OPTICAL SCATTERING (TURBIDITY AND BACKSCATTER) SENSOR SELECTION

NIWA

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Front cover: Severe biofouling on a YSI EXO sonde recovered from Wainono Lagoon, Canterbury [Julie Grant, ECan]. Back cover: Avoiding hazards during a sediment gauging on the Mataura River, Southland [Andrew Willsman, NIWA].

CONTENTS

ABSTRACT

The growing commercial availability of bulk optical scattering (turbidity & backscatter) sensors creates opportunities to measure a useful surrogate at high frequencies. The values output by these sensors should be converted, via site-specific relationships, to indicators of interest such as suspended sediment, total phosphorus, and visual clarity. It can be challenging to select the "right" sensor; sensors can over-range in Aotearoa New Zealand's rivers in large floods or lack sensitivity in clear waters. The available sensors use differing hardware and software designs which affect their performance and usefulness across different water types.

This chapter provides information to help users select a sensor. It describes the sensors' basic operating principles, identifies key sensor features, compares sensor hardware and software, summarises key sensor selection questions, demonstrates how range selection is critical to success, and showcases the variety of deployments undertaken across New Zealand. Most deployments are unattended and visited on a monthly schedule, which creates extra challenges, particularly sensor fouling. The chapter does not address field maintenance, data editing or data verification procedures in detail.

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 (e.g., optical scattering, nitrate, dissolved oxygen) and provide detailed insights into water quality dynamics at scales of interest (minutes to hours). However, these HFWQ sensors can create technical challenges, and unattended deployments can be resource hungry. HFWQ 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 optical scattering (turbidity & backscatter) 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 sensor selection for measuring optical scattering (turbidity and backscatter) 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 high-quality data using optical scattering sensors.

RELATED RESOURCES

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

- Overviews on the principles of turbidity measurement, including Davies-Colley and Smith (2001), Lawler (2004), e.g., Kitchener et al. (2017), and Matos et al. (2024).
  - Overviews on optical backscattering, including Downing (2006) and Fettweis et al. (2019).
- An overview of technologies for suspended sediment surrogates, including optical scattering, laser optics, acoustic backscatter (Anderson et al. 2010).
  - Lab and field turbidity sensor comparisons such as Davies-Colley et al. (2021b), Snazelle (2020), Rymszewicz et al. (2017) and Boss et al. (2009).
  - Technical guidance on estimating SSC using turbidity, including Haddadchi et al. (2023), Rasmussen et al. (2009) and Helsel et al. (2020), and in coastal waters Fettweis et al. (2019).
  - Revised National Environmental Monitoring Standards (NEMS) for Turbidity recording (NEMS 2025b) and Suspended sediment (NEMS 2025a).

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 turbidity sensor suitable to meet a user's monitoring objectives.

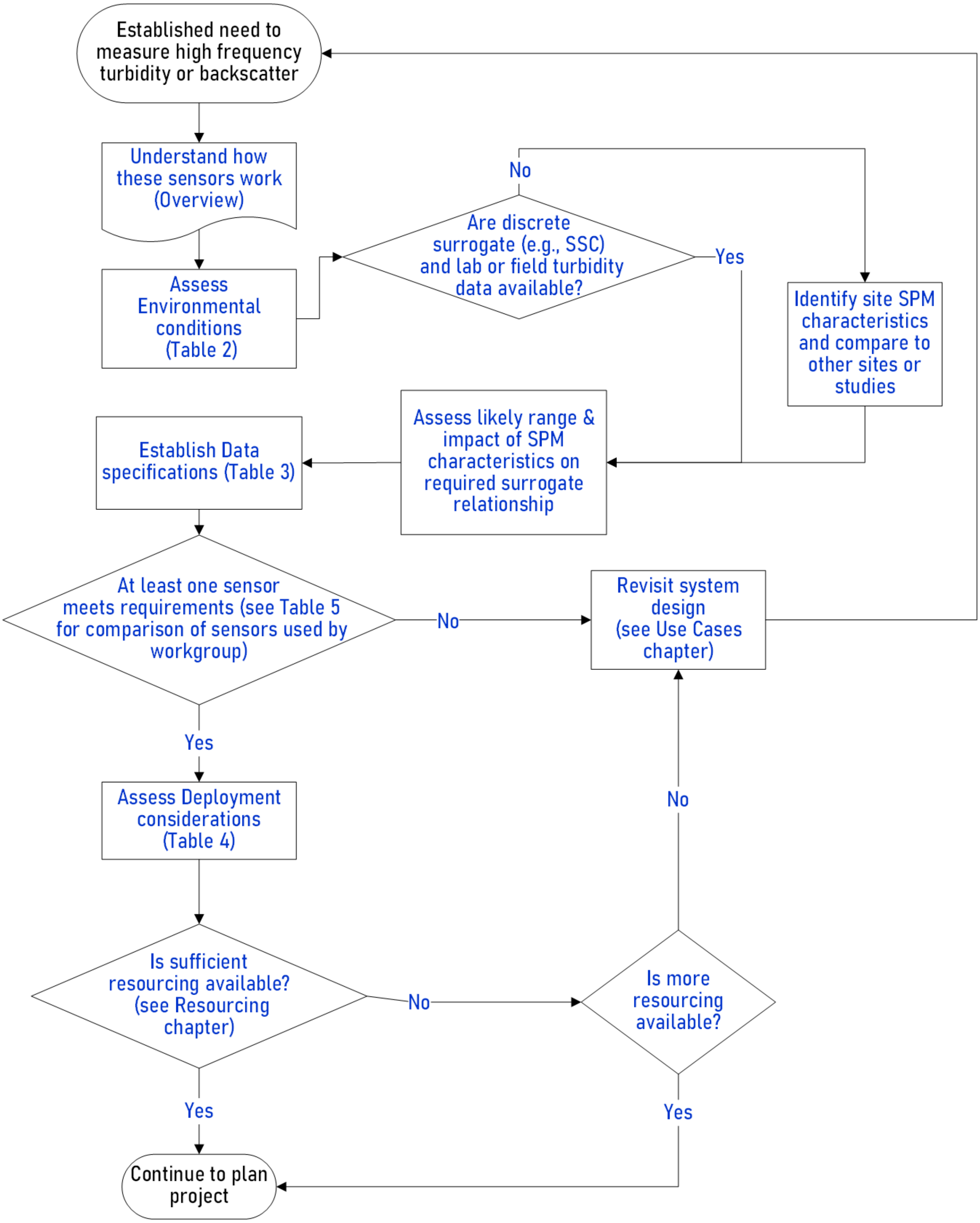

Figure 1. Suggested sequence of steps to guide turbidity sensor selection.

TURBIDITY SENSOR SELECTION OVERVIEW

Turbidity sensors are used across a wide range of environments in New Zealand, from lakes and streams with high visual clarity, to rivers with high suspended sediment during rainfall events, and in lakes and estuaries with sediment plumes and resuspension.

In this chapter we use the term *turbidity sensor* as a general term which includes all optical scattering sensors. Our focus is on sensor designs used in lakes, rivers and estuaries, which are typically side scatter (and nephelometric) and optical backscatter sensors.

Turbidity is a measure of the relative clarity of water and is useful for indicating the presence of suspended particulate matter (SPM). Turbidity is an indirect measure; a turbidity sensor measures the scattering effect that suspended particles have on light (Davies-Colley and Smith 2001).

Turbidity is a convenient metric because it is simple to measure with relatively cheap and widely available sensors. However, it is *qualitative* because different sensors output different values in the same suspension. Design standards were introduced to minimise differences between turbidity sensors but have failed to address the issue.

Measuring turbidity will be more straightforward if a sensor user accepts that turbidity is just a number with meaning established by relating it to concurrent measurements (Downing 2006) of the real target. Turbidity is a useful surrogate for SPM. In estuaries and rivers, turbidity is used to estimate suspended sediment concentrations (SSC). In rivers, turbidity has also been used as a surrogate for visual clarity, total phosphorus (when phosphorus is mostly sediment-bound) or the pathogen indicator, *E. coli*. However, there are challenges which can result in noisy and unstable site-specific relationships: (1) optical scattering varies with particle characteristics *and* concentration, and (2) SPM has dynamic particle characteristics, particularly in rivers. For example, two samples with the same SPM concentration but with different particle characteristics will have different scattering properties and therefore different turbidity values.

With a good understanding of factors that control the response of a given sensor, users will be able to find their way through the complexity surrounding turbidity as a metric and select the best sensor to meet their requirements.

Light and suspended particles

Turbidity is a measure of the interaction between SPM and light. When light meets a suspended particle in water, it can either be scattered in any direction or absorbed (i.e., converted to a different energy form). Light is scattered by bouncing off the particle (reflected), bending as it passes through the particle (refracted), or bending as it passes around the particle (diffracted) (Figure 2). The intensity of light scattering depends on four features of SPM: concentration, size, shape, colour and composition.

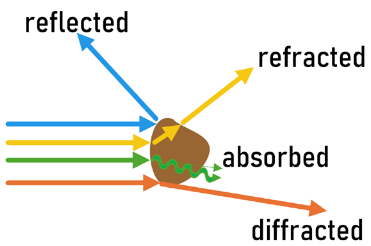

Figure 2. Processes of scattering and absorption when light meets a suspended particle.

As particle concentration increases, the amount of light scattering will increase. But at high particle concentrations, the relationship between turbidity and particle concentration can become non-linear and some sensors can give erroneous results (for more details refer to the section on Over-range and transition responses).

Particle size is an important property of SPM which exerts control on settling velocity and water clarity. The scattering intensity is highest for small particles (in the range 0.1 to 1 μm) and decreases with increasing wavelength. When a particle is a lot smaller than the beam of light, the scattering is symmetrical (Figure 3). Once the particle is larger than the light beam, extreme scattering in the forwards direction occurs (Figure 3) as the result of multiple scattering events. Many small clay-sized particles will result in a higher sensor value than larger sand-sized particles at an equal concentration.

The impacts of colour and particle shape on light scattering are still active research areas. Scattering from a simple sphere will be different to scattering from a complex particle with layers and a larger surface area. For example, plate-like clays such as kaolinite will scatter light more effectively than spherical particles such as quartz and feldspar.

Scattering intensity is also affected by the particle composition; mineral particles are often "hard" scatterers compared to organic particles. Particle composition affects particle density (and therefore settling rate) and refractive index (how light bends).

While the measuring angle and wavelength are constant for a particular turbidity sensor, natural variability in SPM in lakes, rivers and estuaries will alter concentrations and particle characteristics.

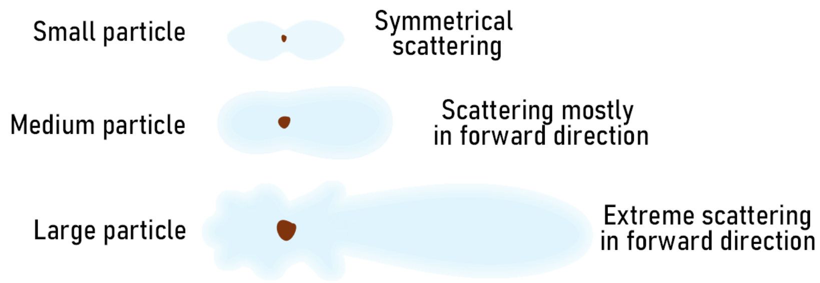

Figure 3. Generalised interaction between particle size and scattering with the same light source (after Vanous et al. 1982).

Absorption occurs when light energy is partially or fully converted to some other energy form (such as heat; Figure 2). The amount of light absorbed depends on the nature of the suspended particle, its size and the light wavelengths; absorption increases with increasing concentrations of the absorbing material, increasing SPM concentrations, and shorter wavelengths.

