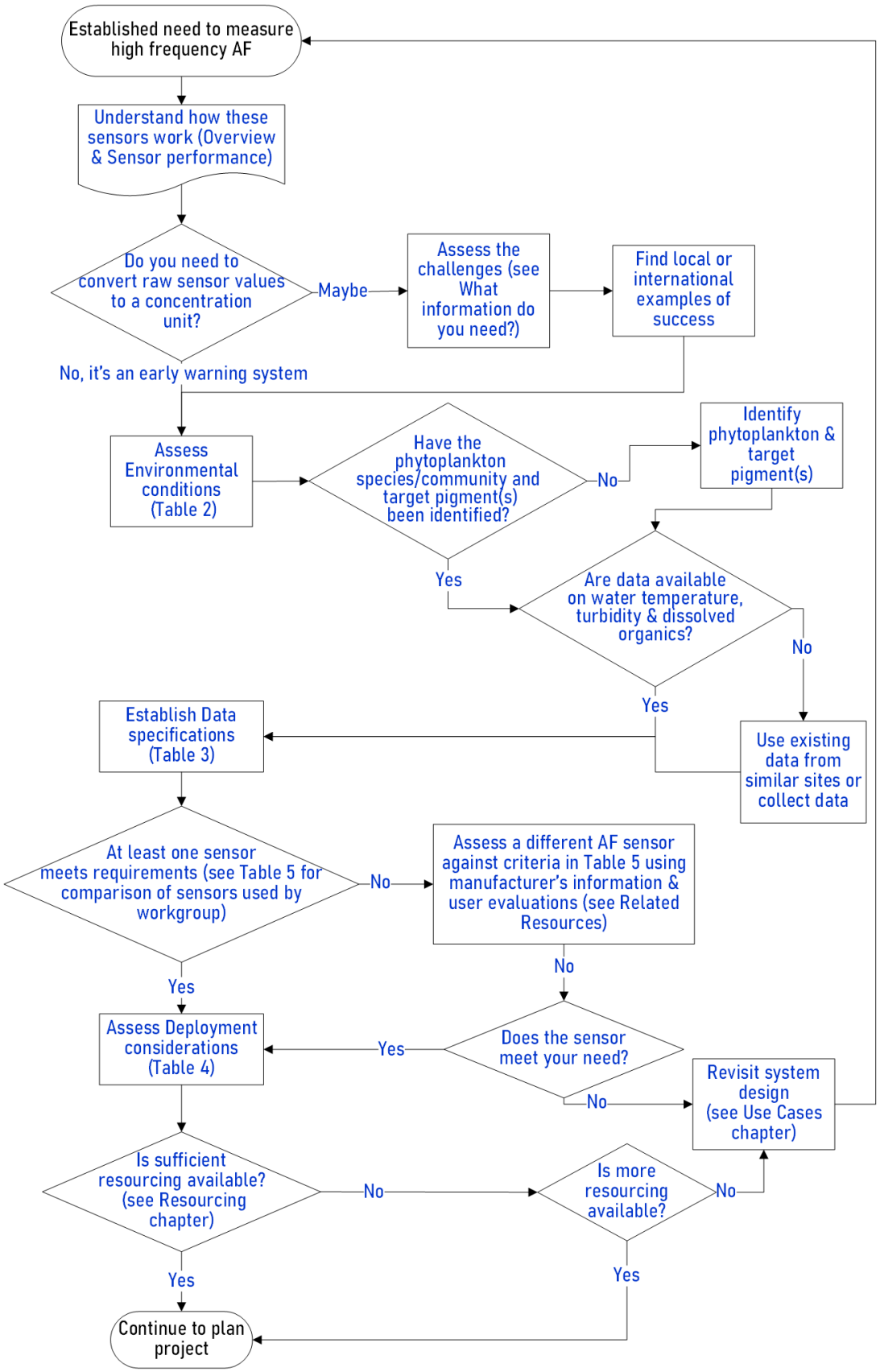


Figure 1. Suggested sequence of steps to guide algal fluorescence sensor selection.

ALGAL FLUORESCENCE SENSOR OVERVIEW

Algal fluorescence (AF) sensors are widely used in lakes and estuaries (and occasionally rivers) across New Zealand as part of algal bloom early warning systems, to ground truth remote sensing imagery and to provide data to help understand system dynamics and support models.

In this chapter we use the term "algal fluorescence sensors" to differentiate sensors designed to detect and measure phytoplankton from those designed to measure fluorescent dissolved organic matter (fDOM) or artificial fluorescent dyes (e.g., rhodamine).

Phytoplankton are microscopic plankton that live suspended in water and get their energy through photosynthesis. Phytoplankton communities are usually a diverse mix of photosynthesising microalgae and bacteria, and can include diatoms, dinoflagellates, green algae, cyanobacteria and other taxa. They have fast growth rates, and some groups, such as planktonic cyanobacteria, can multiply rapidly and "bloom". All phytoplankton contain photosynthetic pigments to absorb light and convert it to chemical energy. As this happens, a small amount of the converted energy is lost as fluorescence.

Algal fluorescence sensors exploit this loss of energy as fluorescence. The sensors shine a light source on phytoplankton to energise pigments and stimulate them to release fluorescence. By measuring the returned fluorescence, a pigment concentration is inferred and can be used as a proxy for algal biomass.

Many sensors measure chlorophyll (CHL), but some are designed to measure accessory pigments. Phycocyanin (PC) and phycoerythrin (PE) absorb light in a different wavelength range to chlorophyll and can be used to infer cyanobacteria biomass. Using ratios of the accessory pigments (phycocyanin in freshwater or phycoerythrin in sea water) to chlorophyll, a sensor can estimate what portion of the total phytoplankton population is comprised of cyanobacteria.

While AF indicators (CHL, PC, PE) are convenient metrics — being relatively simple to measure with a sensor — the values are only estimates or indicators of biomass. Changes in biological activity are what AF sensors are most useful for detecting. They can only detect bulk temporal changes in algal biomass because:

- measured fluorescence is influenced by the algal species and their physiological status,
- environmental conditions interfere with measurements (e.g., temperature, turbidity or coloured dissolved organic matter), and
- different sensors lack numeric comparability. They operate at different wavelengths, have different optical geometries, and will consequently output different values in the same suspension.

With site-specific information it may be possible to devolve algal composition or estimate biomass, but this can be challenging.

AF sensor users need to be aware that while AF is easy to measure, values can be difficult to interpret because:

- Different sensors put out different values in the same water matrix, so if stationarity is to be maintained at a site, they are not interchangeable (without additional effort). The sensor (make and model) should be specified alongside algal fluorescence values.
- Algal fluorescence is a surrogate measure and sensor units are relative.
- Data may need to be corrected for variables that skew it (e.g., temperature, turbidity, dissolved organics, day-night cycles) and most of these corrections are immature.

With a good understanding of how AF sensors work, users will be able to select the best sensor to meet their data need. Taking the time to consider what an AF sensor measures, collecting information from other sensor users, and understanding the impacts of varying algal species and the water matrix are critical first steps for sensor selection.

Principle

Fluorescence is the term used to describe the re-emission of light after a molecule absorbs a photon of light. Once a molecule is excited to a higher electronic and vibrational state, it returns to its ground state by losing energy through heat loss and fluorescence. The fluorescent light energy is emitted at a lower energy state than it was absorbed at; that is, at a longer wavelength (Stoke's Shift; Figure 2 A). The energy emitted as fluorescence is typically a small fraction (<5 %) of the energy absorbed from the photon (Lin et al. 2016).

Fluorescence is also commonly explained with Jablonski diagrams, which show the various energy levels and transitions that happen to a molecule after it absorbs light (Figure 2 B). Light energy excites the molecules to a higher energy state, and due to conservation of energy laws, that energy is converted to other energy.

When a pigment absorbs energy from a photon and becomes electronically excited, there are four paths for its return to the ground state:

1. transfer of the energy to the photosynthetic reaction centre,
2. heat loss,
3. transfer of energy to an adjacent pigment (e.g., from the light harvesting PC to CHL), and
4. emission of a fluorescent photon at a longer wavelength.

The four processes are in competition; the pigment will fluoresce at its maximum rate when it cannot transfer the energy to the photosynthesis reaction centre or nonphotochemical routes (energy transfer and heat loss). When the energy paths alter, the fluorescence is *quenched*, or happening below its maximum rate.

For more detailed discussions on fluorescence in phytoplankton pigments, refer to Foster et al. (2022) and other references in Related Resources.

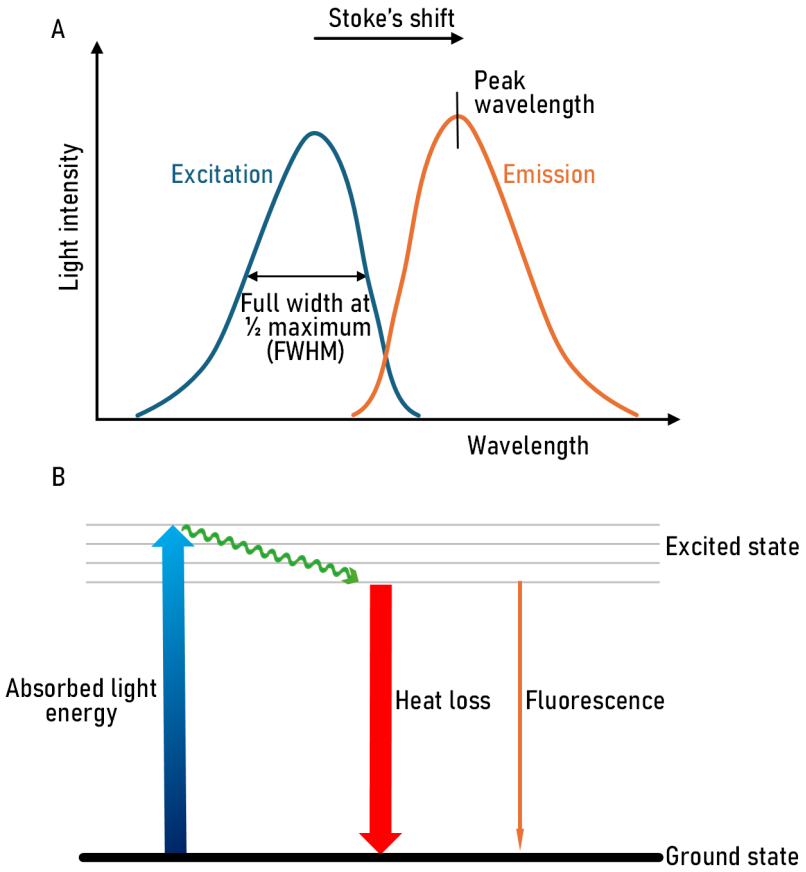


Figure 2. Schematic diagrams of energy transformations by pigments. (A) Stoke's Shift – the absorbed light (blue colour) is re-emitted at a longer wavelength (orange colour) and definitions for some common AF sensor terms (FWHM, peak wavelength). (B) A simplified Jablonski diagram of energy transformations by phytoplankton pigments.

An AF sensor contains a light source which emits light into the surrounding water. This light excites the pigments, which emit fluorescent light that the detector measures. Fluorescence sensors emit flashes of light that are micro- or milli-seconds in duration and therefore measure "steady-state fluorescence" rather than one fluorescence event.

While lab fluorescence sensors output light and detect fluorescence across wide bands of wavelengths, the simplest measurement approach for field fluorescence sensors is to measure the fluorescence of a single excitation-emission wavelength pair.

