HIGH FREQUENCY WATER QUALITY USE CASES & SYSTEM DESIGN

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 and Andrew Hughes with contributions from the Use Cases Workgroup. The workgroup included staff from Auckland Council (AC), Environment Canterbury (EC), Greater Wellington Regional Council (GWRC), Otago Regional Council (ORC), Waikato Regional Council (WRC), and NIWA, and they shared their knowledge and expertise via a survey, workshop and an online forum, contributed case studies and reviewed this document. The input of workgroup members and additional document reviewers is gratefully acknowledged. This report was reviewed by Graham Elley (NIWA), Jenni Gadd (AC), and the workgroup. This report was edited by Andrea Graves.

NIWA Report No: 2025316HN

Citation

McKergow, L., Hughes A. (2025) High Frequency Water Quality Use Cases and System Design. *High Frequency Water Quality Monitoring Guidance*. Envirolink Tool prepared by NIWA. NIWA Client Report 2025316HN.
http://www.envirolink.govt.nz

Front cover: Photo montage (top to bottom): Lake Wānaka WQ buoy [Nick Boynes, ORC]. Sonde and beam transmissometer at Waikoropupū Springs [Mark Gall, NIWA]. Rangatahi III alongside WaiQTahi on the Firth of Thames [Rod Budd, NIWA]. Nitrate sensor servicing on the Mararoa River, Southland [Andrew Willsman, NIWA]. Back cover: Photo montage (top to bottom): Lake Grasmere/Ōpōreaiti WQ monitoring buoy [Hamish Carrad, Environment Canterbury]. DO sensor verification check on the Opihi lagoon [Julie Grant, Environment Canterbury]. DO monitoring on the Rees River, Otago [Emily Olson, ORC]. Divers servicing a simple HFWQ buoy on the Firth of Thames [Iain MacDonald, NIWA].

CONTENTS

ABSTRACT

The commercial availability of high frequency water quality sensors provides an opportunity to explore water quality dynamics at time scales of minutes to hours. This report focuses on the uses of HFWQ sensors for environmental decision-making. We present a summary of current HFWQ sensing use cases for lake, river and estuary monitoring in Aotearoa New Zealand. The report explores the benefits and challenges of adopting HFWQ sensing and the information gains it can deliver. We provide guidance on initial choices around monitoring system design, particularly the decision to switch from routine discrete sampling and field measurement to HFWQ sensing. The report includes three case studies which demonstrate how regional councils are using HFWQ monitoring to support decision-making.

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. Fortunately, high frequency water quality (HFWQ) sensors can be deployed on site to measure environmental indicators (e.g., nitrate, dissolved oxygen) and provide detailed insights into water quality dynamics at scales of interest (minutes to hours). However, these HFWQ sensors can create different 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 operational data collection systems, and (3) well thought-out methods for managing raw data and converting it into knowledge for making decisions.

This report provides guidance on HFWQ use cases and initial system design. It sits alongside guidance reports on HFWQ Resourcing, Sensor Selection, and Automated Anomaly detection as part of the *High Frequency Water Quality Monitoring Guidance* project.

PURPOSE AND SCOPE

This report provides information on the use of HFWQ sensors for decision-making and offers a process for users to evaluate and design robust monitoring systems. It will help support users to confirm whether collecting HFWQ data is justified and required, and if it is, help staff to justify the use of HFWQ sensors prior to starting more detailed planning.

This report does not address developing or writing the management objectives that HFWQ sensing can inform. It assumes that management objectives have been written, a conceptual model of the system exists, and that water quality data is required to support decision-making.

RELATED RESOURCES

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

- Think pieces and editorials on the value of HFWQ such as after Kirchner et al. (2004), Campbell et al. (2013), Blaen et al. (2016), Mantzouki et al. (2018), Jordan and Cassidy (2022), Westerhoff et al. (2022) and Rozemeijer et al. (2025).
- Several recent detailed reviews on HFWQ are available, reflecting the increase in the number of research articles on HFWQ sensor applications since 2015. Key review topics include:
    - catchment science (e.g., Rode et al. 2016, Bieroza et al. 2023),
    - stream metabolism (e.g., Bernhardt et al. 2018, Jankowski et al. 2021, Battin et al. 2023),
    - optical scattering and turbidity as a surrogate (e.g., Kitchener et al. 2017),
    - high frequency nitrate (e.g., Burns et al. 2019),
    - lakes (e.g., Meinson et al. 2015, Rogora et al. 2023),
    - estuary science (e.g., Bailey et al. 2019).
- Books on designing water quality monitoring systems and statistical analysis such as Ward et al. (1991), USDA-NRCS (2003), Timmerman et al. (2010), and Helsel et al. (2020).
- Classic texts on decision-making (e.g., Hammond et al. 2015).

SUMMARY

The commercial availability of water quality sensors provides an opportunity to explore water quality dynamics at time scales of minutes to hours. It is tempting to deploy available sensors to satisfy our natural curiosity about water quality variability. A widely held expectation is that emergent Internet of Things (IoT) technologies will enable high frequency monitoring of water quality everywhere. However, the reality is that many challenges — biofouling, varying environmental conditions, sensor placement and installation, technical problems, sensor limits and limitations — reduce data quality. These challenges can all be managed with a combination of thorough planning and careful sensor operation and maintenance, but that requires sufficient resourcing.

This report aims to help support water quality sensor users to confirm whether collecting high resolution temporal data is justified and required, and if it is, to help regional council and other monitoring organisation staff to evaluate the use of sensors against alternatives, prior to starting more detailed planning.

This report focuses on the use of water quality sensors to collect data over time at a fixed site. For example, a river site to measure the quality of water flowing past, or a monitoring buoy in a lake or estuary with sensors installed at several depths. Multiple fixed sites can increase the volume of spatial data and is necessary to inform some decision-making.

In-situ water quality sensing systems will almost always cost more than discrete sampling systems, but with time, the cost per observation should be lower. To reliably collect data of known quality, steps must be regularly taken to check a sensor is working as it should - before it is installed, while it is installed, and after it is retrieved. These checks can be time consuming, but they are essential to ensure the sensor is collecting data which represents the local water body conditions.

Delivering high-quality data using in-situ water quality sensors requires a high level of technical expertise and thorough procedures. While some water quality sensors are straightforward to operate, many are complex, so expert users require expert-level technical skills. For example, optical nitrate sensors operate well in clear water, but in turbid water their operation is less certain; they may not be able to reliably measure nitrate in rivers during high flow events. In addition, technical expertise is required to ensure that the sensor is installed well so that it provides representative measurements and can withstand environmental conditions (such as floods, waves or changes in water level), and damage by debris or vandals. The time demands on technical staff to manage and troubleshoot sensor systems and sensor data can be large. Data volumes (often > 35,000 values per year per sensor) can be overwhelming if good data management processes and procedures are not in place before data collection starts.

Managing the impact of biofouling on in-situ water quality sensors is also critical for maintaining data quality. Just like the hull of a moored boat, sensors offer a new habitat for algae, barnacles, snails, and other living things. Fouling can prevent a sensor from collecting data that represents the actual water quality over time. For example, a dissolved oxygen sensor with algae growing on the sensor face could correctly be recording 170% saturation as a result of oxygen produced by the algae being trapped on the sensor face, when the actual dissolved oxygen of the surrounding waters is substantially different.

Given resourcing constraints, the user’s goal must be to inform decision-making with reliable, high resolution temporal water quality data that represents the surrounding waters. Sometimes, the data need is driven by regulations (e.g., legislation, regional plans, resource consents) which specify that in-situ sensors are required to measure water quality continuously. This is often the case for indicators which show daily cycles, such as temperature or dissolved oxygen. More often, decisions using water quality sensor data are made weeks or years after data is collected. This data is often collected during investigative studies set up to help councils better understand the rivers, lakes and estuaries they are responsible for managing. The data is often used to understand the impacts of weather events, and seasonal or annual variability. In-situ sensors can deliver data when conditions are unfavourable or unsafe for fieldwork, such as overnight or during weather events.

Three case studies demonstrate the use of high frequency water quality (HFWQ) data for decision-making:

- *Case Study 1* shows how consent data is being used to operate a low oxygen warning system to ensure stakeholders can prevent tuna/eel kill events in the Whangamarino Wetland. Waikato Regional Council (WRC) combine resource consent dissolved oxygen data collected in real-time with other data and weather forecasts to warn stakeholders of expected zero dissolved oxygen conditions.
- *Case Study 2* shows how two buoys operated in the Firth of Thames by Waikato Regional Council can meet multiple delayed data uses: detect change in the state of the environment, improve system understanding, and inform model development.
- *Case Study 3* illustrates how one of the data uses for the water quality sensors on Lake Hayes is to warn Otago Regional Council of changes in suspended algae. These changes in algal indicators may trigger sample

collection for lab analysis to identify if the algae are harmful or toxic, and they help better manage swimming risk in near real-time. In addition, measuring the nutrient and sediment loads entering Lake Hayes from Mill Creek with in-situ water quality sensors helps Otago Regional Council understand the balance between new inputs and resuspension of contaminants from the lake bed.

Sometimes in-situ water quality monitoring programmes are not cost effective or not yet feasible. There are no benefits to installing water quality sensors when low-frequency data are adequate or required by regulations. And for some indicators, water quality sensors are not yet mature enough for unattended deployments (e.g., total nitrogen, total phosphorus).

In rivers, lakes, and estuaries, spatial and temporal variability in water quality can be high, and the challenge of system design is to represent this variability. For example, water quality in rivers varies with different sources at different locations, varying flow, in-stream nutrient cycling, and local conditions (e.g., turbulent water increasing DO, shading lowering water temperature, variable sediment loads). In some catchments, spatial variability is greater than temporal variability, so collecting many data values at a fixed site on a river contains less useful information for decision-making than gathering low frequency data at many sites.

Changing the system design from lab-analysed water quality samples and discrete field measurements to installing in-situ water quality sensors requires careful planning to ensure that the HFWQ data collected is high quality and can be readily used for decision-making. This report contains a scoping framework to ensure a well-justified initial proposal is prepared which outlines how HFWQ sensing will support decision-making. The eight steps in the framework will help those considering using HFWQ sensors to confirm whether collecting high resolution temporal data is justified and required.

Step 1 is defining the decision problem, and the suggested syntax is **problem + impaired use + water body + cause + source**. If the cause or source is unknown, this should be stated. Step 2 checks for any statutory requirements that help define system design. Step 3 covers the reason(s) why an in-situ WQ sensor collecting high resolution data is required, and the suggested syntax is **system + information gain + action/analysis**. Step 4 focuses on the key stakeholders, partners and experts involved. Step 5 examines if the decision can be made with existing data, for example historic data, consent monitoring, or community-based monitoring.

Step 6 in the framework is completing a robust evaluation of the alternatives. The alternatives to in-situ water quality sensors include: (1) routine scheduled discrete samples for lab analysis and field measurements (the 'status quo'), (2) passive sampling devices which bind contaminants to thin gels which are sent for lab analysis, and/or (3) targeted sampling (that is, extra sampling to collect information on conditions under-represented by routine sampling) (Figure 1).

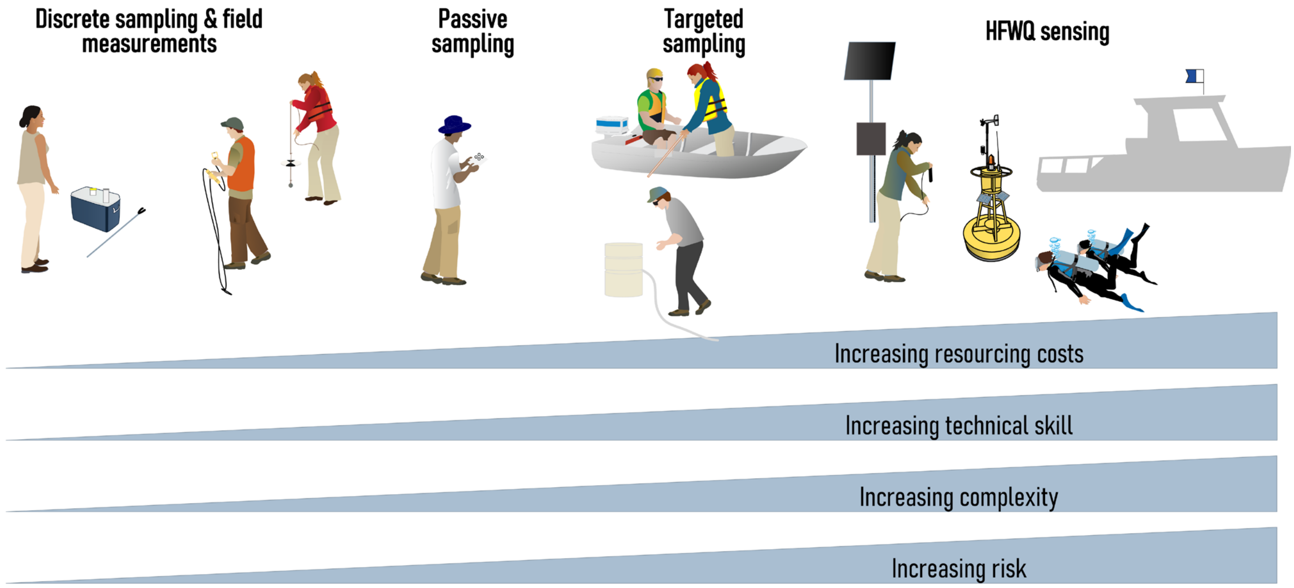

Figure 1. Summary of methods to collect water quality data and the increasing cost, technical skill, complexity and risk of failure to deliver data for decision-making (IAN symbols [ian.umces.edu/media-library], licensed under Attribution-ShareAlike 4.0 International (CC BY-SA 4.0).

Discrete ('grab' or 'spot') sampling and field measurements are collected by all regional councils at regular intervals, across their long-term water quality monitoring networks. Discrete samples can be analysed in the lab for many different physicochemical and biological indicators, and for many indicators lab analysis is the only widely available method (e.g., total nitrogen). Field measurements are required when certain indicators would alter state during sample transport to the lab (e.g., water temperature, dissolved oxygen, pH) or when water quality varies with depth (for example, measuring water quality at regular depth intervals in a lake or estuary). This approach provides low frequency (typically monthly) data for a point in time at a single location. For the samples, there is a short delay (days to weeks) in receiving the results from the lab. Routine sampling may best represent water quality variability when (1) the natural temporal variability is low or (2) when the sampling record is long and represents the full range of conditions (e.g., a stable system with little anthropogenic change, reference sites). In many waterbodies, water quality varies through time depending on the time of day, weather conditions, tides, season and climate.

Passive and targeted sampling are two additional methods which can be used to gain more information on water quality variability (see Table 1). Passive sampling is reasonably straightforward if a DGT® (Davison and Zhang 2016) has been developed for the environmental contaminant of interest (currently nutrients and metals are available, but other analytes are in development). The device is installed for a short period of time (hours to days) and the film accumulates an average concentration and is analysed in the lab. Targeted sampling can be useful to collect additional data as required. For example, if an algal bloom develops, additional samples can be collected for species identification and toxicity analysis. Targeted sampling is frequently used in rivers to collect samples using an automatic sampler when it is unsafe or inconvenient for a technician to collect samples. Automatic samplers can collect a limited number of samples in response to changing conditions and are often used for suspended sediment and nutrient sampling during infrequent high flow events.

Table 1. Key advantages and disadvantages of water quality sampling alternatives.