Light scattering and absorption in lakes, rivers and estuaries results from the interaction between light and the mixture of suspended particles – clays, silts, colloids, microbes, plankton, organic detritus and bubbles (see Figure 4). SPM composition is dynamic in space and time due to varying transport processes (e.g., floods, currents or waves) and sources (e.g., algal blooms, erosion, human activities). In addition, organic and mineral particles combine to form aggregates and flocs which have varied and dynamic scattering and absorption properties.

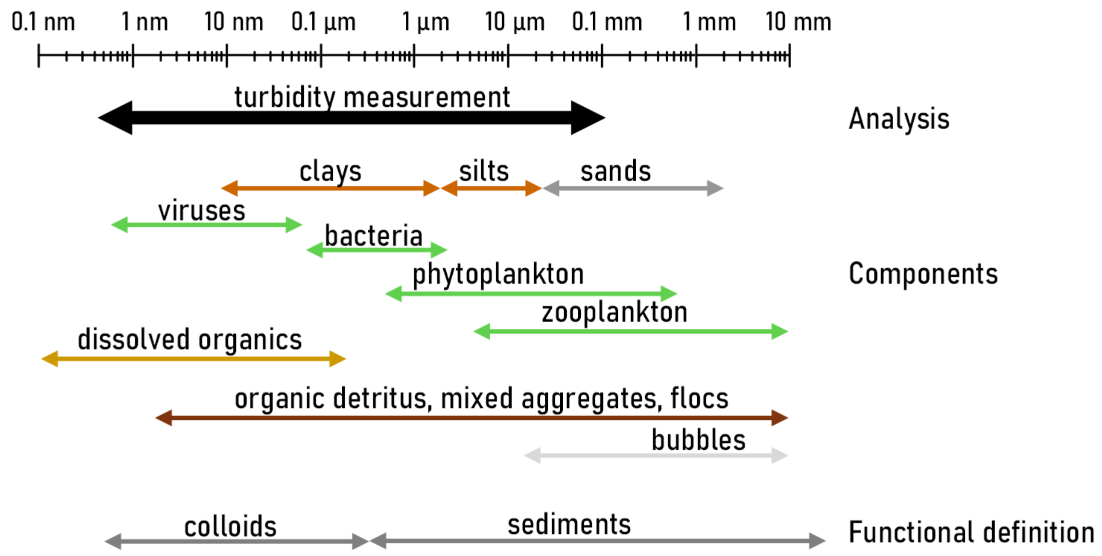

Figure 4. SPM components in water over the size range of 0.1 nm to 1 cm (after Vanous et al. 1982).

SENSING METHODS

Sensor design

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

– a light source,
– a lens to collimate the light beams (make them parallel)
– a detector which measures the scattered or absorbed light
– electrical circuitry to convert the detected signal to an electronic signal.

Sensor dimensions vary with different optical geometries (Figure 5). To create a small diameter sensor, additional reflectors are required to direct the outgoing and incoming light beams (Figure 5 B). Most optical scattering sensor designs have a flat face, and the light source and detector sit at angles behind a protective lens (e.g., YSI EXO, Sea-Bird ECO NTU) or lenses (e.g., Seapoint, Aanderaa).

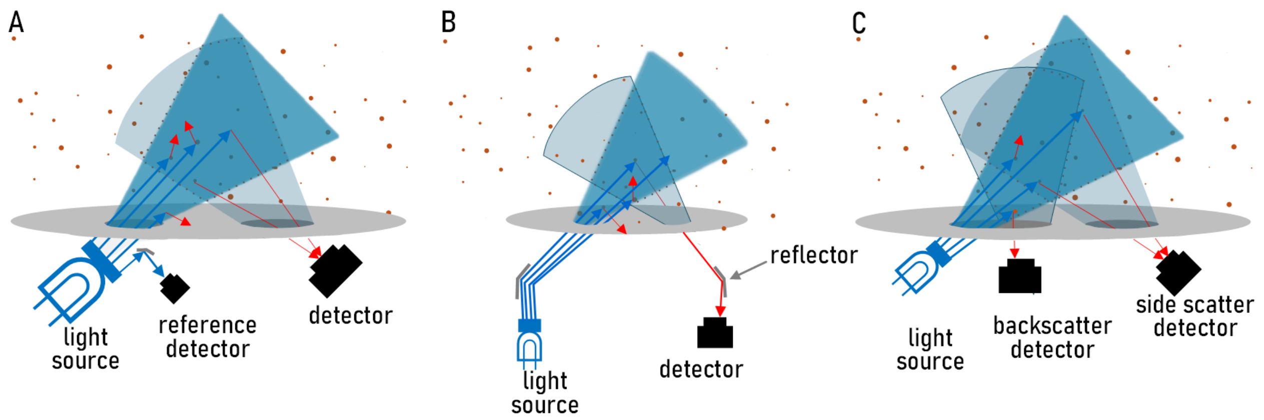

Figure 5. Generalised diagrams of turbidity sensor optics. (A) A large diameter side scatter sensor with a reference detector. (B) A small diameter side scatter sensor. (C) A sensor with dual detectors.

Standards

Standards define the physical properties to which the sensor must conform and the measurement units. Two commonly cited standards are referenced by sensor manufacturers, US EPA Method 180.1 and ISO 7027-1:

– The US EPA Method 180.1 is suitable for measuring low turbidity values without colour interference (because the detector wavelengths overlap with dissolved organics emission wavelengths). The method specifies a tungsten lamp with a colour temperature of 2000-3000 K which outputs a broad spectrum (~360-2400 nm) and is sensitive to smaller particles. Most sensors adopting this standard are designed for drinking water monitoring. The sensors require daily calibration (due to the incandescent decomposition), so they are not typically used for in-situ field deployment.
– The ISO 7027-1 Standard focuses on sensor calibration procedures and outlines two sensor geometry specifications. The standard covers both side-scatter (nephelometry) and direct beam (turbidimetry) sensor geometries.

The key requirements of these standards are summarised in Table 1. Additional information on these and other turbidity standards is available in Kitchener et al. (2017) and Matos et al. (2024).

Due to the lack of numerical comparability between sensors, the standards are less useful for sensor selection than might be expected. Despite meeting the relevant standards, different models of sensor output different values in the same suspension (see Rymszewicz et al. 2017, Snazelle 2020, Davies-Colley et al. 2021b). This creates challenges for anyone operating a turbidity sensor fleet.

In a previous Envirolink project, four different models of field turbidity sensor that met ISO 7027 were lab-tested in three different suspensions (river silt, kaolinite and algae) across a range of visual clarities (Davies-Colley et al. 2021a). For each suspension there was variation in response between the different formazin-calibrated sensors; while their responses were linear, they put out different numeric values. For example, in river silt at a visual clarity of ~0.95 m (beam coefficient 5.5 m^{-1}), one sensor model output ~500, while another output ~1020. None of the sensors tested should be considered the “best” or better than the others with regards to numerical output.

Table 1. Elements of the two most-referenced turbidity sensor standards.

Standard	Requirement
US EPA 180.1	- Tungsten light source (colour temperature between 2000–3000 °K) - Detector response peaks between 400–600 nm - Detector angle 90° ± 30° (and multiple detectors are allowed) - Beam pathlength < 10 cm - Should measure between 0–40 NTU - Standard reference is formazin (also styrene divinylbenzene polymer) - Units are NTU
ISO 7027-1 (2016) Nephelometry	- Light source bandwidth shall be within 830 and 890 nm (full width at half maximum) - The light source shall not divert from parallel (convergence < 1.5°) - Detector angle shall be 90° ± 2.5° (note can have a secondary detector and meet the standard) - Aperture angle of detector should be between 20 and 30° - Standard reference is formazin or stablised formazin (e.g., StablCal) or secondary standards (e.g., styrene-divinylbenzene bead suspensions such as AMCO Clear or YSI standards) - Units are FNU
ISO 7027-1 (2016) Turbidimetry	- Light source bandwidth shall be within 830 and 890 nm (full width at half maximum) - Detector angle shall be 0 ° ± 2.5° - Aperture angle of the light source should be between 10 and 20° - Standard reference is formazin or stabilised formazin (e.g., StablCal) or secondary standards (e.g., styrene-divinylbenzene bead suspensions such as AMCO Clear or YSI standards) - Units are FAU

Optical configuration

Differences between optical scattering sensor values arise because of differences in the light source, detector and optical geometry. The optical geometry includes the detector angle and the path length of the light (sensing volume).

Light source & detector

Optical scattering sensors use a range of light sources that are typically LEDs or tungsten lamps. Many manufacturers choose to meet standards which specify the light source peak wavelength and band (Table 1).

Many field turbidity sensors used by regional councils use a LED with a peak at ~860 nm (ISO 7027-1) which helps eliminate the effect of colour and minimises the effects of stray light. Near-infrared light (~ 750 to 1500 nm) is rarely absorbed, so dissolved organic matter will not affect sensors using these wavelengths. To meet the ISO 7027-1 Standard, most sensors use an LED. LEDs emit light in all directions, so sensors need lenses to produce a collimated (parallel beam) light. Some sensor manufacturers also choose to use mirrors and the optical properties of sapphire glass to reduce sensor size.

White light sources are used in sensors designed to detect smaller particles. The EPA Standard 180.1, which is mostly used for drinking water in the range of turbidity from 0 to 40 NTU, requires a tungsten lamp (Table 1). Sensors using a tungsten lamp require frequent calibration and are not typically used for unattended monitoring.

Little information is available about detectors used in turbidity sensors, but they are likely to be photodiodes to minimise cost. The Campbell OBS range (discontinued in 2019) was widely used in estuaries and had silicon PNN+ photodiodes with good linearity and low noise.

Some sensors have multiple detectors, either to extend the measuring range or to compensate for instrument noise. For example, the Hach Solitax has side scatter and backscatter detectors (Figure 5 C); addition of the backscatter detector extends the sensor's range by at least an order of magnitude (see Table 5). The In-Situ Aqua TROLL has a reference detector to reduce instrument noise, such as the impact of varying LED light intensity and sensor temperature (Figure 5 A).

Detector angle

The optical geometry between the light source and detector is a key design feature to consider in sensor selection as it affects the sensor's range.

Sensors measuring light attenuation – the reduction in the light intensity as it passes through a water sample – have the detector at 0° (Figure 6 A). Sensors designed to measure scattered light have the detector at an angle between 0 and 180° (typically 15 to 140°). Depending on the angle between the light source and detector, sensors are referred to as backscatter (typically 105–160°; Figure 6 B), side scatter (90°; Figure 6 C) or forward scatter (Figure 6 D).

There can be confusion in how the detector angle is specified (Kitchener et al. 2017) so check the manufacturer's specifications carefully. Sometimes a direct beam is specified as 0° and at other times 180°. It is common, but not standard, to refer to the angle between the light and detector after light and particles meet (as in Figure 6).

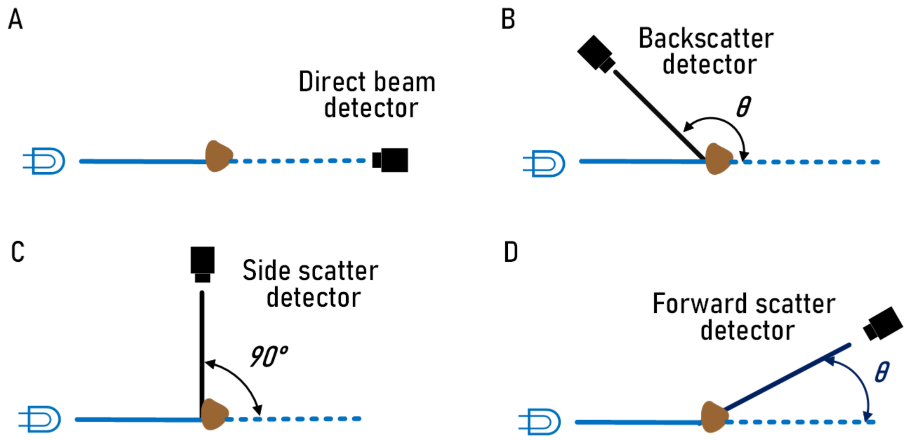

Figure 6. Schematic of the different detector angles used in turbidity sensors.