At its simplest, sensor fluorescence is a proxy for pigments – the more phytoplankton, the more pigments, the more fluorescence. But:

- under light-limiting conditions, fluorescence is a proxy for photosynthesis
- under increasing light levels, photosynthesis reaches maximal rates and fluorescence also increases

– under saturating (or excess) light levels, fluorescence is not a proxy for pigments, but it may be a proxy for photosynthesis.

Pigments

Chlorophyll is a photosynthetic pigment present in all phytoplankton, including eukaryotic (algae) and prokaryotic organisms (cyanobacteria). It is a good and commonly used indirect marker of the total phytoplankton biomass.

Chlorophyll pigments collect light from various wavelengths and transfer it to a special pair of chlorophyll-a molecules in the photosynthesis reaction centre. Chlorophyll-a has two absorption peaks (Figure 3); it absorbs blue light (absorption peak ~440 nm) and reddish wavelengths (peak ~660 nm), and emits fluorescence in the reddish to infrared wavelengths (peak ~685 nm; Figure 3). There are many kinds of phytoplankton, and each division has distinct accessory pigments (including chlorophyll b and c) that fluoresce at different wavelengths. The USGS recommends reporting values as *chlorophyll* because current AF sensors are unable to distinguish between chlorophyll a, b and c.

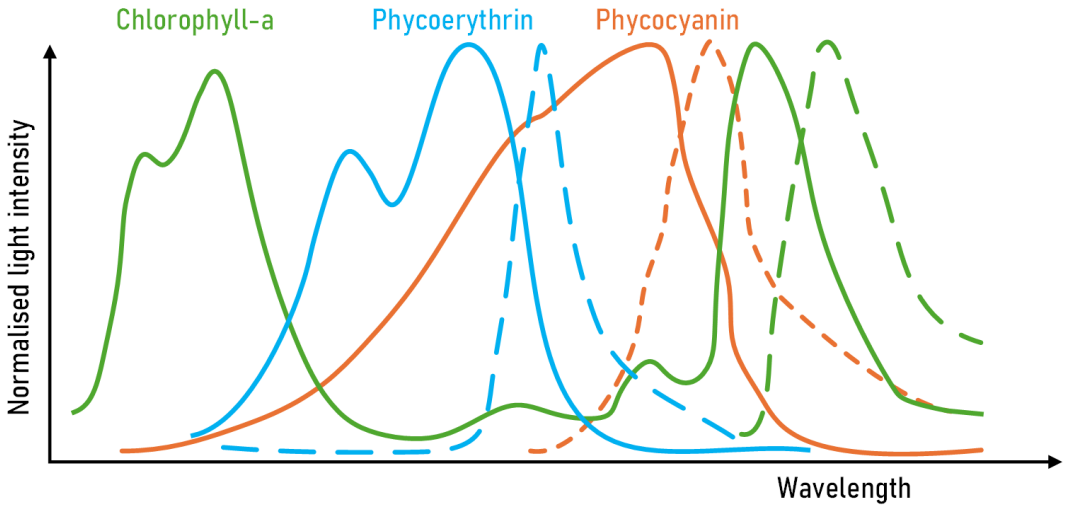


Figure 3. Schematic diagram of the absorption (solid lines) and emission (dashed lines) spectra of chlorophyll-a, phycocyanin and phycoerythrin.

Accessory pigments in cyanobacteria also harvest light and pass the energy on to chlorophyll. These accessory pigments are located on light-harvesting antennae. Phycoerythrin is a major light-harvesting pigment found mostly in marine phytoplankton, while freshwater phytoplankton tend to be rich in phycocyanin.

– Phycocyanin (PC) is a blue protein-pigment. It absorbs orange light (absorption peak at ~620 nm) and emits fluorescence in the band of wavelengths from 600 to 700 nm (emission peak at ~650 nm, reddish light).
– Phycoerythrin (PE) is a red protein-pigment. Phycoerythrin is present in cyanobacteria, red algae and cryptophytes, and harvests green light (480 to 560 nm). It has absorption peaks at ~490 and ~550 nm, and emits fluorescence in a band of wavelengths from ~570 to 600 nm (peak at ~575 nm, Figure 3).

The advantages of measuring phycoerythrin and phycocyanin are: (1) they occur in cyanobacteria, and (2) they fluoresce at higher wavelengths than dissolved organics (emission ~340-500 nm).

However, there are also challenges: (1) some algal groups contain phycocyanin and/or phycoerythrin, and (2) identifying algae is difficult. For example, cryptomonads are common in New Zealand's freshwaters (especially lakes) and can be mistaken for cyanobacteria. Cryptomonads are small, unicellular algae with two flagella and can have PC and/or PE in their cells rather than on light-harvesting antennae; see Cunningham et al. (2019).

Sensor design

While sensors vary between manufacturers, the basic optical AF sensor consists of:

– a light source to excite electrons in the pigment,
– a filter to fine-tune the excitation wavelengths,
– a detector which measures the fluoresced light emitted,
– filters and/or internal processing to limit the wavelengths measured, and
– electrical circuitry to convert the detected signal to an electronic signal.

There are no international standards for AF sensors, so each sensor has a unique optical configuration of light source(s), filter(s), detector(s), detector angle and sensing volume (see Figure 4). The source light beam and field of view of the detector are both conical volumes that intersect to form the sensing volume.

Most AF sensors suitable for unattended monitoring use LEDs as a light source and photodiodes as detectors as they are small, inexpensive and have low power requirements. Some field sensors are designed to measure multiple pairs or pigments (typically two, sometimes three), but each of the pairs requires a different LED (and filters) to tune in the required excitation wavelength. Some sensor manufacturers use the same detector for multiple pigments, while others add a light and detector for each pigment (see Table 5).

AF sensors used by regional councils in NZ have open, flat faces (see Table 5). Some other manufacturers may use a design that looks more like a direct beam sensor, but the detector angle will be slightly less than 180° to ensure the light source cannot shine directly into the detector.

The optical geometry of each sensor is different; the detector angle (relationship between the light source and detector) and sensing volume (zone where light source and detector overlap) are unique. Often the optical geometry is not disclosed in manuals and brochures, but most sensors will operate at a detector angle between > 90° and < 140°. Manufacturers will use different techniques (reflectors, mirrors, refracting lenses) to align the fluorescing light with the detector so the detector will not always be positioned at the same angle as the sensor face (see Figure 4).

Several manufacturers add a reference detector to account for LED light output variability (e.g., temperature, ageing; see Table 5). Any change in the LED output affects both the reference detector and signal detector by the same amount. Other manufacturers may use an internal thermistor to correct for LED light output variability with temperature. Some manufacturers (e.g., Sea-Bird ECO) encourage the user to track the sensor's dark counts (in water with black tape over the sensor face) to detect a change in the sensor's baseline.

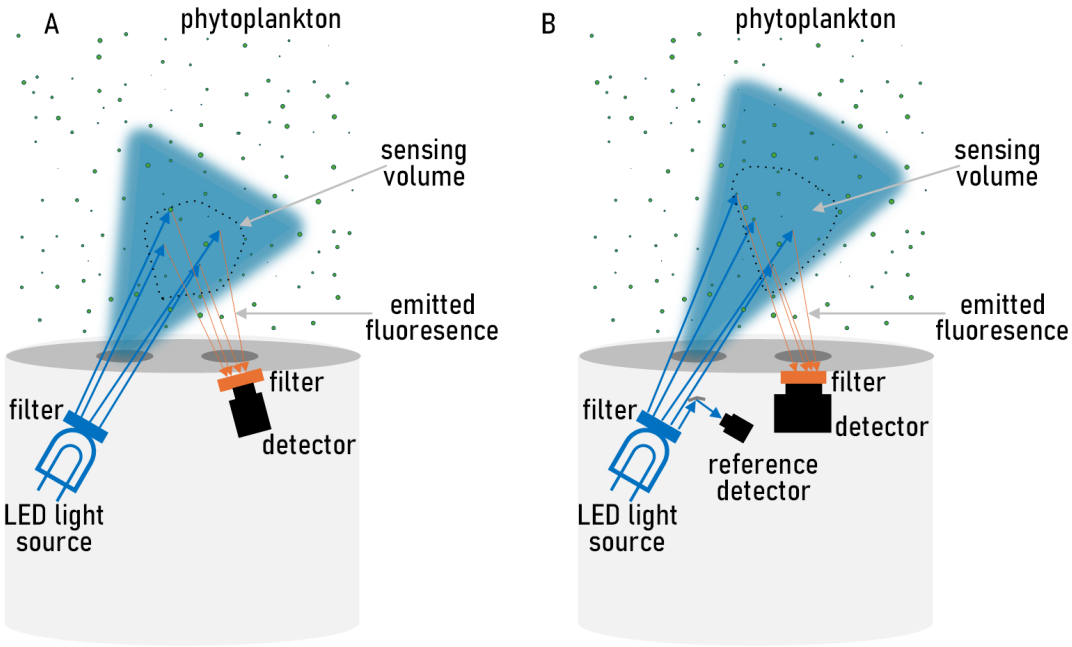


Figure 4. Schematic diagrams of AF sensor optical designs. (A) A common design with LED light source, filters and detector. (B) Some sensors include a reference detector to monitor the LED optics.

AF sensors contain filters which limit the wavelengths of light to the required range (Figure 5). These filters let wavelengths within a certain range through and reject wavelengths outside of the desired range. The sensor filters determine the ratio between the sensitivity (i.e. how accurately it can detect changes) and selectivity (i.e., is it measuring the target pigment).

Filters can reject light above (short pass) or below (long pass) a specific wavelength, or both (bandpass; Figure 5). The light source filter allows wavelengths to pass through that excite fluorescence in the pigment of interest. The detector filters isolate emitted fluorescence from other light sources, thereby reducing background noise and improving the signal-to-noise ratio. The filters are typically characterised by their centre wavelength and width (see Table 5 for examples).

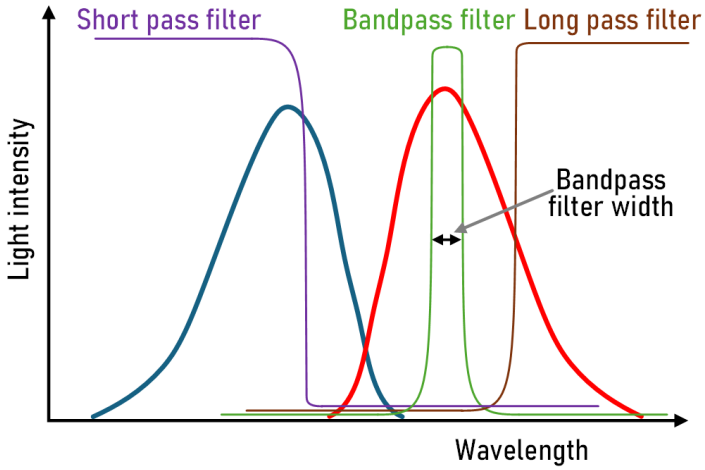


Figure 5. Filters are used to tune AD sensors – after the light source and before the detector. Bandpass filters (green line), which allow a narrow band of light to be emitted or detected, are common in AF sensors.

Limited information is supplied by sensor manufacturers on LED operation modes and signal processing approaches. Raw current from the detector is converted to output values by the signal processor in the sensor electronics. Some sensors have automatic gain settings to help measure fluorescence values (see Table 5). For example, if the number of pigments is low, the automatic gain settings can increase the LED output intensity to help detect a signal.

Units

Understanding AF sensor units is critical for sensor selection. There are three basic AF sensor units: raw, relative and concentration. These units are arbitrary – each sensor has a different optical geometry, and the conversion algorithms are proprietary (and not disclosed).

Raw units from AF sensors are typically digital counts or volts. Raw units of handmade sensors cannot be identical for every sensor.