	In-situ water quality sensors	**Discrete sampling and field measurements**	**Passive sampling**	**Targeted sampling**
Description	*In-situ sensor installed at a fixed site collecting data at minutes to hours*	*Technician collects samples for lab analysis and field readings using water quality sensor at regular intervals*	*Small device with a thin gel film accumulates metals or nutrients over hours to days, analysed in lab*	*Additional samples collected (algal toxicity, river high flow samples) and analysed in lab*
Data reflects temporal water quality variation	Yes	Sometimes	Averages	Sometimes
Data reflects spatial water quality variability	With multiple sites	With multiple sites	With multiple sites	With multiple sites
Real-time water quality data can be delivered	Yes	No	No	No
Feasible for many indicators	Limited	Yes	Limited	Yes
Straightforward to budget and deliver on budget	No	Yes	Yes	Mostly
Staff schedules are known in advance	Sometimes	Yes	Yes	No
Data can be safely collected at nighttime and during bad weather	Yes	Limited	Yes	Maybe – depending on goal and equipment
Data quality procedures are supported by NEMS	Some	Yes	No	Yes
In-house expertise for staff training is available	Sometimes	Yes	Sometimes	Sometimes
Data gaps impact on analysis	Common	Inherent	Rarely	Rarely
Cost to collect data	Moderate-high (expertise, training, contingencies)	Low	Low	Moderate
Operations & maintenance	Complicated to complex	Simple	Simple	Complicated
Overall efficiency of method	High cost for good temporal data	Low cost for snapshots	Low cost for time averaged data	Low to high cost for additional snapshots of temporal data
Lead time to decision-making	Months to years (complex system)	Years	Days to years	Days to years
Risk of failure	Could be high	Low	Low	Low-moderate

The potential information gains on water quality dynamics from in-situ sensors are large – but the gains depend on how much the water quality varies. The benefits of using in-situ water quality sensors are therefore big in dynamic systems, for example when water quality varies with tidal cycles, daily cycles, high flow events, lake turnover, or a combination of these. Sometimes the water quality dynamics are unknown and HFWQ sensors are deployed to investigate; a time-bound pilot study is a useful approach. Real-time data from water quality sensors can also be used to make near real-time decisions, for example to collect additional samples or forecast water quality. On the other hand, there are real risks of failing to deliver data, collecting poor quality data or having large data gaps at critical times.

Step 7 in the framework examines resourcing. Significant investment tends to be required in both capital and operational expenditure. Careful sensor selection can ensure the sensors are suitable to meet data objectives, can operate under site field conditions, and are straightforward for a team to deploy and operate. Investment in staff training, developing standard operating procedures for field work and data processing, and preparing for things that might go wrong are all critical to support successful HFWQ sensor operations.

Step 8 is the final step in scoping an initial system design and focuses on the 'next steps'. It is anticipated that several iterations of the framework would be required before an initial proposal is submitted for approval to proceed with the next planning steps.

HIGH FREQUENCY WATER QUALITY OVERVIEW

What is high frequency water quality?

High frequency water quality (HFWQ) is the use of sensors to measure water quality indicators at intervals from minutes to hours. The resulting data is sometimes referred to as a 'continuous' record. HFWQ sensors include electric thermometers, electrochemical sensors, optical sensors, and portable auto-analysers.

This report focuses on the use of HFWQ sensors to collect data over time at unattended fixed or stationary sites. HFWQ sensors are widely used in industrial settings (e.g., water and wastewater treatment plants, manufacturing) where sensors are maintained frequently by staff. Their widespread use in lakes, rivers and estuaries is comparatively recent, and sensors are typically unattended for long periods (i.e., 1–3 months). Operating unattended sensors in the natural environment can be technically challenging, and success relies on thorough design and planning processes.

Twenty years ago, Kirchner & others proposed that new sensor technology would enable us to look at the fine structure of water quality dynamics and that we would be "almost guaranteed to learn something new and interesting" (Kirchner et al. 2004). While new insights have been gained, the uptake and progress has possibly been slower than anticipated.

It is tempting to deploy new commercially available HFWQ sensors to satisfy our natural curiosity about water quality variability. A widely held expectation is that emergent IoT technologies will enable monitoring of HFWQ everywhere. However, in reality there are many challenges which reduce data quality: biofouling, varying environmental conditions, technical problems, sensor limits and limitations. Given resourcing constraints, the HFWQ sensor user's goal must be to inform decision-making with the high resolution temporal data.

HFWQ sensing requires a high level of technical expertise, and data volumes (often > 35,000 values per year) can be overwhelming if good processes and procedures are not in place before data collection begins. Many steps must be carefully planned to ensure data collection supports decision-making (Figure 2), including:

1. Make a well-justified use case which can answer the decision problem(s).
2. Develop a system design.
3. Plan and document resourcing, monitoring design, and deployment.
4. Have detailed technical guidance on quality assurance procedures.
5. Select sensors which will operate in the relevant water matrix and meet data specifications.
6. Undertake field operations and ensure data of known quality is collected.
7. Follow good data processing procedures.
8. Complete data analysis to meet objective(s).
9. Interpret data to inform decision-making.

Approaching these steps with an understanding of their complexity, risks, and the required technical skills will help ensure that resources invested in HFWQ sensing inform decision-making. Thorough planning and design should prevent users from being 'data rich but information poor' (Ward et al. 1986) and sidestep the 'Syndrome of the Gigabyte' (Marcé et al. 2016) where huge amounts of data are stored without any quality checks and not readily used for decision-making.

This report focuses on use cases and system design, which must be done as an initial scoping step. It provides an overview of use cases which require councils to use in-situ WQ sensors and offers a scoping framework to guide people wanting to use HFWQ sensors through a thorough initial system design process.

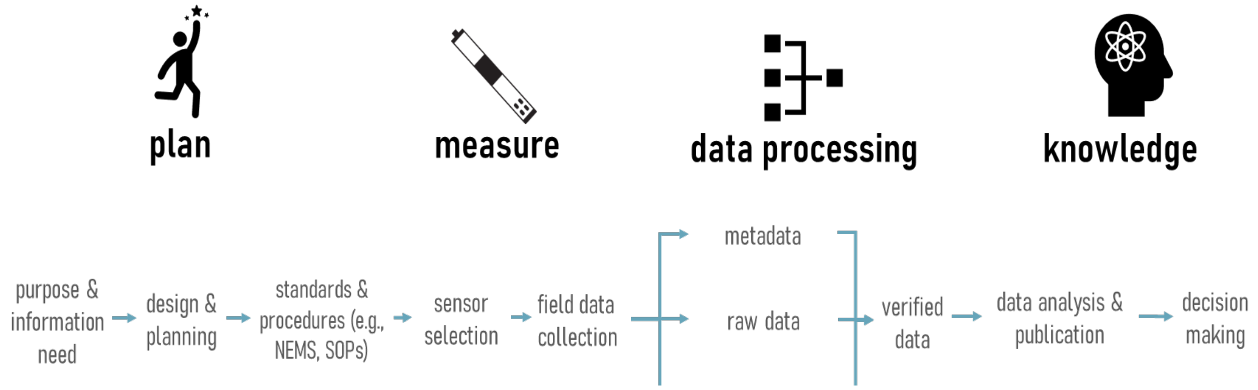

Figure 2. Key steps required in successful HFWQ projects.

What are the drivers of HFWQ monitoring uptake in Aotearoa New Zealand?

In New Zealand, the use of HFWQ sensing has grown rapidly in freshwater management and research over the past decade. This is largely because of the:

- Requirement for HFWQ for some NPS-FM 2020 attributes
- Recognition of the inadequacy of discrete WQ for some purposes, such as ecosystem metabolism, assessing the efficacy of mitigation systems, and infrequent events (e.g., illegal discharges, anoxia)
- Rapid growth in new sensing technologies
- Demand for real-time access to data and warning systems
- Potential for high-frequency data to inform and test water quality models

Use of HFWQ monitoring in estuaries has a long history but is less common. Many regional councils anticipate increasing their investment in HFWQ sensors for estuary monitoring. A current estuary example includes Waikato Regional Council's collaboration in the Firth of Thames (for more details refer to Case Study 2 – Integrated Coastal monitoring in the Firth of Thames). Several coastal moorings continue to collect long-term data (e.g., HAWQI off the coast of Napier, see Coastal Water Quality | Hawke's Bay Regional Council), while others have operated for short periods (e.g., WRIBO on Wellington Harbour).

Regional councils operate HFWQ sensors to support their environmental management role. Many HFWQ sensors are linked to telemetry systems, which enables real-time delivery of data to council staff, decision-makers, and in some cases the public. The data is useful for improving our understanding of how water quality changes through time in response to stressors (e.g., land use change, extreme weather) and for tracking progress towards targets or water quality limits (e.g., the Canterbury Land and Water Regional Plan requires seasonal monitoring of HFWQ dissolved oxygen in rivers).

HFWQ sensors are currently used for two key purposes:

- Surveillance – to characterise and detect change in the state of the environment to fulfil regulatory and statutory requirements. Surveillance tends to be long term and may include warning systems, consent monitoring, statutory monitoring (e.g., SoE and NPS-FM), and adaptive management (see Stoffels et al. 2022).
- Investigations – to better understand a system and fulfil basic information needs on a water body or receiving environment (e.g., turbidity sensors to quantify river sediment loads from catchments to inform ecosystem health restoration in an estuary). Regional councils undertake many investigative studies, and they are typically short-term (e.g., seasonal, 2–5 years).

These two roles are often interlinked in programmes, such as those that provide data to more than one user, and address multiple decision problems (see Case studies 2 and 3). In addition, 'science unseen' can emerge from previously undetected temporal patterns, unknown processes, and links between WQ and biological responses. For example, HFWQ sensors in the United Kingdom enabled researchers to link major peaks in total phosphorus (TP) concentration to when air temperature fell below 2 °C and river biofilm broke down (Bowes et al. 2012).

What can be measured with HFWQ sensors?

A wide range of sensor technologies are available for HFWQ (Table 2). Sensors currently available include:

- non-optical sensors (e.g., thermistors for temperature, electrodes for conductivity, pH)
- optical sensors (e.g., fluorescence for chlorophyll and cyanobacteria, absorbance for nitrate and visual clarity, luminescence for dissolved oxygen)
- portable auto-analysers (e.g., colorimetry for phosphate, nitrate, total phosphorus, and total nitrogen).

Sensor development is an active research field and many new technologies show promise under lab and short-term field tests. However, the leap to unattended deployments can be large – fouling, power supply, and interferences are real challenges. It can take decades to develop and refine HFWQ sensors for operational use. For example, optical nitrate sensors emerged from university R&D labs in the early 2000s and are on their second or third models (e.g., s::can spectrolyser v1 to v3, TriOS ProPS to OPUS), with current models more suited to low power, unattended deployments.

Table 2. Overview of common WQ indicators, their use across water environments, and HFWQ methods and research stage (after Davies-Colley et al. 2013, Marcé et al. 2016). Grey shaded indicators are the focus of this Envirolink Tool project; refer to the Sensor Selection reports for more detailed descriptions of sensing methods.

Indicator	Environments used in			HFWQ sensing	
	Lakes	Rivers	Estuaries	Method	Research stage
Water temperature	Often	Often	Often	- Electric thermometer	- Mature
Turbidity	Often	Often - surrogate	Often - surrogate	- Optical scattering	- Mature but challenging
Visual clarity	Often	Often	Often	- Beam transmissometer - Via turbidity surrogate in rivers	- Mature (in coastal waters) - Research
Suspended sediment concentration (SSC)	Seldom	Often	Often	- Via turbidity surrogate in rivers - Via optical backscattering in estuaries - Acoustic sensors in rivers	- Mature but challenging - Mature but challenging - Research
Electrical conductivity	Sometimes	Sometimes	Often	- Conductive, inductive, capacitance	- Mature
pH	Sometimes	Sometimes	Sometimes	- Electrochemical	- Mature
Dissolved oxygen (DO)	Often	Often	Often	- Luminescence	- Mature
Nitrate	Sometimes	Often	Sometimes	- UV absorbance - Colorimetry in portable auto-analyser	- Maturing but challenging - Research
Total N	Often	Often	Sometimes	- UV absorbance in portable auto-analyser	- Research
Total P	Often	Often	Sometimes	- Colorimetry in portable auto-analyser	- Research
Dissolved reactive P	Often	Often	Sometimes	- Colorimetry in portable auto-analyser	- Research
Metals	Seldom	Sometimes	Seldom	- Ion selective electrode	- Challenging
CDOM	Seldom	Seldom	Seldom	- UV absorbance and fluorescence	- Research
Chlorophyll	Often	Sometimes	Often	- Fluorescence	- Challenging
Cyanobacteria	Often	Sometimes	Often	- Fluorescence - Genetic	- Challenging - Research
E. coli	Often	Often	–	- Portable auto-analyser of viable cells - Via turbidity surrogate in rivers	- Research - Research

Portable auto-analysers

For some indicators, portable auto-analysers (PAA) are available that replicate high-grade lab instruments but in miniaturised form. River water quality dynamics have been explored with PAAs such as the Hach Phosphax (colorimetric detection of dissolved reactive phosphate) and VWM ColiMinder (enzymatic detection of viable *E. coli*; e.g., Shore et al. 2016, Burnet et al. 2019).

Inside a PAA, samples and reagents are placed into micro-reservoirs and then moved through a series of tubes before a detector measures the indicator concentration. PAAs are well-suited for analytical methods which require the addition of reagents and can range in size and shape from a small suitcase (~50 cm x 50 cm) to long tubes (~70 cm x 15 cm). The key challenges manufacturers need to overcome to enable unattended environmental monitoring by PAAs include: (1) reducing the cost of each sensor, (2) reducing the impact of matrix interferences (including fine sediment blocking tubes), (3) improper mixing in channels, and (4) refining low-power systems (Nightingale et al. 2015, Wang et al. 2020).

Bankside operation of more advanced laboratory instruments is also possible. Bankside 'field labs', which combine sample pumping, filtering, and auto sampling with lab-grade instruments, have been implemented to measure WQ at high frequency. However, these systems are complex, include many components and require substantial resourcing. One example used successfully in research projects is bankside ion chromatography systems which separate and measure the concentration of ions such as sodium, potassium, ammonium, calcium, magnesium, nitrate, and phosphate (Floury et al. 2017, von Freyberg et al. 2020).

Surrogates

While HF sensors are available for many indicators, sometimes using surrogates is necessary or more cost effective. A surrogate is a proxy measure for an indicator of true interest that is too difficult or costly to measure directly. By establishing a relationship between the sensor measurement(s) and indicator of interest, a time series of the indicator concentration can be estimated. Turbidity was recognised as a useful surrogate in the late 1970s (Walling 1977) and has been widely used to estimate suspended sediment concentration (SSC), but it has also been used to estimate visual water clarity, total P and *E. coli* (e.g., McKergow and Davies-Colley 2010, Hughes et al. 2014, Hudson et al. 2023). Surrogate relationships historically used linear regression approaches (see Horsburgh et al. 2010, Helsel et al. 2020, Haddadchi et al. 2023), but now non-linear data-driven approaches are being investigated to predict nutrient concentrations using multiple HFWQ indicators (e.g., Castrillo and García 2020). In-situ fluorescence measurements are also surrogates; for example, chlorophyll and cyanobacteria pigments (phycocyanin and phycoerythrin) are surrogates for phytoplankton biomass (see Algal Fluorescence Sensor Selection report, McKergow 2025a).

HFWQ USE CASES

What decisions can HFWQ sensing inform?

Further investments in HFWQ sensing need to be based on a well-defined use case. At its simplest a 'use case' is 'how people use a thing'. The purpose of a use case is to manage scope and establish requirements. For HFWQ use cases, the 'thing' is the sensor and logger, and the 'use' must specify the reason(s) for unattended, in-situ, and high-frequency measurements, and the action or analysis required.

All HFWQ use cases require detailed data on WQ dynamics over short timescales (minutes–hours–days) for decision-making (Figure 3). Sometimes the use case is driven by statutory regulations (e.g., regional plans, resource consents). Some use cases, such as warning systems, require real-time knowledge of a change in WQ conditions, and HFWQ sensors are often a good choice. HFWQ sensing also supports deferred decisions made weeks or years after data were collected. Extremes, events, seasons, or annual variability are often the focus of these use cases. While most use cases for real-time water quality data require HFWQ sensing, there may be alternatives for deferred decisions. HFWQ sensing can also deliver data when conditions are unfavourable or unsafe for fieldwork, such as during nighttime or during extreme weather.

Figure 3. A HFWQ use case will require assessment of the balance between compelling (brown boxes) and uncompelling (white boxes) features.

It is equally important to identify use cases for which HFWQ sensing does not provide the information required to make the decision (Figure 3) because it is:

- not cost effective (refer to HFWQ Resourcing report, McKergow and Hughes 2025)
- not yet feasible (see Table 2)
- low-frequency data are adequate or required by regulations
- spatial variability in water quality is larger than temporal variability.