Forward scattering (0–90°) and backscattering (90–180°) sensors do not have a standard which defines the allowable detector angle, so different manufacturers use different angles. Many manufacturers specify the detector angle in brochures and manuals. Backscatter sensors, with detector angles often between 120° and 140°, are often used in oceanography. They are most useful when SSC is high (greater than 1 g/l). Forward scatter sensors are used to improve the accuracy at low values and can detect larger particles due to their strong forward scattering (Figure 3), but careful design is required to ensure the light source cannot enter the detector directly.

Photometers or spectrophotometers (direct beam detectors; Figure 6 A) that measure visible wavelengths (~380 to 700 nm) output a "turbidity" value (e.g., s::can spectrolyser, TriOS VIPER and LISA color). Sensor pathlengths (which vary from 5 mm to 250 mm) may limit their useful range as a sensor for optical scattering because all light may be scattered before it can reach the detector.

Some sensors use multiple detectors, commonly a combination of side scatter and backscatter. The signals may be processed separately or combined. Sensors using a combined signal are known as ratiometric because the value is the ratio of the light received by the different detectors (e.g., Hach Solitax). This technique is used to overcome some of the effects of water matrix properties, such as colour (both coloured particles and dissolved organics), and to extend the sensor's range. For example, the backscatter detector on the Hach Solitax is located close to the light source and detects scattered light within a small sensing volume.

Sensing volume

The distance travelled by the scattered light affects values. A longer light path between the light source and detector improves sensor resolution at the low range as there are fewer scattering events. A shorter path length (e.g., backscatter detector in Figure 5 C) increases the sensor's high range.

The path length or sensing volume is not often disclosed in detail. More commonly clearance distances are provided, such as the submergence depth or clearance required during calibration, sidewall clearance or bottom clearance. Some sensors require a guard, shroud or cap to ensure the sensing volume is constrained (see Table 5).

Original equipment manufacturer

There is a smaller pool of sensor technology than the number of sensor brands suggests, because many manufacturers purchase optical turbidity sensor technology from the original equipment manufacturer (OEM). These OEM components can range from a sensor head to a complete sensor. Some OEM purchases include RBR's use of the Seapoint turbidity sensor on their RBRsolo³ Tu sensor, and PME's loggers for the Turner Designs C-FLUOR turbidity sensors. The Turner Designs and Seapoint optical turbidity sensors are used by several manufacturers (e.g., Sequoia, RBR, Aquatec). Some OEM purchases are disclosed on brochures, while others are not publicised. In the absence of information in brochures and manuals, careful examination of the sensor design and specifications including LED wavelength, detector angle, diameter, materials, sensing volume or path, and registered trademarks will reveal commonalities between sensors.

Units

There are many different turbidity units. Each sensor light source and optical geometry has its own units, which results in an array of units (Figure 7), and this can be confusing for sensor users.

However, the real problem is the lack of numeric comparability between sensors. For a while it was thought that values output by sensors *with different optical designs* differed by a factor of two in the same water (Anderson 2005), but more recent tests have shown that turbidity measured with sensors with the *same optical design* can differ by a factor of two to five in the same water (Rymszewicz et al. 2017, Davies-Colley et al. 2021b). Therefore, sensor outputs are specific not only to the sensor's make and model but sometimes also to the instrument itself. Any turbidity or scattering unit is therefore an arbitrary unit, lacking comparability to other values measured with different turbidity or scattering sensors.

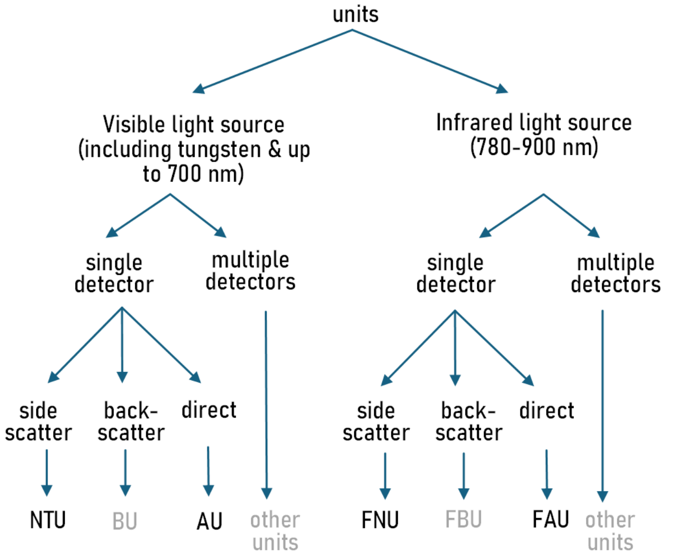

Figure 7. Simple classification of turbidity sensors with a range of configurations and resulting array of units (after Rasmussen et al. 2009). To meet NEMS Turbidity Recording V2.0, ISO 7027-1 compliant sensors are required, while for NEMS Suspended Sediment V 2.0, ISO 7027-1 sensors are preferred.

Despite this, a short discussion on units and calibration standards is warranted. The units mostly commonly output by sensors are NTU (EPA 180.1) and FNU (ISO 7027-1), which are both relative to formazin. Sensors designed for industrial uses also have their own turbidity units, for example EBC (European Brewery Convention), and some countries have their own units (e.g., TE/F, Trübungseinheit/Formazin, a German unit). Some manufacturer specifications suggest that the sensor can output FNU and NTU, which is not possible (Figure 7). However, sometimes this dual unit output is justified for legacy reasons, and the manufacturer will advise on how to adjust turbidity values due to optical design differences between sensors. For example, the YSI EXO outputs FNU and NTU, but NTU is a legacy unit. The changes in optical design between the YSI EXO and series 6 sensors result in different turbidity values; both YSI and USGS (Foster et al. 2021) document the step change and how to deal with it.

While the various formazin units output by a sensor (e.g., NTU, FNU) are equivalent in formazin, in all other suspensions the sensor will output different values. Formazin is often recommended as a calibration standard because it has a wide range of particle sizes (0.1 µm to 10 µm) and shapes, and can be made from raw materials within tight specifications. However, it becomes unstable once diluted, is carcinogenic, temperature affects the particle size distribution, and primary standards do not state a concentration uncertainty (Buzoianu, 2000 cited in Kitchener 2017). While the sensor standards require calibration to formazin, some manufacturers recommend alternative standards such as AMCOClear, Hach StablCal or a proprietary product (e.g., YSI polymer).

To prevent data users from comparing turbidity values from different sensors, there are several pragmatic options:

- Output raw units (if available), such as mV or counts, as this reduces the likelihood of incorrectly comparing numerical values between different sensors.
- Ensure HFWQ turbidity sensor time series are stored with the make and model (and possibly serial number) metadata.
- Convert turbidity values to the indicator of interest using a site-specific relationship and report the information in SI units (e.g., SSC in g/l, or visual clarity in m).

SENSOR PERFORMANCE

The performance of a field optical turbidity sensor in the real world is determined by many factors, including:

- fouling,
- the water matrix: bubbles, SPM concentration, colour, size, shape and aggregation,
- sensor optical configuration,
- instrument noise (electronic fluctuations in light, detector and circuitry).

Fouling

Any material that builds up on a turbidity sensor window will change how it responds. Fouling is not standard; it is local, varies 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, SPM, etc.), hydraulic conditions, depth, season, and local fauna and flora. Fouling on the sensor face will have the most impact on turbidity values, but fouling near the optical window can often float in and out of view, resulting in spikes in the turbidity values.

In freshwater environments, fouling on the sensor face is predominantly algae (slimes through to filaments). Chemical films can also foul sensor faces, and they tend to result in a decline in background values. Algae growth on the sensor face will ramp up values (see Case study 2 – Two sensors in).

In coastal waters there's the additional challenge of organisms such as barnacles, sea squirts and tube worms adhering to any exposed surface. If these organisms adhere to a sensor window, background values can increase as light reflects off the organism straight into the detector, or they may block the detector and reduce the values.

Biofouling typically follows a series of steps (Figure 8):

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

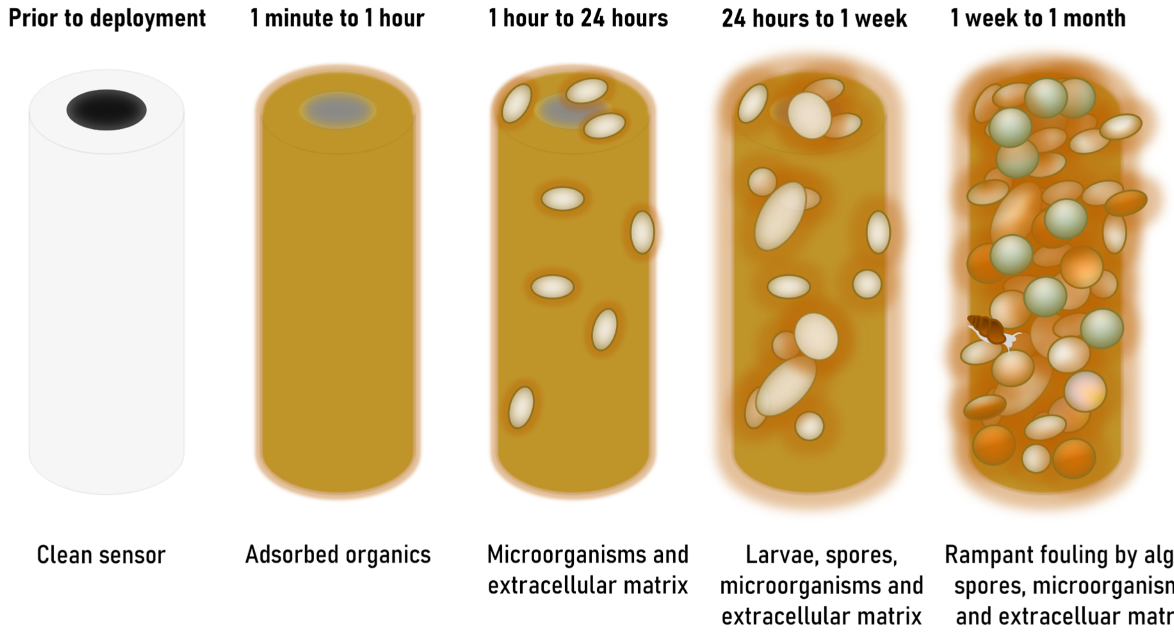

Figure 8. Simple illustration of the stages of biofouling. Each of the stages can occur in the order described, or in parallel or all at the same time (after Chambers et al. 2006).

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

Bubbles

Bubbles can also be detected by turbidity sensors. Clifford et al. (1995) found that larger bubbles streaming past a direct beam turbidity sensor had an effect on values. The impact of bubbles will likely depend on whether they are sitting on the sensor window or in the sensing volume. Bubbles on a sensor window are often evident as a pattern in the values, particularly if the wiper is operated less frequently than the sensor (see Figure 9). If a sensor needs to be installed where bubbles are likely (e.g., downstream of rapids, in rapidly moving water, or in waves), then wiping more frequently or adjusting the lens orientation may help reduce a build-up of bubbles on the sensor window.

