NIWA
Taihoro Nukurangi

DISSOLVED OXYGEN SENSOR SELECTION

Acknowledgements

This guidance was funded by MBIE's Envirolink Scheme (C01X2301) and supported by NIWA's Strategic Science Investment Fund (C01X1703—NIWA Platforms Plan). The Envirolink scheme funds research organisations (Crown Research Institutes, universities, and some not-for-profit research associations) to provide regional councils with advice and support for research on identified environmental topics and projects.

The High Frequency Water Quality Guidance Monitoring Tool is supported by:

This document was prepared by Lucy McKergow (NIWA) with contributions from the Dissolved Oxygen Sensor Selection Workgroup. The workgroup contributed to the content and design through a survey, workshop and discussions. They also provided feedback on the draft guidance. The input of workgroup members and additional document reviewers is gratefully acknowledged. This chapter was reviewed by Iain MacDonald (NIWA), the workgroup and a group of external reviewers. This chapter was edited by Andrea Graves.

NIWA Report No: 2025310HN

Citation

McKergow, L. (2025). Dissolved oxygen sensor selection. High Frequency Water Quality Monitoring Guidance. An Envirolink Tool prepared by NIWA. NIWA Client Report 2025310HN http://www.envirolink.govt.nz/assets/

Front cover: DO monitoring at Hurunui River hāpua (river mouth lagoon), Canterbury [Hamish Carrad, ECan].

Back cover: DO monitoring at Rees River, Otago [Emily Olson, ORC].

CONTENTS

ABSTRACT

The growing commercial availability of optical dissolved oxygen (DO) sensors creates opportunities to explore DO and stream metabolism dynamics. However, it can be challenging to select the right sensor for a project or programme. The currently available sensors use differing hardware and software designs which affect their performance and data quality.

This chapter describes the sensors' basic operating principles, identifies key sensor methods, compares sensor hardware and software, summarises key sensor selection questions, and showcases the variety of deployments undertaken across Aotearoa New Zealand. Most DO sensor sites are unattended and visited on a monthly schedule, which means users need to plan preventative fouling management.

BACKGROUND

Obtaining information about water quality dynamics over short time scales (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) sensors can be deployed on site to measure indicators of interest (e.g., nitrate, dissolved oxygen) and can provide detailed insights into water quality dynamics at scales of interest (minutes to hours). However, these HFWQ sensor can create technical challenges, and unattended deployments can be resource hungry. HFWQ monitoring projects are most 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 optical DO sensor 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 how to select sensors for measuring DO saturation or concentration in-situ, at high frequency in rivers and lakes. 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 high-quality DO data using optical sensors.

RELATED RESOURCES

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

- The NEMS (National Environmental Monitoring Standards) for Continuous DO (NEMS, 2025, under review) guidance, which outlines data standards, data grades and an overview of field and office operating procedures. The NEMS Data Processing (NEMS 2023) guidance outlines office procedures for environmental time series.
- More detailed technical overviews of DO sensor technology used in environmental monitoring, which are available in review papers (such as Wang and Wolfbeis 2014, Wolfbeis 2015, Bittig et al. 2018, Werner et al. 2021).
- Sensor evaluation reports available at Alliance for Coastal Technologies (act-us.info). The 2016 DO evaluation included the PME miniDOT, HOBO U26, YSI EXO DO, JFE ARO, Sea-Bird HydroCAT, Hach Hydrolab and In-Situ TROLL 9000. For each evaluation there is an overall report which summarises the tests and deployments, and a report on each sensor's performance.
- Multiparameter sonde evaluations completed by USGS (such as Snazelle 2015, Snazelle 2017).
- Many useful documents support successful ocean operating systems and can be found at Ocean Best Practices (oceanbestpractices.org), Integrated Marine Observing System (imos.org.au), National Estuarine Research Reserve System (coast.noaa.gov/nerrs), Integrated Ocean Observing Systems (ioos.noaa.gov).

SENSOR SELECTION STEPS

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

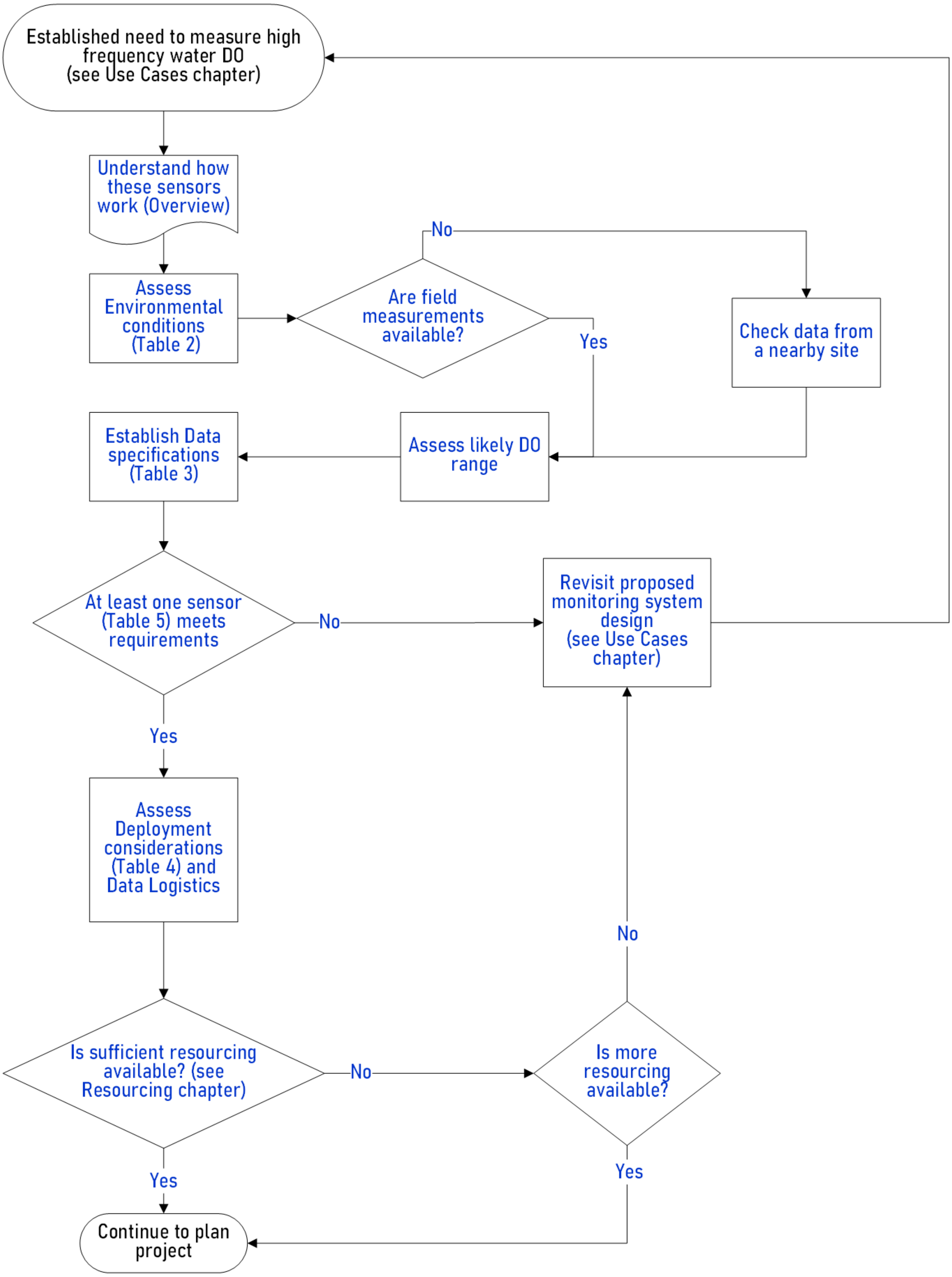


Figure 1. Suggested sequence of steps to guide optical DO sensor selection.

OPTICAL DISSOLVED OXYGEN SENSOR OVERVIEW

For environmental monitoring, optical DO sensors are superior to other DO sensing technologies (e.g., galvanic or polarographic sensors) because they (1) do not consume oxygen during measurements, (2) have good precision and accuracy, (3) have fast response times, (4) have high sensitivity at low DO, and (5) are simpler to maintain. An optical DO sensor normally consists of a light source, a luminescent dye in a matrix, a permeable membrane which lets oxygen interact with the dye, and a detector to measure the response.

Principle

Optical DO sensors operate on the principle of luminescence quenching. When the light source is turned on, it excites electrons in a dye which then release energy by emitting light (Figure 2). When dissolved oxygen collides with the excited electrons, the energy is transferred from the dye to the oxygen (Figure 2), resulting in a reduction in both the luminescence intensity and decay time. Quenching in optical DO sensors is a photophysical process, so it's fully reversible and does not alter the sensor.

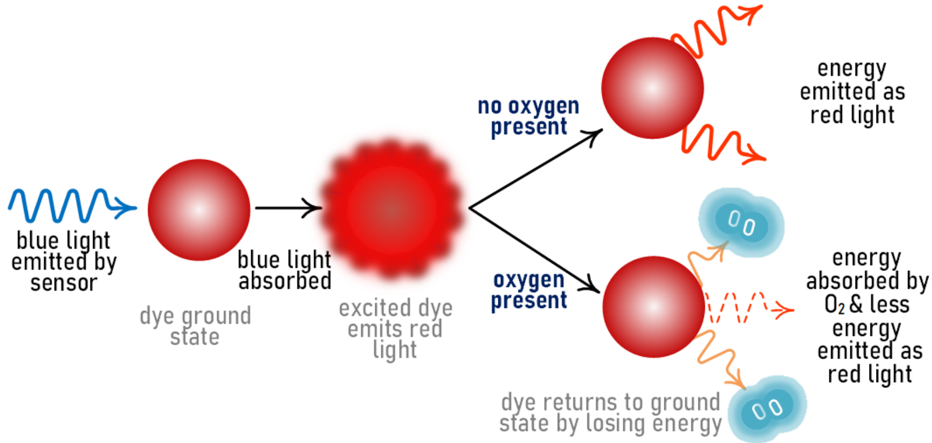


Figure 2. Luminescence sequence in the presence and absence of oxygen (after PreSens Precision Sensing GmbH, Regensburg, Germany).

Sensor design

While sensor materials vary between manufacturers, the basic optical DO sensor (Figure 3) consists of:

- a light source (typically a blue LED)
- a reference LED (typically a red LED)
- a luminescent dye suspended in a matrix (typically in a replaceable/serviceable cap)
- a protective layer, which is selectively permeable to oxygen
- fibre optic cables which transmit the light
- a detector to measure the red light returned from the sensing layer
- electrical circuitry to convert the detected signal to an electronic signal.

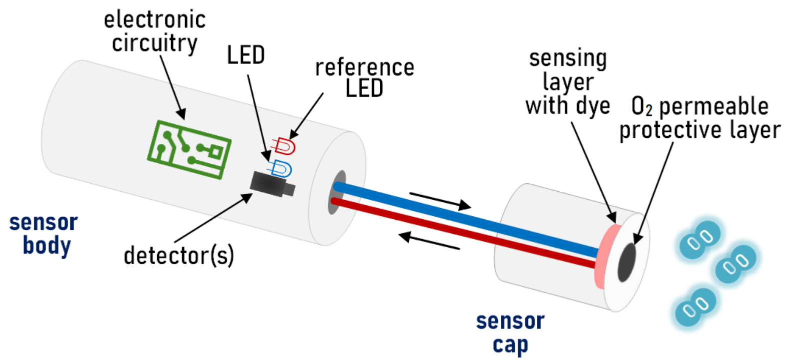


Figure 3. Generalised schematic of an optical DO sensor (with sensing layer in a cap) in the presence of oxygen.