Relative fluorescence units (RFU) are not an absolute measure of fluorescence intensity; the output in raw units is converted to a percentage of full scale (0–100%) of a reference standard. RFU are not directly tied to a quantitative value like concentration – they are arbitrary units, unitless, and vary between sensors. For example, an In-Situ Aqua TROLL CHL sensor will output ~3.6 RFU in a 625 µg/l Rhodamine WT standard at 25 °C, while a YSI EXO TAL CHL will output ~15.5 RFU in the same standard. When calibrated (with 2+ points) to rhodamine WT (or similar standard), sensors may be plug-and-play within a sensor brand. A doubling of RFU does not mean there has been a doubling in algal pigment concentration.

Despite masquerading as SI units (mass/volume), AF sensor concentration units are sensor-specific and determined under laboratory conditions. Manufacturers typically use a single primary reference to convert the raw signal to other output units. For example, a manufacturer may use one commercially available algal culture of a single species to convert raw signal to concentration units. The monoculture used is unlikely to represent natural waters, which contain a mix of algal species.

Manufacturers use commercially available algal pigments and cultures to derive concentration units for sensor specifications. Pigment standards are widely available (e.g., Merck chlorophyll-a from spinach, Agilent phycoerythrin from red algae and phycocyanin from spirulina) and are used by several manufacturers (see Table 5).

Algal cultures are also available commercially; for example, in New Zealand the Cawthron Institute Culture Collection of Microalgae (https://www.cawthron.org.nz/ciccm/) holds over 300 species of cryopreserved toxic microalgae and cyanobacteria strains. Other countries also hold collections, such as the Provasoli-Guillard National Center for Marine Algae and Microbiota in the US (https://ncma.bigelow.org/).

Most manufacturers do not always disclose the culture(s) or standard(s) used to convert raw units (or RFU) to concentration units. As a result of the different reference pigments and cultures, comparing numeric values for different sensor models in concentration units is meaningless for sensor selection.

To ensure any data user does not misuse algal concentration values from different sensors, there are several pragmatic approaches:

- Output and archive raw units (if available), such as V or engineering units, as this reduces the likelihood of incorrectly comparing numerical values between different sensors.

- Include the sensor manufacturer/model in the time series label.
- If needed and possible, convert raw units to concentration using a site-specific relationship.

Original equipment manufacturer

Original Equipment Manufacturer (OEM) purchases of AF sensors are widespread and tend to be disclosed. Some OEMs of optical algal fluorescence sensors include YSI, In-Situ, Turner Designs, Chelsea Technologies, RBR, Seapoint, and Sea-Bird (formerly WetLabs). Turner Designs sensors are used widely by many manufacturers (e.g., RBR, Eureka, PME, innovasea, Hach Hydrolab). For example, PME manufactures battery powered loggers and miniWIPERs for the Turner Designs C-FLUOR sensor and offers fixed or interchangeable sensor options.

SENSOR PERFORMANCE

AF sensors will always be less precise than lab methods but have the advantage of sensing temporal dynamics and measuring during unsafe conditions for discrete sampling (e.g., high winds, low light or darkness). The field performance of an AF sensor depends on:

- changing environmental conditions (e.g., light intensity, water temperature),
- pigment dynamics,
- interferences, such as suspended particles or dissolved organics,
- managing fouling,
- sensor design.

Light and AF

Phytoplankton adjust their pigments, both the type and concentration, depending on light conditions. This allows them to regulate light harvesting and direct excitation energy along different pathways. Under high light conditions, excess light can overwhelm their ability to process it, so to protect their cells they decrease the efficiency of photosynthesis and dissipate the excess energy as heat (light-induced non-photochemical quenching). Non-photochemical quenching is highest in near-surface waters and can occur from shortly after sunrise until sunset.

Both spatial and temporal variations in light can alter the relationship between fluorescence and algal biomass. At the water's surface during the daytime, phytoplankton may be present, but they may be directing captured light energy towards heat dissipation rather than photosynthesis, which reduces fluorescence. In contrast, at depth where light is minimal, they optimise their pigments to capture all available light, which increases fluorescence. Diel variations in light intensity could cause bias for AF sensors.

Experimental work by Rousso et al. with a cyanobacteria (*Dolichospermum variabilis*), a green algae (*Ankistrodesmus gracilis*) and three commercial AF sensors demonstrates that light-induced non-photochemical quenching can reduce CHL and PC fluorescence by up to 79% and 59%, respectively. Recent light exposure affects the magnitude of fluorescence suppression – light-induced quenching is higher during the afternoon than morning periods at the same light levels. The daily cycle of light variability needs to be considered for both sensor operation and sampling. A site-specific relationship between sensor values and discrete samples collected during daylight hours could be inaccurate.

Temperature and AF

Fluorescence is temperature dependent – pigment fluorescence decreases as water temperature increases. At higher temperatures, energy is preferentially lost through heat and less is available for fluorescence (see Figure 2 B). Temperature is a key cause of photochemical quenching – it reduces the ability of the pigment to lose energy via fluorescence.

For sensor selection, a key consideration is whether a temperature correction is needed by the data user. Dix et al. (2022) suggest that temperature corrections are most needed at sites which experience high temperature variability and high pigment concentrations. In laboratory tests of the YSI EXO TAL sensor, Ma et al. found that when water temperature increased from 6 to 33 °C, sensor values decreased by 8.4 RFU (from 22.8 RFU to 14.4 RFU) in a high-density *Microcystis* suspension.

To implement a temperature correction for photochemical quenching it will be necessary to: (1) collect a water temperature time series, and (2) identify a suitable correction method. Many AF sensors do not include a water temperature sensor. For multiparameter sondes such as the YSI and In-Situ Aqua TROLL, one of the other available sensor ports can be loaded with a conductivity/ temperature sensor. For some sensors (e.g. Sea-Bird ECO range), a thermistor is optional. Other sensors will require an independent water temperature sensor (see Water temperature sensor selection chapter).

There is no universally accepted temperature correction for AF (Foster et al. 2022). While it may be tempting to adopt a temperature correction offered by a manufacturer within their proprietary software or via a general equation (e.g., Turner Designs 1.4%/°C), careful assessment of their approach's suitability is recommended. Watras et al. (2017) demonstrate how temperature coefficients can vary between different natural waters (e.g., appropriate phycocyanin temperature corrections for Wisconsin waters varied from 0.6 to 1.2 % per °C) and recommend that site-specific temperature coefficients are developed.

Scattering and absorption

Ideally, when an AF sensor emits an incident beam of light, the resulting fluorescence is related to the number of phytoplankton fluorophores in the sensing volume. However, when the water matrix also contains suspended particles or dissolved organics, these cause interferences.

Suspended particles scatter light, and this can reduce both the amount of sensor light reaching an algal pigment and what reaches the detector. Scattering in the optical path of the light source will redirect light away from the sensing volume, reducing the excitation energy reaching the pigment and lowering the fluorescence. The emitted fluorescence may also be scattered before it reaches the detector, further lowering the sensor values. In low visual clarity waters (with high suspended particle concentration), the AF sensor may not be able to measure any algal fluorescence because all the light is scattered.

Phytoplankton also scatters light, but less effectively than mineral particles. In a lab evaluation of turbidity sensors (Davies-Colley et al. 2021), the phytoplankton suspension (predominantly green algae) scattered the sensor light – for example, in a sample with a visual clarity of ~0.3 m, the YSI EXO turbidity sensor (side-scatter at 90 °, 860 nm, 30 nm bandpass filter) values were ~ 5 FNU for phytoplankton and ~ 12 FNU for a white clay (kaolinite).

In natural waters, light can also be absorbed by coloured dissolved organic matter (CDOM). Dissolved organic matter also attenuates the excitation energy reaching the pigments and emission energy reaching the detector, but the mechanism by which it does so is different. CDOM absorbs light, and some types of dissolved organics also emit fluorescence. AF sensor manufacturers try to overcome this by tuning their sensors to wavelengths which do not overlap with fluorescing organics. For example, the YSI EXO fDOM sensor emits light at 365 nm (10 nm bandpass filter) and measures the fluorescence emission at 480 nm (80 nm bandpass filter), while the PC sensor measures at emits light at 590 nm (30 nm bandpass) and detects at 685 nm (40 nm bandpass). Lab experiments by Ma et al. (2022) show that lake water with unicellular (*Microcystis* sp.) or filamentous (*Dolichospermum* sp.) cyanobacteria yielded lower YSI EXO TAL PC sensor values when organic matter increased from 0.7 to 11 mg/l dissolved organic carbon. In the same study with the same dissolved organic carbon challenge, at high cell concentrations (100,000 cells/ml) of unicellular cyanobacteria (*Microcystis* sp.), the EXO TAL PC sensor values decreased by 1–3 RFU (between ~5 and 15 %), and lab fluorescence spectrometer emission values decreased by 33%.

There are no widely accepted methods to correct for turbidity and dissolved organic matter for AF sensors. However, Cremella et al. (2018) were able to develop correction algorithms for sensors used on rivers, lakes and estuaries.

Pigment & community dynamics

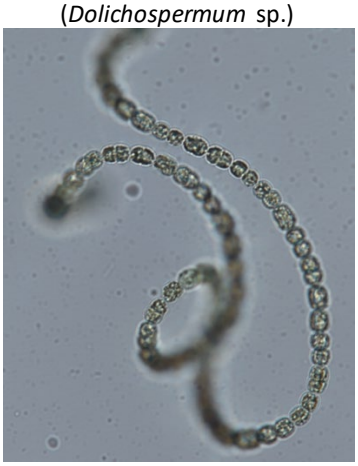
Algal fluorescence is affected by the phytoplankton species community (see Figure 6 and Figure 7 for New Zealand examples), their response to environmental conditions and cell physiology. Phytoplankton, as short-lived organisms, are dynamic and their ecological success is in part due to their ability to respond to fluctuations in natural light.

The life stage and physiological status of phytoplankton also influences fluorescence. Depending on the species, the peak fluorescence might be during the growth phase or when cell division slows down or stops (stationary phase). This means that variations in fluorescence due to cell physiology could alter sensor values.

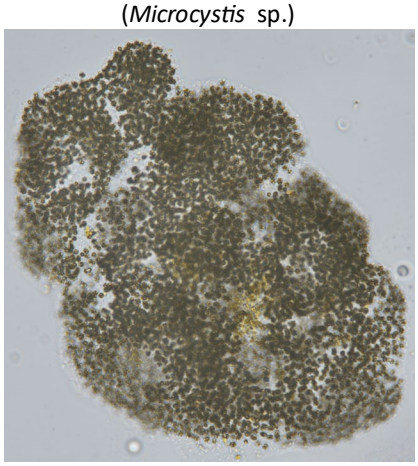
In addition to pigment content, there is also variation across species in cell size, volume and agglomeration. Cell diameters can vary from 0.5 to 40 µm, and some phytoplankton cluster or agglomerate together in jellylike structures (Figure 6). A review by Zamyadi et al. (2016) suggests that variation in cyanobacteria cell size, biovolume and agglomeration could cause between 20 % and 90 % bias in AF sensor values.

Cyanobacteria colonies

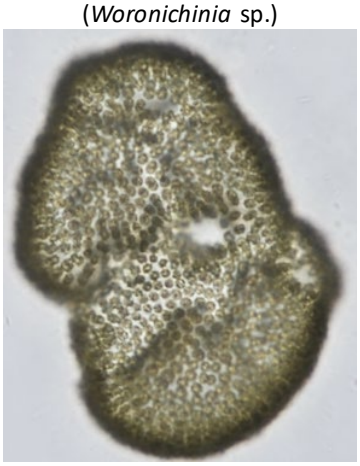
Cyanobacteria filament/chain (*Dolichospermum* sp.)