Water quality commonly varies through time and space, and for some decisions the spatial variability is more important than the temporal variability. Discrete samples and field measurements capture a snapshot of water quality and result in low temporal and spatial resolution data unless they are repeated many times in many places (Figure 4). Sampling in many places, such as in synoptic surveys across rivers in a catchment during stable summer conditions, typically inform data needs on contaminant sources at the time of sampling (e.g., Grayson et al. 1997, Temnerud and Bishop 2005) or interactions between surface and ground waters (e.g., Morgenstern et al. 2023). More recent applications include repeated synoptic surveys (e.g., Pai et al. 2017, Abbott et al. 2018, Gu et al. 2021) across a range of conditions (e.g., high flow, summer flow) to detect whether WQ patterns are spatially persistent. In large waterbodies, the use of HFWQ sensors on moving platforms has allowed greater horizontal spatial resolution on transects (e.g., 1 value per second) (Figure 4). High-speed platforms have been used to rapidly survey water quality in rivers and lakes (Crawford et al. 2015, Schilling et al. 2025) and coastal waters (e.g., Gall and Davies-Colley 2021). Lower-speed platforms fitted with HFWQ sensors are common in coastal waters, for example Argo floats (e.g., Johnson et al. 2022) and fishing boats (e.g., Jakoboski et al. 2024). In freshwaters the use of low-speed platforms is emerging science, for example uncrewed surface vehicles (e.g., Griffiths et al. 2022), drifters (e.g., Ensign et al. 2017) and crewed craft (e.g., Burbery et al. 2021).

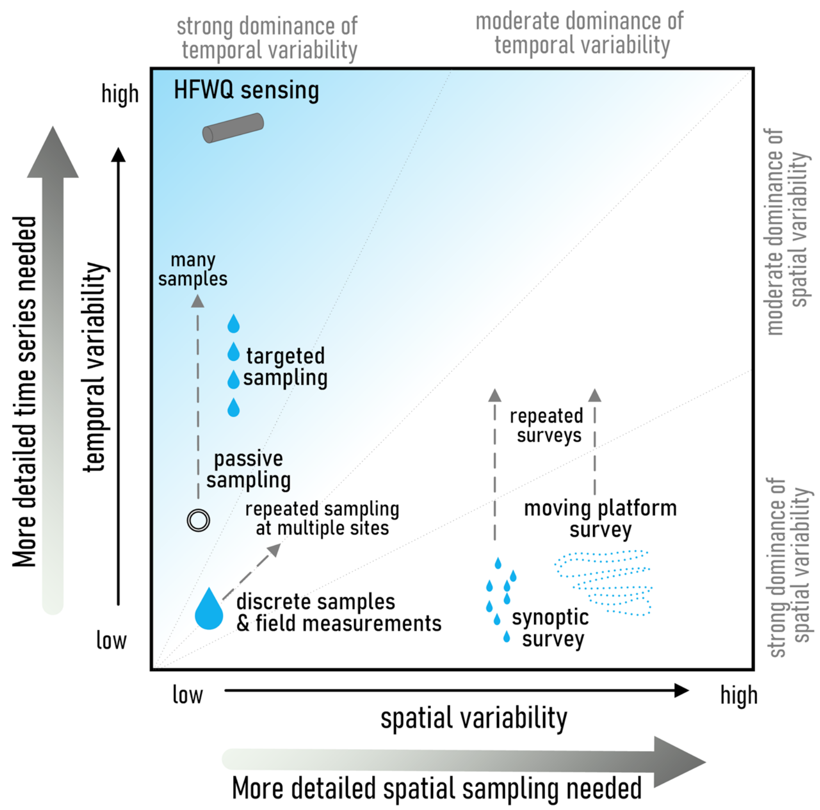

Figure 4. Space-time diagram illustrating alternative water quality sampling approaches commonly used to support decision-making (after Dickey et al. 2006, Schauer et al. 2025).

In rivers, WQ variability results from different contaminant sources at different locations, variable transport and in-stream processing, and local conditions (e.g., turbulence increasing DO, shading lowering temperature). In some catchments, spatial variability is greater than temporal variability, so collecting many data values at a fixed site may contain less useful information for decision-making than gathering low frequency data at many sites. In other catchments, temporal variability is higher than spatial variability. If the type and scale of variability is unknown, a pilot study may be required. Case Study 3 – Integrated monitoring of Lake Hayes, Otago outlines how a two-year catchment nutrient study combined monthly synoptic surveys with several HFWQ sites prior to investment in a single fixed river HFWQ site.

Lake and estuary water quality is temporally and spatially (vertically and horizontally) complex. In lakes, spatial sampling is often biased towards the vertical dimension (i.e., profiling), emphasising stratification and vertical mixing rather than horizontal patterns across space (Crawford et al. 2015). While HFWQ sensors on buoys have advantages for some lake and estuary use cases (e.g., algal bloom warning), they cannot provide spatial coverage unless multiple sites are operated. An integrated approach which combines multiple HFWQ sensors at fixed locations with less frequent discrete sampling and profiling at multiple locations can provide detailed temporal data and some spatial data (see Case Study 2 – Integrated Coastal monitoring in the Firth of Thames).

HFWQ use cases

HFWQ sensing can nevertheless be suited to a wide range of use cases ranging from operational real-time decision-making through to multi-year trend analysis. To capture existing HFWQ use cases across the regional councils, we:

- Engaged with regional council scientists, managers and technicians via a survey and workshop in 2022 (Milne et al., 2023)
- Explored data needs with the Use Cases workgroup
- Requested updates on use cases from the six Sensor Selection workgroups.

We categorised the use cases based on decision-making timeframes – near real-time vs versus deferred (Table 3). Deferred decision-making implies an active, intentional choice to postpone analysis to a future time.

Real-time decision-making in NZ

Many HFWQ sensors are linked to data loggers and telemetry systems which allow for real-time delivery of data to technical staff, researchers, decision-makers and in some cases the public (Table 3). Operations staff and decision-makers can be notified by alerts or notifications when any water quality changes or issues are identified, allowing for rapid responses. Real-time data delivery can meet three main objectives: forecasting, operational decisions and compliance.

Resource consent compliance may require HFWQ sensing for real-time decision-making, such as stopping an activity or discharge. For example, a large thermal power station's resource consent currently requires HF measurement of temperature to ensure the temperature change between upstream and downstream of the station is < 2 °C and the discharge temperature does not exceed 25 °C. For trade wastewater (e.g., dairy factories, abattoirs), HF water temperature monitoring is often required, and consents may also include additional HFWQ indicators (e.g., pH).

Water quality forecasting can support decision-making around public health warnings (Table 3), but most such decisions do not rely solely on HFWQ sensing. Rainfall is the primary real-time data input for current recreational microbial WQ forecasts using models that are simple (e.g., Greater Wellington Regional Council's recreational WQ predictions updated hourly on LAWA) or complex (e.g., Auckland Council, Northland Regional Council and Environment Canterbury's SafeSwim).

Algal fluorescence sensors are often used in algal bloom warning systems, but they are only one data source contributing to public health decisions. Algal blooms are dynamic and complex: (1) the bloom magnitude, duration and severity can change rapidly, (2) species succession and toxicity alter health risk, and (3) blooms are mobile. The use of multiple fluorescence sensors to help distinguish between different species or functional groups is starting to advance the usefulness of real-time indicators (such as the ratio of chlorophyll-a to phycocyanin). Several councils receive real-time alerts of changes in algal biomass and ratios from lake WQ buoys with algal fluorescence sensors (e.g., Otago, Bay of Plenty, Canterbury). The changing fluorescence values, which could indicate the emergence of a new algal bloom, trigger a discrete sampling response to characterise a bloom and its potential toxicity. HFWQ sensors for algal bloom monitoring can shorten the time it takes to develop and validate a functional forecast model (Rogora et al. 2023a suggests < 3 y of HFWQ data). The next generation of in-situ high-frequency and real-time algal sensing – in-situ imaging (see Merz et al. 2021; Kenitz et al. 2023) or in-situ flow cytometers (e.g., Ruiz-Villarreal et al. 2022) – may support real-time public health warning systems for algal blooms.

Table 3. Anonymised examples of current regional council HFWQ use cases.

	Purpose	Goal	Typical HFWQ indicators	Decision problem example **problem + impaired use + water body (+ cause) (+ source)**	HFWQ Use case example **system + information gain + action or analysis**
Real-time decision-making (minutes to hours)	Warning system (surveillance)	Lake algal bloom warning	Algal fluorescence	Recreational users of Lake A require timely warning of algal blooms which result from eutrophication from historic land use change and discharges to the lake.	Telemeter algal fluorescence measured at nighttime to detect changes in algal bloom dynamics to prompt targeted discrete sampling for algal toxins.
	Operational decisions (surveillance)	Rare event detection (e.g., tuna kills, estuary opening)	DO, EC	Tuna/eel deaths in river B are due to low DO events caused by natural events, and river and land management changes.	Telemeter river DO in near real-time to forecast anoxia risk for the next day to week (e.g., see Case Study 1 – Developing an anoxia dashboard using existing data).
		Lake re-aeration	DO	Seasonal stratification of Lake C impacts ecosystem health by depleting lake bottom DO, which increases the availability of phosphorus for weed and algae growth.	Use a telemetered DO sensor to measure real-time lake bottom water DO to trigger aerator use to mix lake waters.
	Assess compliance (surveillance)	Resource consent – discharge to water	Temp, pH	Elevated water temperatures from the discharge of warmed industrial cooling water into river H will reduce ecosystem health.	Measure real-time and in-situ water temperature of an industrial cooling water discharge to river H to manage discharge volume and timing.
		Resource consent – marine aquaculture	Various	Aquaculture farm operations may require mitigating actions (e.g., stocking density, line spacing) to protect ecosystem health.	When the farm is fully established, compare phytoplankton biomass using moored algal fluorescence sensors at 50 m from the Permit Area and a comparable control site.
Deferred decision-making (weeks to decades)	State and trends (surveillance)	Lake thermal stratification	Temp	Thermal stratification of Lake E impacts ecosystem health by depleting lake bottom DO, which increases the availability of phosphorus for weed growth.	Measure lake temperature in-situ at multiple depths to detect the frequency, timing and duration of lake stratification to identify potential periods of high phosphorus release.
		Lake bottom DO	DO	Low lake bottom DO in lake F increases the availability of phosphorus for algal bloom growth, which prevents safe recreation and impacts ecosystem health.	Use a DO sensor with logger to measure lake bottom DO to calculate minimum DO concentrations and assess against NPS-FM attribute bands.
		River nutrient cycling & metabolism	DO, temp	The action plan for river G requires ecosystem metabolism calculations to assess if ecosystem health is maintained or improving (NPS-FM, 2024).	Measure DO in-situ and at nighttime to calculate ecosystem metabolism (e.g., Young et al. 2025).
		Statutory requirement	DO	The action plan for river H requires an attribute grade for summer DO to assess if ecosystem health is maintained or improving (NPS-FM, 2024)	Measure nighttime DO to evaluate minimum summer river DO against NPS-FM attribute bands (e.g., Young et al. 2025)
	Investigative (understand system, surveillance or prediction)	Contaminant source tracing	Nitrate, EC, SSC & TP via turbidity	The timing and volume of sediment entering estuary Y from rivers J and K is required to prioritise land management actions to protect estuary ecosystems.	Use a turbidity sensor to calculate SSC at sub-daily intervals during extreme weather conditions in rivers J and K to estimate event and annual SSC loads.
		Water tracing	EC	Evidence is required to identify groundwater and surface water interactions in River Y to protect ecosystem health.	Measure EC at sub-daily intervals during extreme weather conditions and at nighttime, to develop solute transport and time of travel models in river Y.
		Sampling frequency	Nitrate	Discrete sampling may be inadequate to represent the variability of nitrate transport in a shallow aquifer fed by irrigated pastoral farming.	Measure nitrate at sub-daily intervals to evaluate if the current schedule of discrete samples can capture the temporal concentration variability.
		River plumes entering estuaries	EC, temp, SSC via turbidity, algal fluorescence	Muddy and faecal contaminated river plumes discharging into estuary X are a hazard to aquaculture harvesting.	Measure river inputs (including electrical conductivity, fDOM, and turbidity as a surrogate for SSC and *E. coli*) into the estuary following high rainfall events.
		Mitigation efficacy (e.g., constructed wetland)	Nitrate, SSC & TP via turbidity	Evidence is required on the performance of devices which can reduce the excess nutrients sourced from pastoral agriculture entering river Y and resulting in excessive algal growth.	Use nitrate and turbidity sensors to measure sub-daily dynamics, at nighttime, and during extreme weather conditions, to assess the reduction in annual nitrate, TP, SSC loads between the inlet and outlet of a constructed wetland.
		Land use change (e.g., land clearing, commercial forest harvesting)	SSC and TP via turbidity, nitrate, DO, temp	Eutrophication and algal blooms due to land use change in the catchment of Lake S affect recreation and ecosystem health values.	Use water temperature, DO and nitrate sensors to measure the sub-daily dynamics, in-situ and nighttime DO and temperature extremes, and nitrate exports from the catchment during extreme weather events to Lake S. See Case Study 3 – Integrated monitoring of Lake Hayes.

	Purpose	Goal	Typical HFWQ indicators	Decision problem example **problem + impaired use + water body (+ cause) (+ source)**	HFWQ Use case example **system + information gain + action or analysis**
Deferred decision-making (weeks to decades)	Investigative (understand system, surveillance or prediction)	Climate change impacts	Temp	Increasing water temperature in rivers will reduce ecosystem health as air temperatures rise due to climate change.	Measure the sub-daily dynamics of in-situ water temperature in river Y to compare temperature statistics (1-day and 7-day annual maxima, duration of temperature over 22 °C) with those measured in-situ in reference river X.
		Plan & strategy effectiveness	Various	The effectiveness of plans and strategies to improve ecosystem health and recreational WQ in Lake Z because of land use change requires quantification of internal and external nutrient sources.	Use a nitrate and a turbidity sensor to measure the sub-daily dynamics of river nitrate and phosphorus (via turbidity surrogate) during extreme weather conditions to calculate event and seasonal nutrient loads. See for example, Case Study 3 – Integrated monitoring of Lake Hayes.
		Cumulative effects – impacts of multiple stressors	Various	Water quality degradation in estuary P is the result of multiple stressors.	Use DO, EC, water temperature and algal fluorescence sensors to measure sub-daily WQ dynamics of a well-mixed part of estuary P not impacted by local stressors (such as aquaculture farms, tributaries) to understand cumulative effects of multiple stressors.
		Recovery after extreme weather events	SSC via turbidity, DO, temp	Fine sediment deposited in river Z during cyclone P is a temporary sink of fine suspended sediment which is reducing the ecosystem health in estuary Q.	Use an in-situ turbidity sensor to estimate SSC concentrations at sub-daily intervals to calculate loads entering estuary Q during extreme weather conditions and monitor flushing of event-deposited sediment.
		Zero flow	Temp	Zero flow periods in river F due to natural climate variability impact aquatic ecosystem health.	Use in-situ temperature sensors to detect changes in the timing, frequency and duration of zero flow events.
		Process model calibration and validation	Many	Muddy and faecal contaminated river plumes discharging into estuary X are a hazard to aquaculture harvesting.	Use in-situ water temperature and salinity sensors to measure sub-daily dynamics of salinity and temperature during extreme weather events for model testing (e.g., Collins and Macdonald 2025)
		Spatial model calibration and validation	Turbidity, temp, algal fluorescence	Water quality in estuary B varies spatially and seasonally, and satellite remote sensing products can delivery synoptic views for the estuary.	Measure sub-daily dynamics of algal fluorescence, clarity (via turbidity) and temperature (correction factor) at the water surface of estuary B under all weathers to ground-truth satellite remote sensing (e.g., Gall et al. 2022).
	Operations (surveillance)	Weed harvesting	pH	Rapid growth of introduced weeds in lake M alter the water's pH and nutrient concentrations, which favours the growth of cyanobacteria, which impacts on recreational WQ and ecosystem health.	Deploy a telemetered pH sensor on a mooring to measure real-time pH as an early indicator of lake water quality change to inform weed harvesting operations.
		Groundwater intrusion	EC	Seasonal groundwater intrusion into the V coastal aquifer can reduce access to domestic drinking water.	Use an in-situ EC sensor to measure salinity in near real-time to alert water users to seasonal groundwater quality changes.