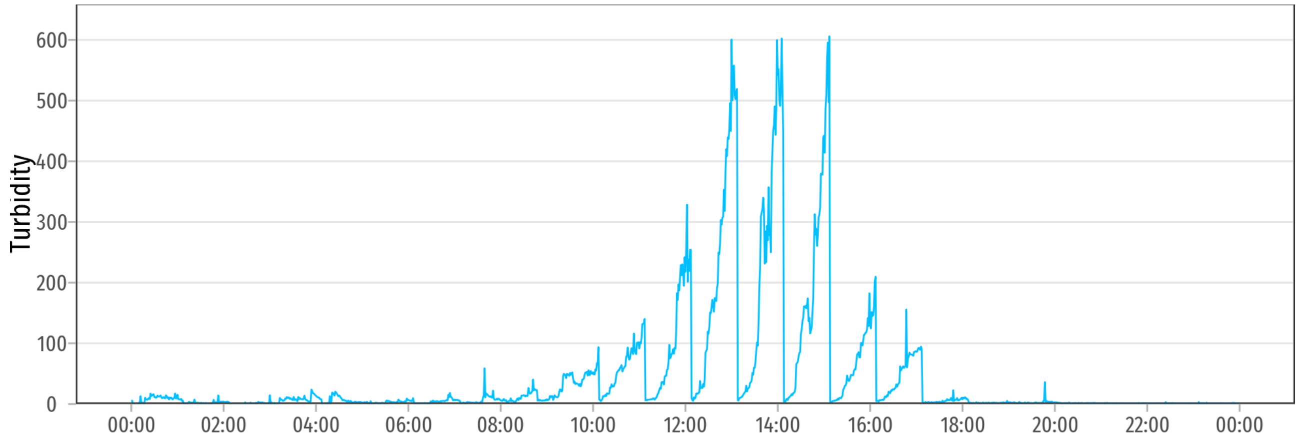

Figure 9. A 24-hour example of how bubbles accumulating on the sensor lens can alter values. The wiper was operated hourly at 15 mins past each hour [data from ECan].

Suspended Particulate Matter dynamics

Natural sediments are a complex mix of particles of different origins (Figure 4), and sediment sinks in the landscape are mobilised and transported under different conditions. In rivers, for example, larger particles will be transported in suspension during high flows when velocities are high. Light scattering will vary with SPM concentration and characteristics, such as size, shape, colour and composition (e.g., mineral, organic, aggregates). These factors introduce noise into optical scattering values (and site-specific relationships). According to Downing (2006), for optical backscatter sensors:

- the effect of SPM concentration is much greater (by a factor of 1000) than SPM size,
- which is much greater (by a factor of 100) than SPM shape,
- which is greater (by a factor of 10) than SPM colour,
- which in turn is greater (by a factor of 2) than degree of flocculation/disaggregation.

Particle size

Generally, as particle size increases, sensor values decrease because forward scattering dominates (see Figure 3). In addition, for the same SPM concentration, there are fewer particles which scatter light as the individual particles are larger. In contrast, small particles (relative to the source light wavelength) show symmetrical scattering. SPM size can alter both the slope and the offset of the relationship between sensor output and SPM concentration.

Two lab experiments which controlled SPM concentration and particle size illustrate how particle size can alter the slope of relationships between sensor output and SPM concentration (Figure 10). Ideally sensors have high sensitivity – a step change in SPM concentration is measured as a large step change in sensor output. However, increasing particle size can reduce sensor sensitivity. Using known ratios of natural silt and sand, Green and Boon (1993) found that backscatter sensor output varied depending on the mix (Figure 10 A); with increasing particle size from silt to sand the sensor had lower sensitivity. Similarly, Bright et al. (2020) used a settling experiment with a high flow event river sample to demonstrate that side scatter sensors were sensitive to particle size (Figure 10 B). They found that for ultrafine SPM (<7.8 µm, very fine silt, clay and smaller) the relationship between SPM concentration and sensor output was stable. But for silts, as particle size increased from fine silt (7.8-15.6 µm) through to coarse silt (31-63 µm), the sensors were sensitive to particle size.

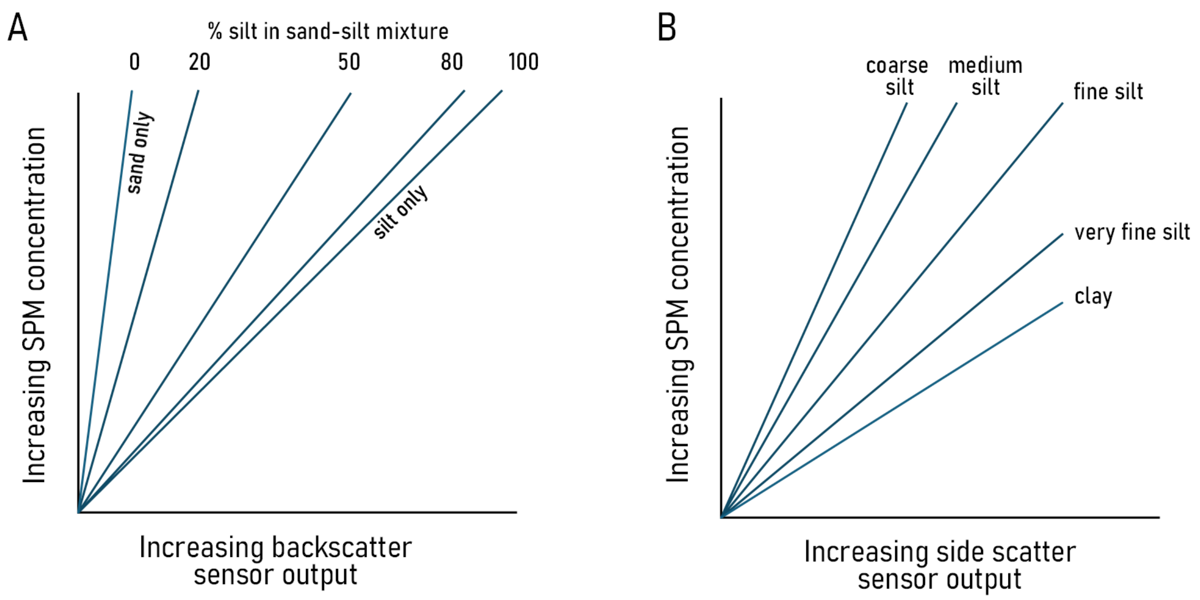

Figure 10. Simplified relationships between sensor output and SPM concentration derived from lab two experiments. (A) Relationship for a backscatter sensor and a sand–silt mix [adapted from Bunt et al. (1999), after Green and Boon (1993)]. (B) Relationship for a side scatter lab sensor (90 °, Hach 2100Q-is) and different size fractions of a high flow river sample [data from Bright et al. (2020)].

Particle shape

Particle shape affects scattering intensity; more spherical particles (e.g., quartz or beach sands) will have a predictable response. In contrast non-spherical particles may scatter light irregularly. Mager and Horton (2025) examined particle shapes from a group of alpine rivers across Otago, West Coast and Canterbury and found that more circular particles gave a lower turbidity sensor response (see Mager and Horton 2025 for examples and photos).

Particle colour

Particle colour can affect sensor response. Darker particles can absorb light; some sensors will 'flatline' in solutions of dark-coloured sediments, probably as the result of increased light absorption and reduced scattering. The lab experiments of Foster et al. (2021) demonstrate interactions between particle colour and sensor response. In one experiment, they compared the response of three side scatter sensors (an EPA 180.1 compliant sensor Hach 2100 and two ISO 7027-1 compliant sensors YSI EXO and YSI series 6) in solutions of black, white and pink clay in deionised water. While all sensor values increased in the pink and white clay (see Foster et al. 2021 Appendices 19 and 21) as the clay concentration increased, there was a large difference between the Hach and YSI sensors for the black clay – the YSI sensor values did not increase in the black clay solution above 200 NTU (see Foster et al. 2021 Appendix 20).

Particle composition

Particle density and refractive index also affect sensor output. SPM can form flocs or colloids which are composed of mineral and organic material with water in the spaces. Waters rich in clay grains are likely to contain flocs and light scattering by these aggregated particles is complex and dynamic (see Bunt et al. 1999).

In practical terms if the refractive index of a particle is close to 1 then the direction light travels when it passes through the particle is almost unchanged. The refractive index varies depending on particle composition and typically reported values for particles in water are ~1.05 for algae, ~1.2 for fine inorganic suspensions, and ~1.25 for medium sand (Lobo et al. 2014). If particles contain highly refractive oxides (e.g., Shotover/Kimiākau, weighted refractive index 1.7) they may refract more light resulting in a higher sensor–SPM concentration slope and more "noise" in the relationship (see Mager and Horton 2025).

Mixed suspensions

Natural SPM are rarely homogeneous and mixed suspensions are normal. Multiple SPM sources with different characteristics can create noise in a surrogate relationship, reducing the value of using optical scattering sensors. For example, in rivers SPM characteristics may vary temporally in catchments with landslides that contribute sediment during some events and not others, or when heavy rain falls in a sub-catchment with different geology or SPM characteristics. Careful consideration of spatial and temporal variability of SPM characteristics is useful prior to any optical scattering sensor deployment. For example,

- In rivers the mass concentration might be dominated by sand-sized particles (> 63 µm) but the scattering signal responds to silt-sized particles. Successful SSC load estimation might require both optical scattering and acoustic sensors to help overcome this challenge; the acoustic sensor can measure the sand sized particles, and the optical scattering sensor can detect the finer particles (see Haddadchi et al. 2023, including Figure 5-3).
- In catchments where ultrafine SPM, such as very fine silts, clays or organic particles are transported under some conditions and not others (e.g., non-event versus event river flows, or summer versus winter) a different relationship between sensor output and SPM may be needed (see Bright et al. 2020). For example, seasonal algal blooms may alter relationships. While phytoplankton are less efficient scatterers than mineral particles they can still contribute significantly to light scattering (for example, see Davies-Colley et al, 2021).

To understand the impact of mixed suspensions on sensor output it may be useful to complete analysis prior to sensor deployment. Some potential approaches include:

- Comparing data from your site to other sites or existing datasets (e.g., Bright et al. 2018, Bright et al. 2020, Mager and Horton 2025 studied rivers in Otago, West Coast and Canterbury).
- Characterising relationships between optical sensor output, SPM concentration and characteristics in samples collected during the target conditions (e.g., high flow event on a river).

In addition to SPM dynamics, water matrix dynamics can also alter the relationship between sensor values and SSC (or another surrogate). For example, tidal dynamics may alter the relationship as two different water sources mix (see examples in Fettweis et al. 2019). Dissolved colour in the water matrix will also absorb light if the sensor light source overlaps with the absorption spectra of the matrix, but use of a near infrared light source (e.g., ISO 7027-1 or similar) and detector(s) can overcome this effect.

Summary

Many factors can influence measured optical scattering sensor values; the left-hand side of Figure 11 summarises the sensor design factors which result in lack of numeric comparability, while the right-hand side alerts users to the complexities of using optical scattering sensors as a surrogate for SPM. While SPM concentration is usually strongly related to sensor values, there can be a lot of noise due to varying SPM characteristics.

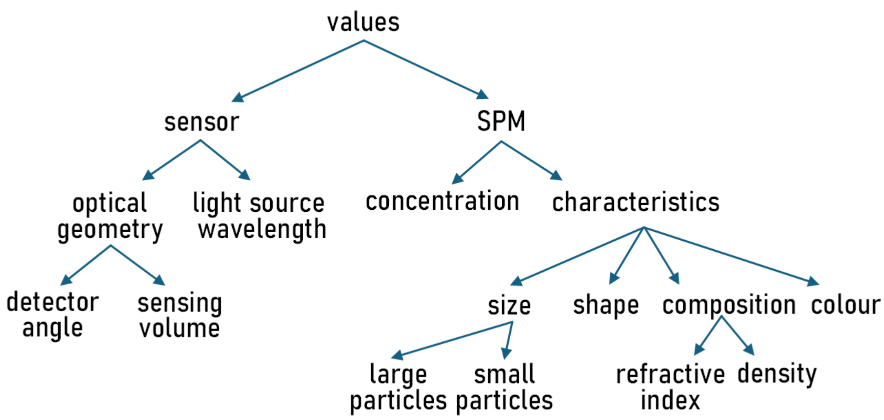

Figure 11. Key sensor and suspended particulate matter characteristics which affect turbidity sensor values.