Cyanobacteria colony in mucilage (*Microcystis* sp.)

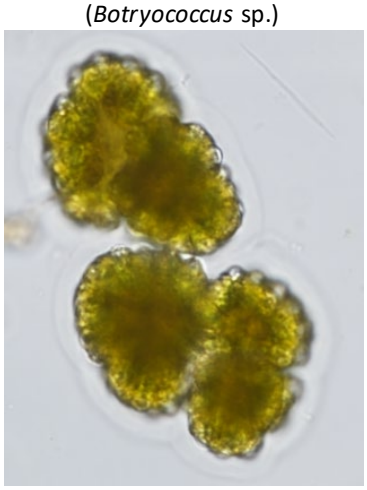


Cyanobacteria colony (*Woronichinia* sp.)



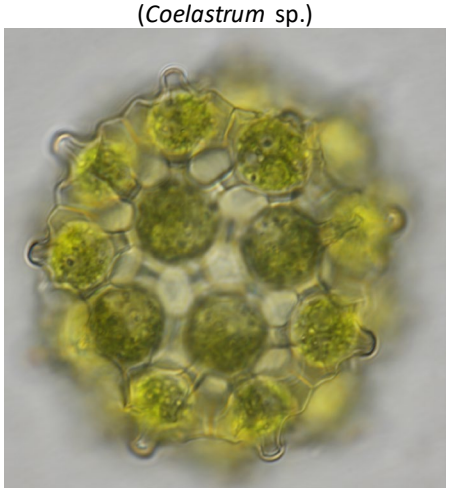
Green algae colonies

Green algae colony (*Botryococcus* sp.)



Green algae colony (*Micractinium* sp.)

Green algae colony (*Coelastrum* sp.)



Brown algae

Golden-brown algae (*Dinobryon* sp.)

Diatoms

Chain forming diatom (*Fragilaria* sp.)

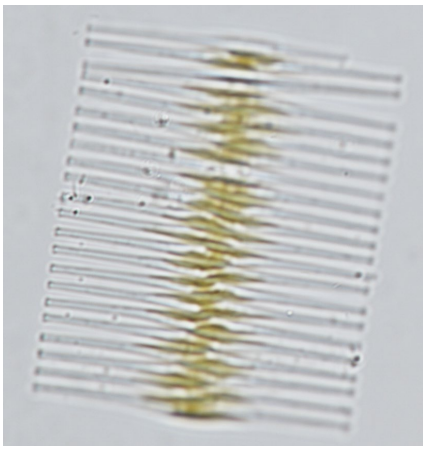
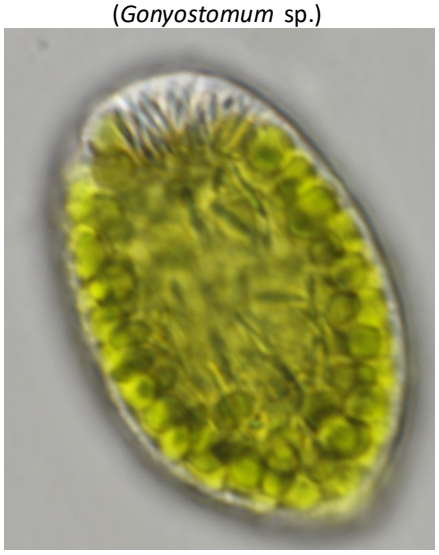


Figure 6. Morphology of different phytoplankton colonies common in NZ rivers, lakes or estuaries [NIWA Algal Services].

Various unicells

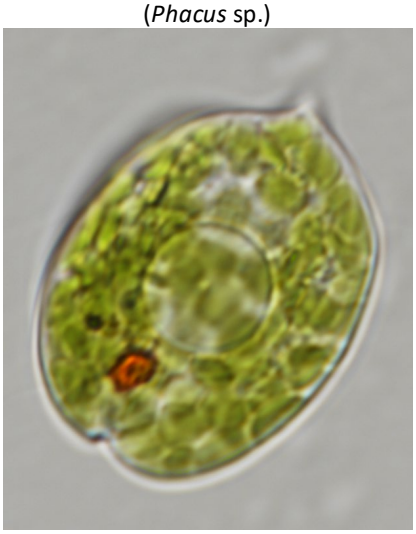
Ochrophyta
(*Gonyostomum* sp.)



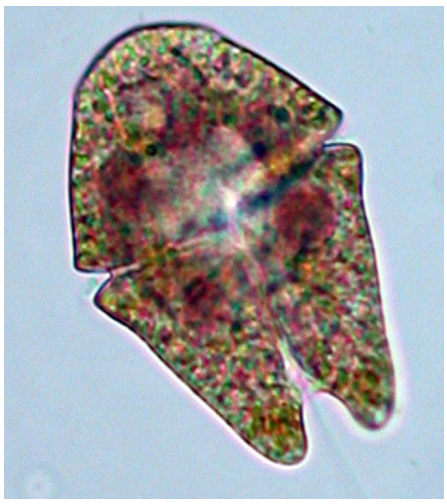
Cryptophyte unicell
(*Cryptomonas* sp.)

Diatom unicell
(*Didymosphenia* sp.)

Eugleniod green algae unicell
(*Phacus* sp.)



Dinoflagellate unicell
(*Akashiwo* sp.)



Dinoflagellate unicell
(*Gymnodinium* sp.)

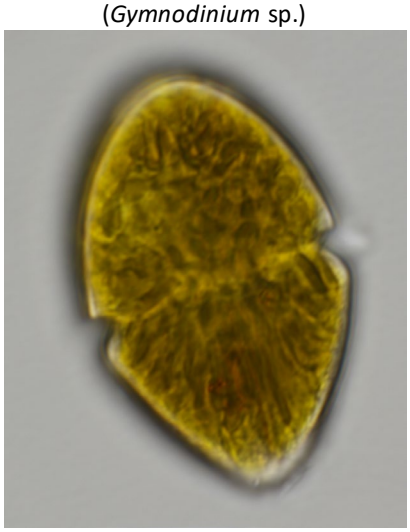


Figure 7. Morphology of different unicellular phytoplankton species in NZ rivers, lakes or estuaries. [NIWA Algal Services]

Sensor design

Sensor design and engineering will impact the AF values returned, and users should be aware that:

- Sensors with a wider bandpass filter (i.e., ~40 nm) will be more effective at dealing with pigment wavelength variability within the phytoplankton community present, but they could be affected by interferences and false positives.
- Most AF sensors are assembled by hand, so each sensor may be slightly different from others of the same model.
- Sensor manufacturers continue to upgrade or discontinue AF sensors. For example:
    - Turner Designs replaced the Cyclops-7 with the Cyclops-7F in 2017, and then (April 2025) discontinued the Cyclops-7F and now sell the C-FLUOR (released 2019). The C-FLUOR has faster response times, a deeper depth rating, lower power consumption, analog (0-5 V) and digital (RS-232) output options, and is factory calibrated.
    - YSI replaced the Series 6 PC with EXO TAL-PC with significant upgrades (including bandpass filters, circuit boards and firmware).
    - Sea-Bird upgraded the ECO range to ECO V2 in April 2025 (more channels, dynamic gain settings, standardised detector angles to 124°, increased on-board storage, improved sensitivity of fDOM, upgraded software and improved download speeds).

    Some of the limitations of older models demonstrated in research papers may have been overcome with upgrades. Other limitations may still exist, and users should ensure they have the latest manual and technical notes to ensure they are up to date with warnings and advice.
- Sensor manufacturer specifications are for the linear range (Figure 8), but users should be aware that as the sample concentration increases, AF sensors may generate non-linear readings. So high concentrations of pigment can produce inaccurately low fluorescence measurements that appear to be within the linear range of the sensor.

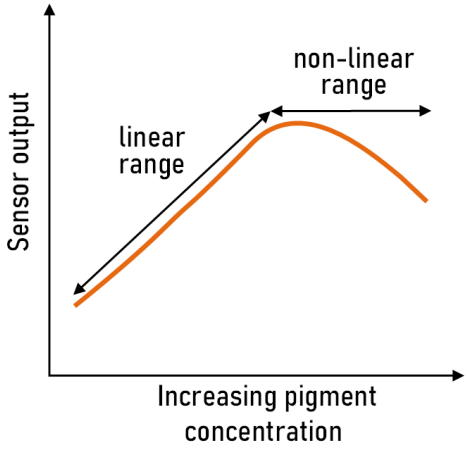


Figure 8. AF sensor response curve. Manufacturers specifications apply to the linear section of the response curve.

Fouling

Managing fouling on AF sensors is the most critical performance issue. The presence of algae on an AF sensor face will undermine the sensor's performance; in the worst case, the sensor values will be for the pigments in the fouling rather than pigments suspended in the water column.

Fouling is not uniform; it's local, can vary through time, and is the result of many physical, chemical and biological factors. Fouling development depends on the water matrix (pH, conductivity/salinity, temperature, DO, nutrient status, organic carbon, turbidity, etc.), hydraulic conditions, depth, season, and local fauna and flora species. In freshwater environments, fouling is predominantly algae (slimes through to filaments), although chemical films can also occur. In coastal waters there is the additional challenge of organisms such as barnacles, sea squirts and tube worms adhering to any exposed surface.

Fouling typically follows a series of steps (Figure 9):

1. Adsorption of organic and inorganic molecules immediately after immersion, forming the primary film (within an hour).
2. A more complex film develops after bacteria attach and an extracellular matrix develops (1 to 24 hours).
3. Development of a more complex community, with the presence of multicellular species, microalgae, spores, debris, sediments, etc. on the surface (24 hours to a week).
4. Attachment of macroalgae, grazing by freshwater invertebrates (e.g., NZ mud snail), or attachment of marine invertebrates (e.g., barnacles or mussels) after a week.

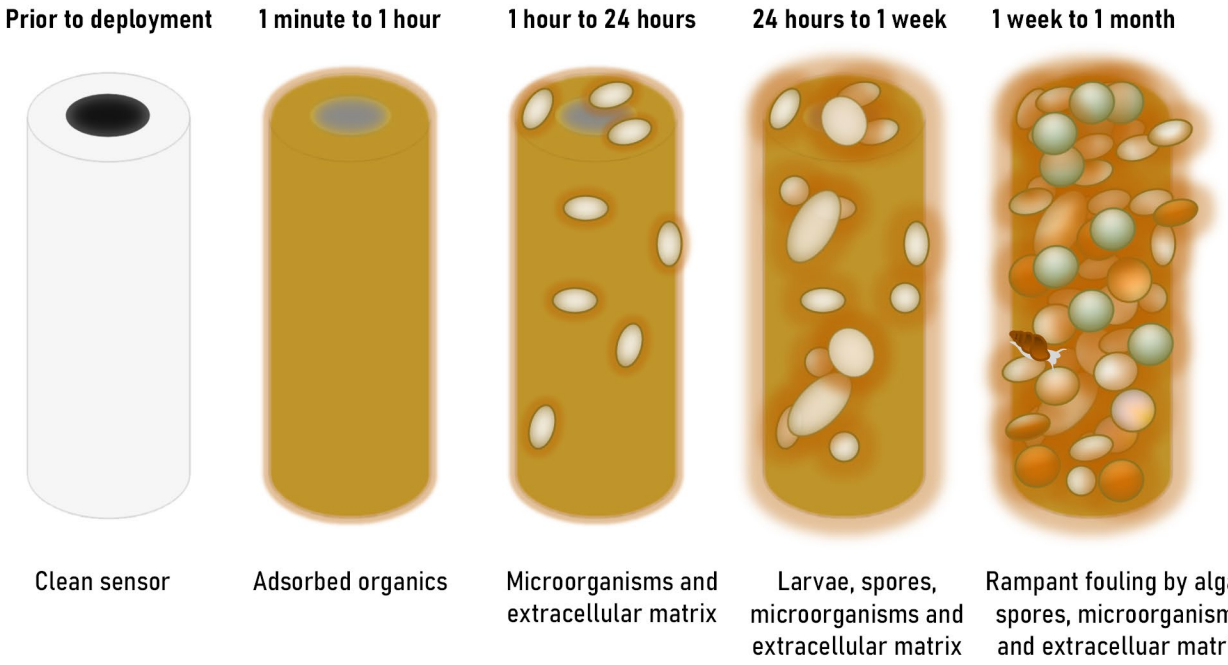


Figure 9. Simple illustration of the stages of biofouling. Each of the stages can occur in the order described, or in parallel or all at the same time (after Chambers et al. 2006).