The sensing layer is on the watery side of the optical window, and the light sources and detector(s) are inside the sensor body (Figure 3). Some sensors have their sensing layers (or foil) directly attached to the optical window, while other designs place the sensing layer in a replaceable cap. Sensor caps are used to simplify sensor operations; with care, users can replace the sensing layer easily in the field, and the manufacturer's calibration data for the individual sensor layer can be stored in a chip on the cap, making them 'plug and play'.

Light sources vary depending on the fluorescent dye used; most sensors use a light source with blue wavelengths (~380-500 nm), but some use blue-green (505 nm) light. Each dye requires a specific wavelength to luminesce, so the sensor light source must be tuned to the correct wavelength.

The choice of dye will determine the sensor's performance – a dye with a longer decay time makes it easier to detect the signal and to obtain stable readings. The luminescent dye in optical DO sensors may have fluorescent or phosphorescent properties. The glow of fluorescent dyes stops right after the light source is switched off, while excitation of phosphorescence dyes will result in an afterglow or light emission after the light source is switched off. Phosphorescence-based sensors have lower limits of detection than fluorescent sensors (Wang and Wolfbeis 2014).

Most sensors (or sensor caps) also have a protective or optical isolation layer which is selectively permeable to gases. This is to prevent naturally occurring luminescing materials in the water from interfering with the sensor operation. Some protective layers need to remain hydrated and require additional hydration caps containing wet sponges.

Often the dye used is not disclosed in DO sensor specifications. Commercial environmental DO sensors typically use three dye complexes – platinum or palladium porphyrin complexes, or ruthenium complexes (Wolfbeis 2015). Both platinum (II) and palladium (III) porphyrin complexes phosphoresce and offer good photochemical stability and longer decay times (Table 1). Ruthenium (II) complexes can fluoresce and/or phosphoresce depending on their chemistry, but they typically have moderate brightness and short decay times (Table 1). Some manufacturers use different dyes; for example, JFE Advantech use a transparent and luminescent acrylic resin (PMMA) on their RINKO DO sensor face (Bittig et al. 2014).

Table 1. Characteristics of widely used dyes in optical DO sensors (after Quaranta et al. 2012, Wang and Wolfbeis 2014, Wolfbeis 2015).

Dye complex	Stability	Decay time (µs)	Brightness
Platinum (II) porphyrin complex (PtTFPP)	photostable	long, typically ~60 µs	excellent
Palladium (III) porphyrin complex (PdTFPP)	photostable	long, around ~1000 µs	excellent with UV light, moderate with visible light
Ruthenium (II) complexes	fairly photostable	short, typically < 6 µs	moderate

The range of sensing layers (often called foils, dots or spots) used across the different sensor brands is small. Many of the latest generation of optical DO sensors use the PreSens PtS3 (requires 24 hours of rehydration from dry) or the WTW FDO foils.

The PreSens PtS3 foils are well researched by oceanographers (see Bittig et al. 2018). When new, they show significant drift during storage. They are more stable when deployed in the ocean but typically have negative drift, and they become more stable over time (unless mechanically damaged). The PreSens PtS3 has a standard black opaque protective layer over the pink sensing layer. When 'fast' response foils are required, manufacturers may remove the protective layer to reduce response times (see Bittig et al. 2014). Since 2018, white PreSens 'fast' foils have been available; they are less sunlight-sensitive and have are less noisy (for more details on foils see López-García et al. 2022).

Foils on some DO sensors are not robust enough to support the use of a wiper. For example, a shutter is the recommended fouling option for the D-Opto as the foil is too soft for wiper use. Fast foils are frequently not robust enough for wipers, although some manufacturers make wipeable fast response sensors. For example, the WTW FDO 701 foil has a PtTFPP dye and is designed to be robust against mechanical wear (i.e., the use of wipers) and has a long lifespan (10+ y) unless mechanically damaged (Aanderaa Data Instruments AS 2024).

There can be aging and drift in the sensor light source and electronic circuits, but most optical DO sensors have red reference LEDs to check for these factors. There are two common reference LED configurations: (1) the reference light is directed towards the sensing layer (see Figure 3), or (2) the reference light is directed at the detector. If the red reference light is directed at the sensing layer, the red light bounces off the dye layer and returns to the light detector (e.g., YSI EXO). When the red reference light is sent straight to the detector, the path it travels is the same length as that taken by the blue excitation LED light travelling to the sensing layer (e.g., WTW FDO, all Aanderaa sensors). Sensors that bounce the reference light off the sensing layer tend to have smaller diameters than those using an equal pathlength.

Original equipment manufacturer

There is a smaller pool of sensor technology than the number of sensor brands suggests, because many manufacturers purchase optical DO sensor technology from the original equipment manufacturer (OEM). These OEM purchases may be components ranging from a foil to a sensor head and circuitry (often called a puck) or a complete sensor. Some OEMs of optical DO sensor components include WTW, Aanderaa, In-Situ, InSite IG, Pyxis, Sensorex, PyroScience, Hamilton and PreSens.

Oceanographic sensor manufacturers (e.g., Sea-Bird, RBR, Aanderaa) generally disclose OEM purchases, and if they are the original manufacturer, they provide detailed technical information. However, manufacturers in the freshwater domain less commonly disclose OEM purchases. An example of an OEM purchase is Onset's use of In-Situ RDO Basic technology in the battery-powered internal logging HOBO U26 DO sensor. In-Situ also sell their RDO Basic, RDO-X and RDO fast technology to other manufacturers.

In the absence of information in brochures and manuals, careful examination of the sensor design and specifications including LED colour, diameter, presence of a cap, cap size, materials and registered trademarks will reveal commonalities between sensors. In addition, the OEM often advertises its optical DO sensor products and provides detailed information (particularly on light source specifications such as colours or wavelengths).

SENSING METHODS

Optical DO sensors measure the light intensity returned from the interaction between the light, dye and oxygen (Figure 2). Some sensors use luminescence intensity to calculate DO, while others use decay time (or lifetime) methods. Decay-based measurements are preferable to intensity-based methods because they avoid or minimise the effects of dye leaching, photobleaching (degradation of the dye), poor stability of the light source, and signal drift due to lamp or detector aging, stray light and background luminescence (Wang and Wolfbeis 2014, Bittig et al. 2018).

More detailed explanations of optical DO sensor design and operation can be found in Wolfbeis (2015), Bittig et al. (2018) and Werner et al. (2021).

Intensity-based methods

Intensity-based methods work by sensing the luminescence quenching after a short pulse(s) of light (Figure 4). The LED light is turned on and a pulse of light emitted before the LED is turned off. The intensity of the red photons recorded by the detector is higher without the presence of oxygen (Figure 4).

The single pulse intensity method does not require complex instrumentation. However, intensity changes can be influenced by a wide variety of factors (such as photobleaching/dye degradation, poor light source stability, stray light, drift in sensor sensitivity, background luminescence, non-uniform dye distribution in the sensing layer, etc.) which will alter the measurement.

To overcome some of these challenges, some manufacturers use a ratiometric method: two different dyes are used, one which is oxygen-sensitive and a reference dye. Both dyes are excited by the LED and oxygen is determined by measuring the ratio of the red light emitted by the two dyes. This method helps eliminate noise as the reference dye is also affected by noise (in the LED, detector, etc.) and increases the precision of the sensor (Werner et al. 2021). The reference dye must not be quenchable by oxygen, must be photostable in the presence of oxygen, and its emission spectrum should have little or no overlap with the oxygen-sensitive dye (Quaranta et al. 2012).

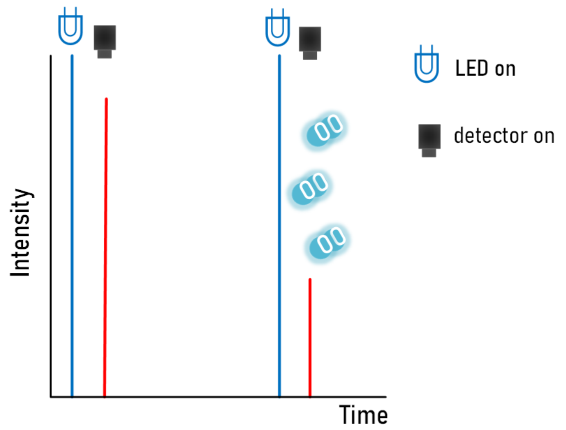


Figure 4. Simplified diagram of the intensity-based method with a short LED pulse and resulting intensity of a fluorescent dye. The first LED pulse and response are without oxygen, the second LED pulse shows the reduced intensity when oxygen is present.

Decay time-based methods

Luminescence decay time (or lifetime) methods overcome some of the key disadvantages of intensity-based methods. We use the term *decay* to clearly differentiate the concept from sensor *lifespan*. Decay-based measurements can be made in either the time domain or frequency domain. Time domain sensors measure the decay directly, while frequency domain sensors measure a phase lag. Both methods require modulation, i.e., the light emitted by the LED is varied. Time domain sensors are simpler to design but can be sensitive to stray light, depending on how the detector is operated.

Time domain sensors

Time domain sensors use a pulse of light and measure the resulting decay in luminescence. The method can use a single pulse or a series of pulses. There are several signal processing methods for calculating time-based decay time depending on the dye(s) and the timing and frequency of detector use.

The rapid lifetime determination (RLD) signal processing method is commonly used as it does not require complex instrumentation and can measure decay times in the range of 0.1 to 1 ms. In the RLD method, the LED is turned on and a short blue light pulse is directed at the sensing layer (Figure 5 A); some of the energy is absorbed and the dye starts to emit red photons. The dye in the sensing layer is excited until a steady state emission of red photons is reached and then the LED is turned off (Figure 5 A). Once the LED is off, the dye does not emit all the red photons at the same time, resulting in a decay curve. The decay time is calculated using the areas under the decay curve when the detector is operating (A_1 and A_2 in Figure 5 A) and calibrated against the oxygen concentration. With this method it's possible to eliminate the effects of background luminescence and any residual LED light (just after the LED turns off) by delaying the first detector opening (A_1). The RLD method is susceptible to interference from stray light, so sensors using this method should be shielded. By requiring users to shield a time domain sensor from stray light, a manufacturer can simplify its sensor and remove a filter between the sensing layer and detector.

When a time domain sensor does not require shielding from stray light, it uses an alternative signal processing method such as dual lifetime referencing (DLR). DO sensors using the DLR method have two dyes – the oxygen sensitive dye has a short decay time and the reference dye has a long decay time. DLR also measures two areas, but the first (A_1) is measured during the LED pulse and so measures the red photons from both dyes, while the second area only measures the reference dye (Figure 5 B). This method has a higher signal-to-noise ratio because the two measuring time intervals can be longer. However, sensors using DLR cannot separate out background luminescence and need a filter between the sensing layer and detector, which adds to manufacturing costs.