Deferred decision-making in NZ

Use cases with deferred decision-making tend to focus on improving understanding of how water quality changes through time or how a system responds to stressors, such as land use change, extreme weather or climate variability. The range of such use cases is large (Table 3) and includes understanding short-term WQ dynamics, water and contaminant source tracing, estimating contributing loads, monitoring for state and trends, predictive modelling and non-urgent operational decisions.

HFWQ sensing allows us to capture how water quality changes over time at intervals that are ecologically relevant – most biogeochemical processes change over hours to days, driven by light and microorganisms. Some key ecologically relevant processes suitable for HFWQ sensing include thermal stratification, ecosystem metabolism and ecosystem health.

Thermal stratification happens mostly in deeper (>10 m depth) lakes when the sun heats their upper layer. This layer (the epilimnion) sits on top of colder, denser water (the hypolimnion) and prevents oxygen re-supply to the bottom waters. The oxygen in the bottom waters gets used by decaying organic matter and other processes, which increases the risk of biogeochemical release of nutrients from lake bottom sediments. Shallow lakes (< 10 m depth) are less likely to become stratified, because wind-driven currents mix layers. Several regional councils use temperature strings (see Water Temperature Sensor Selection report McKergow (2025e) for examples) to detect thermal stratification in lakes. Some councils also add a DO sensor near the lake bottom to detect low DO conditions and assess them against the NPS-FM attribute.

Ecosystem metabolism is viewed as an integrated ecosystem health measure and is listed in the NPS-FM as an Action Plan attribute for rivers. Ecosystem metabolism (EM) is the cycles and fluxes of DO, carbon and nutrients in an ecosystem. Changes in river DO concentrations are a key measure of EM because they are driven by reaeration (exchange between the water column and the atmosphere), photosynthesis and ecosystem respiration. In-situ, high-frequency DO measurements are therefore required for metabolism modelling, and a suite of ancillary indicators (e.g., water level, temperature, aquatic light, etc.) are useful to fine-tune model predictions.

There is emerging use of 'big data' projects in metabolism science, especially using DO data measured across climate, land use and river size gradients (e.g., Appling et al. 2018, Bernhardt et al. 2022). It can be argued that EM measures can help: (1) separate biological drivers (e.g., decomposition) from physical drivers (such as light, flow, fine sediment) of ecosystem health (Jankowski et al. 2021), and (2) detect a change from phytoplankton to macrophyte domination (Diamond et al. 2021).

Ecosystem health surveillance often involves HFWQ. The NPS-FM 2020 requires high-frequency DO monitoring downstream of point sources on rivers, and it includes high-frequency DO monitoring to inform action plans to maintain and improve ecosystem health. The action plan DO attribute offers councils the flexibility to use both regulatory and non-regulatory methods to bring together actions from diverse groups to achieve freshwater goals. HFWQ monitoring is required because seasonal extremes are the relevant measures (NPS-FM 2020 Tables 7 & 17 require 7-day mean minimum and 1-day minimum for the period 1 Nov–30 Apr), and although decision-making is deferred, councils need to monitor DO at high frequency for the entire summer period to accurately identify the minima statistics.

Estimating contaminant loads and sources is a common HFWQ use case for streams and rivers, especially those which are chemo-dynamic, sensitive to eutrophication, or drain to sensitive lakes or estuaries (Table 3). For example, in a eutrophic lake, using HFWQ sensing to estimate catchment contaminant loads and specific yields can help identify the relative importance of internal nutrient sources (from lake sediments) versus external nutrient sources (see Case Study 3 – Integrated monitoring of Lake Hayes). Calculating contaminant loads (mass per unit time) and specific yields (mass per unit time per unit area) at different locations along a river can help pinpoint input loads from different sub-catchments.

An additional use case in rivers is examining changes in the relationship between concentration and discharge to identify weather, biogeochemical processes and land management practices that drive contaminant exports (see review by Speir et al. 2024 for more details). Contaminant load estimation is also important for evaluating WQ mitigation tools, such as constructed wetlands or bioreactors. Several regional councils were partners in a recent constructed wetland project which used turbidity and optical nitrate sensors to measure sub-daily dynamics and changes during extreme weather conditions to meet multiple use cases: to evaluate wetland efficacy, to inform guidelines (Table 3), to collect data for developing and testing wetland process models, and to gain insights into nitrate dynamics in headwater streams and wetlands (Goeller et al. 2024).

A SCOPING FRAMEWORK

Designing and implementing WQ monitoring projects is a complex and iterative task – there are typically many people involved and numerous components to design, review, re-design and finalise (Figure 5). When considering the use of HFWQ sensors, it's useful to undertake an initial scoping exercise to justify the use case and system design.

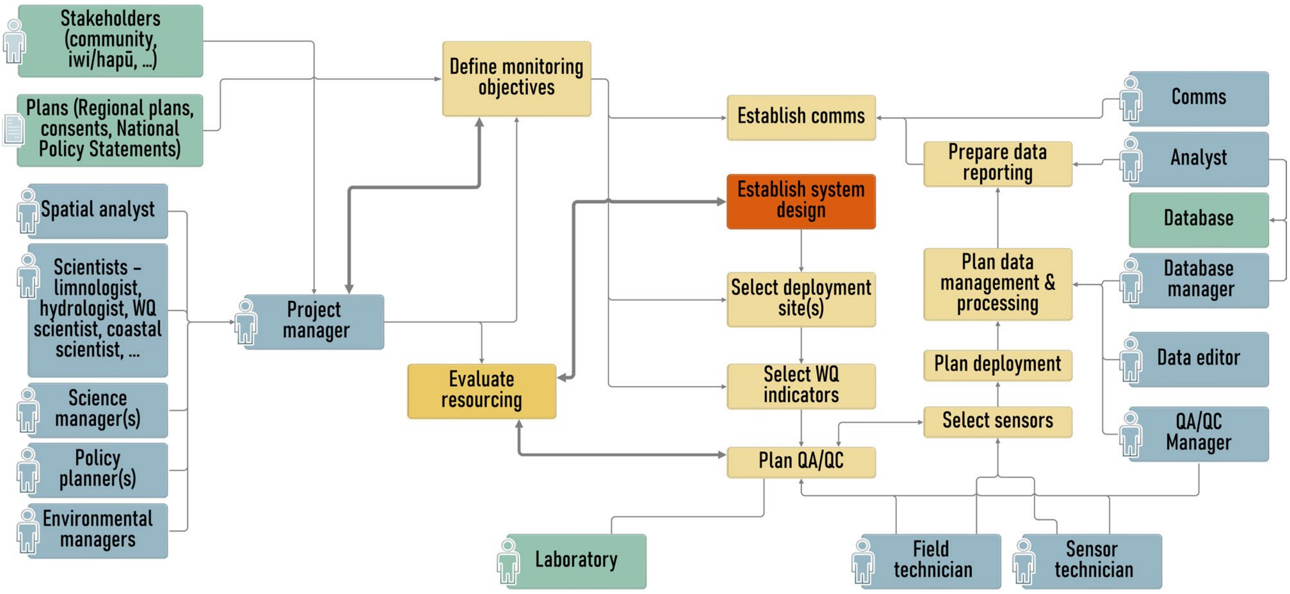

Figure 5. Components of a WQ monitoring programme design (after Behmel et al. 2021).

Use of a scoping framework (Figure 6) will ensure a well justified initial proposal is prepared which outlines how HFWQ sensing will support decision-making. The eight steps (Figure 6) will help those considering using HFWQ sensors to confirm whether collecting high resolution temporal data is justified and required. It is anticipated that several iterations of this framework would be required before an initial proposal is submitted for approval to proceed with the next planning steps.

A clearly stated decision problem will help to define objectives and support the use case for HFWQ monitoring. The framework is laid out with the decision problem at the centre (Step 1, Figure 6) to ensure that it remains in focus during the scoping exercise. A suggested syntax for a water quality decision problem (USDA-NRCS 2003) is:

problem + impaired use + water body (+ cause) (+ source).

If the cause or source are unknown, the statement many need to include some uncertainty (e.g., "from unknown sources").

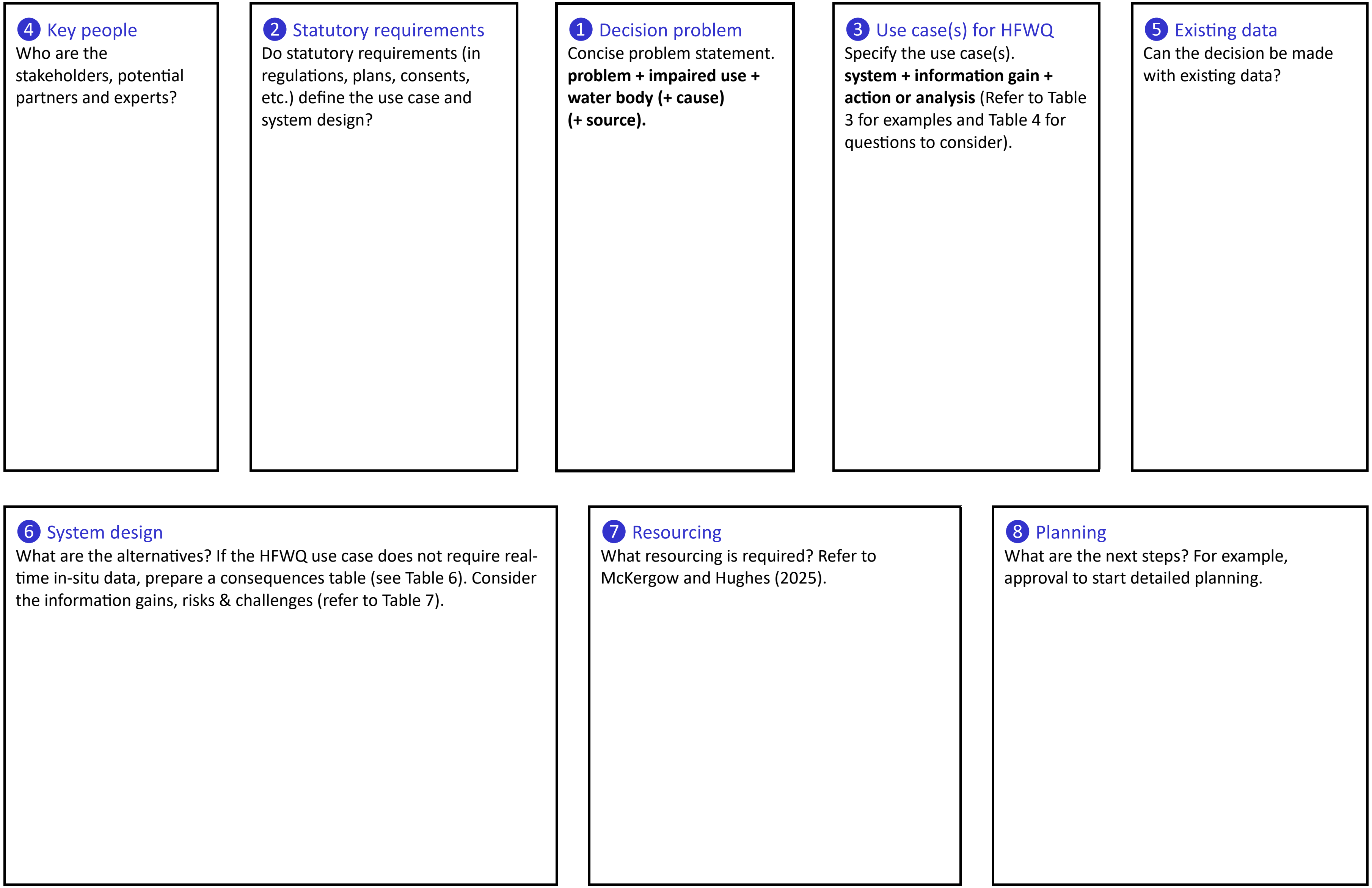

Figure 6. Framework to support initial planning to design and justify a HFWQ monitoring system to support decision-making (adapted from Timmerman et al. 2022). The decision problem is deliberately positioned in the centre of the framework to ensure it remains in focus.

REFINING A USE CASE

All HFWQ use cases require data on WQ dynamics over short timescales (minutes–hours–days) for decision-making. Sometimes the use case is driven by statutory requirements (e.g., legislation, regional plans; Step 2 in Figure 6). Other use cases, such as warning systems, require immediate knowledge of a change in WQ conditions. HFWQ sensing also supports deferred decisions made weeks or years after data were collected after analysis of extremes, events, seasons or annual variability. Some key questions should be answered to build a robust use case (Table 4). A clearly stated HFWQ use case will guide an evaluation of existing data and/or develop the design of a new system. A suggested syntax is for a HFWQ use case is:

system + information gain(s) + action or analysis

Table 4. Considerations for specifying a HFWQ use case.

Key questions	Potential consequence of not considering key questions	Possible solutions
Is temporal variability more important than spatial variability?	- Mismatch between data collection and decision-making.	- Consider the balance between temporal and spatial variability (see What decisions can HFWQ sensing inform?). - An integrated system which considers both time and space may be required (refer to Case Studies 2 and 3).
How will HFWQ data inform the decision?	- Mismatch between data collection and decision-making.	- A concise statement on the features of HFWQ sensing that will directly contribute to decision-making (see What decisions can HFWQ sensing inform?)
What indicators are required?	- Collecting unnecessary data will increase cost and complexity.	- A concise statement of required indicators and a quick justification (e.g., DO for ecosystem health).
Is sensor technology available for the indicator?	- Sensor technology cannot provide the required information at the required accuracy level.	- Check Table 2 and assess the maturity level of the technology currently available. - Consult the relevant Sensor Selection reports (McKergow 2025 a, b, c, d, e, McKergow and Vincent, 2025) to understand current sensor technology. - Include any correction factors or supplementary data (e.g., water temperature for DO unit conversions in freshwater). - Carefully consider the requirements and risks of using a surrogate measure (e.g., use of turbidity to estimate SSC, see McKergow 2025d).
Is real-time WQ data required for decision-making?	- Possible resourcing overspend if real-time data is not required.	- Check if existing data sources are available (see Case Study 1 – Developing an anoxia dashboard using existing data) - Consider alternative real-time data sources (e.g., models using real-time rainfall data).
Is HFWQ sensing required?	- Monitoring system is larger than the minimum required to make decisions. - Resourcing overspend.	- Stop here if the answer is 'No'. If the answer is 'Maybe' or 'Yes' continue to Step 5 - Can you make the decision with existing data?

CAN YOU MAKE THE DECISION WITH EXISTING DATA?

Having developed the initial use case (Steps 1-4; Figure 6), existing data sources should be found and evaluated. By seeking out existing data, decision-making may be able to start immediately, rather than waiting years for a new project to be designed, resourced and implemented. Potential existing data sources include but are not limited to:

- resource consent monitoring
- national networks
- research projects
- operational systems (e.g., water treatment plant intakes)
- community-based monitoring.

The use of existing data requires an understanding of the advantages and disadvantages. Evaluating whether it can contribute to the required decision should include assessing its availability, currency and quality.

Data availability can be better than it first seems. Existing data often appears to be lost, so it's important to ask people who have been in your organisation for some time. Historic data may not have been moved into WQ data archives, particularly if it was collected prior to widespread storage of digital data. For example, valuable discrete data can be hiding in the appendices of university theses or reports written by catchment boards (regional councils inherited their responsibilities) or other agencies (e.g., Ministry of Works and DSIR). Data can also be lost when the data collectors move positions or complete projects (e.g., research theses). In addition, HFWQ data may have been collected by another agency or company for another purpose and might be available on request (e.g., a research organisation, water treatment plant operator, etc.).

Data currency, or how recently it was collected, may be an important criterion for evaluating existing data. Some sources will be more current, particularly resource consent monitoring and community-based monitoring.

Data collected for consent monitoring purposes will often be held outside of a regional council's WQ and hydrology data management systems. However, it can be a valuable data source, and Case Study 1 – Developing an anoxia dashboard using existing data demonstrates how existing resource consent data can be a cost-effective starting point for decision-making.

Community-based monitoring (CBM) that adopts guidance on quality assurance should be recognised by regional councils as credible. The CBM QA framework (Milne et al. 2023) supports those monitoring stream health to design monitoring plans and ensure the data collected are accurate, reliable and fit for the intended use. CBM data will also likely sit outside of regional council WQ and hydrology databases. Water temperature and DO are the HFWQ data most likely to be collected by volunteers, but some may also collect turbidity and electrical conductivity data.