See the Fouling Management section for more information on preventative steps to manage fouling on AF sensors. Fouling management is an active research area, particularly for coastal waters. For more details on sensor fouling, refer to Delgado et al. (2021) and Delgado et al. (2023).

Stray light

Stray light can alter AF sensor values. Several approaches can help overcome this issue: (1) shielding the sensor from ambient light by using housing and/or a guard, shroud or cap (see Table 5), (2) some sensors can measure the background fluorescence (with the LED off) or have filters which attempt to remove ambient light effects, and (3) focusing analysis on night-time data (but this could create challenges for collecting samples to develop site-specific relationships).

CASE STUDY 1 – IMPACT OF STRAY LIGHT ON SENSOR VALUES

ECan operate a Chelsea Technologies TriLux on a monitoring platform in Te Waihora/Lake Ellesmere, a turbid coastal lake in Canterbury (Figure 10 A). The sensor is installed ~30 cm below the water surface. Initially the sensor was not shielded from ambient light and the data was noisy during daylight hours, with large negative and positive spikes. A shroud was placed above the sensor and the data became less noisy (Figure 10 C).

A

B

C

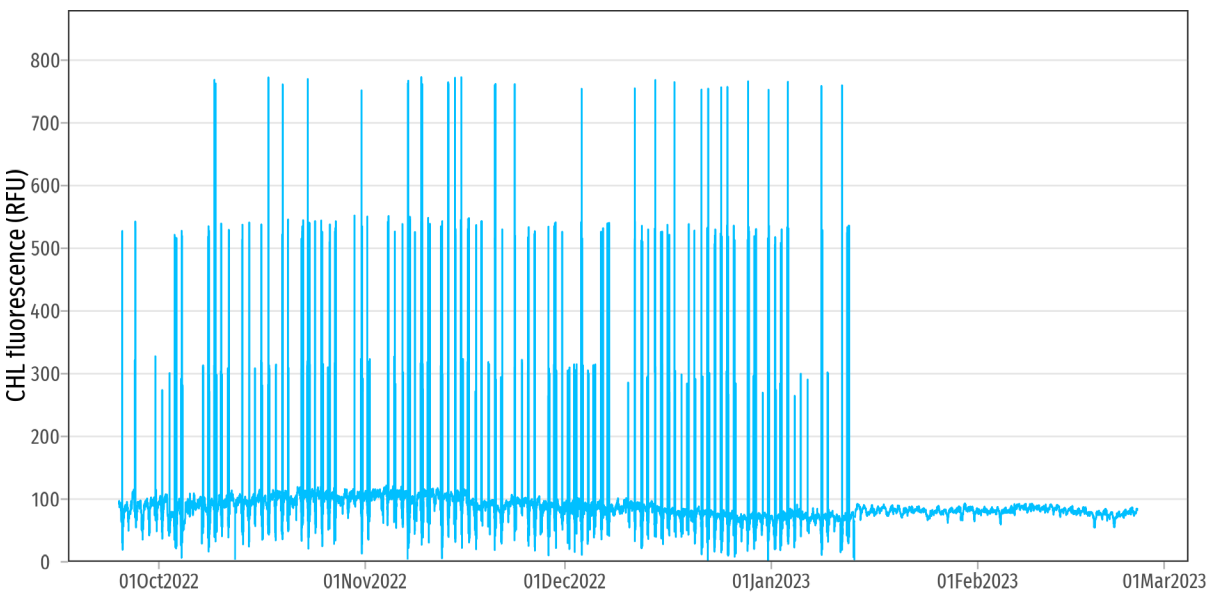


Figure 10. (A) HFWQ deployment on a coastal lake, Te Waihora, Canterbury [Alex Ring, ECan]. (B) Macro-fouling on a custom-built shroud installed to prevent stray light impacting the Chelsea Technologies TriLux sensor [Hamish Carrad, ECan]. (C) CHL fluorescence time series impacted by stray light before 14 Jan 2023 when a shroud was installed.

Summary

Submersible AF sensors are suitable for real-time monitoring of the temporal dynamics of phytoplankton, and with careful pigment selection can differentiate between algae and cyanobacteria. Table 1 summarises the key benefits and challenges when using in-situ AF sensors. For more detailed discussion, refer to review articles such as Bertone et al. (2018) and Zamyadi et al. (2016).

Table 1. Summary of key benefits and challenges when using algal fluorescence sensors.

Benefits	Challenges
- Relatively simple to measure. - Real-time AF sensor data are useful as an early warning system. - Temporal patterns in pigment fluorescence can help indicate when (and where, if the sensor is profiling) to collect samples for lab analysis. - Careful pigment selection can help differentiate between all phytoplankton (via CHL) and cyanobacteria (via PC). - Sensors can be deployed at different depths or on profilers to measure vertical changes.	- High light intensities reduce (quench) fluorescence. - Fluorescence changes with water temperature, turbidity and dissolved organics. - Converting fluorescence to algal biomass, biovolume or abundance requires a carefully designed sampling programme. - Measured fluorescence is affected by phytoplankton size, structure, type, physiological state and communities. - Sensor fouling distorts results, so frequent site visits and lens cleaning procedures are required. - It is not usually possible to differentiate between different forms of CHL (a, b and c).

Phytoplankton communities are dynamic, and blooms which result in high AF sensor values may be short-lived (days to weeks; see for example Figure 13), so sensors can detect changes that occur between field visits. It is critical that sensor users understand how the many biotic, environmental and sensor factors influence sensor values (Figure 11) so that sensor selection decisions can be informed and made carefully.

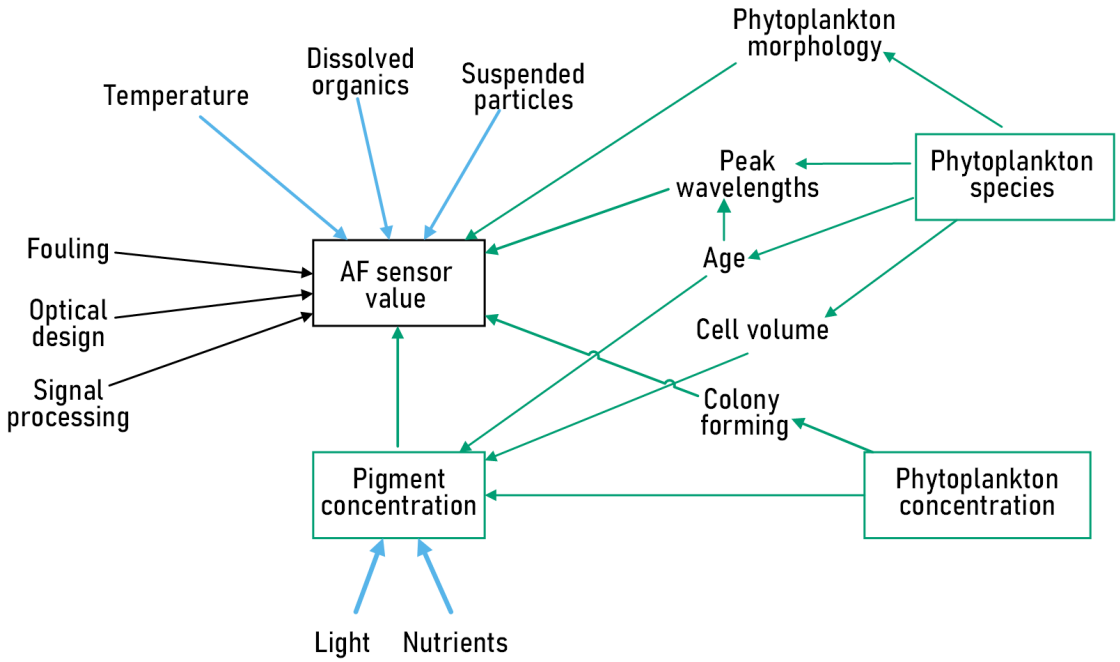


Figure 11. A summary of factors influencing AF sensor values. There are three key groups of factors: biotic (green), environment (blue) and sensor (black) (after Bertone et al. 2018).

CHOOSING A SENSOR

A handful of different AF sensors are routinely used by regional councils for fixed site deployments, and experienced users typically have a small number of trusted sensor models in their fleet. Workshop participants were asked to nominate their preferred turbidity sensors, sensors they had stopped using, and features they consider when selecting a sensor. The range of preferred sensors cover all the sensors in Table 5. The workshop participants identified information needs as a key factor in sensor selection. They also highlighted problems with managing multiple sensor models within a fleet, minimum detection limits and lack of numeric comparability.

What information do you need?

AF sensors are useful as early warning systems because they signal that the fluorescence has changed, but they do not provide information on what has changed. The details of the change will need to be investigated with discrete samples.

If the user requires more information than an early warning system, some challenging decisions need to be made before a sensor is selected. A method for converting sensor values to derived indicators (e.g., pigment concentration) requires careful planning.

To develop a site-specific relationship, concurrent sensor values and discrete sample values are required from the water next to the sensor. The basic principle is straightforward, but its success is not guaranteed. For example, across four Rotorua lakes during the summers of 2016 and 2017, the relationships between a PC AF sensor (Turner Designs Cyclops-7 as a field meter) and cyanobacterial biovolumes were generally weak (r^2 <0.25), except for one lake (Rotoehu, r^2 = 0.66), which had a high biovolume and was dominated by large-celled cyanobacteria (Cotterill et al. 2019).

Collecting surface water samples or depth-integrated samples will likely result in a weak relationship if the sensor is 2 m or more below the water surface. Similarly, collecting discrete samples from the water column to correlate with a profiling sensor will require specialist sampling equipment able to sample alongside the profiling sensor. Care must also be taken to ensure samples are collected in suitable containers and preserved and stored correctly.