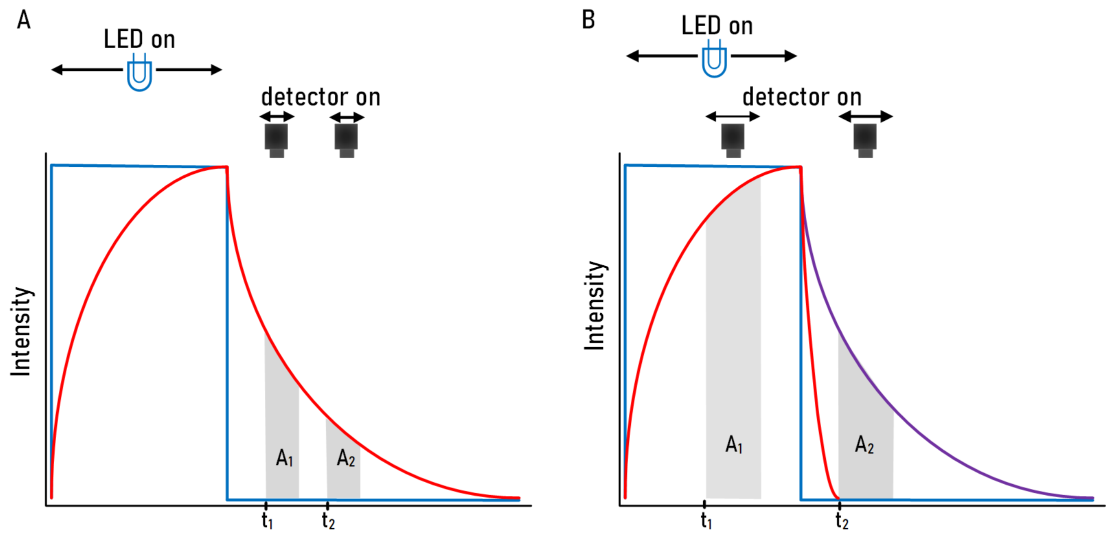


Figure 5. Simplified diagrams of decay time signal processing. (A) The RLD method with the LED pulse (blue) and resulting emission of photons (red) from the dye. The decay time is calculated using the grey areas (A_1 and A_2) under the decay curve (after Wang and Wolfbeis 2014). (B) The DLR method with A_1 measured when the LED is on and both dyes are emitting and A_2 on the decay curve of the reference dye (purple line).

Frequency domain sensors

Frequency domain-based sensors measure the phase shift between the modulated LED light and the resulting wave of red photons across several cycles. The LED emits a sinusoidal modulated wave made up of many individual light pulses (Figure 6 A) with different intensities. Different manufacturers may use different frequencies; for example, Sea-Bird uses 3840 kHz (0.00000026 s), while Aanderaa uses 5000 Hz.

In simple terms, the detector senses the light decay from the modulated wave, and the decay is determined by measuring the phase shift between the LED and detected red light. When dissolved oxygen is present, the phase shift is shorter (Figure 6 B) because more energy is emitted as red photons. For a more detailed explanation refer to Bittig et al. (2018). In the frequency domain there are also different signal processing methods depending on whether one or two different dyes are used. Sensors using two dyes measure the total signal, composed of emitted light from the oxygen-sensitive dye and the reference dye. Frequency-domain based sensors tend to have high signal to noise ratios and are typically less affected by scattered light.

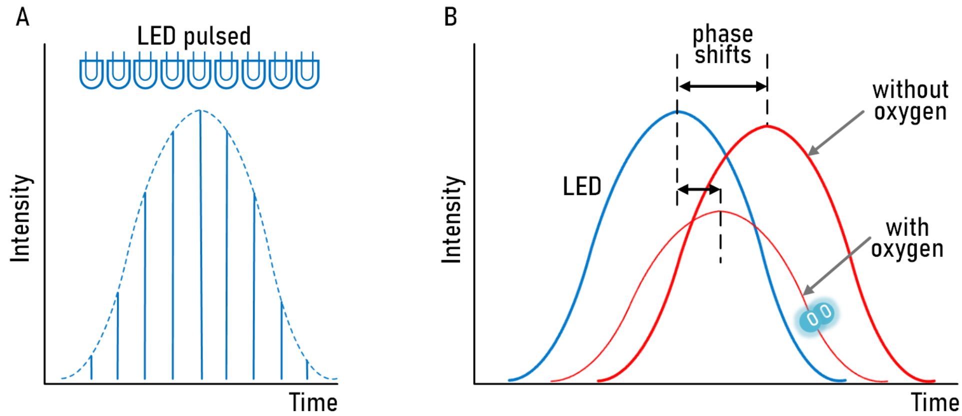


Figure 6. (A) Single light wave formed by a modulated LED pulsing at different intensities across one cycle. (B) Simplified diagram of decay frequency phase shifts without oxygen (wide red line) and with oxygen (thin red line) (after Bittig et al. 2018).

Comparison of sensing methods

DO sensor users should understand how the sensing and signal processing methods impact on sensor performance. Table 2 summarises the major strengths and weaknesses of the different sensing methods.

Table 2. Summary of the major strengths and weaknesses of different optical DO sensing and signal processing methods (after Werner et al. 2021).

Sensing method	Strengths	Weaknesses
Intensity	- No complex chemistry required - Low-cost instrumentation	-Significantly influenced by instrument drift, dye bleaching, interference from stray light - May be less precise
Ratiometric intensity	- Moderate instrument drift	- Complex chemistry (two dyes) - Complex instrumentation - Aging of two dyes (photo bleaching, photodecomposition) may differ, affecting calibration
Decay time RLD	- No complex chemistry - Robust method with single dye and no emission filter	- Requires a dye with long decay time - Susceptible to drift and stray light
Decay time DLR	- High precision - Self-referenced - Deals with stray light, background fluorescence, dye bleaching, instrument drift	- More expensive instrumentation - Two dyes with different decay times are required
Decay frequency	- High precision - Measures an average decay time - Deals with stray light, background fluorescence, dye bleaching, instrument drift	- Appropriate selection of dye(s) required - More complex chemistry

Converting sensor output to DO

The measured values need to be converted to an electronic signal which represents the DO concentration. While the relationships are ideal for the luminescing dyes in solution (grey lines in Figure 7), in the sensing matrix there is heterogeneity in both the dye and its matrix, and the thin layer hinders molecular motion, resulting in non-ideal behaviour (Figure 7).

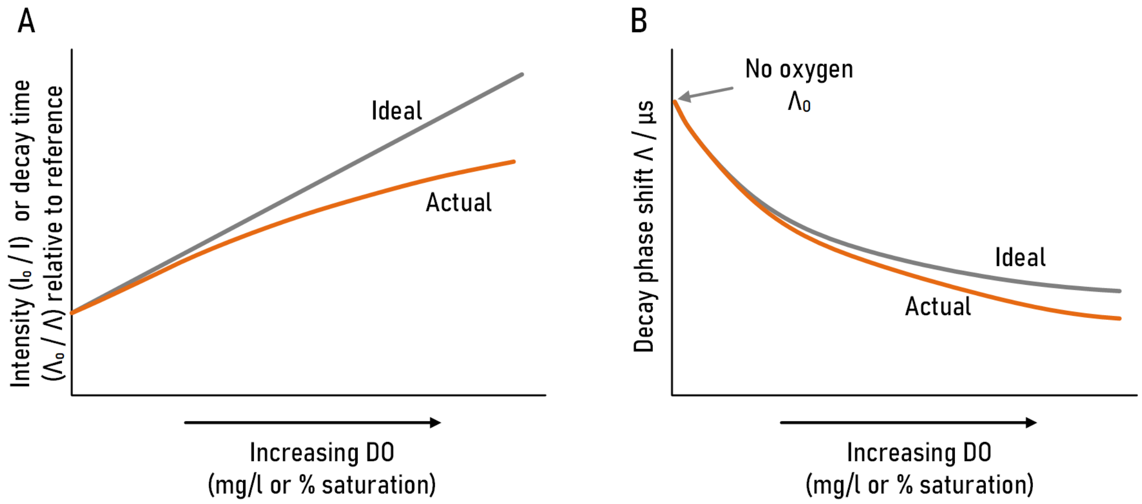


Figure 7. Generalised relationships between increasing dissolved oxygen concentration. (A) Stern-Volmer equation for intensity or decay time domain measurements, and (B) frequency domain decay phase shift relationship. The actual behaviour departs from the ideal (after Bittig et al. 2018).

Both the change in intensity and time-based decay time are correlated with the DO concentration (Figure 7 A) via the Stern-Volmer equation:

$$\frac{I}{I_o} = \frac{\Lambda}{\Lambda_o} = 1 + K_{SV}[O_2]$$ **Equation 1**

Where: I is the measured intensity in the presence of oxygen, I_o is the reference intensity (no oxygen), Λ is the measured decay time in the presence of oxygen, Λ_o is the reference decay time (no oxygen), K_{SV} is a property of the luminescent dye and $[O_2]$ is the DO concentration in the water (gaseous or dissolved).

The Stern-Volmer equation is not valid for decay time frequency phase shifts, and the relationship between DO and phase shift is non-linear (Figure 7 B).

DISSOLVED OXYGEN UNITS

DO sensors typically output values as a weight/volume metric (e.g., mg/l) or as a percentage saturation (% sat). The saturation of oxygen in water is a function of temperature, salinity and pressure, so these parameters are required to convert between mg/l and % saturation or vice versa.

Several useful tools for understanding and completing unit conversions include:

- ICES calculator Oceanographic Calculator (ices.dk)
- R package respR (available on The Comprehensive R Archive Network cran.r-project.org)

% saturation

DO saturation (DO%) is the ratio of measured DO concentration relative to DO solubility (or theoretical saturation value) at the temperature, pressure and salinity of the sampled water (Equation 2).

$$\% \, saturation = \frac{DO \, concentration}{DO \, solubility} \, x \, 100$$

Equation 2

The % saturation is usually calculated onboard the sensor using the concurrent temperature measurement. A range of equations are used for calculating DO solubility (see Rounds 2011). Oceanographic sensors are more likely to offer users a selection of solubility equations, but most sensors do not offer a choice.

Concentration units

A range of concentration units are used in HFWQ monitoring and sometimes unit conversions require conversion and/or correction factors. Mass concentration (mass per unit volume, SI unit kg/m³) is commonly used in freshwater environments, but the units used are mg/l. Oceanographic sensors offer a wider range of concentration units, including molar concentrations. Molar concentration is the amount of a constituent (in moles) per unit volume, and while the SI unit is mol/m³, units of µmol/l are common. To convert between mass concentration and molar concentration, a conversion factor is used; the molar weight of oxygen is 31.998 g or 0.031998 mg, so 3.2 mg/l is equal to 100 µmol/l. This conversion does not require correction factors. Other unit conversions, such as mg/l to ml/l, require both conversion and correction factors.

Other units

Other units, including raw engineering values, are available on some sensors. Oceanographic sensors tend to output engineering units such as phase shift (µs), or phase amplitude (mV) and phase measurement (°). They may also output partial pressure. Partial pressure is the pressure exerted by any gas among a mixture of gases. To convert from DO partial pressure to DO concentration, the correction factors are required. The sensor manufacturer should supply details on units and unit conversions in the sensor manual. In many cases, additional information (such as technical notes, white papers or application notes) is available to support sensor users.

SENSOR PERFORMANCE

The performance of an optical DO sensor in the real world is determined by many factors, including:

- the sensor method and its challenges (which may include stray light interference, dye leaching, signal and lamp aging, slow response times, etc.)
- instrument noise (fluctuations in lamp, detector and circuitry)
- poor temperature sensor performance
- environmental factors (e.g., temperature, salinity, barometric pressure, fouling).

Sensor operations

Our experienced users identified sensor method and poor temperature sensor performance as factors to consider when selecting sensors. The different sensor methods and the consequences of selecting one method over another should be assessed. In addition, temperature sensor specifications should be checked. If the temperature sensor performs poorly, the DO values may be incorrect because the temperature value determines the DO solubility in Equation 2. Consult the Temperature Sensor Selection chapter for more details on electrical thermometers.