Data quality depends on the tools and practices used at the time of data collection. Consistent data collection and processing was less common until National Environmental Monitoring Standards (NEMS) started to grow in number from the mid-2010s. Historic WQ data is likely to be discrete samples or field measurements, although continuous water temperature records are sometimes available. Historic sensor technology is also important to consider; for example, membrane DO sensors were less reliable than optical DO sensors.

CASE STUDY 1 – DEVELOPING AN ANOXIA DASHBOARD USING EXISTING DATA

Waikato Regional Council (WRC) used existing data to develop an anoxic risk dashboard to support management of the Whangamarino Wetland. The dashboard informs decisions outlined in an inter-agency response plan (iwi, Department of Conservation, WRC, Fish & Game) designed to reduce wildlife kills as a result of poor water quality. The dashboard combines resource consent data with WRC data and weather forecasts to predict anoxia (absence of dissolved oxygen) risk.

The Microsoft Power Bi dashboard (Figure 7) pulls data from two DO sensors operating for resource consent compliance, and it displays the current DO minimum concentration and time series plots. The consent monitoring also provides daily mean water temperature. The dashboard uses WRC data also, including rainfall and water level and discrete WQ sample results and field measurements. The key discrete water quality indicator on the dashboard is Absorbance at 440 nm which is used as a measure of coloured dissolved organic matter. Forecast rainfall is included from MetService via an automated process .

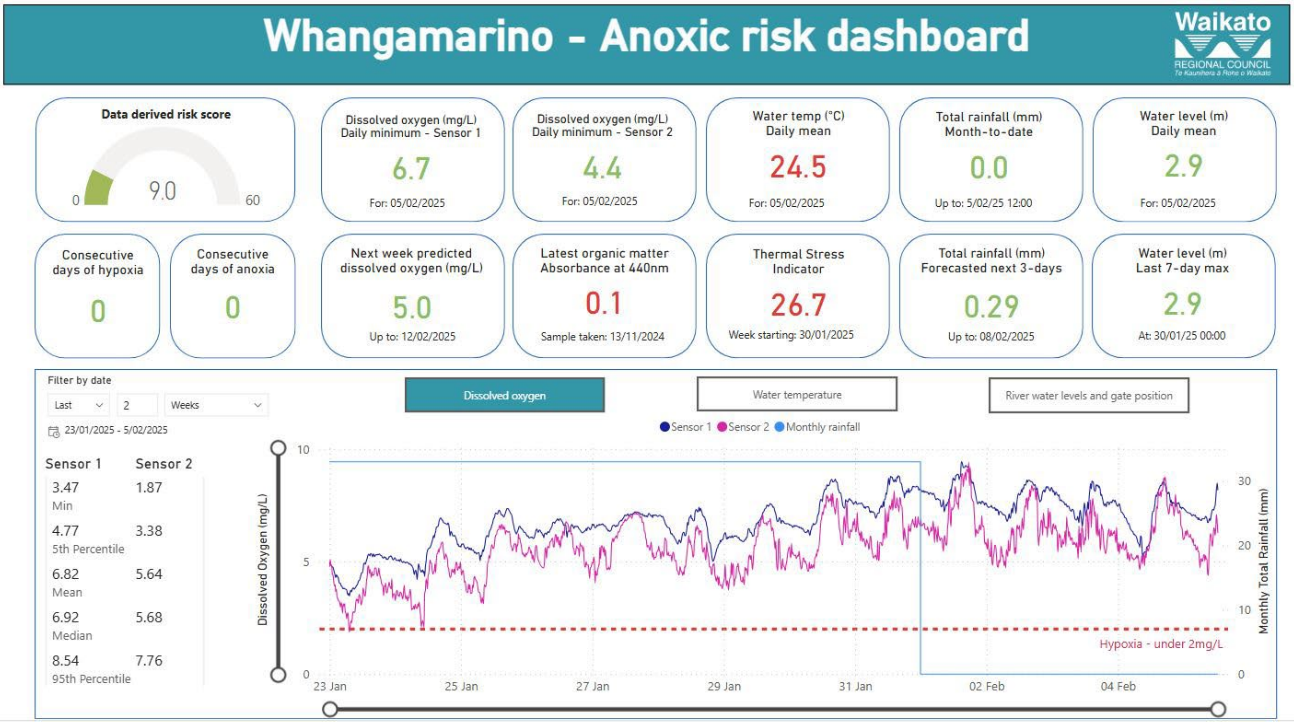

Figure 7. Screenshot of the Whangamarino Anoxic risk dashboard. In the DO graph, sensor 1 is the navy line, and sensor 2 is the pink line.

Indicators are colour-coded, similar to a traffic light, with the transition from green to orange to red indicating an increasing risk of anoxic conditions (Figure 7). Anoxia risk is highest with high temperatures and high water levels (with high levels of organic matter). The colour codes were developed using modelled relationships. To colour code continuous water temperature and water level, the anoxia risk was modelled with continuous DO from partial dependence plots in a boosted regression tree model. Partial dependence plots can be used to visualise and analyse interaction between the target response (DO) and a set of input features (water temperature and water level). A similar method was used to colour code anoxia risk for Abs_{440} using concurrent discrete DO measurements.

Using the data and the relationships, the dashboard uses a simple multiple linear regression to forecast DO concentrations for the next week. If hypoxic or anoxic conditions are measured by Sensor 2, then the days of consecutive hypoxia or anoxia are counted.

The dashboard has a data-derived risk score that relates to alert levels in the Whangamarino Response Plan. Actions and responsibilities are outlined at each alert level. If an alert level changes, the dashboard automatically emails stakeholders who then carry out the required actions (as per the collaboratively developed response plan).

The dashboard has been successful in sharing data and improving collaboration between stakeholders. The 2024/25 summer was the second during which it was operational. The dashboard also automatically emails weekly summaries to stakeholders (iwi, Department of Conservation, WRC, Fish & Game, landowners).

The ability to use data that was being recorded for another purpose was useful for examining the relationships of DO with water level and water temperature, both of which feed into the simple anoxia risk model. A limitation is that there were no other field measurements to verify the sensor DO, so there may be drift in the DO datasets. The existing data was also useful for planning future monitoring. The plan is to add two telemetered YSI EXO sondes and improve sensor verification, update the dashboard to include the new sites, and make the dashboard public.

These HFWQ results using existing consent monitoring data have influenced decision-making by establishing that the Maramarua and Whangamarino rivers differ to each other and there are two mechanisms of fish kills in these rivers. This has given WRC the ability to inform the response plan, and it shows the value of high frequency data for sites where more than routine State of Environment (SoE) monitoring is needed to understand the system and WQ issues.

SYSTEM DESIGN

System design (Step 5) requires decisions about the required methods and data frequency (the time interval between observations). The resourcing and effort required to develop the system design will largely depend on the number of decisions to be made. The case studies illustrate how as the number of decisions increases, more effort and resourcing is needed for the design process:

- The “simplest” case study (Case Study 1 – Developing an anoxia dashboard using existing data) makes use of real-time HFWQ data collected for resource consent compliance and other existing and forecast data to enable daily river management decisions to reduce the risk of low oxygen conditions.
- Case studies 2 and 3 illustrate how historic data (Case Study 2 – Integrated Coastal monitoring in the Firth of Thames) and a pilot study (Case Study 3 – Integrated monitoring of Lake Hayes, Otago) can inform the design of larger systems (i.e., more sensors at multiple sites or depths). These case studies also illustrate the lead times from first steps to data delivery.

This section is designed to support the design of “simple systems” or the first steps for larger systems. For larger systems, this section may help support a case for resourcing to invest in system design (see for example the reviews undertaken to design the current Firth of Thames monitoring system).

CASE STUDY 2 – INTEGRATED COASTAL MONITORING IN THE FIRTH OF THAMES

The success of ocean observing systems — particularly in New Zealand — requires collaboration between multiple organisations. The goal of the Firth of Thames monitoring programme is to provide system understanding and detect change in the state of the Firth of Thames, and to subsequently support management decisions and outcomes in the Firth of Thames and wider Hauraki Gulf/ Tīkapa Moana.

The Firth of Thames (FoT) is a large estuarine embayment on the east coast of the North Island. It is New Zealand's largest shallow embayment (~1100 km², mean depth 15 m) and sits between the Hunua and Coromandel Ranges at the southern end of the Hauraki Gulf/Tīkapa Moana. The FoT is a significant cultural site for many iwi. Furthermore, the FoT is used for a range of recreational activities, for commercial and recreational harvesting of seafood, and for aquaculture.

The FoT is showing signs of degradation, including eutrophication, sedimentation and mangrove expansion, acidification, and bottom water hypoxia. The embayment's hydrodynamics are complex, with tidal and wind-driven currents, mixing and stratification, which all influence biogeochemical processes. The FoT is under pressure from multiple simultaneous anthropogenic stressors, including farming intensification, marine farming, urban development and climate change. Historically the FoT received a large amount of sediment and nutrients from mining and land clearance in the catchment. The two largest rivers discharging into the FoT are the Waihou and Piako rivers, which flow across the Hauraki Plains and their headwaters. Prior to human habitation, the Hauraki Plains were mainly native forest-clad, but today they are dominated by agricultural land use (primarily dairy). The FoT contains the largest spawning and nursery grounds for New Zealand's most valuable inshore fin-fishery (snapper) and some of NZ's largest marine farms. Aquaculture in the inner FoT is presently dominated by mussel farming. In the outer FoT, oyster farms operate in harbours around Coromandel, and a coastal permit for a new offshore marine farm (finfish, kelp and other species) was recently approved.

The current WRC monitoring programme in the FoT constitutes the most comprehensive coastal water quality monitoring programme of any marine water body in New Zealand. The monitoring programme carries on from decades of research and monitoring combined with a thorough design process.

The FoT has a long history of water quality research, including studies on sea level, mangrove sedimentation, catchment loads and the nearshore environment. In the late 1990s, NIWA began a large oceanographic study focused on the North-East Shelf and Hauraki Gulf known as the Cross-Shelf Exchange Programme (see Box 1). As part of the broader monitoring programme, two oceanographic moorings were maintained in the FoT between ~1995 and 2023. These moorings were fundamental in providing depth-resolved understanding of physical and biogeochemical dynamics in the FoT, in particular helping to inform knowledge of the FoT's trophic status (see Box 1 for monitoring system design). Beginning in 2001, the WRC implemented the benthic Regional Estuarine Monitoring Programme at five intertidal sites in the inner FoT to monitor estuarine ecological health.

Box 1: The Cross-Shelf Exchange Programme – Firth of Thames

The Cross-Shelf Exchange Programme was designed to examine how coastal and continental shelf ocean systems exchange water, heat, salt and nutrients. The programme combined voyages to undertake spatial surveys with maintenance of oceanographic moorings collecting high resolution temporal data (Zeldis et al. 2004, Zeldis et al. 2022).

During each voyage (quarterly/biannual), transects were surveyed across the Hauraki Gulf/Tīkapa Moana and FoT from NIWA vessels (RV *Kaharoa,* RV *Tangaroa* and RV *Rangitahi III*). Water column profiles were completed, and discrete samples were collected for biogeochemistry and biological analysis.

Two moorings were operated in the FoT: (1) outer FoT (west of Coromandel township,~38m water depth ~1995-2023) and (2) middle FoT (west of Ruamahunga, ~15m water depth, 2016-2023). At the outer FoT mooring, sensors were deployed at multiple depths to measure: (1) conductivity, temperature, depth, dissolved oxygen (Sea-bird MicroCAT with ODO at 10 and 35 m), (2) photosynthetically active radiation (PAR) and chlorophyll-a via fluorescence (Biospherical Instruments fluorometers at 7 and 20 m), and (3) pH (Sea-bird Sea-FET at 4 m). The inner FoT mooring was installed later and instrumented with two Sea-bird MicroCATs (7 and 15 m) and a Sea-FET at 5 m.

This extensive NIWA dataset continues to inform our understanding of the current state of the FoT, supports initiatives such as the Hauraki Marine Spatial Plan, Sea Change, the Hauraki Gulf Forum, and aquaculture-focused modelling and consent monitoring (e.g., Wilson Bay Marine Farming Zone, Pare Hauraki Kaimoana).

The present WRC FoT monitoring programme is the product of a region-wide monitoring review and integrated monitoring framework to address the cumulative effects of multiple activities in the coastal marine area. In the mid-2010s, the proposed Pare Hauraki finfish aquaculture venture led WRC to examine coastal monitoring more closely. Supported by the Aquaculture Growth Fund, WRC engaged with the Cawthron Institute to develop an integrated monitoring framework for the region (see Forrest and Cornelisen 2015, Keeley et al. 2015). The regional framework addressed some key technical elements of monitoring programme design: (1) ensure a consistent set of indicators which reflect changes in stressors and activities, (2) improve monitoring efficiency by linking fine-scale consent monitoring with broad-scale SoE monitoring, (3) include reference condition monitoring, and (4) decide on monitoring methods and spatial scales of sampling, including where technologies (such as WQ buoys) are valuable.

The HFWQ monitoring is designed to meet both real-time and deferred decision-making timeframes and multiple data objectives:

- To inform SoE monitoring for indicators and attribute state (deferred)
- To improve system understanding by monitoring key marine environment indicators – dissolved oxygen, pH, pCO2 and chlorophyll-a – which vary in space and time (deferred)
- To enable model validation and support future forecast model development to inform management (deferred)
- To identify when targeted sampling would be beneficial (real-time)
- Provide environmental information to the public and key stakeholders (real-time and deferred).

The integrated monitoring programme in the FoT includes discrete samples and water column profiles at 10 sites, and two fixed moorings with sensors for weather, HFWQ and current measurements (Figure 8 B). In 2019, two telemetered oceanographic monitoring buoys constructed by Cawthron were deployed by WRC in the inner FoT to collect data to verify a marine management model developed by Cawthron and MetOcean (supported by MPI's Aquaculture Planning Fund). The monitoring buoys continue to collect real-time data (current speed and direction, water temperature, salinity, turbidity, DO, chlorophyll-a, waves and weather data; see Figure 8).

Since May 2020, NIWA has been contracted by WRC to collect monthly water samples and measure water column profiles of temperature, salinity, DO, pH and turbidity, fDOM and chlorophyll-a at 10 sites in the inner FoT using a YSI EXO sonde (red dots in Figure 8 B). At each station, depth profiles are completed and discrete water samples are collected for a suite of physicochemical parameters, nutrients, microbial indicators, and algal composition and size fractions.

The telemetered monitoring buoys are known as Wai-Q-Tahi and Wai-Q-Rua (Figure 8). Wai-Q-Tahi is deployed in ~30 m water depth (Figure 8 A & B) and has four monitoring stations – one above surface and three below the surface. A weather station sits above the water surface and measures wind, air temperature and barometric pressure (Figure 8 C). One metre below the surface is a Sea-Bird CTD (conductivity, temperature, and depth instrument) with a DO sensor and a current meter. At 8 m depth, another Sea-bird CTD+DO is augmented with chlorophyll-a and turbidity sensors. The deepest sensor, a Sea-Bird CTD+DO, sits at 19 m depth. Wai-Q-Rua is a smaller buoy sitting in ~12 m water depth (Figure 8 B). A weather station sits on the buoy and measures wind, air temperature and barometric pressure. A Sea-Bird CTD is positioned at 1 m deep and also measures DO, chlorophyll-a and turbidity (Figure 8 D).

Cawthron maintains the telemetered data feed through their buoy network, and WRC receives that data via WRC's Hydrotel network. In addition, raw sensor datasets are retrieved by NIWA when it services the buoys. A framework for data processing and an improved data management framework are currently being developed.

The funding for the buoy monitoring programme was supported by the WRC 2015–2025 Long Term Plan (LTP), in which a business case was approved to support the buoy monitoring, with budget allocations for 10 years. Some funds were allocated to the buoy CapEx and the remainder to operations. Initial development of the monitoring programme was prioritised before focus was transferred to the buoy deployments. Currently, the buoy programme is funded from 2024-2030 and the resourcing covers both OpEx and CapEx associated with running and maintaining the programme.