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.

- Understand what you are trying to achieve – what are you measuring turbidity for?
- Understand how much work will be needed to meet your data need. How will you collect data to develop a surrogate relationship? Will you use field samples? Will you use a lab calibration?
- Understand the sensing methods – side scatter, backscatter and forward scatter. Side scatter sensors only measure silt and mud well.
- Plan for fouling – 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.
- If using a wiper, make sure it's got bristles – rubber wiper blades are not suitable in most conditions.
- Ensure technicians are well-trained to calibrate and maintain sensors.
- Not all sensors are created equal – some are poor quality. Reliability can be poor with some brands.
- Stationarity of a brand (if not individual instruments) is important.
- In rivers, site design is critical to reduce sediment and debris buildup around the sensor and its housing.

CHOOSING A SENSOR

Many different turbidity sensors are used by regional councils. Workshop participants were asked to nominate their preferred turbidity sensors, sensors they had stopped using, and features they consider when selecting a sensor. Experienced users typically have several trusted sensor models in their fleet and select an appropriate sensor for each application. Most regional councils limit their fleets to two to four sensor brands to simplify operations. The variety of preferred sensors covered all the sensors compared in Table 5.

The workshop participants identified four key factors in sensor selection: a well-defined purpose and well-thought-out methodology, reliability, range, and sensor response to over-ranging.

Purpose and approach

Experienced turbidity sensor users suggest that the first step in sensor selection is to critically examine whether high frequency turbidity is an efficient and effective way to meet a data need. There are risks in the data collection phase and a useable surrogate relationship is not guaranteed.

To reduce the risk, it could be worth (1) investigating SPM characteristics and turbidity in the lab, (2) assessing alternative methods such as sediment source tracing, or (3) using a different type of sensor.

- If SSC prediction is the purpose (and the sand fraction is not of interest), analysis of sub-catchment and sediment source (e.g. hillslope erosion vs bank erosion) could help identify potential issues between turbidity and SSC prior to sensor selection. It is common in oceanographic work to develop relationships between backscatter sensors and SSC in the lab. This approach is pragmatic – it is a safe and rapid way to develop a site-specific relationship for waters which contain a range of particle sizes. This approach is less favoured for rivers, and a more common approach is to collect storm event samples (auto samples and sediment gaugings; see Haddadchi, 2023).
- If sediment source identification is required, other approaches such as sediment source tracing (e.g., Hughes et al. 2021) can provide information on the relative contribution of sediment sources from different types of erosion or from sub-catchments.
- If sensing of the sand fraction is required, then additional or alternative sensor technologies are worth investigating. For example, in rivers, SSC can be measured at high frequency using acoustic backscatter sensors (ABS) or side looking Acoustic Doppler Current Profilers (H-ADCP). For more information on field tests of acoustic sensors, refer to Haddadchi et al. (2023) and also check the USGS resources.
- If visual clarity information is required, consider using a beam transmissometer. Beam transmissometers are widely used in oceanography and can be used in estuaries, lakes and rivers. Beam transmissometers, like turbidity sensors, are sensitive to fouling. An example of a freshwater deployment of a beam transmissometer can be found in Gall (2018).

Reliability

Reliability is a key factor when selecting an optical scattering sensor because different models are not usually interchangeable. Experienced users aim to operate one sensor model at a site; if you change the sensor model you will probably need to create a new surrogate relationship (i.e., model A versus SSC, model B versus SSC). One way to ensure stationarity of the record is to operate both sensors concurrently, side-by-side, over a wide range of turbidity conditions and estimate a conversion factor (Rasmussen et al. 2009). This approach is not feasible if a sensor fails and cannot be replaced.

Reliability information can only be gained from experienced users who have operated a sensor over many years. All turbidity sensor users will be developing a site-specific surrogate relationship between turbidity and another indicator (such as suspended sediment concentration), and having a reliable sensor is vital (to work within resourcing available).

Our experienced users have stopped using several turbidity sensors due to reliability issues, including:

- inability to "plug and play" a sensor of the same model
- calibration drift
- failure of components (e.g., antifouling systems)
- short sensor lifespan
- lens scratching.

According to our experienced users, lower cost turbidity sensors are more likely to have reliability issues. For example, while a new and well-maintained lower cost sensor can produce excellent data for 18 months, it may fail and need to be replaced. If the model/make is not consistently manufactured with the same optical components, then a replacement sensor will output different numeric values under similar conditions.

Range

For visual clarity, a sensor with a small range and high sensitivity will be required, while for many New Zealand rivers, a large range (nominally 0–4000 NTU) is required (Haddadchi et al. 2023). Typically, turbidity sensors using multiple sensing methods (typically side scatter and backscatter) will have a larger range.

However, selecting a sensor range using the manufacturer's specification could be misleading because of:

- The lack of numeric comparability between sensors.
- Manufacturer specifications for turbidity are for formazin, which has different particle characteristics from natural waters.
- Sensor range may be specified in SI units, such as g/l or mg/l, using sediments such as kaolinite or diatomaceous earth.

The usefulness of stated suspended sediment concentrations will depend on how the natural sediments at your site differ from the standard. Diatomaceous earth (diatomite), which is primarily composed of silica dioxide (SiO_2), is available as standard solutions for manufacturers. Kaolinite is a layered clay mineral and has a long history as a turbidity standard.

Lab and field turbidity sensor tests are a useful resource for checking sensor range and response in natural waters with natural SPM. The tests typically use multiple sensors, different SPM and sometimes different water matrices. If you have information on SPM concentrations and characteristics or have data for one sensor (lab or field) you may be able to gain insights on how a different sensor may respond at your site.

- Silica was used by Bakker et al. (2024) in their lab sensor comparison along with 11 other natural sediments from rivers across France. The natural sediments were mostly silts with varying colours (see Bakker et al., Figure 2). The sensors they tested included: Hach Solitax, WTW ViSolid, Observator NEP, MJK SuSix, and Ponsel.
- High-purity halloysite clay (a type of kaolin clay) from Matauri Bay in Northland was used by Davies-Colley et al. (2021a) in their lab sensor comparisons (Hach Solitax, WTW VisoTurb, Observator NEP, YSI EXO), alongside river silt and green algae.
- Rymszewicz et al. (2017) tested 12 sensors (10 field sensors) in their lab and field sensor comparison. They lab tested YSI EXO & 6136, Hach Hydrolab, Ponsel, Pentair TS1000, Turner Designs Cyclops-7, Seapoint, Chelsea Technologies UniLux and two Campbell Scientific OBS (300+ and 500) sensors on a fine-medium silt from one Irish river. Their field test included four sensors (Ponsel, Seapoint, Turner Designs Cyclops-7 and Chelsea Technologies UniLux).
- The USGS has completed several lab and field tests (Snazelle 2020, Foster et al. 2021) on a range of turbidity sensors including: Hach Solitax, In-Situ Aqua TROLL, YSI EXO, YSI 6136, Observator NEP-5000, Campbell Scientific OBS501).

Sensor manufacturer white papers or application notes may also supply users with additional information on sensor performance.

Over-range and transition responses

Many single-signal (i.e., SS 90°) sensors will over-range in New Zealand rivers (see Haddadchi et al. 2023 for an example during a Rangitata River flood). Due to differences in signal processing, different sensors will have different responses. Sensors may:

- flatline and output a constant value (green line in Figure 12 A),
- return a non-numeric value (-999 or NA) (purple line in Figure 12 A), or
- output incorrect values (the other lines in Figure 12 A).

The consequence of over-ranging is that two values that can be obtained (i.e., the linear range response and an over-range response; Figure 12).

Voichick et al. (2018) demonstrated the over-range response of a side scatter (90°) sensor (YSI 6136) in the field and lab. By operating an H-ADCP instrument and turbidity sensor side-by-side in the Little Colorado River, it was clear that the turbidity sensor over-ranged and the sensor response was no longer proportional to the SSC for several hours at the flood peak. In the lab experiment, the sensor flatlined once it over-ranged in the silt and clay suspension between ~4 and 40 g/l, but then between 40 and 62 g/l the response was non-linear with SSC (the cyan line in Figure 12 A). Consequently, a single turbidity value can correspond to at least two different SSCs.

When a high percentage of light is scattered or absorbed by suspended sediment (or other matter) and less light reaches the detector, the sensor will output lower values than expected. Figure 12It is useful to know the sensor response above the stated maximum when selecting a sensor because there is quite a range (Figure 12). This information is seldom in sensor brochures or manuals but can sometimes be found in application notes.

Some sensors offer a larger range by placing an additional detector adjacent to the light source (see Figure 5 C), which allows the instrument to measure in highly turbid water. When a sensor has dual detectors (typically side scatter and backscatter, see Table 5) the response after the transition between methods may continue to be approximately linear (blue line Figure 12 B) or become non-linear (yellow line in Figure 12 B). However, each dual detector sensor uses a different approach; some may switch between the detectors, others use a ratio, and much of the information is proprietary.

For example, the Seapoint STM-S Extended Range sensor outputs two signals, one for the lower range (to ~1000 FTU) and another for the high range (to ~50000 FTU). Having two detectors ensures the sensor maintains a unique non-linear relationship between turbidity and SSC up to 50 g/l (clay; Seapoint STM-S brochure).

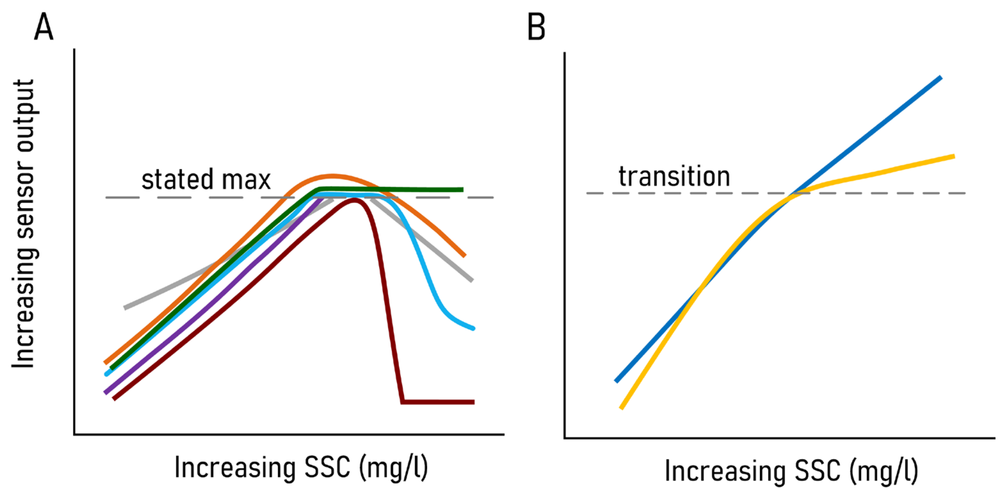

Figure 12. Generalised schematic of sensor responses versus suspended sediment concentration (after Voichick et al. 2018, Bakker et al. 2024). (A) Differing sensor output in response to over-ranging at the stated maximum range. (B). Differing sensor responses to the transition between sensing method (such as SS to BS, after Bakker et al. 2024).

CASE STUDY 1 – LOW RANGE SENSORS FOR VISUAL CLARITY

Recently NIWA worked with Mangatoatoa Marae (south of Kihikihi, Waikato) on a recreational water quality project named WaiSpy (an MBIE Endeavour Fund Smart Idea). As part of the project, two turbidity sensors were operated side by side on the Puunui River for ~5 months. The YSI EXO sonde, with a turbidity sensor (side scatter 90°, 860 nm), was installed in December 2023. A second turbidity sensor, a Sea-Bird NTURT (backscatter 124°, 700 nm, fitted with a ZebraTech HydroWiper), was installed in December 2024 alongside the EXO sonde (Figure 13).