Manufacturer specifications for DO sensors may not reflect sensor performance in natural waters because: (1) they are the results of lab testing, (2) response times may be in air rather than water, (3) the accuracy might have been assessed immediately after calibration, (4) the accuracy might be for a limited concentration range, and (5) the specifications do not include the challenges of unattended monitoring (predominantly biofouling).

Most sensor testing and real-world performance research of optical DO sensors is conducted by oceanographers who face additional challenges, such as low DO concentrations, decreasing dissolved oxygen concentration and increasing pressure with depth, validation of gliders, and rapid profiling to vast depths. A useful resource is the Alliance for Coastal Technologies DO sensor evaluations conducted in 2016 (see Related resources section).

Environmental factors

Our experienced DO sensor users identified numerous environmental factors which affect DO sensor performance; some of these are deployment challenges. Challenges include:

- fouling by macrophytes, algae (including in/on sensor housing), invertebrates (particularly in coastal environments) and fish eggs
- bubbles
- correction factors – temperature, salinity and pressure
- debris accumulation or mobile bed sediment
- abrasion of sensor lens by gravel
- pollution
- tidal effects.

Fouling

Fouling is often the single biggest factor affecting the operation, maintenance and data quality of in-situ sensors. Even a slight buildup on the sensor head will degrade the sensor's ability to return high quality, representative values. Biofouling can coat sensor windows (see Figure 8) or intermittently sit on the optical head, causing drift and altering the response time, which in turn causes the sensor to return unreliable values. If fouling is in the form of algae that produce or consume oxygen, the measurement might not correctly reflect the oxygen concentration in the surrounding water (see Case study 1 – Fouling impacts on DO values).

Fouling is not standard; it's local, can vary through time, and is the result of many physical, chemical and biological factors. Fouling development will depend 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.

[Hamish Carrad, ECan] [Hamish Carrad, ECan]

[Emily Olson, ORC] [Hamish Carrad, ECan]

Figure 8. Fouled DO sensors. (A) Heavily fouled In-Situ RDO Pro-X with macrophyte-filled wiper brush. (B) Heavy fouling on a ZebraTech D-Opto logger in a highly productive stream. (C) Lightly fouled In-Situ RDO Pro-X. (D) Macro-fouling on an In-Situ RDO Pro-X in a coastal lagoon.

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

1. Adsorption of organic and inorganic molecules immediately after immersion, forming the primary film (1 min to 1 hour).
2. A more complex film develops after bacteria attach and an extracellular matrix develops (in 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 1 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 1 week.

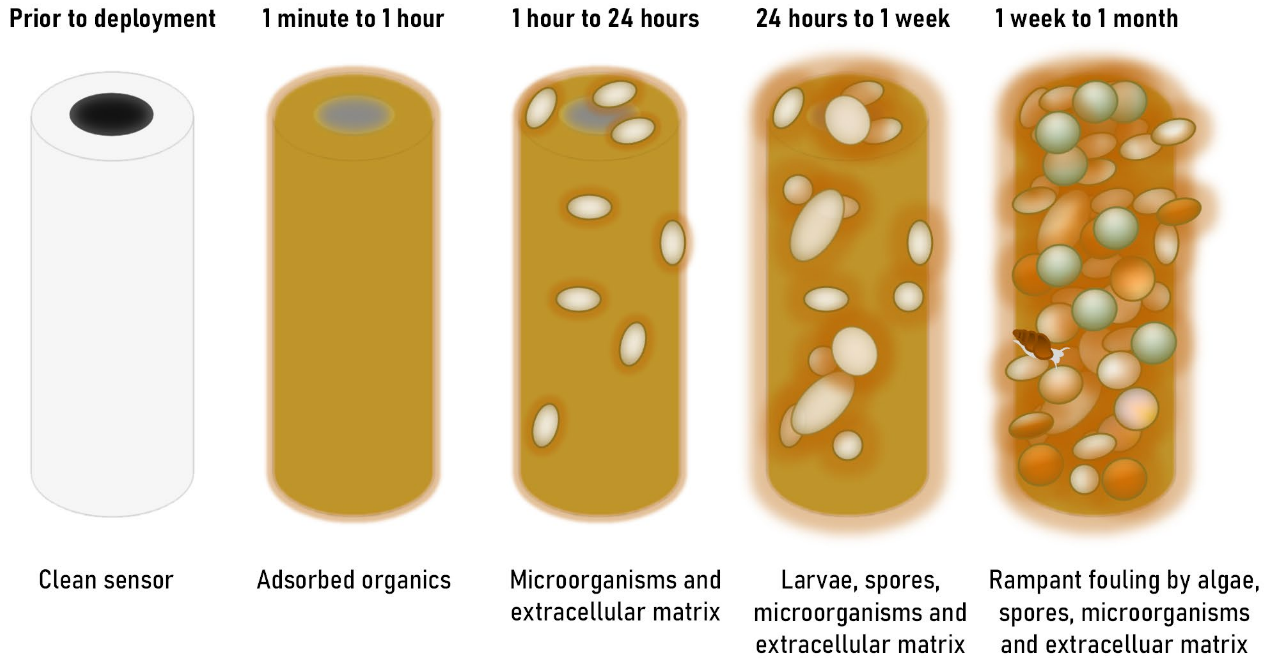


Figure 9. Simple illustration of the stages of biofouling. Each of the stages can occur in the order described, or in parallel or all at the same time (after Chambers et al. 2006).

See the Fouling Management section for more information on preventative steps to manage fouling. 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).

Bubbles

Bubbles can also create noise in the sensor signal as they pass across or adhere to a sensor face. Bubbles on a sensor face can elevate values as the oxygen partial pressure in the bubbles is higher than the dissolved level in the water. There are several approaches for combatting bubbles:

– select a sensor with an angled face (e.g., WTW FDO), which is less likely to catch bubbles

– select an installation angle that prevents bubbles from gathering on the sensor face

– cycle the wipers or shutter before the reading to brush off the bubbles from the face of the instrument.

Correction factors

Temperature, atmospheric pressure and salinity determine the amount of oxygen that can physically be dissolved into the water.

– With increasing temperature, the amount of oxygen that water can hold decreases. Cold water has slow-moving molecules and holds more dissolved oxygen than warm water. As water heats up, the molecules within it move faster, pushing some of the free oxygen atoms into the atmosphere, so the water holds less oxygen.

– Over recent geological time, oxygen consistently makes up 20.9% of the atmospheric volume. The number of atmospheric oxygen molecules interacting with a body of water increases with barometric pressure, thereby increasing the amount of oxygen dissolved in the water.

- Salinity also effects oxygen saturation – seawater holds about 20% less oxygen than freshwater at the same temperature and barometric pressure. For example, saturation DO at 15 °C in seawater is 7.9 mg/l compared with 10.1 mg/ l in freshwater.

So when measuring DO, key correction factors include: (1) temperature, (2) barometric pressure, and (3) salinity (where applicable). All optical DO sensors measure temperature, and some may also measure atmospheric pressure and/or salinity.

Temperature increases also affect sensor responses. Multiple factors – both environmental and sensor operations – change with temperature (see Bittig et al., 2018 for a more technical summary). An increase in temperature:

- reduces the decay time of the excited state (i.e., both Λ_0 and Λ are reduced)
- increases the efficiency of quenching because of increased oxygen diffusion
- decreases the oxygen solubility, which reduces quenching.

The overall effect of these *partially counteractive influences*, however, is an increase in quenching and a reduction of decay with rising temperatures. These principles are universal for all optical DO sensors.

Atmospheric pressure varies with altitude and the passage of weather systems. Many instruments do not measure barometric pressure, so a correction is needed using data from a local weather station or barometer (refer to NEMS DO (2025) for details).

Seawater oxygen solubility is a function of salinity, so in saline environments salinity must be measured to ensure accurate DO measurement. Salinity is important for the conversion of measured partial pressures to DO concentration; it does not affect the sensor operations. Sensor membranes are only permeable to gases (N_2, O_2 and water vapour) and are not permeable to salts.

CHOOSING A SENSOR

Many different DO sensors are used by regional councils. Workshop participants were asked to nominate their preferred DO sensors, sensors they had stopped using, and features they consider when selecting a sensor. Experienced users typically have a few sensor models in their fleet and select an appropriate sensor for each application. Most regional councils limit their fleets to 2 to 4 sensor brands to simplify operations. As optical DO sensor technology has evolved, some regional councils have upgraded their sensors and their current sensor fleets have decay-based sensors. In some regions, the intensity-based D-Opto sensor works well as part of their monitoring programmes.

The workshop participants' preferred sensors were not always their ideal sensor, due to historic purchasing choices and current resourcing constraints. The range of preferred sensors covered all the sensors compared in Table 6. A key selection factor was the data retrieval method – telemetry or internal logging. For short-term or low-cost projects, internal logging is often used, while for long-term installations, sensors which can pair with a logger are preferred (see Internal logging and telemetry section).

Another key factor in sensor selection is whether a combination of indicators are required for a site; sometimes a multiparameter sonde or custom sensor package is required to meet the project's data needs. Creating custom sensor packages might be technically challenging, but it may be a cost-effective option if: (1) the project requires fewer indicators than a multiparameter sonde, (2) specialist sensors (e.g., algal fluorescence sensor(s)) are required with DO, or (3) the project requires a backup DO sensor on battery power (e.g., In-Situ RDO-ProX telemetered and HOBO U26 with internal logging). With careful design it is possible to attach a single third-party wiper to a custom sensor package if the sensors selected have flat faces.

For coastal waters, a robust antifouling system (e.g., Sea-Bird CTD with SBE 63 DO sensor uses a biocide) is a critical sensor selection consideration. In estuaries and coastal waters, pumped CTD systems with biocides can be left unattended for 2–3 months, while instruments with exposed sensors (e.g., sondes with wipers) require monthly maintenance.

To select the best sensor for an application, experienced users recommend considering (in no particular order):

- ease of use
- reliable and repeatable (allowing swaps without a step change)
- replaceable DO cap or foil with a long lifespan
- software with a good user interface for calibration and deployment settings
- robust antifouling system (e.g., wiper, biocide) or ability to add a third-party wiper

- cost effective (particularly standalone sensor with built-in loggers)
- tough, durable and easy to clean
- internal logger (either as a primary or backup logger)
- appropriate DO response time
- temperature sensor accuracy and fast response time (refer to Water Temperature Sensor Selection chapter for response time definitions)
- coupled with other parameters (e.g. a sonde or CTD) for ease of data management.

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.

- Use sensors which are not sensitive to ambient light.
- Understand the impacts of biofouling on sensor performance.
- Plan for fouling – use wipers and other biofouling tools.
- Create a realistic maintenance schedule so that biofouling is caught early and 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
- Manage biofouling on the sensor body and housing to reduce the chance of filamentous algae or similar interfering with measurements. Large brushes (search tube or milk line brush) can efficiently and effectively clean inside sensor housing pipes.
- Manage macrophyte growth around the sensor so that plants do not alter the local DO or cause sedimentation near the sensor.
- Check the sensor foil or lens cap carefully as chemical films can build up slowly over time. Check your sensor's manual for suitable cleaning solutions (these are sensor-specific).
- Ensure technicians are well-trained to calibrate and maintain sensors.
- In rivers, site design is critical to reduce sediment and debris build up. Take care installing the sensor to ensure it is in flowing water to reduce sedimentation.
- In highly productive estuaries, use oceanographic sensors with multiple antifouling systems.