Maintaining buoys in coastal waters is challenging and often requires collaboration between multiple agencies. The WRC buoys were initially operated by WRC staff, with Cawthron providing technical and data support. However, WRC's ongoing technical capability and capacity was unclear. So in 2018, WRC contracted out the buoy operations to NIWA and Cawthron. The programme's critical components include: (1) funding and strategic direction (WRC), (2) coastal operational infrastructure (boats, skippers, divers), oceanographic instrumentation and deployment skillsets within the region (NIWA Hamilton), and (3) ocean monitoring, telemetry and data provision (Cawthron).

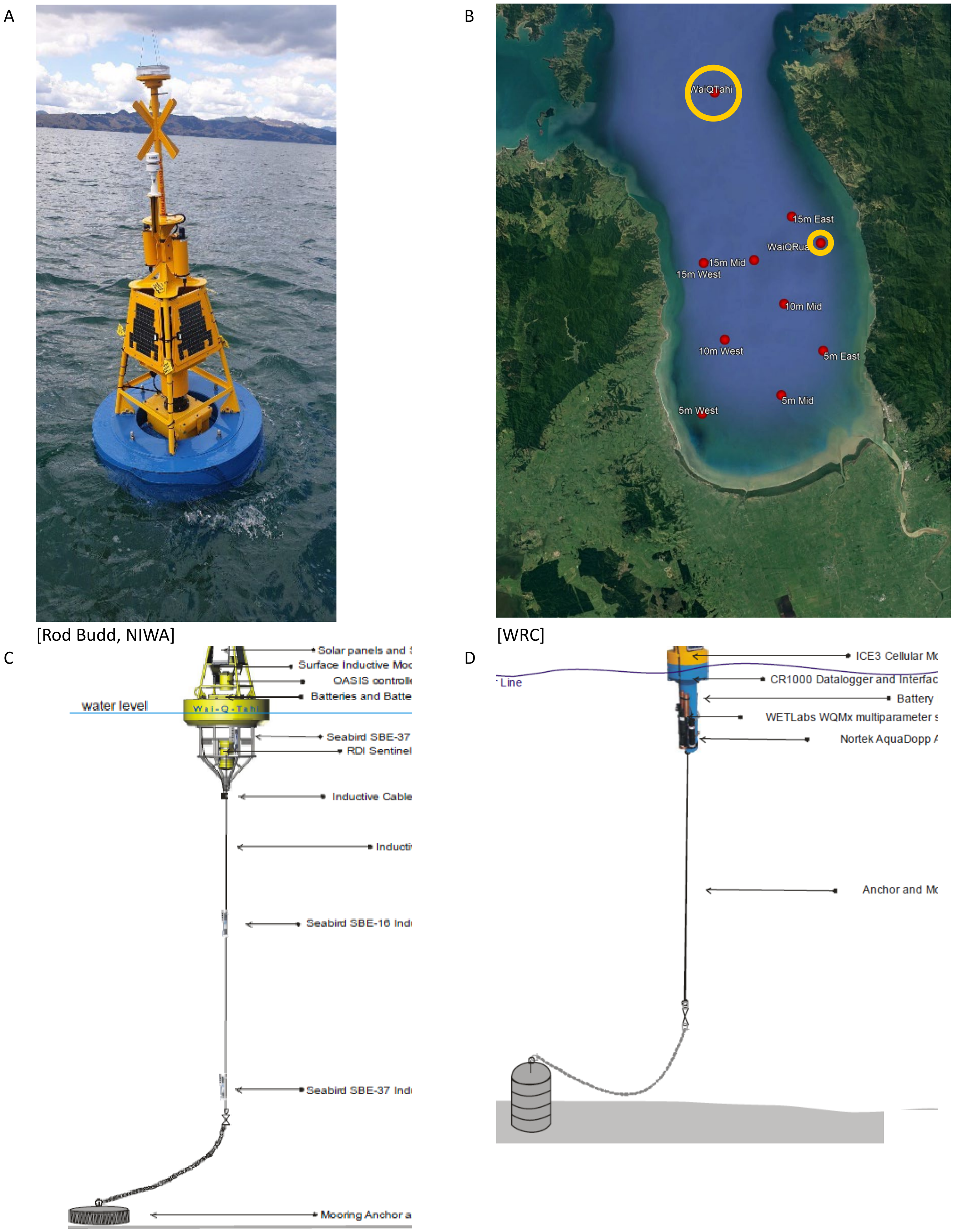

Figure 8. Firth of Thames monitoring buoys. (A) Wai-Q-Tahi. (B) Satellite image of the Firth of Thames with monitoring sites (red dots) and monitoring buoys (orange circles). (C) Schematic of Wai-Q-Tahi monitoring buoy. (D) Schematic of Wai-Q-Rua monitoring buoy (as installed).

The current multi-agency team operating the buoys includes:

- WRC – one coastal water quality scientist/programme manager 0.1 FTE.
- NIWA (contracted) – The Coastal & Estuarine Processes team, including a scientist and a team of experienced technicians/divers, to help maintain, deploy and retrieve the two coastal monitoring buoys.
- Cawthron (contracted) - A senior marine scientist in the Coastal and Freshwater Group provides technical oversight and troubleshoots major issues. He also advises on major servicing of assets, maintains relationships with instrument manufacturers, and if required can provide data QA/QC services.

Currently, there have been no formal publications using information gathered by the integrated monitoring programme. However, recent data are being used to help inform science and policy objectives including the Regional Coastal Plan and Freshwater Policy Review (see Figure 9). Data from the buoys will also be critical for informing SoE reporting in the near future.

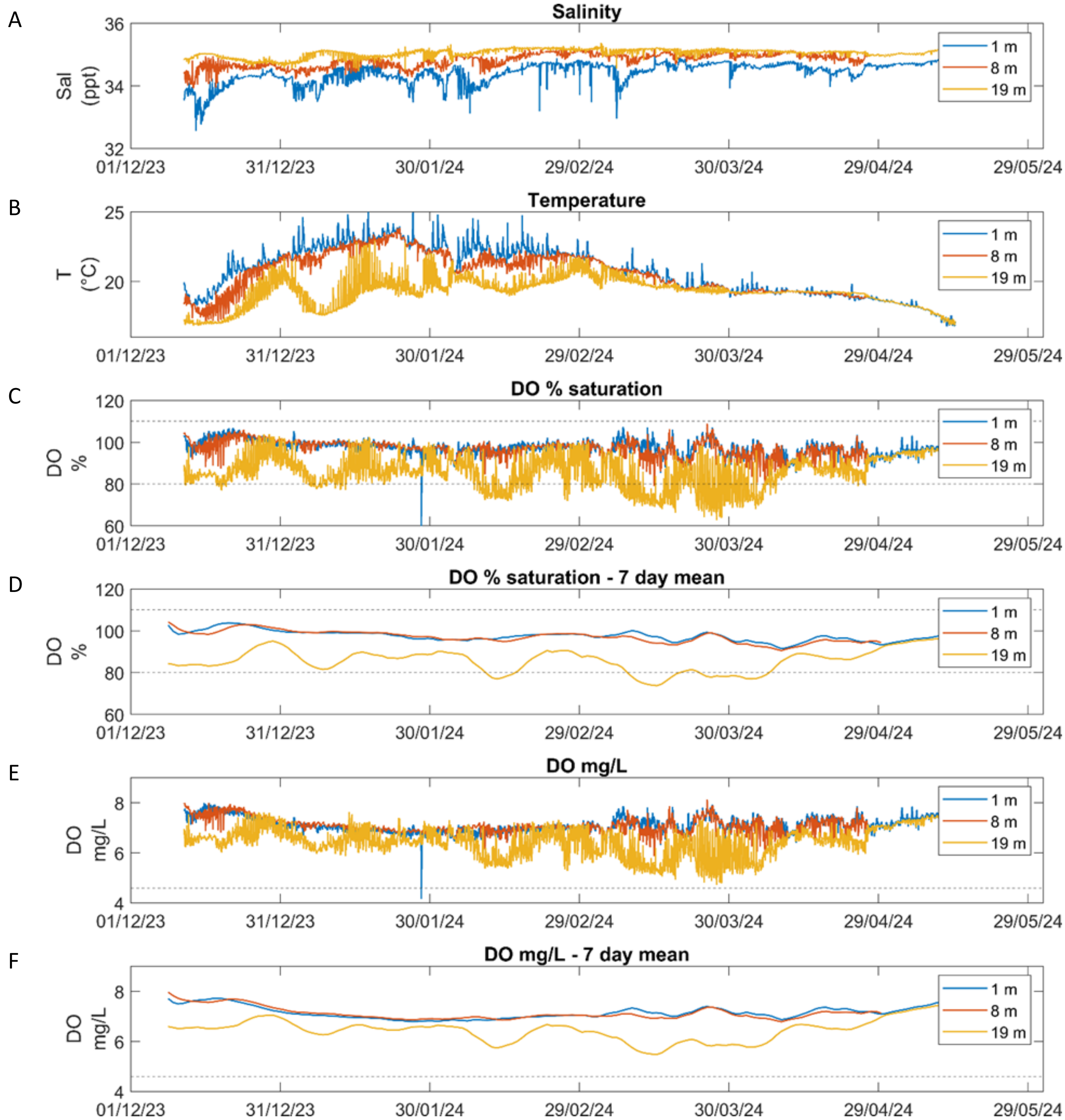

Figure 9. Selected time series from Wai-Q-Tahi from Dec 2023–May 2024 at three depths. (A) Salinity, (B) Water temperature, (C) Dissolved oxygen (DO) % saturation, (D) 7-day mean dissolved oxygen (DO) % saturation, (E) Dissolved oxygen (DO) concentration, (F) 7-day mean dissolved oxygen (DO) concentration. Dashed lines indicate upper and lower thresholds from the Proposed Waikato Regional Coastal Plan WQ Standards.

THE ALTERNATIVES

HFWQ sensing is not the optimal strategy for all decisions because high volumes of data are not necessarily an advantage. All HFWQ projects are resource-constrained, so it is important to separate 'needs' from 'wants' and to complete a robust evaluation of the alternatives.

The alternatives to in-situ sensors at fixed sites in rivers, lakes and estuaries are (1) routine discrete samples and field measurements, (2) passive sampling, and (3) targeted sampling (Figure 1). For some indicators there are limited options (e.g., water temperature must be in-situ), while for others there are several options (e.g., nitrate).

The resourcing available will also be relevant, but that needs to be secondary to ensuring the right data is collected. HFWQ sensing will always cost more than discrete sampling (see Ausseil 2023a, c, b, d, McKergow and Hughes 2025). In addition, the technical skills available within the organisation to manage sensors must be assessed. The time demands on technical staff to troubleshoot sensors and logger systems and to manage data can be large (refer to HFWQ Resourcing report, McKergow and Hughes (2025), for more details).

Discrete sampling – the status quo

Discrete ('grab' or 'spot') sampling provides data for a point in time at a single location, providing a snapshot of water quality. This traditional approach includes both samples collected for lab analysis and field measurements undertaken during a field visit. In New Zealand, discrete sampling is undertaken across water quality networks by all regional councils for state assessment and trend analysis. Discrete sampling requires considerable labour, and there is a short delay (days to weeks) in receiving the results from the lab, which can limit the applicability of this approach for short-term decision-making.

Lab analysis uses standard test methods to provide accurate and precise water quality data. A single sample can be analysed for many indicators (see Table 2). Samples must be collected, handled and transported carefully to ensure the analysed sample represents the water quality at the time of sampling and is not changed by storage or transport (see NEMS Water Quality Parts 2-4; NEMS (2019b, 2019a, 2020)).

Field measurements are collected using field meters equipped with WQ sensors and provide data on indicators which vary in time or space and would be altered during sample transport to a lab (e.g., DO and temperature). Field measurements can also be used to identify spatial water quality gradients; for example, vertical profiling is widely used in lake and estuary monitoring to provide in-situ data on WQ variation with depth. Field WQ sensors require regular calibration and validation to ensure data is of known quality (refer to NEMS Water Quality Parts 2-4).

Passive sampling

Passive sampling provides a time-weighted average concentration at a location. Passive samplers offer an easy-to-use sampling method – the sampler is deployed in-situ and then retrieved and analysed by a lab. Passive sampling has a long history in research and is becoming more widely accepted, particularly for nutrients and metals (Gadd and Milne 2019; Corbett et al. 2020), emerging contaminants (see Nguyen et al. 2021), groundwater (see Imbrigiotta and Harte 2020) and sediment sampling (e.g., Phillips et al. 2000, Hughes et al. 2021). In the context of this project, DGTs (diffusive gradients in thin films) for nitrate are a passive alternative to HFWQ sensors in flowing waters.

DGTs are commercially available and suitable for a range of dissolved substances in fresh and sea waters, including nitrate (freshwater only), phosphorus, metals, pharmaceuticals, pesticides and some emerging contaminants (refer to DGT Research, operated by Lancaster University, UK at https://www.dgtresearch.com). During deployment, a diffusion gradient is established within a DGT, and the compound of interest passes through a membrane filter and diffusive gel, accumulating in the thin film (Davison and Zhang 2016). The film is analysed in a lab and the resulting concentration value represents a time-weighted average over the deployment period.

DGTs have been compared to other approaches for nutrient and metal monitoring in New Zealand's freshwaters. They were compared with alternative approaches in a previous Envirolink project (see Gadd and Milne 2019) and are a cost-effective and reliable option for some compounds (for which a DGT is available). More recently, DGTs were compared to high frequency discrete sampling for evaluating nitrate removal efficacy over short periods (up to 36 hours) in two denitrifying bioreactors. While loads calculated using the two methods were comparable, DGTs were easier to use and had reduced analytical requirements (see Corbett et al. 2020).

The key advantages of passive sampling devices such as DGTs are: (1) the concentration is time-weighted and integrates the temporal variability, and (2) the concentration in the measured extract will usually be higher than discrete sample concentrations, reducing the uncertainty in analysis and improving detection limits. DGTs are suitable for moving water and must be fully submerged for the deployment period. Some of the disadvantages of DGTs are: (1) contamination risk, (2) deployment is limited to short durations (hours to days) depending on the indicator, binding layer material and biofouling risk, and (3) higher cost than discrete samples due to purchase costs and possibly multiple site visits. However, costs could be reduced with new deployment methods which enable multiple DGTs to sample in sequence per deployment. For example, using a Thöe device (www.ael-environnement.nc) it is possible to expose a sequence of DGTs for 2–3 days each and gain a time series of time-weighted average concentrations.

Targeted discrete sampling

For some decisions it is necessary to collect data at critical times. More frequent sampling may be required when a WQ issue emerges or is anticipated (e.g., during extreme weather conditions). For example, when algal indicators (such as pigments measured by algal fluorescence sensors) exceed limits in rivers, lakes or estuaries, targeted sampling is often commenced to closely monitor the changing conditions. This typically involves collecting additional discrete samples which are submitted to a lab for analysis of potential toxins and/or algal species identification.

For unattended monitoring during extreme weather conditions, discrete samples can be collected using simple sampling devices (such as Nalgene bottles) or automatic samplers (e.g., ISCO, Sigma, etc.) (see Gadd and Milne 2019). Automatic samplers can be pre-programmed to collect samples at pre-specified time intervals or in response to sensor data (e.g., water level, flow, turbidity, etc.). Automatic samplers can also be used to collect HFWQ time series at daily or sub-daily intervals for indicators that cannot be measured directly with sensors (see Table 2).

What are the alternatives for the decision(s)?

The first step is to identify which alternatives are available for the indicator(s) required. Table 5 provides an overview of the alternatives for each of the HFWQ sensors included in this project. For some indicators, discrete samples are less frequently collected; for example, Winkler titrations for DO are seldom used, and targeted algal sampling is more common for algal toxins.

When multiple indicators are required to make the decision(s), ensure the alternatives are evaluated for each indicator separately. For example, for a decision requiring summer DO minima and summer nitrate loads for a river, there are several alternatives for measuring the nitrate concentration to estimate the load (see Table 5), but for the DO minima there are no practical alternatives to in-situ sensing (as DO minima often occur outside of work hours in the early hours of the morning).

Table 5. Matrix of commonly used alternatives.

	HFWQ sensing	Discrete sample	Field measurement	DGT	Targeted sampling
Water temperature	✓		✓		
DO	✓		✓		
EC	✓	✓	✓		✓
Turbidity	✓	✓	✓		✓
Nitrate	✓	✓		✓	✓
Algal pigments	✓	✓	✓		✓

Evaluating the alternatives

To evaluate the alternatives for the decision(s), it's useful to assess the information gains, constraints and other considerations which might add support for a particular alternative for each indicator.