Phytoplankton biomass can be measured using direct or indirect methods. Depending on the method selected, the phytoplankton abundance in discrete samples is commonly expressed as the number of cells per millilitre (cells/ml) or as a concentration (e.g., µg/l), but it could also be expressed as biovolume (mm^3/l). There are many methods available to characterise phytoplankton (see Almuhtaram et al. 2021), but the most common discrete sample methods will be lab extractions (indirect), microscope counts (direct) and flow cytometry:

- *Lab extractions* of chlorophyll pigments are a bulk measure – the method is rapid and simple but also quantifies all the chlorophyll pigment in the sample. There are various methods, but generally the sample is filtered and then the pigment is chemically extracted using a solvent (acetone or alcohol) before being analysed by spectrometry, fluorometry or chromatography. NEMS Discrete WQ for rivers, lakes and estuaries specifies method APHA 10200 H by fluorometry, with acetone as the solvent (with use of spectrometry is allowed when the annual median chlorophyll-a (CHLA) concentration is greater than 0.005 mg/l) (NEMS 2019a, NEMS 2019b, NEMS 2020). The resulting value will be a pigment concentration (µg/l) for all phytoplankton, regardless of cell types or colonies.
- *Microscopic counting* requires minimal equipment beyond a microscope, but the method can be time consuming (minutes to hours, depending on number of species and accuracy required) and relies on skilled analysts with extensive experience. This method can provide cell concentration (cells/ml), biovolume (mm^3/l) and relative abundance to the genus and/or species level.
- Flow cytometry uses lasers to detect and measure the size of cells and can differentiate phytoplankton groups using their pigment pattern. Simple instruments can estimate the abundance of types of phytoplankton (e.g., picoplankton < 2 µm, nanoplankton < 20 µm) and are a rapid and cost-effective way to estimate total phytoplankton. Imaging flow cytometry systems can go further, and in some cases can distinguish phytoplankton even to species level based on many morphological features. However, these systems are subject to other issues (e.g., aperture limitations, fouling, focal imaging length, separation of chain or colony forming algae).

Techniques using digital image analysis and other more comprehensive genetic methods are emerging but are not currently routine practice.

A key consideration is how to successfully capture temporal variability in the phytoplankton community. Developing a site-specific relationship is more likely to be successful when the phytoplankton community is not complex. For

complex multi-species and/or multi-form (colony vs unicellular) blooms, it may be challenging to link sensor values and algal biomass indicators.

Additional indicators

Additional indicators are useful for understanding variability in phytoplankton biomass and the processes contributing to bloom formation. Some will also be useful for applying sensor corrections (see Table 3). A useful technical resource is Johnston et al. (2024); they operated three HFWQ sensing platforms equipped with 40 sensors (200 time series) to better understand harmful algal blooms, and they thoroughly document the project design, deployment and lessons learnt.

Sensor fleet

One of the key challenges is working out how a sensor fits with your existing sensor fleet. Limiting the number of different models in a fleet can simplify operations because:

- verifying an AF sensor's performance is most easily done by using the same sensor model as a field reference sensor. An alternative but less robust approach is to build a site-specific relationship between an in-situ sensor (model A) and a field reference sensor (model B).
- transferring knowledge around site-specific relationships between sensor output and algal species is made possible.

Minimum detection limits

While manufacturer specifications could state a detection range from 0–Y mg/L, the lower limit of detection (LOD) will not be 0 – rather, it will depend on the phytoplankton species/community and the calculation method. In a lab comparison of six sensors and four cyanobacteria species, Choo et al. (2018) found that LOD were different for the species and calculation method. For example, the MDL for the YSI EXO 2 were 0.41 RFU for *Microcystis aeruginosa*, 0.05 RFU for *Dolichospermum circinale*, and 0.15 RFU for *Cylindrospermopsis raciborskii* using the U.S. EPA (2016) method (minimum concentration of an analyte that is distinct from the blank results with 99% confidence).

Numeric comparability

Algal sensors of different brands and models are not numerically comparable with each other – turbidity sensors, for example, are more numerically comparable (see Turbidity Sensor Selection chapter). The lab comparison of Choo et al. (2018) shows that for the same species, fluorometer outputs vary by more than two orders of magnitude. They also plot the CHL and PC sensor wavelengths on the excitation-emission spectra for the tested cyanobacteria species to emphasise how important it is to understand sensor optics (see Choo et al. (2018) Figure 4). In the field, ECan have found that in Te Waihora/Lake Ellesmere, a Chelsea Technologies TriLux might output values of 30 RFU, while the YSI EXO TAL sensor outputs 4-5 RFU. This lack of numeric comparability is due to different optical designs, including wavelengths, hardware and signal processing.

ADVICE FOR NEW USERS

We asked our experienced users to share advice for new users and highlight one thing they wish they'd known earlier. They said:

- Understand what you are trying to achieve – for what reason are you measuring AF?
- Understand how much work will be needed to meet your data need. Do you need to estimate biomass? If so, how will you collect data to develop the site-specific relationship between AF and algal biomass?
- Measure AF alongside other HFWQ indicators (including temperature, turbidity, fDOM for corrections, and other indicators if possible).
- Have a robust fouling management plan.
- Use wipers and other biofouling tools.
- Create a regular maintenance schedule and telemeter data so that biofouling is caught early.
- Ensure antifouling systems are well-maintained because wipers do fail, might be damaged or worn, and at times aren't able to keep the lens clean enough.
- Ensure users are well-trained to calibrate and maintain sensors.
- Noisy data might be real. Phytoplankton are dynamic (see Pigments section) and mobile. They will migrate with currents or surface winds, some can alter their buoyancy and migrate vertically (at ranges ranging from minutes to weeks), and some can swim (e.g., dinoflagellates).
- Plan to eliminate stray light effects. Sometimes housings and sensor guards/shrouds can fill with algae.
- Consider calibration routines carefully.
- Don't over-calibrate algal sensors. Validate sensors regularly and only calibrate if needed.
- Consider selecting a sensor with a solid-state standard (see Table 5 for details on which manufacturers offer them).
- Access expert knowledge – these sensors are complex.

CASE STUDY 2 – EARLY WARNING SYSTEM ON A TIDAL RIVER

ECan monitors the Kaiapoi River in Kaiapoi, North Canterbury, to gain information on the river's ecological health and conditions which give rise to algal blooms and scums flowing through the river town. The Kaiapoi River is a low-gradient tributary of the Waimakariri River, and saline intrusion events occur. The algal fluorescence sensor is part of an early warning system – when fluorescence values rise, ECan staff collect discrete samples for lab analysis of pigment concentration and algal toxins.

In early 2025, ECan installed a Chelsea Technologies TriLux sensor alongside a TriOS OPUS optical nitrate sensor and near an In-Situ Aqua TROLL (DO, temperature/conductivity, turbidity). The TriLux is deployed about 1 m below the mean low tide level. The data is telemetered back to ECan so that daily checks are possible.

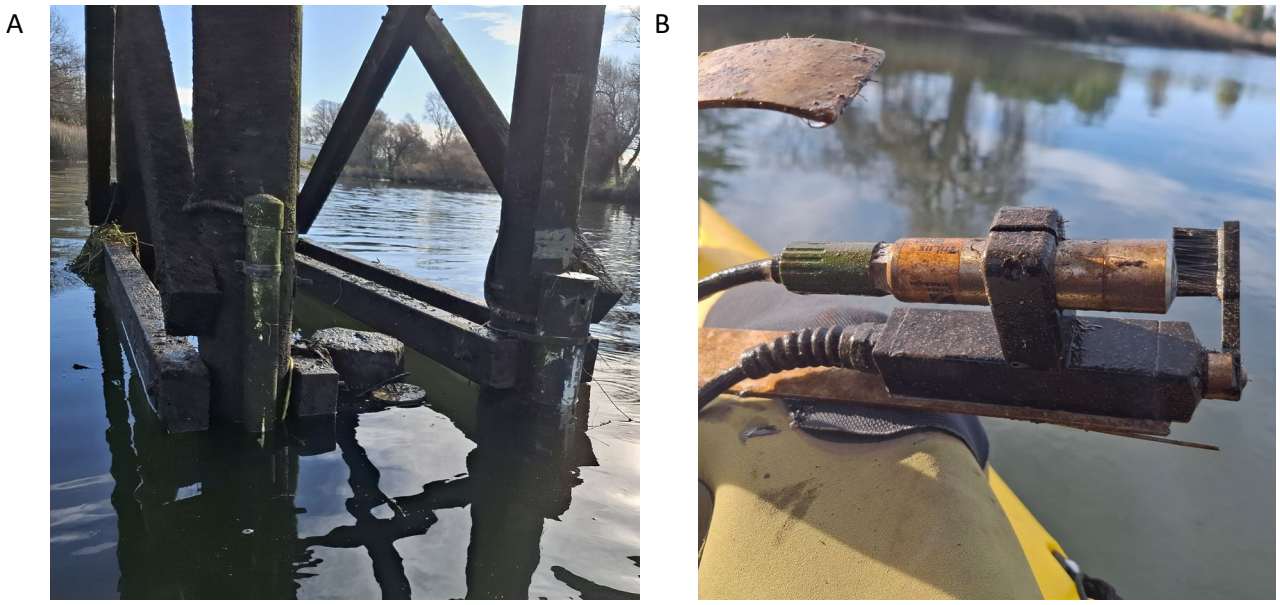


Figure 12. Kaiapoi River water quality sensors. (A) Sensors deployed on a footbridge pier [Hamish Carrad, ECan]. Also see the back cover. **(B) Servicing the Chelsea TriLux with ZebraTech HydroWiper by kayak [Hamish Carrad, ECan].**

Between late January and late March 2025, the CHL fluorescence was elevated (>40 RFU) compared to values measured during early–late January (<10 RFU). Discrete samples collected during this period confirm that CHLA concentrations were elevated due to chlorophyll-a pigments in phytoplankton. The CHL values also vary with the tidal cycle – lower values are generally recorded during the high tide phase.

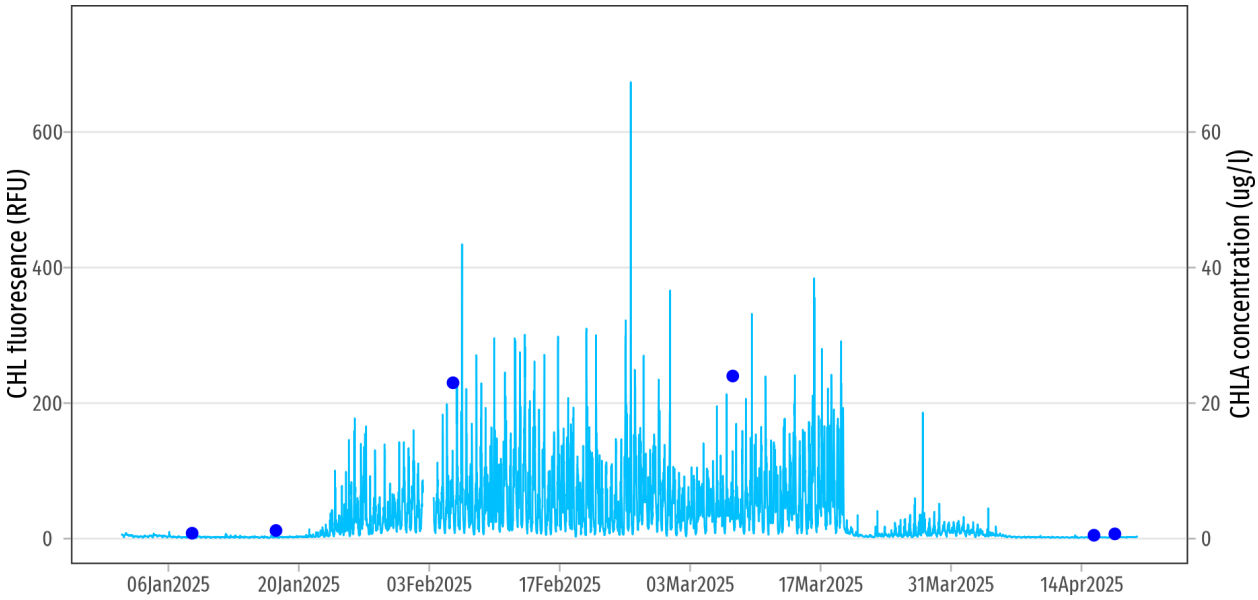


Figure 13. Time series of algal fluorescence CHL on the Kaiapoi River, Canterbury, with discrete sample CHLA concentrations (blue dots).