A B

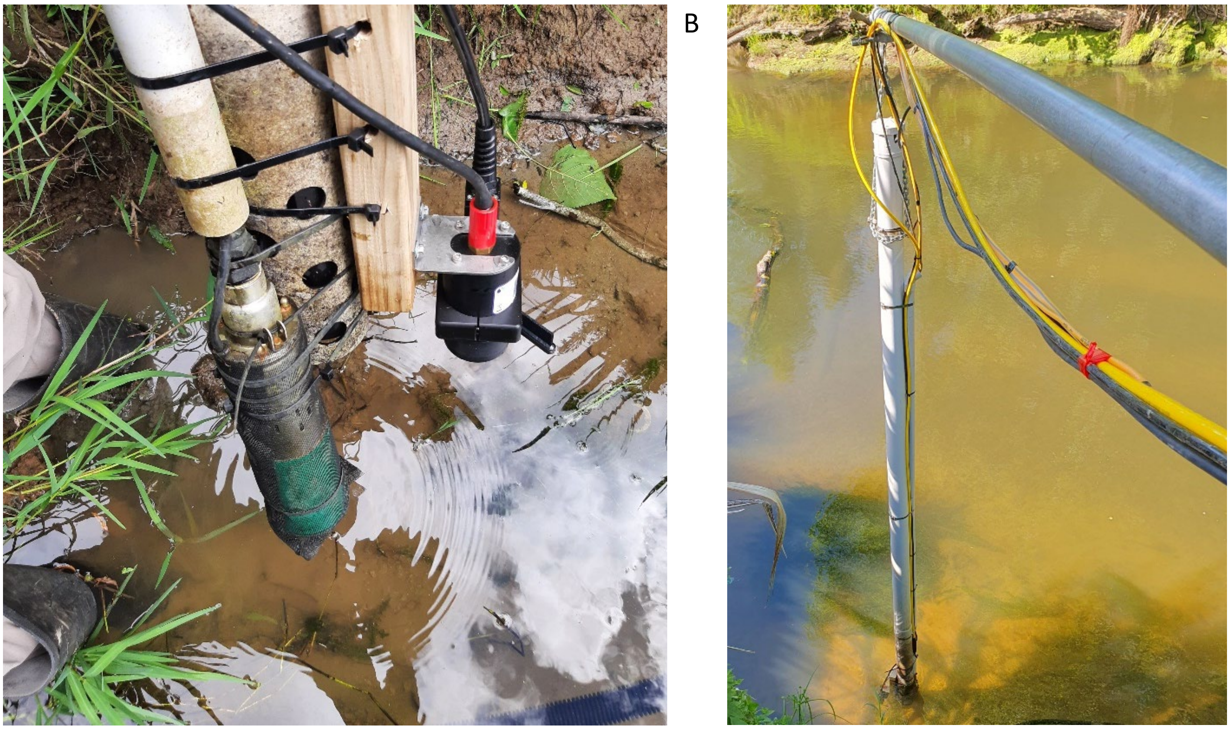

Figure 13. Puunui River sensor deployment. (A) YSI EXO sonde in PVC pipe with holes (centre) and Sea-Bird NTURT with ZebraTech HydroWiper (right) [Gareth van Assema, NIWA]. (B) Sensors deployed from scaffolding pipe due to unstable sandy bank [James Sukias, NIWA].

During the monitoring period, rainfall was below average and the river was clear and shallow. During a period of low water level, the YSI EXO sonde turbidity sensor housing and guard became clogged with sediment, so three shorter periods of good quality data are compared (Figure 14).

The two turbidity sensors responded similarly to changes in suspended particulate matter in the Puunui River. The sensor values are not numerically comparable, so the normalised sensor values are plotted as a time series (Figure 14 B). The two sensors respond similarly to changing suspended particulate matter across the range of flow conditions (Figure 14 A) – from very low flows (early April 2025) to a high flow event (May 2025). Some spikes in the sensor record, particularly mid-afternoon, are the result of swimmers stirring up the bed sediment. The Sea-Bird sensor is more sensitive to this localised activity as it was deployed at this site without an external housing (Figure 13 A) and was averaging 60 values over a minute.

A strong linear relationship ($r^2 = 0.985$) between the sensor values is evident over the range measured (approximately 70–4300 mV for the Sea-Bird NTURT and 0–120 NTU for the EXO turbidity sensor; Figure 14 C). Above 4300 mV, as the Sea-Bird approaches the top of its range (4980 mV), there are only six concurrent data values due to a power failure during the May 2025 event.

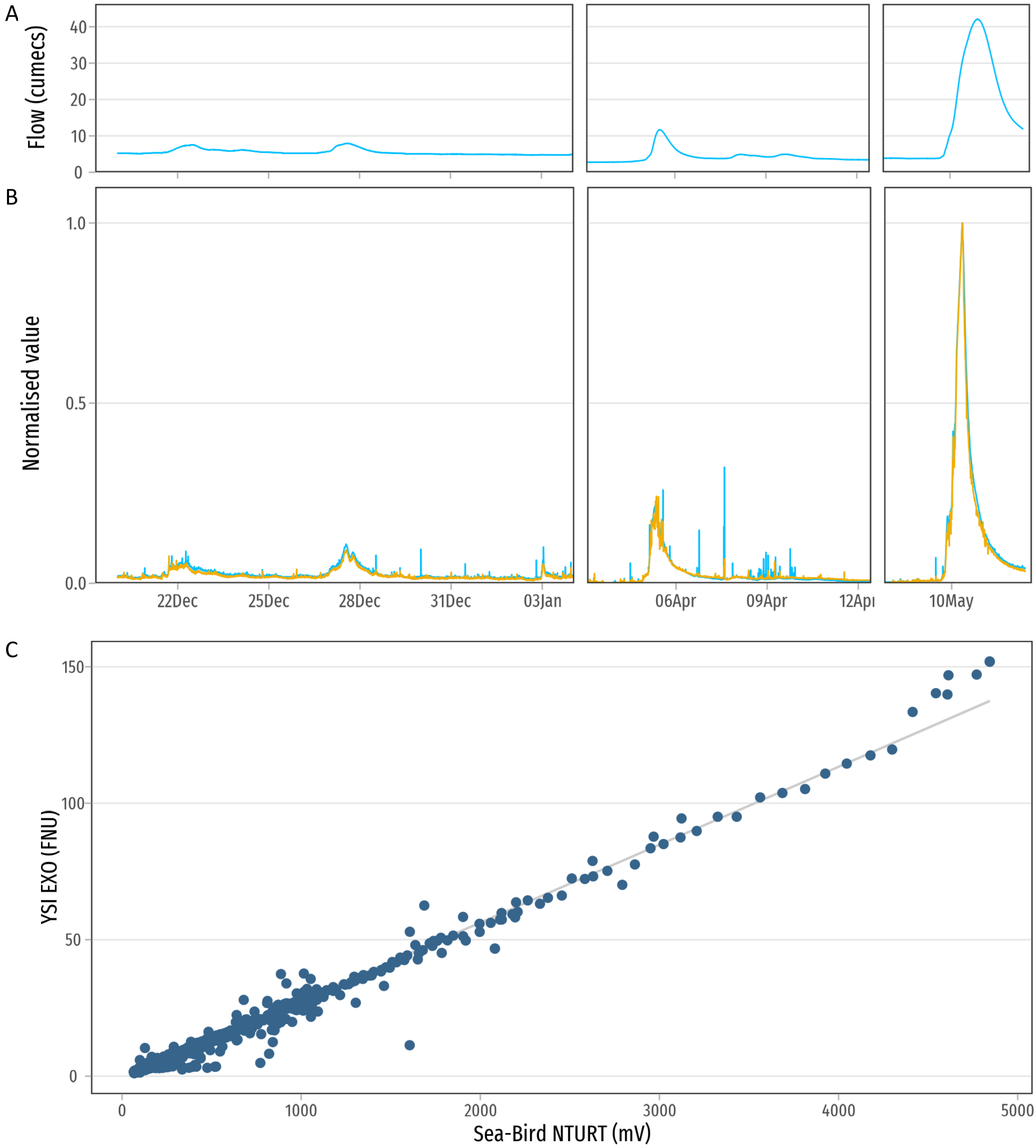

Figure 14. Sensor values for the Puuniu River, Waikato, during the 2024–25 summer. (A) Discharge at Barton Rd [WRC]. (B) Normalised values for Sea-Bird NTURT (blue line) and EXO sonde (orange line) sensors. (C) Scatterplot of values shown in the plot above in sensor units (n = 4059).

This case study demonstrates that:

- While the two sensors operate at different light wavelengths and have different optical geometries, they respond similarly to changing suspended particulate matter.
- At this site, during this monitoring period, the strong linear relationship between the sensors across the range of conditions allows gaps in either dataset to be filled by data estimated from the other sensor.
- For visual clarity monitoring during the summer bathing season, either sensor is suitable for developing a surrogate relationship for the Puuniu River.

CASE STUDY 2 – TWO SENSORS IN A TIDAL RIVER

ECan monitors the Kaiapoi River in Kaiapoi, North Canterbury, to gain information on the river's ecological health. The Kaiapoi River is a low-gradient tributary of the Waimakariri River, and saline intrusion events occur. In early 2025, ECan installed a Chelsea Technologies TriLux (unknown optical geometry) alongside an In-Situ Aqua TROLL (side scatter 90°). The TriLux was fitted with a ZebraTech Hydro-Wiper and the Aqua TROLL had a central wiper.

The sensors are not side-by-side but sit at different depths in the river. The Aqua TROLL sits about 1 m below the TriLux and is more affected by the salt wedge on a high tide (Figure 15).

A B

Figure 15. Kaiapoi River water quality sensors. (A) Sensors deployed on a footbridge pier [Hamish Carrad, ECan]. (B) Servicing the Chelsea TriLux with ZebraTech Hydro-Wiper by kayak [Hamish Carrad, ECan].

Despite being at different depths, the two turbidity sensors responded similarly to changes in suspended particles in the Kaiapoi River. The sensor values are not numerically comparable – the values output by the TriLux are typically 2 to 3-fold lower than the Aqua TROLL values (Figure 16) at this site. During the high turbidity event starting on 30 April, both sensors responded to the changing suspended particles. The TriLux values were initially spikey for a period of 2 hours (minimum spike ~75 and maximum spike 400 FTU). The Aqua TROLL values spiked between ~200 and ~350 FNU over a ~12-hour period (Figure 16).

While the sensors output similar turbidity patterns, they have different optical configurations which means they will be sensitive to different components of the transported suspended particles at the different depths. The TriLux light source is at 685 nm, which may make it more sensitive to smaller particles, while the Aqua Troll is a side scatter sensor with a light source peak at 855 nm.

After 7 May 2025, the Aqua TROLL wiper was unable to maintain a clean lens and the background turbidity ramped up (Figure 17) to values higher than during the late April high flow event. The sensors were cleaned on 17 May.