For example, for a decision requiring catchment annual nitrate load estimates (concentration x discharge), the alternatives might be:

- Alternative 1 – HFWQ sensing with an optical nitrate sensor (~ 35,000 points),
- Alternative 2 – DGTs (say, 100 time-weighted samples),
- Alternative 3 – routine discrete samples (~12 per year), or
- Alternative 4 – a combination of discrete and targeted samples (12 monthly + ~6 high flow events).

Each of these alternatives has information gains, data quality and operational challenges which may introduce statistical uncertainty into the load estimate and impact on resourcing required. There may also be multiple ways to approach some of these alternatives; for example, Alternative 4 could use autosamplers or rising stage samplers for the targeted sampling, and these alternatives will have different operational challenges and resourcing requirements.

By setting out a consequences table, the alternatives can be evaluated against each other using performance measures. A simple qualitative consequences table with many of the common performance measures is provided in Table 6. A more detailed version for each decision to be made could also include initial budget estimates (refer to the budgeting template in McKergow and Hughes (2025)).

The potential information gains from HFWQ sensing can be large, but the actual information gains can depend on how dynamic the water quality is. Information gains for highly dynamic systems may be larger than for less variable systems. For example, if river nitrate concentrations are dynamic (i.e., diluted during some rainfall events and more concentrated during others), this information on variability will be unseen without using a method that delivers information on short-term dynamics (e.g., HFWQ sensing, DGTs, targeted sampling). However, if a river has a steady nitrate concentration (e.g., a small spring-fed river) then HFWQ sensing may be less cost effective than the alternatives (e.g., discrete sampling). The advantages of HFWQ sensing are therefore greater in dynamic systems, for example those with tidal cycles, diel cycles, high flow events, lake mixing cycles, or a combination of these (see Case Study 3 – Integrated monitoring of Lake Hayes, Otago).

Time biases can be a feature of manually collected water quality datasets as a consequence of sampling occurring during 'fair weather' and during work hours. Rand et al. (2022) demonstrated that a manually collected lake field measurement dataset was biased by wind speed, rainfall intensity and air temperature due to the tendency to collect samples during 'fair weather'. They concluded that manual field measurements will always record higher water temperatures, higher chlorophyll and lower DO than in-situ HFWQ sensing. In some monitoring programmes it may be possible to overcome this 'fair weather' bias, but for fieldwork that requires vessels (e.g., boats, helicopters), health and safety concerns prevent fieldwork in poor weather conditions (e.g., high winds, low visibility). The use of HFWQ sensors is one possible solution to overcome weather biases, particularly on lakes and estuaries. On rivers, the use of automatic samplers or specialist sampling bottles can overcome these health and safety issues. Nighttime sampling is often necessary for detecting some features of water quality dynamics. For example, DO minima typically occur during the early hours of the morning (~ 3–6 am), which is outside of normal work hours. In addition, algal pigments respond to light conditions, and many analysts use nighttime data to overcome this challenge (see Algal Fluorescence Sensor Selection report (McKergow 2025a) for more information on algal dynamics).

A key consideration when evaluating HFWQ sensing against alternatives is the risk of large data gaps and/or poor-quality data. Missing records are common in HFWQ sensing and can occur despite a technician's best efforts. Data gaps in HFWQ records may be caused by:

- out-of-range sensors (e.g., turbidity during extreme events exceeding the sensor's range)
- sensor or logger failure (e.g., water ingress, power loss)
- the inability of sensors to measure under some conditions, such as when they are heavily fouled or there are water matrix effects that affect sensor performance
- damage or loss to equipment (e.g., vandals, during extreme events).

The HFWQ Resourcing report (McKergow and Hughes 2025) contains a detailed list of operational challenges and outlines possible solutions suggested by experienced sensor users.

Fouling and water matrix effects can affect sensor performance. Managing fouling is a major challenge when equipment is deployed in water in many environments. Turbidity and nitrate sensors are affected by suspended particles and dissolved organics dynamics, while algal pigment dynamics affect algal fluorescence sensor performance. These water matrix challenges and fouling management are discussed in detail in the relevant sensor selection reports (McKergow 2025a, c, d, b, McKergow and Vincent 2025).

Telemetry systems can be used to transfer data to the office and help ensure data is loss is minimised (refer to Table 8 in McKergow (2025b) for a comparison of internal logging vs telemetry). Sometimes independent backup sensors are operated (see case study in Water Temperature Sensor Selection report (McKergow 2025e)). While operating backup sensors is common in hydrology (e.g., often three water level sensors are used), it is not widespread in HFWQ due to capital and operational costs.

Missing data or data of a poor or unknown quality may compromise an analyst's ability to calculate statistics and generate useful information for decision-makers. Analysis of Auckland Council's DO data (2020-2024) illustrates the challenges of HFWQ data collection and low-quality data (Young et al. 2025). All 27 sites had periods of lower quality DO data (synthetic, poor quality, unknown quality); 7 sites had more than 25% lower quality data (Figure 10).

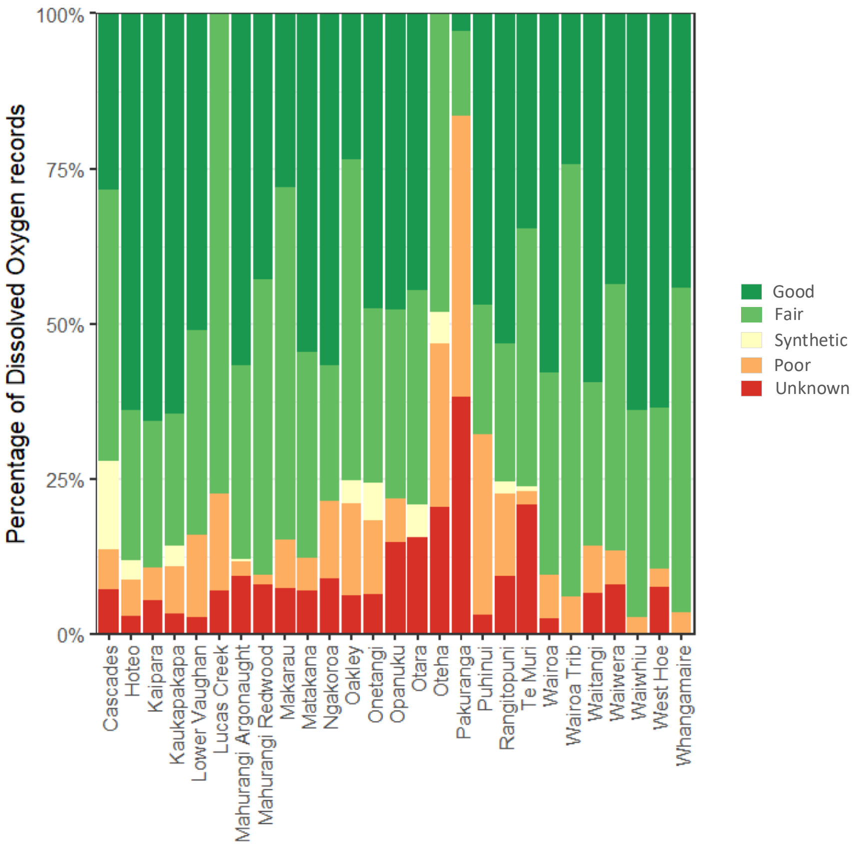

Figure 10. DO data quality for Auckland Council sites (2020-2024; Young et al. (2025)). Good and fair quality data was used for the DO and metabolism analysis.

For some of the alternatives, the equipment required can be simple (e.g., electric thermometer, sample bottles, DGTs), but for other alternatives the equipment is complicated (e.g., autosamplers, multi-parameter field meters, optical nitrate sensors). Operating complicated equipment requires high levels of technical expertise which can be gained through field experience and training (see HFWQ Resourcing report, McKergow and Hughes (2025)).

Table 6. Simple qualitative consequences table for assessing HFWQ sensing against some alternatives (after Pellerin et al. 2013, Davis et al. 2021, Rand et al. 2022).

Considerations	Measure	Alternatives				
		HFWQ sensing	Discrete sample	Field meter	DGT	Targeted - autosampling
Information gains	Short term WQ dynamics	Yes	No	No	Maybe	Yes
	Real-time decision-making	Yes	No	No	No	No
	WQ analysis suite	Limited (see Table 2)	Extensive	Limited	Limited	Extensive
	Temporal dynamics	Hourly-annual (e.g., min, max)	Snapshot	Snapshot	Time-weighted average concentration	Series of snapshots
	Nighttime data	Yes	No	No	Yes	Yes
	Sampling biases due to weather	No	Possibly	Possibly	No	No
	In-situ measurements	Yes	No	Yes	No	No
Statistical challenges	Susceptible to aliasing[1]	No	Yes	Yes	No	No
	Serial correlation[2]	Yes	No	No	No	Possibly
Data quality	Data gaps	Occasional–common	No	No	No	No
	Water matrix effects[3]	Yes for nitrate, turbidity & algal fluorescence	No	Maybe	No	No
	NEMS available	Some[4]	Yes	Yes	No	No
Resourcing	Budgeting effort	Challenging	Simple	Simple	Simple	Simple[5]
	Capital expenditure	Small (water temperature) to large (telemetered buoy)	No	Small	No	Moderate
	Operational expenditure	May be large, needs contingency planning	Known cost	Known cost	Known cost	Known cost, may need contingency planning
	Technical training level	Expert	Beginner	Competent	Beginner	Competent
	Equipment lifespan	Long, often 6[+] y	–	Long, often 6[+] y	Short, 3 mo shelf life	Long, often 6[+] y
	Risk of equipment loss	Low–high	Low	Low	Low	Low–high
Operations	Field maintenance	Significant	No	No	No	Moderate
	Deployment	Simple to complex			Simple	Complicated
	Biofouling	Challenging	No	No	Restricts deployment length	No
	Data management editing & auditing tools required	Preferably time series software	Simple	Simple	Simple	Simple
Overall	Efficiency summary	High cost for high resolution temporal data	Low cost for infrequent data	Low cost for infrequent data	Low cost for time weighted average data	Low to high cost for snapshots of moderate resolution data
	Lead time to decision-making	Months (existing data or simple system) to years (complex system)	Years	Years	Days–Years	Days–Years
	Risk of failure	Could be high	Low	Low	Low	Could be moderate

Notes:

1. Low sampling frequency does not accurately reflect the temporal variation of water quality.
2. Closely spaced samples will tend to give similar information.
3. Refer to Optical nitrate, Optical scattering and Algal Fluorescence Sensor Selection reports (McKergow 2025d, a, McKergow and Vincent 2025).
4. NEMS are available for DO, water temperature, turbidity and suspended sediment load (NEMS 2025b, a, 2026a, b).
5. For a sample of conditions (e.g., budget can be limited to sampling up to 5 events during a year).

REFINING A SYSTEM DESIGN

Which alternatives (or combination of alternatives) will support decision-making (Step 6, Figure 6)? The transition from discrete sampling to unattended HFWQ sensing comes with increasing resourcing cost, technical skill requirements, complexity and risk of failure (Figure 10). It is important to evaluate the alternatives carefully. Table 7 provides a template for evaluating the consequences of choosing an alternative – but it is generic and so a more detailed version will be required for the decision.

Table 7. Considerations for HFWQ system design (refer to Table 6).

Key questions	Potential consequence of not considering key questions	Possible solutions
What are the alternatives?	- Data collected are not required or suitable for decision-making.	- Select the alternatives which can be used to make the decision. Select alternatives for each WQ indicator (as there may be numerous alternatives for some indicators e.g., nitrate in Table 5).
What is the anticipated variability in each indicator?	- Mismatch between system and required temporal/spatial resolution.	- State the expected variability for each indicator (e.g., diel, storm events, seasonal, etc.).
What are the information gains for each alternative?	- Resourcing overspend due to not adopting the simplest monitoring system that meets information needs.	- Evaluate the information gains – real time, short term WQ dynamics, in-situ measurements, and sampling biases (see Table 6).
What statistics are required?	- Mismatch between data and statistics required.	- List the statistics required (e.g., summer 1-d minima, concentration time series to estimate annual loads). - If required, document statistical models (e.g., surrogate relationships) - Assess the impact of serial correlation and aliasing.
Are additional indicators required to correct the indicator of interest?	- Sensor corrections cannot be completed, leading to low-quality data.	- Check each indicator for required corrections (e.g., water temperature for DO and EC; refer to McKergow 2025a, b, c, d).
Are technical staff with appropriate skills available?	- Delays in data delivery. - Increased risk of failure. - Resourcing overspend.	- Check technical skills of staff involved (in your organisation or external contractors). - Consider the guidance on training in the HFWQ Resourcing report (McKergow and Hughes 2025).
Do you have a fit-for-purpose data management system?	- Data processing may be delayed and not managed well.	- Evaluate whether your current data management system is suitable for HFWQ data.
What is the required lead time to decision-making?	- Inability to deliver data in the time frame required.	- Consider how long it might take to deliver new data. Refer to the three Case studies and Table 6.
What are the risks of your chosen approaches?	- Challenges may outweigh information gains.	- Check the Challenges section in the HFWQ Resourcing report (McKergow and Hughes 2025). - Consider the detailed guidance and case studies available in the six Sensor Selection reports (McKergow 2025a, b, c, d, e, McKergow and Vincent 2025).

In practical terms, the alternatives are not always mutually exclusive; often a combination is required to meet data or data quality objectives. Some use cases may combine less frequent spatial resolution data (discrete samples and field measurements) at multiple sites with HFWQ sensing at one or two of the sites (e.g., Case Study 2 – Integrated Coastal monitoring in the Firth of Thames). In addition, verifying HFWQ sensor operation often requires discrete samples and field measurements (consult NEMS 2025b, 2026a, b). The use of surrogates (see Table 2) also requires a combination of methods to collect data for the surrogate relationship (e.g., autosampling during high flow events in rivers to relate sensor turbidity to suspended sediment concentration).

For long term sites it is almost inevitable that the sensor technology will evolve, or a manufacturer will discontinue a sensor (refer to McKergow (2025a) for some recent examples). For some indicators, a change in sensor technology or model will not have a large impact (e.g., water temperature). However, when sensors which lack numerical comparability — two different sensors output different values in the same solution — additional resourcing may be required to ensure that data output by the new and old technology create a continuous time series. For example, to meet site stationarity requirements simply and efficiently, ideally the same sensor make/model should be used to measure optical scatter/turbidity through time (or algal fluorescence).

CASE STUDY 3 – INTEGRATED MONITORING OF LAKE HAYES, OTAGO

Lake Hayes is a scenic and highly valued lake used for many recreational activities, such as boating, fishing and swimming. Since human settlement the land and lake have changed (including land clearance, pastoral grazing, fertiliser application, drainage works, industrial waste), impacting the streams entering the lake and Lake Hayes itself. Signs of the lake's declining water quality include increasing algal blooms over the last 20 years, decreased water clarity and a deterioration in the quality of recreational fishing.

While Lake Hayes has a long history of discrete WQ sampling and field measurements, starting with university research projects in the 1940s, HFWQ sensing is more recent. In 2018, Otago Regional Council (ORC) established HFWQ monitoring on the main tributary, Mill Creek, as part of a two-year nutrient study which combined HFWQ sensors at two sites with monthly sampling across the major tributaries. In 2019, a monitoring buoy with a weather station and WQ sensors was deployed on Lake Hayes.

The current HFWQ monitoring strategy is designed to meet both real-time and deferred decision-making timeframes and multiple data objectives:

(1) Deliver real-time information on lake weather and water quality for public health (real-time).

(2) Better understand the lake system and its response to change (deferred).

(3) Reduce uncertainty in tributary load estimation (deferred).

(4) Evaluate the effectiveness of plans and strategies to improve water quality in Lake Hayes (deferred).

Continuous data from the lake buoy provides real-time information on lake weather conditions, and water quality changes (such as change in chlorophyll fluorescence indicating the start of an algal bloom) can be quickly communicated to lake users. The goal at Mill Creek is to reduce uncertainty in estimates of contaminants entering the lake: total phosphorus, nitrate and suspended sediment load (mass per unit time) and specific yield (mass per unit time per unit area). Turbidity is used as a surrogate to model records of continuous suspended sediment and total phosphorus concentration. An optical nitrate sensor, verified with discrete samples, provides high-frequency nitrate concentration data. The calculated loads can then be used to identify the impact of different seasons and events on lake water quality and guide actions to improve water quality.