KEY QUESTIONS TO CONSIDER

Each optical dissolved oxygen sensor should be considered against the monitoring objectives and deployment requirements. Key questions are grouped into Environmental considerations (Table 3), Data specifications (Table 4) and Deployment considerations (Table 5).

Environmental considerations

Table 3. Environmental conditions: Considerations and challenges to help guide sensor selection.

Key questions	Consequences	Possible solutions
What is the expected DO range?	- Sensor may not have required range or sensitivity.	- Select a sensor that spans the range of interest (where possible). - Freshwater environments with lots of plant or algal growth may cause large DO swings. The marine environment may require more sensitivity and a lower limit of detection. - For waters likely to become super-saturated (> 100% saturation), consider selecting a sensor/sensor cap which is factory calibrated and can be reset to the factory calibration. Factory calibrations typically include > 40 points over a wide range (see Table 6).
How rapidly will the DO change?	- Sensors may have an excessive response time and values may not represent DO change well.	- Check the response time. If the DO can change rapidly (e.g., downstream of a discharge), a short response time sensor will be required.
What is the maximum depth?	- Damage due to lack of sensor water tightness.	- Check maximum sensor depths (see Table 6) to ensure the sensor housing will withstand the pressure. On a sonde or CTD, also check the pressure rating of any pressure transducer. - Check if the cable can be extended by the user or must be returned to the manufacturer (see Water Temperature Sensor Selection chapter).
What is the minimum depth?	- Data gaps if sensor is not submerged.	- Check if the sensor foil needs to be stored in a moist environment (see Table 6 or check the manual). If a sensor should always capped or requires a moist sponge during storage, the foil may be damaged by exposure to air. - For sensor foils which can be stored dry, the foil may take time to hydrate once immersed in water again (see Table 6 or check the manual).
How will you manage fouling?	- Data loss. - Unknown data quality.	- Check if the sensor can be wiped. Some sensing layers/foils should not be wiped – particularly fast-response sensors. - More detailed guidance on managing fouling is available in the Fouling management section of this document.
How robust is the sensor?	- Sensor damage from vibrations or knocks.	- Use a sensor with a thermistor which can withstand knocks and vibrations.
Is the environment corrosive?	- Sensor damage.	- Plastic or stainless-steel materials are good for freshwater applications; consider titanium for brackish/ocean water to reduce corrosion.
What correction factors are required?	- Missing or inadequate correction data.	- In freshwater environments, temperature is the key correction factor. Local barometric pressure would ideally be available too. - In marine environments, temperature and salinity must be measured alongside DO (by a multiparameter instrument or independent EC sensor). Check if the sensor software can also process the salinity correction.
Will abrasion be a problem?	- Sand or pumice may damage the window.	- Use protective housing to reduce the water velocity near the optical window.
Are bubbles likely at the site?	- Bubbles from sediment decomposition may bias the values.	- Use a sensor with a wiper or fit a wiper to remove bubbles before each measurement. - Consider a horizontal mounting.

Data specifications

Table 4. Data specifications: Considerations and challenges to help guide sensor selection.

Key questions	Consequences	Possible solutions
What performance is required?	- Data will not meet requirements for decision-making.	- Check DO sensor performance specifications, such as range, accuracy (precision and bias), resolution (level of detail), limit of detection (lowest concentration) against project requirements. - Check the electrical thermometer specifications.
What is the required response time?	- DO data may not meet required specifications. - Temperature data may not meet required specifications. - Longer response times.	- Check the DO response time information carefully to ensure the sensor has the desired response time. Take care to understand the terms used, for example, T63 (or time constant or tau) is the time taken for a sensor signal to rise to 63% of its final value after an abrupt change in measuring conditions (see Water Temperature Sensor Selection chapter for more details on response time definitions). - Check the response time of the electrical thermometer. If the thermometer is thermally buffered, the DO and temperature measurements might not be concurrent.
Are real-time data required?	- No real-time data available for decision making.	- Choose a sensor which can be connected to a logger with telemetry.
Is burst sampling (short period of many values) required?	- Data might not meet required temporal resolution.	- Use a sensor capable of delivering a short response time. This might be a version with a fast membrane (e.g. RBR |fast or In-Situ RDO fast) or a software setting (e.g., YSI EXO rapid).
What is the required observation interval?	- Sensor might not be able to provide data at required interval.	- Check observation interval exceeds sensor measurement interval. - Check the sensor warm-up time if the sensor is turned on and off. Some sensors can take a while to warm up if they have been powered off between measurements (e.g., EXO DO takes ~70 s in this mode).
Is averaging user-controlled?	- Smoothed data may look good but might preclude measurement of extremes.	- Check how sensor averaging works and the ability of the user to fully configure averaging. On some sensors you can turn averaging off, while on others all data is averaged.
Does the sensor & logging system have the required performance?	- Loss of data resolution.	- Check the performance of the combined sensor and logger system prior to deployment. Most new loggers will have 16 or 24-bit ADC on the analog channels, but if you're using an older model, check the ADC convertor specifications.
Are data gaps acceptable?	- Consequences for analysis, particularly if large periods are missing or poor quality.	- If a complete record is required, compare the resourcing required for telemetry and rapid troubleshooting versus operating a backup sensor. A backup sensor would ideally be adjacent to the primary sensor.
What metadata does the sensor provide?	- User unaware of sensor faults or maintenance required.	- Check the sensor outputs. Some sensors will output metadata to assist with sensor operations (e.g., PME miniDOT Q value, HOBO U26 cap expiry countdown). - If the sensor has a built-in wiper, also check if metadata on the wiper's park position or similar is available to use in data processing.
Is the site short-term?	- Resourcing may be limited.	- Consider using a sensor with internal logging after assessing the risk of data loss.
Is the site a long-term operation?	- Sensor may need replacing.	- Consider resourcing & availability of replacement sensors. If possible, select a sensor which has user-replaceable caps or can be serviced locally (NZ/AU). Some sensors must be sent overseas for servicing, so if data gaps are not acceptable an extra sensor may be required. - Consider telemetry to ensure data loss risk is minimised and troubleshooting is prompt.

Deployment considerations

Table 5. Deployment considerations: Considerations and challenges to help guide sensor selection.

Key questions	Consequences	Possible solutions
How will you access the sensor across the range of environmental conditions?	- Poor access may make download of data from a sensor with onboard logging difficult.	- Consider if access to the sensor is required during high flows. One option is to select a telemetered sensor so you can frequently check the data continuity and quality. - If you plan to use a sensor with a cable, select a sensor model/option with a waterproof connector so it's simple to disconnect the cable from sensor for annual checks, inspections or replacement.
How long will it take to deploy the sensor?	- Resourcing overspend.	- A DO sensor with onboard logging can be deployed quickly. In contrast, connecting a sensor to a logger may require more checks and steps.
Does the sensor have user-replaceable caps?	- Ongoing resourcing required to purchase caps. - Cost of returning sensor to manufacturer for servicing.	- Consider the sensor maintenance costs across the lifespan. - Evaluate the cost, availability, shelf-life and lifespan of user-replaceable caps. - Estimate the cost of returning the sensor to the manufacturer for servicing/foil replacement.
Is there existing site infrastructure?	- Time and resources required to install a new site.	- If no housing or logger are available, select a sensor with sufficient internal memory (with redundancy in case the sensor cannot be accessed).
What is your anticipated site visit schedule?	- Fouling may cause sensor drift. -Data loss if the sensor has a fault.	- If the sensor does not have a wiper, frequent (weekly or fortnightly) site visits may be required.
Do you have the technical expertise to manage the sensor?	- Incorrect calibration will bias values.	- Careful calibration is required. Errors may result in data gaps. - Some sensors cannot be calibrated but DO values should be validated.
Availability of sensors in stock in New Zealand?	- Data gaps.	- Consider if you can source a replacement sensor at short notice.
How user-friendly is the software interface?	- Discouraged technicians and more time spent setting up & downloading sensors.	- Check the software interface (and experienced user comments about software interfaces in Table 6). - Check the format of downloaded data. Is it text, csv or a proprietary format? (see Table 6).
Is the calibration data stored on the sensor or sensor cap?	- Sensor parts might not be plug and play.	- Check where the calibration data is stored. Managing sensors that have caps with embedded chips can reduce the opportunity for user error.

SENSOR COMPARISON TABLE

Table 6. Qualitative assessment of optical DO sensors used by the workgroup (in 2023) (arranged alphabetically). At least one sensor user contributed to each column. All costs in NZD. See notes below table for detailed additional comments on each sensor. To evaluate a different sensor, gather equivalent information from brochures, manuals, manufacturer and other users.

Feature	HOBO U26	In-Situ Aqua TROLL 600 [a]	In-Situ RDO-ProX	PME miniDOT	RBRduet³ T.ODO |slow	Sea-Bird SBE 63	WTW FDO 700	YSI EXO sonde	ZebraTech D-Opto
Cost ($ < 3K, $$ 3 - 5K, $$$ 5 - 10K, $$$$ > $10K)	$	$ (+ $$$$ sonde & wiper)	$$	$$ (wiper $$)	$$$$	$$$$ (+SSSS CTD)	$$$ (with controller)	$$ ($$$$ sonde & wiper)	$$/$$$
Sensor basics									
OEM (if known)	No - In-Situ RDO	Yes	Yes				Yes	Yes	No - InsiteIG
Type - Intensity (I) or decay (D)	D-Freq	D-Freq	D-Freq	D-Time and I [p]	D-Freq	D-Freq	[w]	D-Time	I
Versions available (e.g. fast)	No	Yes[at], RDO-X. Fast caps available	Yes, RDO-X. Fast & Classic available	No	Yes, use |slow for moorings [r]	No	Yes, M and FW. Cap versions [w]	No - software options	Sensor: cable, Logger: battery
Light colour	Blue	Blue	Blue			Blue	Green	Blue	Blue (475 nm)
Luminescent sensing layer	PreSens PtS3	PreSens PtS3	PreSens PtS3		PtOEP [r]	PreSens PtS3	WTW FDO 700		Ruthenium (II)
Hydration required	No	No	No	No [p]	Yes - 5 days	No	Yes - 5 days	Yes, 24 h [e]	No
Thermistor location	Internal	External	External	Internal	External	Internal-pumped	Internal	External	External
Replaceable cap/ cap lifespan	Yes, 7 mo	Yes, 1 y	Yes, 1–2 y	No	User replaceable foil	No	Yes, 3–5 y	Yes, 1 y	No
Cap shelf life & warranty	2 y/1 y	No limit/2 y	3 y/2 y	–		–	?/6 mo	no limit / 1 y	–
Calibration coefficients on cap	Yes	Yes	Yes	–	No	–		No	–
Factory calibration procedure		90 pt (0–600% sat)	90 pt (0–600% sat)	96 pt (12 DO x 8 temp)	49 pt, 1.5-30 ° C, 0-120% sat	24 pt (4 DO and 6 temp)			
Sensor metadata		Abrasion warning	Abrasion warning	Q value [p]					
Face angle	flat	flat	flat	flat	45 °	flat but internal	45 °	flat	flat
Durability with field use (H, M, L) & lifespan	High	High, well protected.	High, some ~8 y [x]	High, 5+ y		High – 10+ y	High, 10+ y sensor, ~5 y controller	High, 12+ y	Medium-High; some ~10 y [z]
Dimensions (cm)	4 x 26.7	Sonde: 4.7 x 46/60	4.7 x 20.3	5 x 18.7	3 x 31	Total dimensions depend on CTD	4 x 40	EXO2: 7.6 x 71.1	4.8 x 15/20
Max depth (m)	100	100–250	100	300	6000	600 or 7000	100	250	30
Data logging	Internal	Both[at]	External	Internal	Both	Both	External	Both	Either
Minimum log interval	1 min			5 s	|slow 30 s	1 s		Many options	Logger: 1 min, Sensor
Power options	Battery	Cable & battery	Cable	Battery	Battery	Battery	Cable	Cable & battery	Cable or battery
Battery life (if applicable)	3 years (at 1 min)	6+ mo	–	2–3 mo (see manual)	Estimated in Ruskin [r]	3–6 mo	–	EXO2: 3 mo	3 mo, 15 min logging
Data transfer & cable options	USB with shuttle	Cable, Bluetooth, WiFi. Screw cap connector [at]	Cable, 10 m [x], fixed or connector	USB	USB	Connects to Sea-Bird CTDs	Cable & controller	Cable (many options), Bluetooth	Cable, up to 100 m, user specified
Communications	USB	SDI-12, RS-485 Modbus	RS-485 Modbus, SDI-12, 4–20 mA	USB	USB-C	Depends on CTD, SDI-12 or RS-232	Analog 4-20 mA or RS-485 Modbus	SDI-12 via DCP, RS-232, RS-485 Modbus	Logger: serial cable Sensor: 4–20 mV, SDI-12[z]