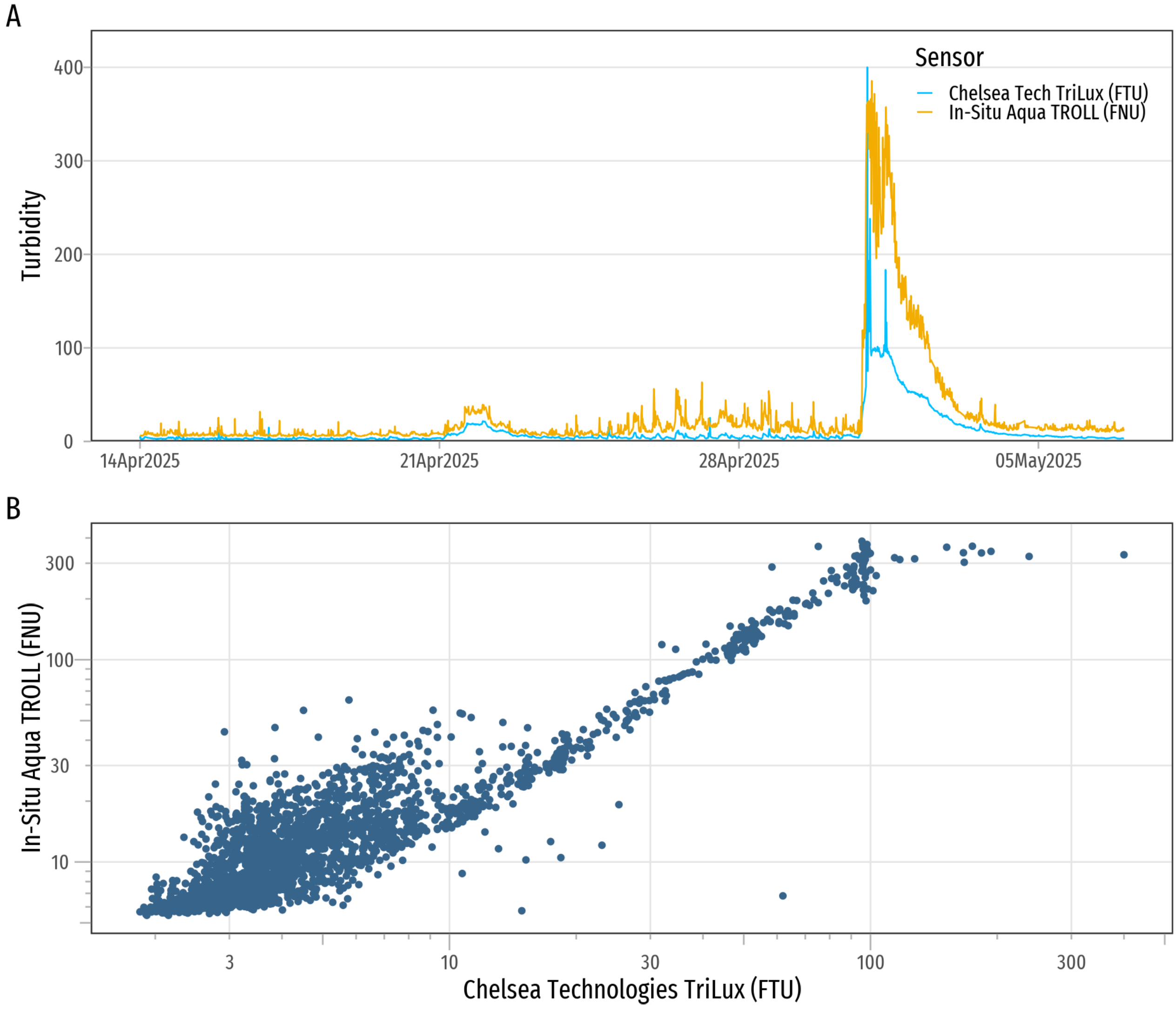

Figure 16. Raw turbidity recorded at two depths on the Kaiapoi River over the period 14 April 2025 through to 7 May 2025. (A) Time series of the data across a range of conditions. (B) Scatterplot of values (n = 2305).

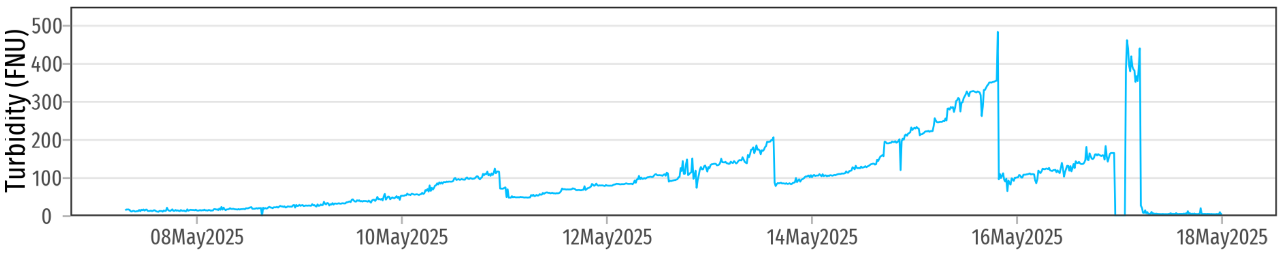

Figure 17. Raw turbidity recorded by the In-Situ Aqua TROLL for the period 7–18 May 2025 showing repeated fouling and sloughing events.

This sensor comparison demonstrates that:

- These two sensors output different numeric values – the Aqua TROLL values are ~3 times higher than the TriLux values.
- In this tidal river, during this overlapping data period, the strong linear relationship between the sensors would allow gaps in either dataset to be filled by estimation from the other sensor.
- A robust wiper is required at this site to ensure that the sensor face is clean and good quality data can be collected.

KEY QUESTIONS TO CONSIDER

Each candidate optical turbidity sensor should be considered against the monitoring objectives and deployment requirements (Table 2–Table 4). Lack of numeric comparability makes turbidity and backscatter sensor selection complex. 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
For use as a SS surrogate, are SSC high after rain?	- Sensor lenses may be damaged. - Sensor may over-range	- Select a sensor with a sapphire glass window (Mohs hardness of 9). - Select a sensor with dual detectors (side scatter and backscatter).
For use as a visual clarity surrogate, is visual clarity high?	- Low resolution data because a small part of sensor range is used.	- Select a turbidity sensor with a low range or gain settings (see Table 5).
For use as a TP surrogate, does total phosphorus dominate P transport?	- Weak relationship between turbidity and TP.	- For rivers, analyse TP:DRP ratios during events and under baseflow conditions. If particulate P dominates during events, turbidity may be a useful surrogate.
Does the water have a high organic concentration or colour?	- Colour may lower the values. - Dissolved organic matter may foul the lens.	- Select a side scatter sensor with a near infrared LED (i.e., ISO 7027-1 or similar). - 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 particle size coarse (i.e., medium silt to sand)?	- Unreliable values. - Unreliable SSC load estimates.	- Use a sensor with optical backscatter capability. - Check out different sensor technologies (e.g., acoustic and laser diffraction sensors). This is a challenge for large rivers, particularly those which carry sediment from landslides.
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. 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 sensor body clean by wrapping in duct tape. 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 and marine sites, select a titanium sensor casing (if available).
Are bubbles likely to be an issue?	- Bubbles increase apparent light scatter and increase sensor output.	- Consider the deployment site carefully. Avoid installing the sensor in turbulent water (e.g., below rapids). Check if seasonal macrophyte growth could result in bubbles.

Data specifications

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

Key questions	Consequences	Possible solutions
What sensor performance is required for study?	- The sensor may not be able to measure at the resolution required over the required range.	- Consider the trade-offs between range and fouling management options. - Decide if the sensor needs to meet a data standard. For example, the current NEMS Continuous Turbidity V2.0 for rivers, estuaries and lakes limits users to sensors which meet ISO 7027-1 (see Table 1).
What values does the sensor output when it over-ranges?	- Data values returned may be incorrect.	- Find out how the sensor behaves when over-range or outside its linear range. Some sensors return NA, while others may flatline or return negative values (see Figure 12).
What challenges might non-linear sensor output create?	- Difficulties interpreting data.	- Consider how to collect data for a high-resolution calibration in the non-linear range. - Consider if a lab calibration with dried sediment will be suitable. Do you have a system to resuspend sediment? NIWA Hamilton has a calibration tank. Check
What is the required observation interval?	- Sensor may not be able to take measurements at required frequency.	- Check observation interval exceeds sensor measurement interval.
What units will you output?	- Incorrect units stored.	- Check if you can output raw units (e.g., mV or counts) so future data users are not tempted to compare turbidity values from different sensors.
What approach will you use to verify the sensor's output?	- Method selected causes additional work or cost.	- Use of lab turbidity will downgrade the highest NEMS quality code to QC500 (NEMS 2025b). - Can you purchase and operate the same sensor make/model for verification (e.g., install YSI EXO and use a YSI EXO as a field meter)? Using a different make/model will require you to develop a relationship between the two sensors.
How frequently will does the sensor need calibrating?	- Frequent calibration results in higher cost.	- Consider buying a more expensive sensor with a lower calibration frequency (Table 5). - Consider using the factory calibration and keeping the sensor face clean. - Choose one calibration standard and stick with it to meet stationarity requirements. Check if your organisation's workplace safety policy allows the use of formazin; if it doesn't, carefully select an alternative. - Consider the cost of calibration, including the shelf life of standards. - Consider alternatives to using liquid standards to check for lamp aging and sensor window degradation. Solid state standards are commonly used in water treatment and are commercially available (e.g., Endress and Hauser CUY52 at ~4 NTU for 45 ° sensor face, TriOS TTurbCal ~790 NTU for 45° sensor face, Pyxis T-Cal range for 36 mm diameter flat face sensors 0.1, 8, 25, 600 NTU white and infrared light). Solid state standards are best used in the lab where it's clean and at a near constant temperature.
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 (e.g., Hach Solitax, YSI EXO) output averaged data. For example, the Hach Solitax takes readings continually at 1 Hz (1 s) and averages the data over a 0–300 s period.
Are real-time data required for decision-making?	- Data delivery requirement not met.	- Use telemetry.
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.
Is the site a long-term operation?	- Replacing a sensor could be costly (in terms of surrogate relationships). - Long service times if sensor must return to manufacturer.	- 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 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.
Will the sensor be buried by sediment or debris?	- Data gaps. - Wiper wear.	- Check if bed sediment is mobile. - Use a deployment method which enables seasonal adjustments in sensor position. Use guard stakes 2–3 m upstream to collect debris.
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. - Select a sensor with a removable mounting rod system (e.g., fibreglass rod) which makes installation in a PVC pipe simpler (compared to a clamp).
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 floods. Sensors can be buried during floods in rivers with high sediment loads. - Consider how water level may change seasonally and how to mount the sensor to overcome changing water levels. If possible, schedule the install during summer low flows so the housing can be secured and set at a low level.
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, Turner Designs Cyclops-7 on a PME logger, or Seapoint on RBRsolo³ Tu sensor.
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 if additional equipment (e.g., new logger, solar systems) required. - 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 samples across the full range of conditions. - Data loss due to fouling, burial, sensor loss.	- Telemeter data and metadata to enable daily checking of sensor performance and issues.
How will you develop the surrogate relationship?	- Unable to develop surrogate relationship due to a lack of representative samples.	- Choose a method to develop the surrogate relationship. Decide whether a field- or lab-based method is appropriate. For example, use field measurements of visual clarity to develop a site-specific surrogate relationship. Lab-based methods could include discrete sample analysis (TP or SSC) or use of deposited sediment in a resuspension tank (SSC). - In rivers, consider using an automatic sampler to extend verification dataset beyond baseflow conditions.
Do you have the technical expertise to manage the sensor?	- Frustration, wasted time, poor data quality.	- Pre-deployment checks and deployment should be well planned.
Do you have the level of technical expertise required to create site-specific relationship?	- Unable to use turbidity as a surrogate.	- Consider if you have access to resources for advanced data processing (R/python/MatLab). - If in-house expertise is not available, check if an external provider is available.
What is the level of technical expertise available in New Zealand?	- Time lost due to slow service from overseas.	- Can the NZ sensor rep offer technical help beyond the basics? - 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.	- Test drive the software interface. - Request training and ongoing support as part of your purchase.

SENSOR COMPARISON TABLE

Table 5. Comparison table of optical turbidity sensors used by the workgroup (in 2024). At least one sensor users contributed to each column. All costs in NZD. See notes below the table for detailed additional comments on each sensor. To evaluate a different sensor, gather equivalent information from brochures, manuals, manufacturers and other users.