KEY QUESTIONS TO CONSIDER

Each candidate AF sensor should be considered against the monitoring objectives and deployment requirements (Table 2 – Table 4). These sensors are complex – there are many factors to consider and challenges to overcome. The key questions are grouped in three tables: environmental conditions, data specifications and deployment considerations.

Environmental considerations

Table 2. Environmental conditions: Considerations and challenges to help guide sensor selection

Key questions	Consequences	Possible solution
Which pigment(s) are present?	- Incorrect pigment combination selected.	- Examine existing data or collect discrete samples to characterise the phytoplankton target species or community composition. Based on this, decide if you need a CHL, PC or PE sensor or a combination.
Does the water have high turbidity?	- Incorrect fluorescence values.	- Consider measuring turbidity and AF concurrently. Some sensors offer this option out of the box (Table 5). - Consider running a lab investigation on your water matrix to check if a turbidity correction is required (see Downing et al. 2012, Dix et al. 2022 for possible lab experiment designs)
Does the water have a high organic concentration or colour?	- Colour will lower AF values. - Dissolved organic matter may foul the lens.	- Consider operating a dissolved organics sensor alongside the AF sensor. - Consider running a lab investigation on your water matrix to check if dissolved organics correction is required (see Downing et al. 2012, Dix et al. 2022 for possible lab experiment designs). Consult Booth et al. (2023) for guidance on corrections for fDOM sensors. - Check what the manufacturer suggests for cleaning off dissolved organic matter fouling (e.g., you can use citric acid with YSI EXO sondes).
Is the water temperature highly variable?	- Varying temperature may make interpretation difficult.	- Consider if a temperature correction is required (see Downing et al. 2012, Dix et al. 2022 for possible lab experiment designs).
Does the water contain iron, manganese, runoff from asphalt surfaces?	- The sensor and lenses may be chemically fouled.	- Plan how to identify the presence of chemical fouling on the lenses and in the data. - Plan how to remove chemical fouling from your sensor. This may require advice from the manufacturer. Use a LED-lit magnifying glass to check the lenses after cleaning (to protect your eyes, ensure the sensor is not powered). - Keep the sonde/sensor body clean by wrapping in tape (see Fouling management). This will reduce your cleaning effort considerably and ensure your focus is on keeping the lenses clean.
Is the environment corrosive?	- Sensor may corrode.	- Stainless steel body material is good for freshwater applications. - For estuarine deployments, select a titanium sensor casing (if available).

Data specifications

Table 3. Data specifications: Considerations and challenges to help guide sensor selection

Key questions	Consequences	Possible solutions
What sensor performance is required?	- Resolution may be inadequate. - The sensor may over-range.	- Choose a higher sensitivity sensor or one with a gain setting for a low chlorophyll environment. - Check the minimum and maximum limits are appropriate for your environment.
What challenges might non-linear sensor output create?	- Difficulties interpreting data.	- Find out what value the sensor returns when it is "saturated" or over-range. Does it continue to output values (for example, a fixed value or varying values over the max) or a code (e.g., -999, NA)?
Are correction factors required to meet your purpose?	- Inadequate data for corrections.	- Operate an AF sensor concurrently with turbidity, temperature, coloured dissolved organics (i.e., CDOM or fDOM). See Table 2 for more details. - Select or develop correction methods prior to deployment to ensure all necessary data is collected.
What is the required observation interval?	- Sensor may not be able to take measurements at required frequency.	- Check required observation interval exceeds minimum sensor measurement interval (see Table 5). - Check the sensor warm-up time if using a data logger. - Work out how the data will be used: Will you use night-time data only? Is hourly data required?
What units will you output?	- Wrong units selected.	- Most sensors output RFU, but outputs are not comparable between different makes/models. - Conversion to concentration units will require a site-specific relationship between AF values and algal biomass.
How will you develop the relationship between sensor values and algal biomass?	- Unable to develop site-specific relationship due to a lack of representative samples.	- Choose a method to develop the site-specific relationship. Lab methods vary. - Consider how to apply the relationship: (1) some sensors can load user calibrations (as X-Y pairs or equations), (2) program into logger, or (3) apply it in time series or statistical software.
What approach will you use to verify the sensor's output?	- Verification method selected causes additional work or cost.	- Purchase and operate the same sensor make/model for verification (e.g., install Sensor A and use a different Sensor A as a field meter). Using a different make/model will require you to develop a relationship between the two sensors. For example, the YSI 6-series BGA-PC sensor (discontinued from 31 Dec 2025) and YSI EXO TAL-PC sensor are optically different - the 6-series PC sensor detects at 640 ± 40nm (for more details see YSI 2019)
How frequently does the sensor need calibrating?	- Frequent calibration results in higher cost. - Factory calibration will require international shipping.	- Consider using the factory calibration and keeping the sensor face clean. - Choose one calibration standard brand and stick with it to meet stationarity requirements. - Consider the cost of calibration, including the shelf life and care of secondary standards.
Is averaging user-controlled?	- Averaged data may not be needed.	- Check how averaging works on the sensor (see Table 5) or read the manual. Some sensors can only output averaged data.
Are real-time data required for decision-making?	- Data delivery requirement not met.	- Telemeter data.
Are data gaps acceptable? What size gaps are acceptable for decision-making?	- Large gaps, or gaps at critical times, may render data less useful for decision-making.	- Consider how you will fill gaps in the record. - Telemeter data and metadata to detect sensor failure. Consider resourcing (or arrange to borrow) a backup sensor to cover system technical malfunctions.
What values does the sensor output when it over-ranges?	- Data values returned may be incorrect.	- Check how the sensor behaves when saturated or over-ranging. Some sensors return numeric values (such as a constant value), while others return NA or negative values.
Is the site a long-term operation?	- Replacing a surrogate relationship could be costly. - Long service times. - Sensor model may be discontinued or upgraded.	- Consider lifespan of the project versus sensor lifespan. Replacing a sensor could be costly if a new surrogate relationship is required. - If the site is long term, consider sensor servicing timeframes. Sending a sensor to the manufacturer for repairs can take months.

Deployment considerations

Table 4. Deployment considerations: Considerations and challenges to help guide sensor selection

Key questions	Consequences	Possible approach
How will you manage fouling?	- Data quality will be reduced.	- Consult the Fouling management section for more details. - Learn how to notice the signs that a sensor is starting to foul (e.g., baseline drift). - Check maintenance requirements for a supplied wiper. For example, how frequently should be brush/blade be replaced? Check the cost and whether the brush/blade can be sourced locally.
How will you manage light interferences?	- Data may contain large data spikes during the day.	- Choose a sensor which has a shroud/guard/cap. - Build custom housing for the sensor. Consider how reflectance off light-coloured surfaces (such as white PVC) might differ from a dark-coloured surface. Ensure the housing has a uniform reflecting surface so stray light scattering direction is consistent (e.g., a solid section near the sensing volume).
How will you access the sensor for cleaning?	- Users will be unable to clean the sensor.	- Select sensor model/option with a SubConn® connector to disconnect the cable from the sensor.
Access to instrument across the range of environmental conditions?	- Users will be unable to service or retrieve the sensor.	- Consider if access to sensor is required during challenging conditions. For example, will you be using a kayak or boat to access the sensor? What environmental conditions (e.g., wind, swell) will delay scheduled visits? - Consider how water level may change seasonally and how to mount the sensor to overcome changing water levels. Is a fixed structure available and representative of conditions? Do you need a buoy?
What are the power options?	- Data gaps due to power failure.	- If no mains power, select a sensor able to run on solar or battery power. - If using solar power, check whether the sensor operates at 12 or 24 VDC. - Or select a sensor which can be attached to a battery powered logger. For example, a multiparameter sonde or Turner Designs C-FLUOR on a PME logger with miniWIPER.
What are the data storage options?	- Data may be lost if not stored in multiple locations.	- Consider where the raw data values are stored. Some sensors, such as the In-Situ Aqua TROLL, store the data on an SD card and in the sensor's memory.
Can the sensor be integrated into existing site infrastructure?	- Additional cost (e.g., new logger). - Data loss.	- Use a sensor which integrates with existing data collection platforms. - If no housing/logger available, select sensor with sufficient memory. - If no mains power, select sensor able to run on battery and/or solar power.
What is your anticipated site visit schedule?	- Inadequate verification. - Data loss due to fouling, or sensor loss.	- Telemeter data and metadata to enable daily checking of sensor performance and issues.
How will you ensure the lens remains clean?	- Lost data due to fouling.	- Compare available wiper options. For sondes you will need to use the manufacturer's wiper. - Consider using copper tape to reduce algal growth near the sensor face. Duct tape can be useful for protecting the sensor body. For marine deployments, consider using biocides.
Do you have the technical expertise required?	- Frustration, wasted time, data loss.	- Pre-deployment checks and deployment should be well planned.
What is the level of technical expertise available in New Zealand?	- Time lost due to slow service from overseas.	- Consider where you can access help at short notice – you will need it! - Sign up to manufacturer's support portal to download latest versions of manual and special support documents. Subscribe to manufacturer's newsletter to stay up to date.
How user-friendly is the software interface?	- Time wasted due to software challenges.	- Check notes and comments in Table 5. - Test-drive the software interface. - Request training and ongoing support as part of your purchase.

SENSOR COMPARISON TABLE

Table 5. Comparison table of algal fluorescence sensors used by the workgroup (in 2024). At least one sensor user contributed to each column. All costs in NZD in 2024, excluding GST. See notes below the table for more detailed comments on each sensor. To evaluate a different sensor, gather information from brochures, manuals, the manufacturer and other users.

Feature	Chelsea Technologies TriLux	In-Situ Aqua TROLL 500/600	Sea-Bird ECO FL	Turner Designs Cyclops 7F	Turner Designs C-FLUOR	YSI EXO TAL
Cost ($<5K, $$ 5K–10K, $$$>10K)	$$	$+($$$ sonde)	Discontinued 2025 [sb] (ECO V2 $$$)	Discontinued 2025 [t] (replaced by C-FLUOR)	$/$$	$$+($$$ sonde)
Sensor basics						
Suited environments	F, M	F, M	F, M	F, M	F, M	F, M
Pigments	2 or 3; 1 on UniLux	1	1, 2 or 3	1	1	2
Sensor versions	TriLux or UniLux	CHL, PE or PC	Many options [sb]	high CDOM [t]	high CDOM [t]	PC+CHL, PE+CHL
Operations	Requires logger	Requires sonde	Internal or external options	Cable or integration partner options	Cable or integration partner options	Requires sonde
Light source	LED	LED	LED	LED	LED	LED
CHL Ex/Em (nm) with (bandpass filter width)	Ex: 470 Em: 685	Ex: 430 Em: 675–750 (75)	Ex: 470 Em: 695	Blue: Em: 465 (170) Ex: 696 (44)	Blue: Em: 470 (60) Ex:696 (44)	Ex: 470 (30) Em: 685 (40)
PC Ex/Em (nm) with (bandpass filter width)	Ex: 610 Em: 685	Ex: 590 Em: 640–690 (50)	Ex: 630 Em: 680	Ex: 590 (30) Em: >=645	Ex: 595 Em: >=645	Ex: 590 (30) Em: 685 (40)
PE Ex/Em (nm) with (bandpass filter width)	Ex: 530 Em: 685	Ex: 498 Em: 575–625 (50)	Ex: 530 Em: 595	Ex: 515–547 Em: >=590	Ex: 515–547 (32) Em: >=590	Ex: 525 (30) Em: 685 (40)
Sensing volume		Limited by restrictor	1 cm^3 at 1 cm from window	Limit by shade cap or greater than 7.6 cm clearance; recommended sensing volume 623 cm^3	Limit by shade cap or greater than 7.6 cm clearance; recommended sensing volume 623 cm^3	Limited by guard
Face angle	Flat	Flat	Flat	Flat	Flat	Flat
Detector details		Reference detector	Reference detector, detector 140° [sb1]			
Lens material	Sapphire glass	Sapphire glass	Epoxy	Epoxy	Sapphire glass	Sapphire glass
OEM	Yes	Yes	Yes	Yes	Yes	Yes
Construction materials	Titanium	Plastic	Plastic or Ti	stainless steel, Ti or delrin	Ti	stainless steel
Power source	External (11–25 VDC)	External or both (8–36 VDC or D cell)	External (7–15 VDC)	External (3–15 V); battery options from partners	External (3-15 V); battery options from partners	External or both (9-16 VC or D-cell)
Correction factors available	Turb (backscatter if selected at purchase)	Sonde: Turbidity (side scatter), Temp	Triplet: Turbidity backscatter	None	None	Sonde: Turbidity (side scatter), Temp, fDOM
Max depth	2000	250	Triplet: 600 FL: 300/600	600 (100 with PME)	2000	
Gain settings	Yes [c]		1 (dual 5)	3	1	
Response time		T63: <1 s, T99: <1 s		T99: <1 s	T99:<0.6 s	
Warmup time				1 s		
Minimum observation	0.1–3 Hz	0.5 Hz	8 Hz	1 Hz	2 Hz	
Wet-mate connector	Yes	Yes	Yes	Yes	Yes	Yes
Fouling options included	None. Use ZebraTech HydroWiper	Aqua TROLL wiper [at]	Wiper [sb] & copper faceplate option	None. Use ZebraTech HydroWiper	None. Use ZebraTech HydroWiper	EXO Wiper