Feature	HOBO U26	In-Situ Aqua TROLL 600 [a]	In-Situ RDO-ProX	PME miniDOT	RBRduet³ T.ODO |slow	Sea-Bird SBE 63	WTW FDO 700	YSI EXO sonde	ZebraTech D-Opto
Sensor specifications									
DO range	0–30 mg/l	0–60 mg/l	0–60 mg/l	0–150%	0–120%	120%	0–20 mg/l, 0–200%	0–500%, 0–50 mg/l	0–250% [z]
DO resolution	0.02 mg/l	0.01 mg/l	0.01 mg/l	0.01 mg/l	<0.04 %	0.2 umol/kg	0.01 mg/l, 0.1%	0.1 %, 0.01 mg/l	0.01%, 0.001 mg/l
DO accuracy (precision and bias)	<0.8 mg/l: ±0.2 mg/l. 8–20 mg/l: ±0.5 mg/l	0–20 mg/l: 0.1 mg/l	0–20 mg/l: 0.1 mg/l 20–60 mg/l: 2%	max of ± 5% or ± 0.3 mg/l	max of ± 2 µmol/l or ± 1.5%	0.1 mg/l or ± 2%	< 1 mg/l ± 0.05 mg/l; >1 mg/l ± 0.1 mg/l	0–20 mg/l: ± 1% value or 0.1 mg/l [e]	max of ± 1% value or 0.02 mg/l
DO dynamic response	T90 < 120 s	T63 < 15 s, T90 < 30 s, T95 < 60 s	T90 < 45 s, T95 < 60 s @ 25 °C	T63 30 s	T63 < 30 s	T63 < 6 s @ 20 °C	T90 < 150 s @ 25 °C; T95 < 200 s [w]	T63 > 5 s	T95 < 60 s
Temp type	Thermistor	Thermistor	Thermistor	Thermistor	Thermistor	See CTD specs	Thermistor	Thermistor	Thermistor
Temp range (°C)	-5 to 40	-5 to 50	-5 to 50	0 to 35	-5 to 35	See CTD specs	-5 to 50	-5 to 50	0 to 50
Temp accuracy (°C)	0.2	± 0.1	± 0.1	± 0.1	± 0.002	See CTD specs	± 0.5	-5 to 35: ± 0.1	± 0.1
Temp resolution (°C)		0.01	0.01		<0.00005	See CTD specs	0.1	0.001	0.01
Temp dynamic response	T90 < 1800 s	T63 < 2 s, T90 < 15 s		300 s	T63 < 1 s	See CTD specs		T63 < 1 s	T63 < 60 s
Units available	mg/l; % sat (with Pro license)	mg/l, % sat	mg/l, ug/l, % sat, atm, torr	mg/l, % sat	phase, umol/l, % sat	raw phase delay & converted units	mg/l, % sat	mg/l, % sat	mg/l, % sat
User experience									
User calibration possible	Yes	Yes	Yes	Yes - from 2024	Yes	No	Yes	Yes	Yes
Ease of calibration (see notes for issues)	Easy	Easy	Easy	New procedure	Easy, foil needs to be hydrated.	NA	complex - no software interface	Easy	Basic software, needs regular calibration [z]
Antifouling options & performance	Can use copper wire to prevent fouling. Has a protective guard which prevents wiper use.	Central wiper. Wiper slip clutch is good. Wiper struggles with rampant fouling.	No wiper, easy to fit a ZebraTech wiper	Copper ring around lens or [p]	Not wiped. RBR recommend ZebraTech wiper for |slow.	CTDs use in-line pump and biocide which keep sensors clean for several months.	Manual cleaning. Foil should not be mechanically wiped.	Good central wiper. Can use copper tape. Wiper provides basic metadata [e]	Copper ring to reduce fouling. Foil not suitable for wipers. Users do not recommend shutter.
Software	HOBOWare	VuSitu App, Win-Situ 5	Win-Situ 5, CommKit required to use PC	3 bits of software that can be clunky	Ruskin. Python toolbox pyRSKtools	SeaTerm and SeaSoft [s]	Through controller interface	Kor/Kor2	Sensor: D-OptoCom Logger: D-OptoLog
Software user friendliness	Good. Advanced features require a license	Good. App easy to use	Good. App easy to use	Good; multiple steps to get into CSV format	Good	Advanced software [s]	No wizard or UI. OK once you know how controller works	Good	Simple, dated
Data format	.hobo to .csv			.csv				.bin to .csv	.dat [z]
Warranty	1 y	2 y	2 y	1 y	1 y [r]	5 y	2 y	2 y	1 y
Documentation and trouble shooting	OK, limited for trouble shooting.		Manual good. OK software manual.	Good	Good	OK		Good	Manual dated, easy to read
Support	Good online support docs. NZ support not great.	Supplied by Thermo Fisher Scientific in NZ.	VanWalt supports. Supplied by Van Walt & Thermo Fisher Scientific.	Australian based distributors. Serviced in USA.	Australian sales or service in Canada.	No NZ sales rep, closest in AUS, or directly via USA [s]	ENVCO.	ENVCO in NZ. Xylem NZ, also AU & US. [e]	ENVCO sell & service.
Free online training	Videos	Videos, tech notes	Videos, tech notes	Tech notes	Application notes, webinars	Sea-Bird University, application notes		YSI University, tech notes, webinars	

Table 6 Notes:

[at] In-situ Aqua TROLL notes: (1) Two models available: Aqua TROLL 500 cable power only, Aqua TROLL 600 has battery and cable power so can deliver real-time data and back up or log internally. (2) Stores data internally in two places – microSD & internal memory. (3) Cable can be vented or non-vented for pressure.

[e] YSI EXO notes: (1) Rehydration required if dry for > 8 h. (2) Accuracy 0-200%: max of ± 1% value or 1% of Air Sat. (3) Max depth of sonde 250 m, but depth sensor may reduce this. Depth sensor may be rated to 10, 100, or 250 m. (4) Wiper metadata includes wiper park position & current draw which are useful for troubleshooting. (5) Support for challenging issues can be difficult to access.

[h] HOBO notes: (1) HOBOWare is free but you will need a cable. HOBOWare Pro software license can't be shared.

[p] PME miniDOT notes: (1) Uses decay to calculate DO. Intensity used for sensor check (Q). If Q < 0.7 then the sensor needs to be returned for a service. (2) Some users recommend rehydration for 24 hours. (3) Battery-operated miniWiper is robust and outputs detailed metadata. miniWiper has 25 m depth rating, minimum wipe interval 1 hr. Also need a bracket to hold the wiper and sensor together. (4) Avoid using miniPAR/miniWiper bracket with miniDOT/miniWIPER. (5) Careful MiniWIPER brush adjustment is required; with too little pressure it doesn't clean the lens, with too much pressure it could scratch the foil. Wiper brush can be hard on the optical surface. (6) The MiniDOT is available in a clear housing model (depth rating 100 m) which displays the current values, and the user can see the record switch position. These features make operations and field verification simpler.

[r] RBR notes: (1) RBRduet3 T.DO |slow can be wiped, |fast and standard versions cannot be wiped and are suited for profiling (|fast) and vehicles/floats (standard). (2) Are similar to Aanderaa DO sensors, |slow & standard have PtOEP foils (Pt octaethylpophyrin), |fast has Ruthenium (II) complex (Siegel et al. 2020). (3) Battery life depends on sampling rate, sampling mode, water temperature and battery chemistry; see Ruskin manual. (4) Additional warranty periods of up to 2 y can be purchased.

[s] Sea-Bird notes: (1) Factory calibration available in Australia or US; lasts two years; Sea-Bird will not service if treated with antifouling compounds. (2) Python code available for data processing. (3) SeaTerm and SeaSoft are command-based with advanced functionality. Data download and processing not very user friendly. Ability to alter coefficients in software to correct data for specific calibrations. New software, Fathom, released 2024 to support some instruments likely to be more user friendly (3) Sea-Bird email and phone support in US is very helpful and quick to reply. There are many expert users across New Zealand: Cawthron Institute, NIWA Hamilton (Coastal and Estuarine Processes), NIWA Wellington (Moorings), and University of Waikato Earth Sciences.

[w] WTW FDO notes: (1) Marine and freshwater versions, plus different cap versions FDO 701 fast cap (T90 < 60 s); FDO 700 standard (T90 < 150 s). (2) Equal path reference system.

[x] In-situ RDO-ProX notes: (1) Have only written off one in 3 y, some still in use after 8 years. (2) Cable can extend to 60 m SDI-12, 1200 m Modbus or 4-20 mA. (3) Dirk from VanWalt is usually able to answer most questions. (4) RDO-Blue is the low-cost version and has an internal temperature sensor.

[z] ZebraTech D-Opto notes: (1) Occasionally have a unit that needs to be sent away for firmware updates or new lens. (2) Frequent connecting on internal logging "Logger" can wear O-rings & lead to internal water damage. (3) Calibration schedule in lab, nice and easy, able to do many at once for both internal logging and cabled sensors (we have connectors on the cables/sensors that allow us to just change the sensor), but note some users report issues with foil relaxation after zero pt calibration. (4) Software is basic, reasonably foolproof, but it does crash frequently. (5) Sensor has a gain setting. (6) .dat file format can create issues (depends on database).

FOULING MANAGEMENT

Active fouling management can:

- Reduce interferences on sensor window. Biofouling may decrease sensor sensitivity and alter sensor accuracy, response time and sensitivity.
- Maintain a "cleaner" sensor head for post-deployment checks, ensuring cleaning does not modify the status of the sensing area.
- Make cleaning and re-deployment easier.
- Reduce macro-fouling. Macro-fouling could (1) alter the local oxygen concentrations, (2) luminescing material on the sensor body or housing may interfere with measurements by sensors sensitive to stray light, and (3) could drift around the sensor head and intermittently alter values (e.g., strands of filamentous algae).

Recommendations

Fouling should be actively managed for all optical DO sensors. Even a slight buildup on the sensor lens will degrade the sensor's ability to return a high-quality value. Fouling could prevent oxygen from diffusing through the permeable membrane to the sensing substrate.