Feature	Chelsea Tech TriLux	In-Situ Aqua TROLL	Ponsel	Turner Designs Cyclops 7F [t]	WTW VisoTurb	YSI EXO turbidity	Yosemitech 511-A	Hach Solitax	Sea-Bird ECO NTU [sb]	Seapoint
Cost (excl. GST) $ <2K, $$ 2K–5K, $$$ 5K–10K, $$$$ >10K	$$$	$$+($$$$ sonde)	$$	$$/$$$ [t]	$$$+($$ controller)	$$+($$$$ sonde)	$	$$$$+($$$ controller)	$$$$ ECO V2	$$
Sensor basics										
Optical geometry (SS side scatter, BS backscatter, MS multi-scatter)	not specified	SS (90°)	SS (90°)	SS (90°)	SS (90°) [w]	SS (90°)	SS (90°)	SS (90°) & BS (140°)	BS (124°) [sb]	MS (15–150°, 90° peak)
Wavelength	685 nm	855 nm	850nm	850 nm		860 ± 15 nm	~860 nm	860 nm	700 nm	880 nm
Number of detectors	1	1	1	1	1	1	1	2	1	1
Reference detector		Yes								
Sensing volume or clearance distance		Limited by restrictor	Side 5 cm	Shade cap	Field 10 cm, side 10 cm	Limited by guard		Field 30 cm, side 10-50 cm	1 cm³ at 1 cm	5 cm
Face angle	Flat	Flat	45°	Flat	Flat	Flat	Flat	45 °	Flat	Flat
Window material	Sapphire glass	Sapphire glass	Quartz		Sapphire glass	Sapphire glass	Sapphire glass	Sapphire glass	Optical epoxy	Epoxy
OEM	Yes	Yes		Yes		Yes		Yes	Yes	Yes
Integration partners				Numerous [t]						Several [sp]
Sensor versions					Yes ViSolid			Yes, high range	Many options	Yes STM-S
Casing	Ti	Plastic	Plastic	SS, Ti or plastic	SS	SS	SS	SS, plastic	SS, plastic	Plastic
Max depth (m)	2000	100–250	50	600	100	250	30	SS 60, plastic 10	300	6000
Range (nominal)	0–100 or 0–400	0–4000	0–4000	0–1500	0–4000; SiO_2 0–4 g/l	0–4000	0.1–1000	0.01–4,000; SiO2 0.001–50 g/l	0–3 or 0–5 m^{-1}	0–1000
Gain settings	2			3	2				5	4
Minimum observation interval	0.1–3 Hz							1 s averaged at 1 min		0.1 s
Power (volts)	11–24 V	12 V	5–12.2 V	3–15 V	Requires 24 V or 240 V controller	12V or battery	DC 12–14V	24 V	7–15 V	7–20 V, low power draw
Battery option		Yes (D cell)	No	No	No	Yes (D cell)	yes	Yes, 24V	Yes	Yes (partners)
Wet-mate connector	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes
Data output options	Raw or V, FTU if calibrated	NTU, FNU	FNU, NTU, mg/L		NTU, FNU	Raw, FNU, NTU (legacy)	Raw	NTU, FNU, mg/l if calibrated	mV or Counts	mV
Output comms protocols	RS-232 (or SDI-12 [at])	SDI-12 or Modbus	RS-485, SDI-12		0–20mA or Modbus	SDI-12 via DCP, RS-232, Modbus	Modbus RS-485	Analog 4–20mA (or Modbus [h])	RS-232, analog or digital	0–5 V
User experience										
Stability	Good	OK [at]	Good	Very good	Good	Very good	Good	Good	Good	Good
Sensitivity	Good	OK		Very good	Very good			Good	Good	Good

Feature	Chelsea Tech TriLux	In-Situ Aqua TROLL	Ponsel	Turner Designs Cyclops 7F [t]	WTW VisoTurb	YSI EXO turbidity	Yosemitech 511-A	Hach Solitax	Sea-Bird ECO NTU [sb]	Seapoint
Performance overall	Reliable	OK		Reliable	Good	Reliable	Good value	Reliable	Reliable	Reliable
Sensor-to-sensor variability	Minor	Unknown	Minor	Minor	Minor	Minor	Yes	Minor	Minor	Minor
Reliability	Very good	Good	Good	Very good	Good [w]	Very good	Good	Very good [h]	Very good	Good
Real-world lifespan	6+ y	4+ y	4+ y	6+ y	1.5 y [w]	6+ y	1.5 y	3+ y	6+ y	6+ y
Durability with field use	Robust	OK [at]	Robust	Robust	Robust	Robust	Robust	Robust	Robust	Robust
Anti-fouling options available from manufacturer	None	Central wiper	None	None	Ultrasonic [w]	Central wiper	Rubber wiper	Wiper	Wiper or unwiped	None
Interface/controller required	Needs logger	No		Needs logger	Yes, many models	Logger interface required	Needs logger	Yes	Needs logger	Any logger
Calibration (cal) required	Factory cal Validate	Factory cal (6 pt, 0– 4000)	Factory cal Validate	Yes	Yes, not user friendly	Yes	Yes	Yes	Factory cal Validate	Yes
User control of averaging	User control	User control [at]	User control	User control	Yes	Some user control	Yes	Min 3 sec, 1 min av. output	4–8Hz; user control	User control
Setup software user-friendliness		Good mobile app VuSitu			Use controller to cal. Complex to do with a PC.	Good	Need to program	Controller menu, easy to follow	ECOView. Old school but effective [sb]	No software
Data offload options		SD card, phone, PC			Via logger			USB possible from controller	Depends on model	Controlled by logger
Manual usefulness	OK	Good, user-friendly			Good	Good	Poor	OK but has industrial focus	In depth	OK
NZ support options	Other users	NZ sales			ENVCO [w]		None	Hach Auckland can service	Imbros in Hobart are Sea-Bird agents	Other users
Free online training	–	Videos, tech notes	–	–	–	YSI Uni, tech notes, webinars	–	–	Sea-Bird Uni, tech notes, webinars	–

[at] In-Situ Aqua TROLL notes: (1) Wiper not always enough but also cleans the sensor protector/case. (2) Data can be noisy and spikey. (3) Had some sensors fail after knocks. (4) User can set averaging (Linear Average) for 2– 600 values.

[h] Hach Solitax notes: (1) ViSolid – backscatter (120 °) and side scatter (90 °) and has a range up to 300 g/l SiO_2. (2) Does require an annual–biannual service at the Hach agent to get the wiper seals replaced. (3) Needs controller with a digital module for Modbus output.

[t] Turner Designs notes: (1) The Cyclops-7F model was discontinued in Mar 2025. The C-FLUOR model has different specs. Cost is for C-FLUOR. (2) Turner Designs have many integration partners, including PME, Eureka, RBR and Hach Hydrolab.

[sb] Sea-Bird ECO NTU notes: (1) ECO range was discontinued in Mar 2025 and replaced with ECO V2 range with a standard optical geometry (124 °). The ECO V2 NTU sensor has a range of 0–1000 NTU and the optical angle is the same as the ECO range (124 °). The ECO V2 sensor range will be less expensive than the ECO range. (2) Major software changes are available – Fathom replaces ECOView.

[sp] Seapoint STM notes: (1) Seapoint has several integration partners, including RBR and Aquatec. (2) Linear range to ~1250, above that non-linear to 4000.

[w] WTW VisoTurb notes: (1) Reliable sensor but ultrasonic cleaning board tends to fail after 18 months. (2) Sensors were sent to Australia.

[y] Yosemitech notes: (1) Good low-cost option but not interchangeable so risky for long-term project. (2) Manual not a user-friendly interface - user needs programming skills. (3) Works with mayfly Arduino but no specific user interface.

FOULING MANAGEMENT

The workshop participants identified fouling as the key factor reducing sensor performance and recommended actively managing fouling on all optical scattering sensors. Even a slight buildup on a lens will degrade the sensor's ability to return turbidity values and will reduce accuracy. A light beam weakened by fouling of the lenses will be attenuated by fouling and result in reduced scattering. In addition, the scattered light may not reach the detector.

Wipers

The workgroup recommended using robust brush wipers where possible. Brush wipers operate well on many unattended turbidity sensors across New Zealand – they are effective, and the brushes are easy to replace. Some sensors come with wipers attached (e.g., Hach Solitax; see Figure 18 C), whereas other manufacturers offer the option of a wiped or non-wiped sensor (e.g., Sea-Bird ECO NTU; see Figure 18 D). Multiparameter sondes come with proprietary wipers, which mostly are adequate (see Figure 18 A and B). Refer to the Fouling Management section in the Dissolved Oxygen Sensor Selection chapter for more guidance on selecting a wiper.

A

[Julie Grant, ECan]

B

[Adrian Aarsen, NIWA]

C

[Andrew Hughes, NIWA]

D

[Iain MacDonald, NIWA]

Figure 18. (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 had performed well prior to this deployment. The sonde is now operated without an open guard (minus bottom cap) during summer. **(B) Light fouling on a YSI EXO sonde on the Mataura River.** While the turbidity sensor (right of the central wiper) is clean, the worn and splayed wiper brush bristles are outside the wiper guard and it contains debris. **(C) Fouling on a Hach Solitax on the Hoteo River.** While the lens has been wiped, there is filamentous algae draped across the lens. **(D) Fouling on a Sea-Bird ECO FLNTU on the Firth of Thames.**

Ultrasonic cleaning

Some sensors designed for industrial applications (e.g., wastewater) come with ultrasonic cleaning. Ultrasonic sensor cleaning typically involves using a high-frequency sound wave to form, grow and implode tiny bubbles (cavitation), which forms shockwaves that dislodge contaminants from the sensor surface. While this cleaning method can work well, failure of the ultrasonic system can damage the sensor (see Table 5).

Biocides

In marine environments, where macro-fouling is heavy and service intervals lengthy, biocides are usually required. Chlorine or bromine solutions can be used to reduce fouling; for example, NIWA's Squirtek squirts bromine for 15 s every 3 hours. A more detailed discussion on the use of biocides (and alternatives) to manage fouling can be found in Delgado et al. (2021).

Copper

Copper can slow the growth of biofouling by releasing dissolved copper ions into the water (see sensor face in Figure 18 D). Some manufacturers supply copper guards or mesh, and these may offer some protection and slow the fouling rate. Copper tape can also be used.

Antifouling paints

Paints designed for boat hulls can be used to slow fouling on sensors in coastal waters (sensor body in Figure 18 D). Paints such as Pettit Hydrocoat or International Trilux 33 contain copper and/or biocides, and degrade over time. 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 sensors and 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:

- Design the deployment to minimise debris buildup on the wiper which could then scratch the lenses.
- In rivers, orient the wiper rest position downstream so that debris does not trail in the optical window.
- 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 been stuck over the lens.
- Create cleaning routines which include a check or test.
- Actively maintain the fouling system as there will be seasonal variations. For example, during summer low flows, it may be challenging to maintain clean lenses.
- The shells of NZ mud snails (*Potamopyrgus antipodarum*), pumice or sediment caught in wipers can scratch sapphire glass lenses.

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.

Preparing for a sediment gauging on the Mataura River to build a turbidity-SSC relationship for the four turbidity sensors in the PVC housings [Andrew Willsman, NIWA].

Lake Hayes monitoring buoy with profiler package including a turbidity sensor [ORC].

Monitoring platform on a coastal lagoon with Chelsea Technologies TriLux [Alex Ring, ECan].

YSI EXO sonde installed in a small stream, Purukohukohu [Andrew Hughes, NIWA].

Short-term bridge pier deployment of a YSI EXO sonde [Garry de Rose, NIWA].

Side-by-side sonde deployment (YSI EXO and In-Situ Aqua TROLL) on Mangati Stream, Taranaki [TRC].

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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.

NIWA
Taihoro Nukurangi