Feature	Chelsea Technologies TriLux	In-Situ Aqua TROLL 500/600	Sea-Bird ECO FL	Turner Designs Cyclops 7F	Turner Designs C-FLUOR	YSI EXO TAL
Interface/controller required	USB dongle to laptop; cable options	No	Options: logger or internal memory	Needs cable or battery-powered logger	Needs cable or battery-powered logger	DCP or Modbus adaptor for logger
Output comms protocols	RS-232, Analog 0-5 V [c]	SDI-12 or Modbus	RS-232, analog or digital	Analog 0-5 V	Analog 0-5 V	SD1-12 via DCP, RS-232, RS-485 [e]
Units	Raw, RFU	Volts	Raw, RFU	Volts	Volts	Raw, RFU
Derived units	µg/l	µg/l, CHL also cells/l	µg/l			mg/l
Supplied factory calibrated	Yes	Yes	Yes	No	Yes	Yes
Recommended factory service frequency	2 y	1 y (or when needed)	1 y			
Primary cal. pigment CHL (factory) (Foster et al. 2022)	CHLA in acetone	Spinach	*Thalassiosira weissflogii* (diatom)	*Dunaliella salina* (green algae)	*Dunaliella salina* (green algae)	*Chlorella* sp. (Stumpner et al. 2022a)
Primary cal. pigment PC	[c]			Aligent (spirulina)	Aligent (spirulina)	
Primary cal. pigment PE	[c]			Aligent (red algae)	Aligent (red algae)	
Secondary cal. standard	Rhodamine WT and solid state CHL (for Ti and SS)	Rhodamine WT	Rhodamine WT	Rhodamine WT	Rhodamine WT	Rhodamine WT
User experience						
Physical robustness	Robust	Robust	Robust	Robust	Robust	Robust
Stability	Good	OK [at]		Very good	Very good	
Performance overall	Reliable with stray light shield	Unsure [at]	Reliable, oceanographic	Reliable	Reliable	Reliable, needs regular cleaning
Reliability	Very good	Unsure	Excellent	Excellent	Excellent	Excellent
Sensor-to-sensor variability	Yes		Yes	Yes	Yes	Yes
Apply site-specific relationship in software	Logger/post-process	Yes	Yes	Logger/post-process	Logger/post-process	Yes (ug/l or cells/ml) or external logger or post-process
Averaging	User controlled	User controlled	User controlled, 4–8Hz depending on model	Yes, logger controlled	Yes, logger controlled	Yes, not fully user controlled
Setup software user-friendliness	Old school UI. Sensor Monitor software	WinSitu and VuSitu App. App is good.	ECOView, old-school UI, challenging but effective. Fathom 2024.	–	–	Good UI with calibration wizards
Data offload options	Requires logger	SD card, phone, pc	9000 samples internal (depends on model)	Requires logger	Requires logger	Via Kor/Kor2 .bin files, telemetry with DCP
Warranty		2 y		1 y	1 y	2 y
Manual usefulness	Not great	Good	Good			Good
NZ support options	Other RC staff	NZ sales, limited tech support	Imbros (Tasmania) are Sea-Bird reps	Other RC staff	Other RC staff	EXO widely used, but smaller pool of experienced TAL users

Table 5 Notes:

[at] In-Situ Aqua TROLL notes: (1) Wiper looks flimsy but also cleans the sensor protector/case. Wiper can struggle to maintain clean optical sensors. (2) Sensor could use more averaging. (3) One CHL sensor only lasted 8 months.
[c] Chelsea Technologies TriLux notes: (1) User adjustment of LED intensity enables calibration to extend the range by 7.5 times. (2) Other comms options available at time of purchase include SDI-12, RS-422, 4-20 mA. Check calibration of SDI-12 version. (3) TriLux PC and PE data are related to CHL. For PE or PC concentration use a UniLux (one pigment) sensor.
[e] YSI EXO notes: (1) EXO3 has SDI-12 and does not require a DCP.
[sb] Sea-Bird notes: (1) 4) ECO range discontinued 2025, new purchases will be the ECO V2 sensor. ECO V2 has 2–4 channels, so users select 4 channels from: scattering, turbidity (700 nm), fDOM, CHL, PC and PE. ECO V2 range is also lower cost. (2) Sea-Bird has recently standardised detector angles to 140°. Check sensor specs carefully to avoid unintentionally using a combination of sensors with different detector angles. (3) Many models available for ECO – from 1 to 3 pigments, battery or cable, internal memory available. (4) Wiper with neoprene blade may not be adequate, consider deployment conditions before purchasing, and choose either a fitted wiper or third party.
[t] Turner Designs notes: (1) Both sensors also available as 'Red' versions for high CDOM waters. The sensor operates at higher wavelengths (Red: Em: <=635, Em: >695) to reduce overlap with CDOM. (2) Cyclops 7F discontinued Apr 2025 and replaced with C-FLUOR. (3) Multiple integration partners supply battery-powered loggers, including PME, Eureka.

FOULING MANAGEMENT

The workshop participants identified fouling as the key factor reducing sensor performance and recommend actively managing fouling on all AF sensors. Even a slight buildup on a lens will reduce the sensor's accuracy.

Wipers

The workgroup recommended using robust wipers where possible. Brush wipers operate well on many unattended AF sensors across New Zealand – they are effective, and the brushes are easy to replace. Some AF sensor manufacturers offer the option of a wiped or non-wiped sensor (e.g., Sea-Bird ECO) and some users choose to use a third-party wiper. Multiparameter sondes come with proprietary wipers, which mostly are adequate (see Figure 14 A and B), but if they are not adequate for monthly site visits, more frequent visits are needed.

A

B

C

Figure 14. Fouling on AF sensors. (A) Severe fouling on a YSI EXO sonde after a month in Wainono Lagoon, a coastal lagoon near Waimate, Canterbury, during early 2025. The site has operated for 7 years, and the EXO wiper generally performs well. However, over summer the inside of the guard can fill with growth. An open guard (no bottom cap) is used over summer so that any growth can drop out of the guard. The wiper has been replaced at least 3 times in 7 years. [Julie Grant, ECan]. **(B) Fouling on a Sea-Bird ECO FLNTU on the Firth of Thames [Iain MacDonald, NIWA]. (C) Copper-coated YSI EXO sensors (including TAL-PC and TAL-PE) after an estuary deployment [Chris Eager, WRC].**

Biocides

In marine environments, where macro-fouling is heavy and service intervals lengthy, biocides are usually required. A more detailed discussion on the use of biocides (and alternatives) to manage fouling can be found in Delgado et al. (2021).

Chlorine or bromine solutions can be used to reduce fouling; for example, NIWA's Squirtek squirts bromine for 15 s every 3 hours. Several of the Sea-Bird CTD range can be deployed with anti-fouling plugs which contain TBTO (tributyltin oxide). The plugs are placed at the external ends of the cell (both entrance and exit) and work to minimise fouling without altering the cell geometry. The pumped system contains poisoned water when the sensor is not sampling. TBTO was banned by the International Marine Organisation in 2008 as it is considered an environmental toxicant, but Sea-Bird continues to obtain approval for its use for this application. Co-locating an AF sensor with a CTD with biocide will assist with managing fouling.

Copper

Copper can slow the growth of biofouling by releasing dissolved copper ions into the water. Some manufacturers supply copper faceplates (see Figure 14 B), guards or mesh, and these may offer some protection and slow the fouling rate. Copper tape can also be used (see Figure 14 C).

Antifouling paints

Paints designed for boat hulls can be used to slow fouling on sensors in coastal waters. Paints such as Pettit Hydrocoat or International Trilux 33 contain copper and/or biocides and degrade over time (see Figure 14 B). These paints are not suitable for freshwater deployments. Many of these paints contain toxic chemicals, so use good workplace safety practices.

Coatings

Coatings that create a slick surface to prevent organisms from adhering may be useful, but for unattended deployments they may be inadequate. Coatings may be added at the factory or by users, but both versions are generally designed to reduce but not eliminate adhesion.

Factory-added coatings are generally used to reduce the adhesion on sensing surfaces, whereas users can only apply coatings to non-sensing surfaces. For example, YSI markets *C-spray,* a non-toxic, nano-polymer spray, to cover exposed surfaces such as the sensor body (do not apply to sensor faces). An alternative product, which BOPRC uses to protect non-sensing surfaces, is a New Zealand lanoline-based product, Prolan.

Tapes

Many experienced sensor users routinely use duct tape to cover the bodies of multi-parameter sondes to reduce post-deployment cleaning effort. Some users combine duct tape with PVC film (e.g., cling wrap, sandwich wrap).

Additional practical tips for managing fouling

Experienced users suggest:

- Wipe as frequently as infrastructure allows, preferably before each measurement.
- Telemeter data (and wiper metadata) to keep an eye on fouling.
- Select a wiper which can provide metadata on brush position (e.g., home position) to detect if the wiper has got stuck over the lens.
- Create cleaning routines which include a check or test.
- Actively maintain the antifouling system as there will be seasonal and annual variations. For example, during summer it may be challenging to maintain a clean lens in a productive environment.

DEPLOYMENT OVERVIEW

This project does not cover deployment in detail. However, good quality data depends on careful deployment design. The photos on this page demonstrate a range of deployments undertaken in New Zealand. See case studies and covers for additional examples.

Lake Hayes monitoring buoy [ORC]

Profiling with a YSI ProDSS at a lake buoy with an EXO sonde at 2 m depth [Whitney Woelmer, University of Waikato]

Field verification sensor (wrapped in pink tape) alongside a field sonde (in PVC housing) in a Hamilton stream [Gareth van Assema, NIWA]

Monitoring platform on a coastal lake, Te Waihora, Canterbury [Alex Ring, ECan]

SUPPORT FOR NEW USERS

All NZ sensor reps are helpful and approachable; some will be able to give detailed operational guidance, while others will need to defer to colleagues.

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NIWA

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