Experienced users suggest:

- **Regular maintenance**, particularly in spring and summer, including hand cleaning of sensor and sensor face with a non-abrasive, lint-free wipe or cloth and DI water.
- **Use a wiper** – but don't assume it will always be adequate! Data telemetry can assist to identify inadequate wiping frequency and fouling drift.
- **Maintain the sensing environment**:
    - thoroughly clean the housing (inside and outside) to remove nuisance algal filaments
    - clear macrophytes
    - ensure sensor has clearance at sites with a mobile stream bed
    - use copper anti-fouling tape to limit filamentous algae growth on sensor body.
- For **coastal deployments** consider antifouling paint, copper tape and guards, and dosing pumps.

Fouling management tools

Wipers

Some sensors come with wipers, while others require third-party wipers (see Figure 10 for examples). Sometimes the manufacturer's wiper may not be suitable for your application. Wipers can damage sensor windows by abrasion, and macrofouling or debris can obstruct wiper movement (for example, see Figure 10 F).

For telemetered DO sensors it is good practice to telemeter wiper performance values when they are available (e.g., YSI EXO, PME miniWIPER). These values can help identify when the wiper is parked incorrectly across a sensor face or struggling to clear debris.

Wiper design, including materials (scraper, sponge or bristles), controller and power (cabled or standalone) should be considered. Key questions to consider are summarised in Table 7.

Table 7. Wiper selection considerations.

Issue	Consequences	Possible solution(s)
Does the wiper use a scraper, sponge or brush?	- It may be challenging to detect wear on a scraper blade. - A scraper blade may need to be replaced frequently. - Debris may be caught in short brush bristles.	- If possible, use a wiper with long, flexible bristles as dislodged material should fall out of the bristles. Shorter, stiff bristles may retain algae, plants or sediment.
How fiddly is fitting the wiper?	- Frustration and wasted time. - Incorrect fitting could reduce wiper efficiency.	- Read the manual description of how to change the wiper. - Use a third-party wiper.
Does the wiper have metal parts near the optical lens?	- metal parts (e.g. twisted wire holding bristles) may scratch sensor face.	- Check the wiper materials.
How do you align the wiper? Does it have a fixed start point?	- Wiper may park over optical window and affect values.	- Collect wiper metadata.
How do you control the pressure the wiper applies to the surface?	- Too much pressure could damage the optical window and splay the bristles on a brush wiper.	- Purchase tools which help fit the wiper correctly (e.g., a miniature torque wrench).
Is the wiper a smart sensor? Does the wiper controller know where the wiper is parked?	- Wiper may be parked over sensor face. - Incorrect brush position would reduce efficiency. - Incorrect wiper position could alter values.	- Check metadata provided by the wiper (e.g., park angle, time, current draw) and telemeter where possible.
How does the wiper respond to a knock or getting stuck?	- Wiper may not park in the “home” position. - Power draw could be high if a wiper cannot complete the wipe and tries many times.	- Most wipers have slip clutches to protect delicate components, such as a gearbox, from knocks. - Check the wiper can re-park at the “home” position. - Check the wiper deployment settings. If possible, put a limit on wiper activity after a fault is detected. - Use a wiper which has an active troubleshooting mode, such as a blockage detection feature.
Is the wiper battery powered?	- Battery power may fail.	- Check the minimum period between wipes. Cold water may reduce battery lifespan. - An integrated wiper may be able to draw power from internal batteries if an external power source fails.

Tapes

Adhesive tape (e.g., duct tape) can be used to wrap the instrument to simplify the cleaning process – simply remove the tape and the instrument can be cleaned easily.

Coatings

Coatings are an attractive solution, but for unattended deployments they may not be adequate. Coatings are generally designed to reduce the successful adhesion by fouling organisms. For example, YSI markets *C-spray* as a non-toxic, non-water-soluble polymer to cover exposed surfaces.

A

[Stephan Heubeck, NIWA]

B

[Hamish Carrad, ECan]

C

[Hamish Carrad, ECan]

D

[Hamish Carrad, ECan]

E

[Chris Eager, WRC]

F

[Hamish Carrad, ECan]

Figure 10. Examples of fouling on wiped sensors. (A) PME miniDOT (top) with battery operated miniWIPER after an urban stream deployment. (B) In-Situ Aqua TROLL after deployment in Te Waihora, a coastal lagoon. (C) A wiped In-Situ RDO Pro-X sensor after deployment in Te Waihora, a coastal lagoon. (D) In-Situ RDO Pro-X with ZebraTech Hydro-Wiper after deployment near the mouth of Te Waihora, a coastal lagoon. (E) Heavily fouled sensor bodies on an YSI EXO sonde retrieved from an estuary. (F) Heavily fouled YSI EXO sonde retrieved from Wainono, a coastal lagoon.

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. A chlorine injection was available on some Sea-Bird instruments (e.g., discontinued Sea-Bird WQM) – a reservoir holds a small volume of bleach which is pumped into the EC cell. Similar systems have been developed by others, using bromine (e.g., 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.

Copper

Copper is used or recommended by numerous manufacturers to reduce biofouling by inhibiting adherence. Copper can be used to protect the sensor body and face but cannot protect the foil directly. Copper anti-fouling is available in several forms:

- Copper sensor faceplates reduce the likelihood of fouling adjacent to the optical window (e.g., D-Opto, PME miniDOT, see Figure 11).
- Sensor bodies can be wrapped in copper tape to reduce the risk of growths passing in front of the sensor head or becoming tangled in a wiper. When applying the tape, ensure there is no contact between the tape and other metal parts or the tape will lose its antifouling properties.
- Shutters, which may include a copper stud (e.g., ZebraTech Shutter), are available for sensors which cannot be wiped. However, when a sensor foil can be wiped, our experienced users prefer wipers over shutters.

A

B

Figure 11. Example of copper use to manage fouling. (A) PME miniDOT with miniWIPER and copper antifouling plate retrieved after a 4-month deployment in Lake Ohinewai, Waikato [Denise Rendle, NIWA]. (B) YSI EXO sonde sensors wrapped in copper tape after an estuarine deployment [Chris Eager, WRC].

CASE STUDY 1 – FOULING IMPACTS ON DO VALUES

A joint ECan, Department of Conservation, rūnaka (tribal assembly) and landowner project has been underway since 2022 to support the last remaining population of giant kōkopu (*Galaxias argenteus)* in Canterbury. The population lives in Horseshoe Lagoon, a small coastal lagoon north of Timaru, South Canterbury. The lagoon is at risk from coastal inundation, infilling and saltwater intrusion, and reduced freshwater water quality.

ECan identified four key sites for HFWQ sensing to characterise different parts of the system – a spring, a stream, below the freshwater confluence, and the lagoon. At each site a D-Opto sensor (DO with internal logging) and a Solinst LTC (level, temperature, conductivity) sensor were installed. The D-Opto sensor was fitted with a copper antifouling ring. On each site visit, sensors which could be safely accessed were cleaned and verified using a YSI ProDSS field meter.

During the monitoring period there were several challenges: (1) at times major beach inundation events buried the sensors in the lagoon, (2) high water levels resulting from rainfall prevented access to sensors, (3) a summer drought resulted in low water levels exposing all sensors to the air, and (4) fouling was extreme.

In this high growth environment, the copper ring on the DO sensor was inadequate at preventing fouling between site visits (Figure 12 A). Within 14 days of a site visit, fouling started to impact sensor values. Without frequent site visits, the values started to exceed plausible values – the fouling on the sensor face resulted in extremely high DO values during the day and low values overnight (sometimes negative). Cleaning the sensor lens resulted in a large drop in DO, for example in Figure 13 the DO values dropped from 174% before cleaning (red line) to 72% after sensor cleaning. It's likely that photosynthesis by algae in the biofouling on the sensing surface artificially increased the measured dissolved oxygen concentration during the daytime.

A

B

Figure 12. (A) Fouled face of a D-Opto sensor [Julie Grant, ECan]. (B) D-Opto installed in PVC housing at low water level at Horseshoe Lagoon [Julie Grant, ECan].

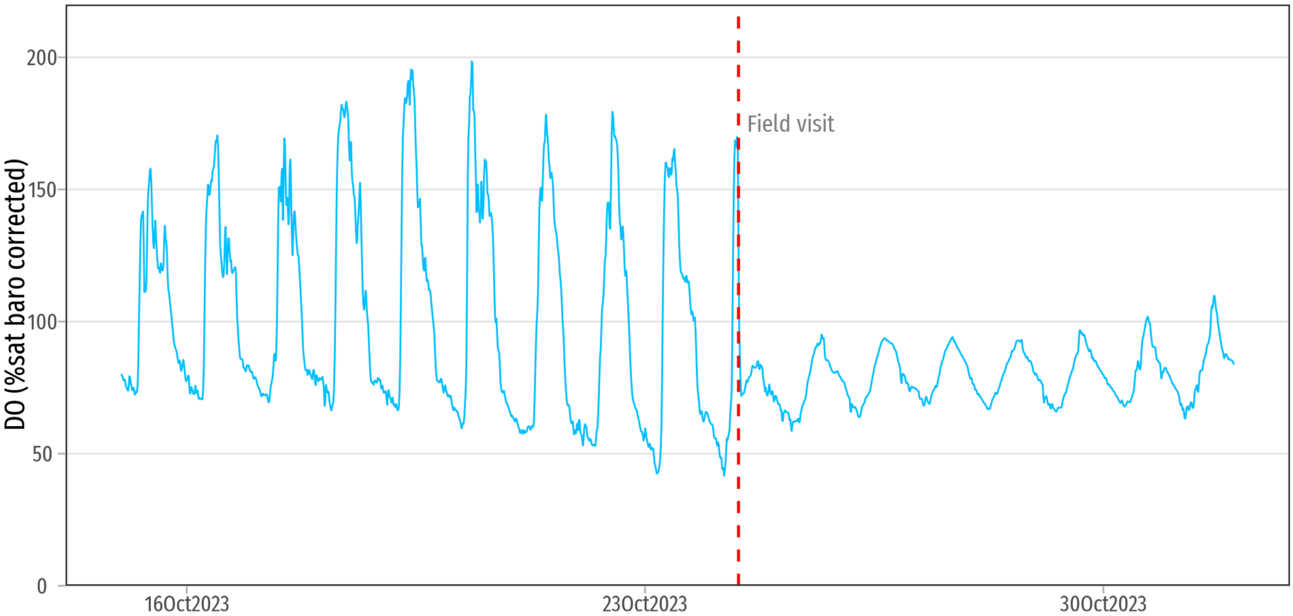


Figure 13. Erroneous dissolved oxygen values prior to sensor cleaning (red line) followed by good quality values [data from ECan].

To manage sensor fouling at the sites, ECan replaced the D-Opto sensors with a wiped sensor, and PME miniDOTs fitted with miniWIPERS were installed. The combination of sensor and wiper has a large diameter which requires a wide housing (Figure 14 A). The miniWIPERs do a good job of cleaning the sensing foil when the wiper is correctly positioned and the brush is in good condition. In this productive environment the PME miniDOTs with wipers return good-quality data. One quirk of the miniDOT is that there is no 'delay to start' counter, so careful deployment timing is required if data is being time-matched to another sensor (the Solinst LTC at these sites). To align the data, the user needs to start the sensor 1 minute before the required log interval (e.g., start logging at 13:14 to get a data value aligned to 13:15).