The monitoring strategy combines discrete WQ sampling, field measurements, targeted sampling and HFWQ sensors (Table 9). Discrete WQ samples are required for SoE monitoring, sensor verification and for use in surrogate models for load estimation. Field measurements are required for HFWQ sensor verification and to contribute to SoE monitoring. Targeted samples are collected for flood events on the tributary and to monitor algal blooms. The HFWQ sensors provide detailed data between site visits.

The addition of the HFWQ sensors builds upon the prior multi-decade monitoring programme – it does not replace it. Monitoring of Mill Creek started in 1983, and the monitoring strategy included monthly discrete samples and field measurements, with additional targeted sampling of floods between 1993 and 2000 to support load estimation (see Table 9 for more details). Lake Hayes was included in the ORC recreational water quality programme in 2005 and the 'State of the Environment' (SoE) monitoring in 2010; this ongoing monthly monitoring includes discrete samples and field measurements (profiling; see Table 9).

Table 8. Lake Hayes monitoring strategy.

	Discrete samples	Field measurements	Targeted samples	HFWQ sensors
Frequency	**Scheduled (fortnightly / monthly)**	**Scheduled (fortnightly / monthly)**	**As required**	**Continuous**
Tributary monitoring	- SoE (many indicators since 2010) - load estimation surrogate models (TP and SSC) - sensor verification (nitrate)	- SoE (since 2010) including DO, temperature - sensor verification (temperature, turbidity, DO)	- flood event samples for load estimation surrogate models (since 1993)	- 5-min DO, pH, conductivity, temperature, turbidity, nitrate (since 2018 with site relocation)
Lake monitoring	- contact recreation (*E. coli*) weekly during summer at shoreline sites - SoE (many)	- SoE (since 2010) - profiling for sensor verification (turbidity, temperature, DO, chlorophyll, conductivity)	- algal analysis for bloom characterisation	- lake buoy with profiler (since 2019) measuring temperature, turbidity, specific conductivity, DO, and chlorophyll and phycocyanin pigments at 3-hour intervals

A monitoring buoy was installed in Lake Hayes (Figure 11 A) in 2019 under a commercial agreement with a New Zealand provider, Limnotrack (refer to the case study in McKergow and Hughes (2025) for more details). A weather station is mounted on the buoy above the water, and water quality sensors are located within the water column. The water quality sensors measure temperature, turbidity, conductivity, algal fluorescence (chlorophyll) and dissolved oxygen every 60 minutes. The buoy uses an electric winch (or profiler) to raise and lower the sensors through the water column (Figure 11 A), enabling WQ to be measured at multiple depths. This data permits an understanding of important water column variables:

- the extent of thermocline (the transition layer between the warmer mixed water at the surface and cooler deep water below)
- the extent of DO depletion. Over summer, the lower lake water column becomes oxygen deficient as microbes break down organic material and use the water's available oxygen
- the vertical distribution of algae
- the onset and timing of stratification.

The raw data feeds into Limnotrack's Hydrotel server and is then published to a dashboard to provide real-time data in a visual format (see Figure 11 C). The monthly CTD profiles are processed in-house by ORC.

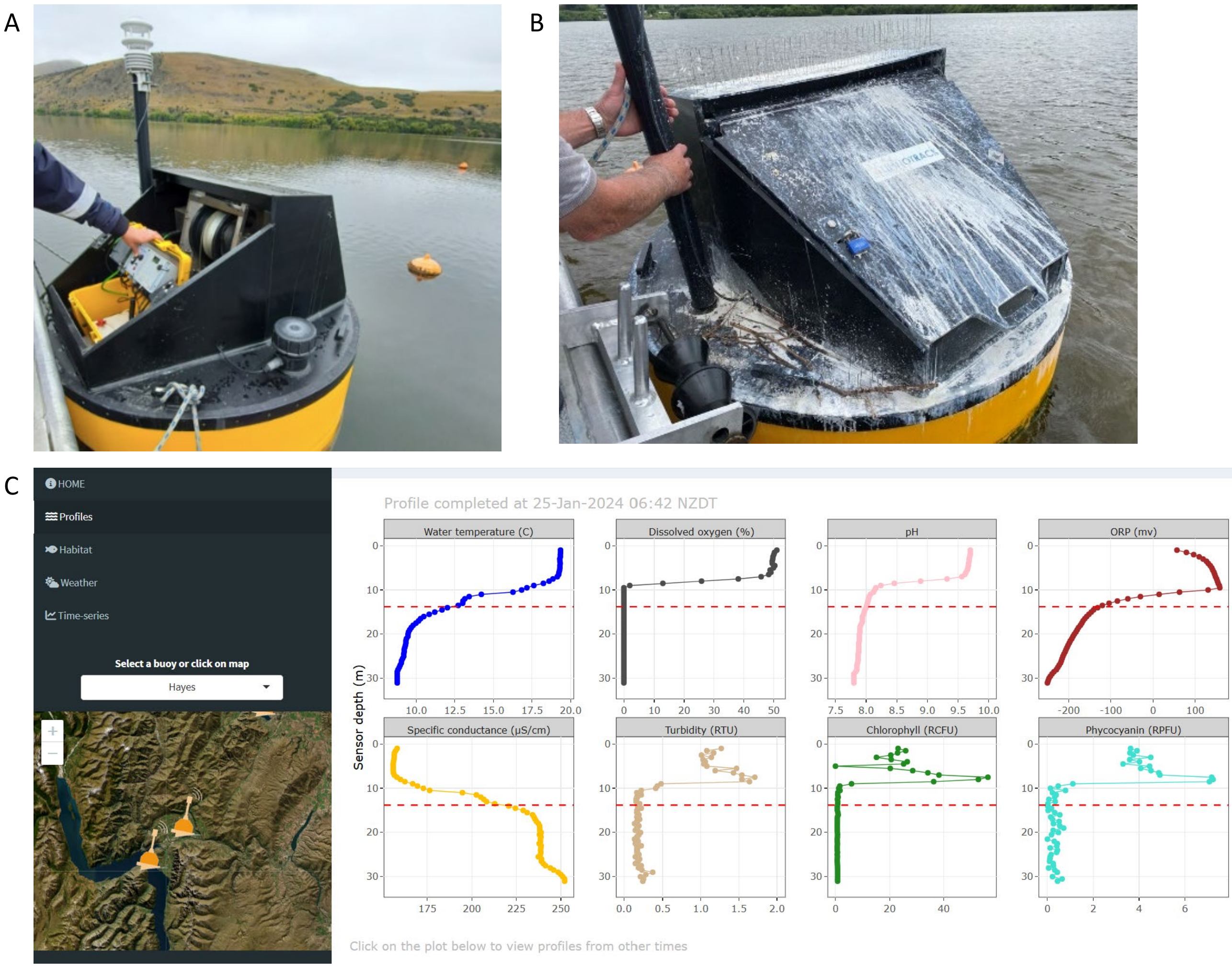

Figure 11. Lake Hayes monitoring buoy. (A) Immediately after installation [ORC]. (B) With additional bird roosting deterrents [ORC]. (C) Screenshot of the Lake Hayes buoy dashboard showing HFWQ data collected during a single profile (Data - ORC Environmental Data Portal).

HFWQ monitoring on Mill Creek commenced in 2018 as part of the Lake Hayes nutrient study (see Figure 12 A). Two sites were established on Mill Creek – the first at Hunter Road (Figure 12 B) and the second just upstream of Lake Hayes (Figure 12 C). At both sites, a YSI EXO sonde measured temperature and turbidity, and stored the data internally. A TriOS NICO nitrate sensor was added in mid-2019 to the Mill Creek at Lake Hayes site, and the site was upgraded with telemetry. However, due to vandalism the sensors were moved in May 2023 about 500 m upstream to the existing Mill Creek at Fish Trap SoE site (Figure 12 D). The move also co-located the sensors with discharge and monthly SoE monitoring, while avoiding the influence of remediation work occurring at the Mill Creek-Lake Hayes confluence.

At the Fish Trap site, a YSI EXO3 sonde equipped with a central wiper measures temperature, conductivity, turbidity, pH and DO every five minutes, as does a TriOS optical nitrate sensor fitted with a ZebraTech wiper. The HFWQ data is telemetered back to the ORC office by the logger via NIWA's NEON system server and then passed to Aquarius Time Series for data processing and publication. The data is publicly available in real-time via ORC's Environmental Data Portal. Receiving data in real-time enables staff to detect equipment failure and sensor fouling early. If a sensor or logger fails, the recent data is secure as it has already been retrieved from the sensor. The site also has good external (solar) power sources, which enables frequent measurements.

Setting up new monitoring sites can be time-consuming, and various physical and regulatory hurdles need to be navigated before they are operational. The key challenges for ORC to implement HFWQ sensing as part of the Lake Hayes monitoring strategy included:

- Locating suitable sites – finding locations on Mill Creek with good mixing and with natural protection from debris during flood events was difficult.
- Working out the best site visit frequency – at Mill Creek the site visit frequency varies with season to manage fouling and ensure the sensors are submerged. Initially, the sites were checked monthly during SoE sampling runs by staff travelling from Dunedin. It became apparent that more frequent site visits were required to ensure sites were operating correctly, and technical staff now operate out of a nearby regional office.
- Staff training – staff have worked hard to learn how to successfully operate the HFWQ sensors (e.g., YSI EXO sonde, TriOS nitrate sensor) and supporting instruments (e.g., automatic sampler). It took time for staff to learn enough about the sensors to be able to reliably troubleshoot any issues (e.g., data downloading, power supply issues).
- Deployment delays – the Limnotrack lake buoy took 12 months to deploy and commission. Its mooring is a custom design for Lake Hayes and there were lengthy international shipping delays. A moorings plan and resource consent were also required.

Currently, three technicians and one scientist work on the Lake Hayes monitoring (Table 9). At Mill Creek a technician carries out inspections of HFWQ sensors three times each month in summer and monthly in winter. The sensors are removed annually for a thorough check and calibration, and this can be time-consuming. The Environmental Data team performs daily checks on the data telemetered to their office for possible sensor or site issues. Lake sampling is completed monthly, with additional contact recreation sampling from the shoreline during summer (Table 9). The current monitoring programme is funded from ORC's SoE monitoring programme and budget. It took several years to secure funding for the lake buoy.

The first report to convert the Mill Creek HFWQ data to information was recently prepared by NIWA (Hudson et al. 2023). It estimates suspended sediment, total phosphorus and nitrate loads using HFWQ data and demonstrates how the nitrate sensor reveals short-term WQ dynamics.

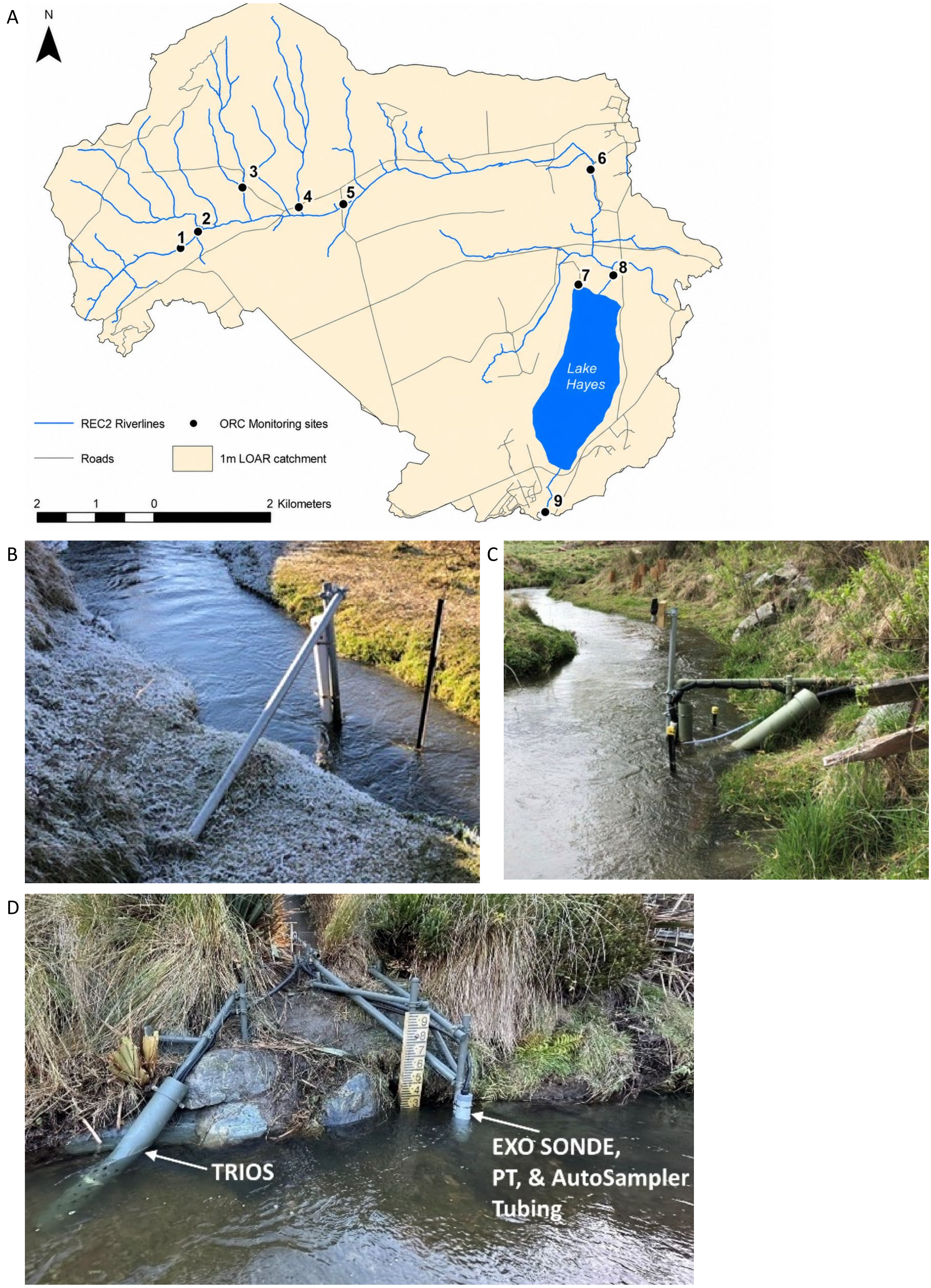

Figure 12. Lake Hayes monitoring sites. (A) Map of the Lake Hayes catchment and ORC water quality monitoring sites for the nutrient study [ORC]. (B) Site 5 - Mill Creek at Hunter Rd [Emily Olson, ORC]. (C) Mill Creek at Lake Hayes – 500 m downstream of site 7 [Emily Olson, ORC]. (D) Site 7 - Mill Creek at Fish Trap [Emily Olson, ORC].

SUMMARY

This report provides an overview of use cases which require councils to use in-situ WQ sensors, and it offers a scoping framework to support initial planning for new decision problems. The framework includes eight steps, and this report addressed three of them in detail – defining the use case for HFWQ sensing, use of existing data for decision-making, and evaluating WQ sensors against the alternatives to ensure the use case and system design are thoroughly scoped and well justified.

A use case should outline the key information gains from in-situ WQ sensors, such as sub-daily dynamics, real-time data, or data collection during extreme events, poor weather and at nighttime. Many natural WQ processes occur outside of office hours (e.g., DO minima, SSC peaks during high flow events) and HFWQ sensors can fill these information gaps while staff are not at work or conditions are not safe for fieldwork.

Existing data may be able to support decision-making immediately, rather than waiting years for a new project to be designed, resourced and implemented. Existing data could be historic (mostly discrete lab data) or contemporary, such as consent monitoring or community-based monitoring. If existing data is available and meets data currency and quality requirements, it is a cost-effective option. If no suitable existing data is available, a new system will need to be designed.

Before starting with detailed planning, it's useful to complete a scoping exercise which clearly outlines the information gains, constraints and challenges of HFWQ sensing and the alternatives (e.g., discrete sampling & field measurements or DGTs). By considering many features – information gains, data quality, resourcing, operations, efficiency, lead time and risk of failure – for HFWQ sensing and the alternatives, the simplest viable system design should emerge. While the framework focuses on commonly used alternative methods, there may be additional alternatives – now and in the future – for some use cases.

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