A

B

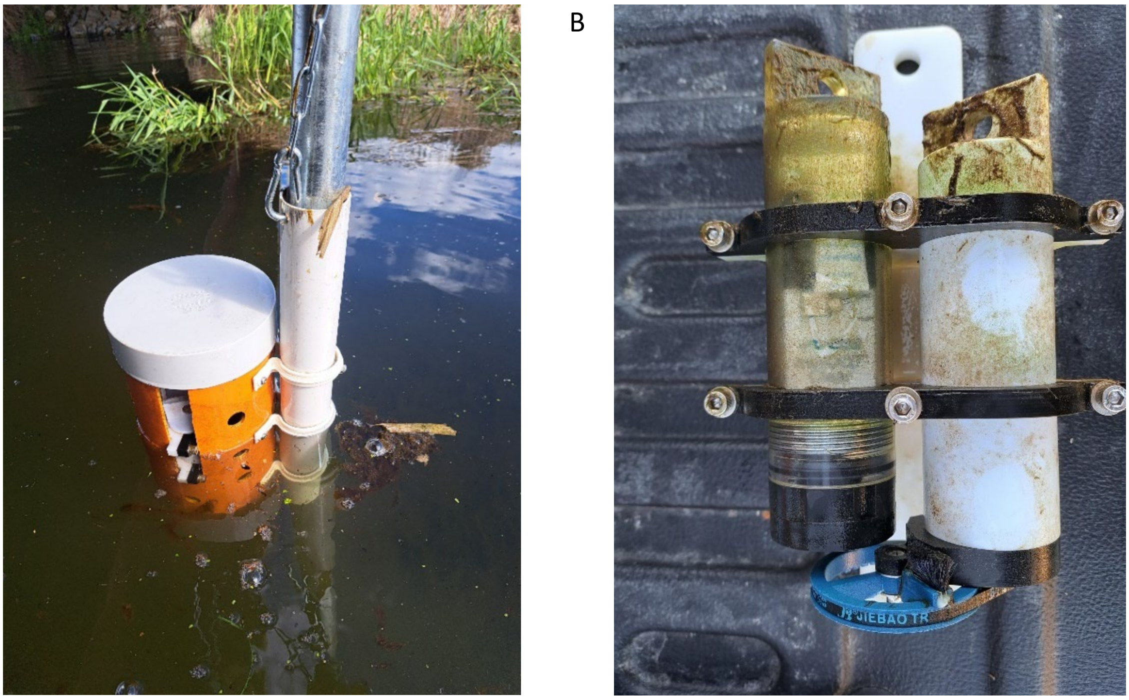


Figure 14. PME miniDOT and miniWIPER (A) deployed and (B) retrieved from Horseshoe Lagoon [Julie Grant, ECan].

Biofouling of all the sensors was rapid, and a wiped optical DO sensor was required to minimise data loss due to extreme fouling. While the D-Opto and PME miniDOT both log values internally, the PME miniDOT is suitable for wiping. The miniWIPER can manage fouling on the miniDOT under most conditions at Horseshoe Lagoon.

LOGISTICS – GETTING THE DATA

Internal logging and telemetry

Internal logging is possible for most DO sensors, and for some it is the only option. The use of internal logging requires robust consideration of the consequences of data loss, while the adoption of telemetry may require additional resourcing. Some regional councils use standalone sensors for short-term deployments, preferring telemetered sensors for long-term sites. The key advantages and disadvantages of using sensors with internal logging or telemetry are summarised in Table 8.

Table 8. Advantages and disadvantages of data communication systems (after Wagner et al., 2006).

Data capture system	Advantages	Disadvantages
Telemetry	- Data secure once transmitted. - Data can be viewed at any time, including on public-facing portals. - Real time decision-making is possible. - Systems can be monitored remotely and additional services carried out in a timely manner.	- Requires additional resourcing (if a logger is not already on site). - More complex system and more faults are possible. - Telecommunications protocol may need to be updated (satellite/mobile system switch off). - Site may attract vandals – particularly solar panels.
Internal logging	- Deployment & location options are flexible. - Vandalism may be reduced due to absence of site infrastructure, particularly solar panels. - Sensor theft may be reduced if the sensor can be well-hidden. - Sensors can be installed and replaced rapidly (reducing resourcing). - Small battery-powered sensors may be less likely catch flood debris.	- Real-time decision-making not possible. - Data are only available during site visits. - Migrating channels or bank erosion may require adjustment to sensor placement. - Status of equipment can only be checked during servicing. - Data cannot be viewed without a site visit. - Loss of data is unknown until site visit. - Battery may lose power. - Water ingress may result in data loss between site visits.

There are several sensor options with internal data logging (see Table 6 for more details). Sensors with the capability to connect to data loggers use a range of communication protocols, including analog (4…20 mA), SDI-12, RS-232, RS-485 (Modbus), and sometimes Ethernet/IP. Workgroup recommendations include:

- If possible, connect using Modbus or SDI-12. Experienced users have had problems using analog signals. If using an analog signal, carefully check the specifications of the sensor and logger Analog to Digital Convertors (ADCs).
- While it can be useful to have a proprietary controller in the lab, you can use a computer to communicate with most sensors (software or a special cable may be required).

Useful metadata

We recommend that in addition to the DO value (and correction factors such as temperature and salinity), available metadata is also archived alongside the data. Metadata supplied by commonly used sensors is summarised in Table 6.

Some sensors output a quality code for each measurement to reassure the user that the sensor foil is operating as expected. For example, the PME miniDOT outputs a Q value, and the In-Situ RDO range outputs a foil abrasion warning (see example of an abraded foil in Figure 15).

Wiper activity is recorded by some sensors and wipers (e.g., YSI EXO, PME miniWIPER, ZebraTech Hydro-Wiper) and can be used to assist with data processing. For example, after receiving a knock or clearing debris, wiper brush can misalign and then park (fully or partially) over the optical face. If the wiper park position is measured and recorded, these values can be used to identify periods of compromised data.

Figure 15. Sensor foil damage on an In-Situ RDO Pro-X after abrasion by coarse sediment transported during a high flow event on the Rees River (see back cover) [Emily Olson, ORC].

DEPLOYMENT OVERVIEW

The photos on this page demonstrate the range of DO deployments undertaken in New Zealand.

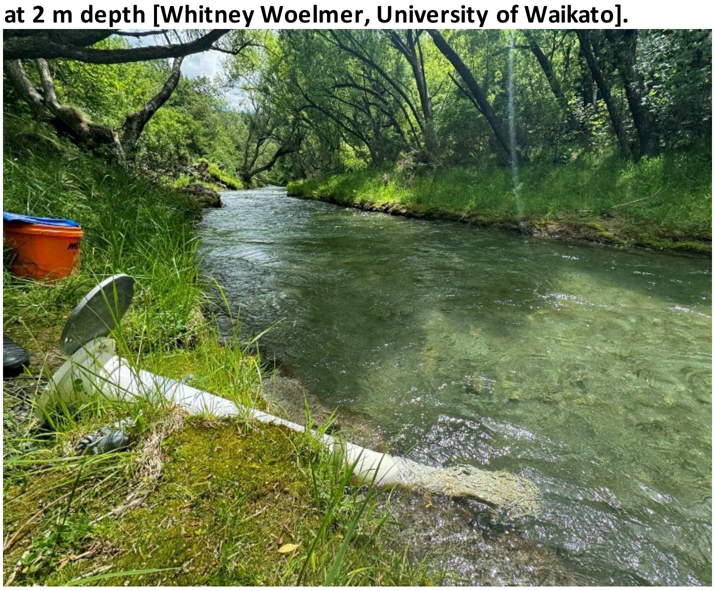
Sonde deployed in an urban stream, Hamilton [Stephan Heubeck, NIWA].

DO sensor verification check on the Opihi lagoon [Julie Grant, ECan].

DO monitoring at Leith Stream, Dunedin [Emily Olson, ORC].

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

PME miniDOT and miniWIPER installed in Horseshoe Lagoon, Canterbury [Julie Grant, ECan].



DO monitoring on the Arrow River [Emily Olson, ORC].

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. Some manufacturers offer online courses with videos and presentations to support new users (see Table 6).

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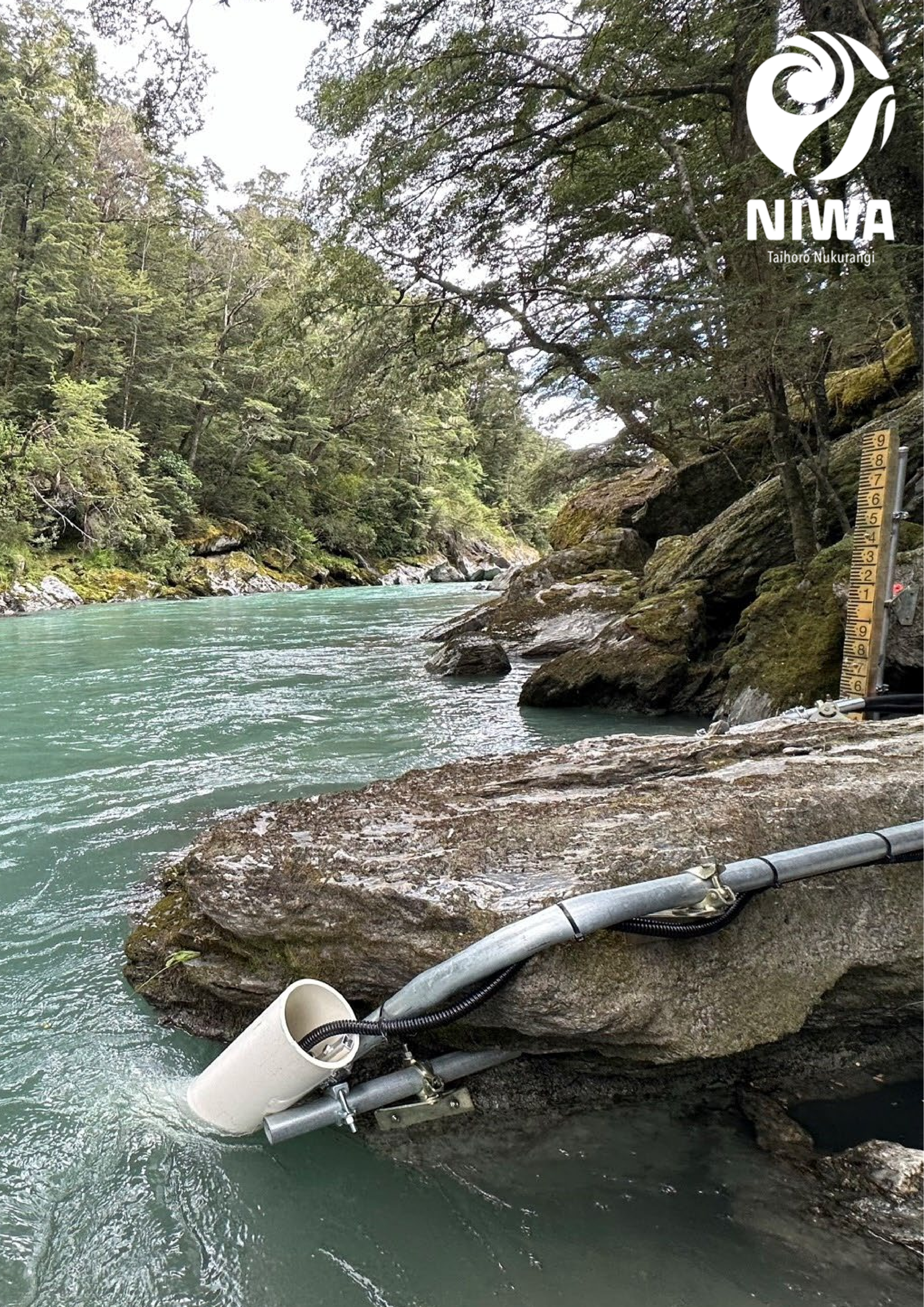
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