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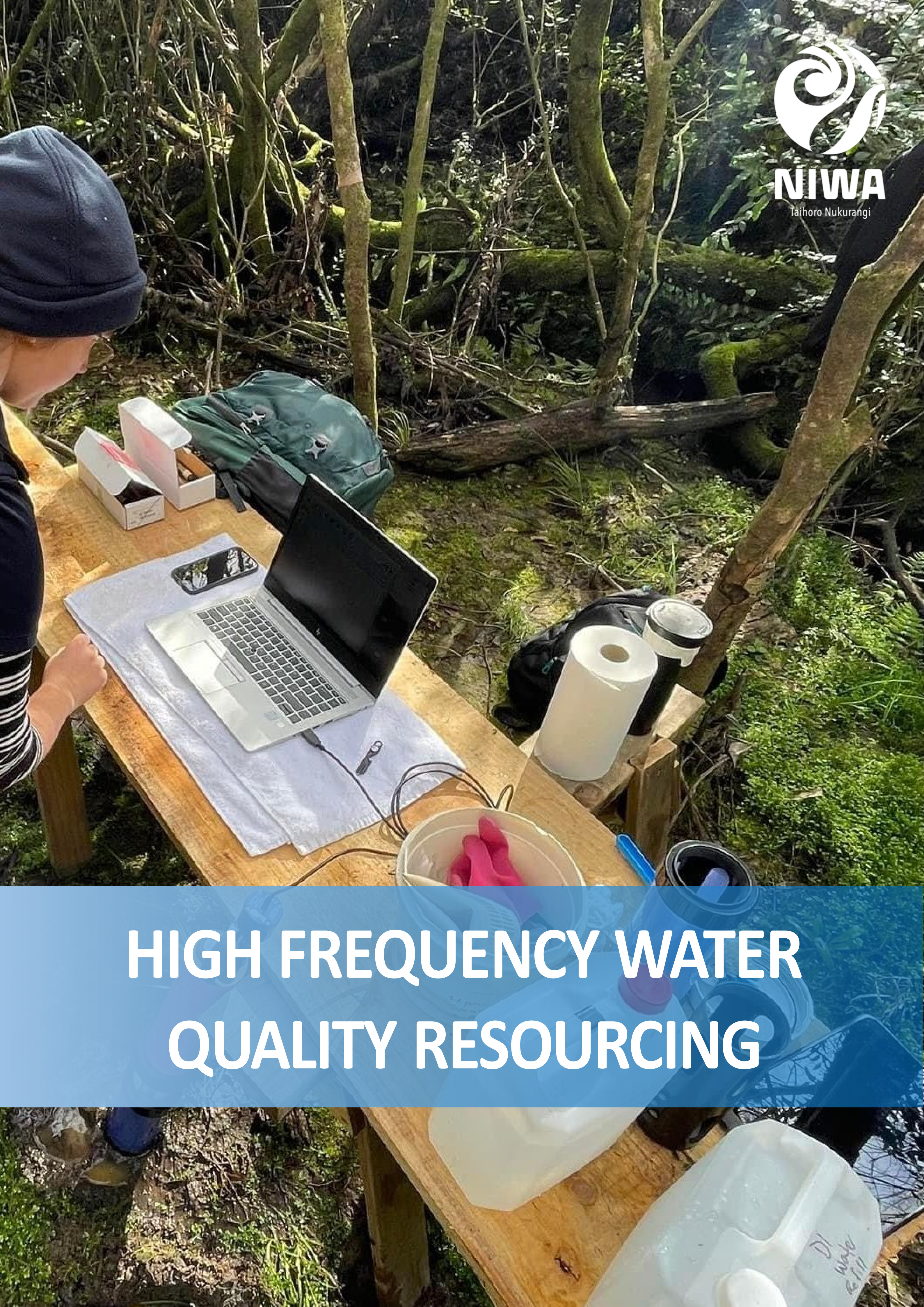

HIGH FREQUENCY WATER QUALITY RESOURCING

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Front cover: Technician servicing a sonde in the Mangakootukutuku Stream, Hamilton [Rochelle Petrie, NIWA].
Back cover: Divers servicing Wai-Q Tahi in the Firth of Thames [Rod Budd, NIWA].

CONTENTS

ABSTRACT

The growing commercial availability of high frequency water quality (HFWQ) sensors has created opportunities to measure concentrations at frequencies and spatial scales that were not previously feasible. However, it's not as simple as placing a sensor in the water and leaving it to do its thing – for reliable data, HFWQ sensors require ongoing maintenance and quality checks.

This chapter describes the resourcing required to operate HFWQ sensors, identifies key challenges, offers potential solutions, and includes case studies. Most HFWQ sites across Aotearoa New Zealand are unattended and visited on a regular (usually monthly) schedule. During these site visits, data quality checks and maintenance are completed.

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 indicators (e.g., nitrate, dissolved oxygen) and provide detailed insights into water quality dynamics at scales of interest (minutes to hours). However, these sensors can create different technical challenges, and unattended deployments can be resource hungry. HFWQ monitoring projects are more likely to succeed if they have: (1) clearly defined objectives, (2) robust data collection systems, and (3) well thought-out methods for managing raw data and converting it into knowledge for making decisions.

This chapter provides detailed guidance on resourcing requirements for HFWQ data collection. It sits alongside guidance chapters on HFWQ Use Cases, Sensor Selection and Automated Anomaly detection as part of the *High Frequency Water Quality Monitoring Guidance* project.

PURPOSE AND SCOPE

This chapter provides information and guidance on resourcing HFWQ sensing at fixed sites in rivers, lakes and estuaries. Its purpose is to help regional council staff to budget and plan for HFWQ deployments.

RELATED RESOURCES

Readers are strongly encouraged to also read the following documents:

- Guidance developed in Our Land and Water outlining basic costings for operating nitrate, turbidity and chlorophyll-a sensors (Ausseil 2023a, Ausseil 2023c, Ausseil 2023b, Ausseil 2023d).
- The NEMS Data Processing (NEMS 2023) guidance, which outlines procedures for various environmental time series.
- The available continuous water quality NEMS guidance for each of DO, water temperature and turbidity (NEMS 2025b, NEMS 2025a, NEMS 2025c), which outline data standards, data grades and an overview of field and office operating procedures.
- International examples of monitoring buoy operations, such as Schroeder and Borghini (2024).
- International examples of resourcing requirements to operate HFWQ sensor networks, including Jones et al. (2017) and Seifert-Dähnn et al. (2021).

RESOURCING STEPS

Planning the resources required for a HFWQ project ideally follows a sequence of steps (Figure 1). Figure 1 also links this guidance to other chapters.

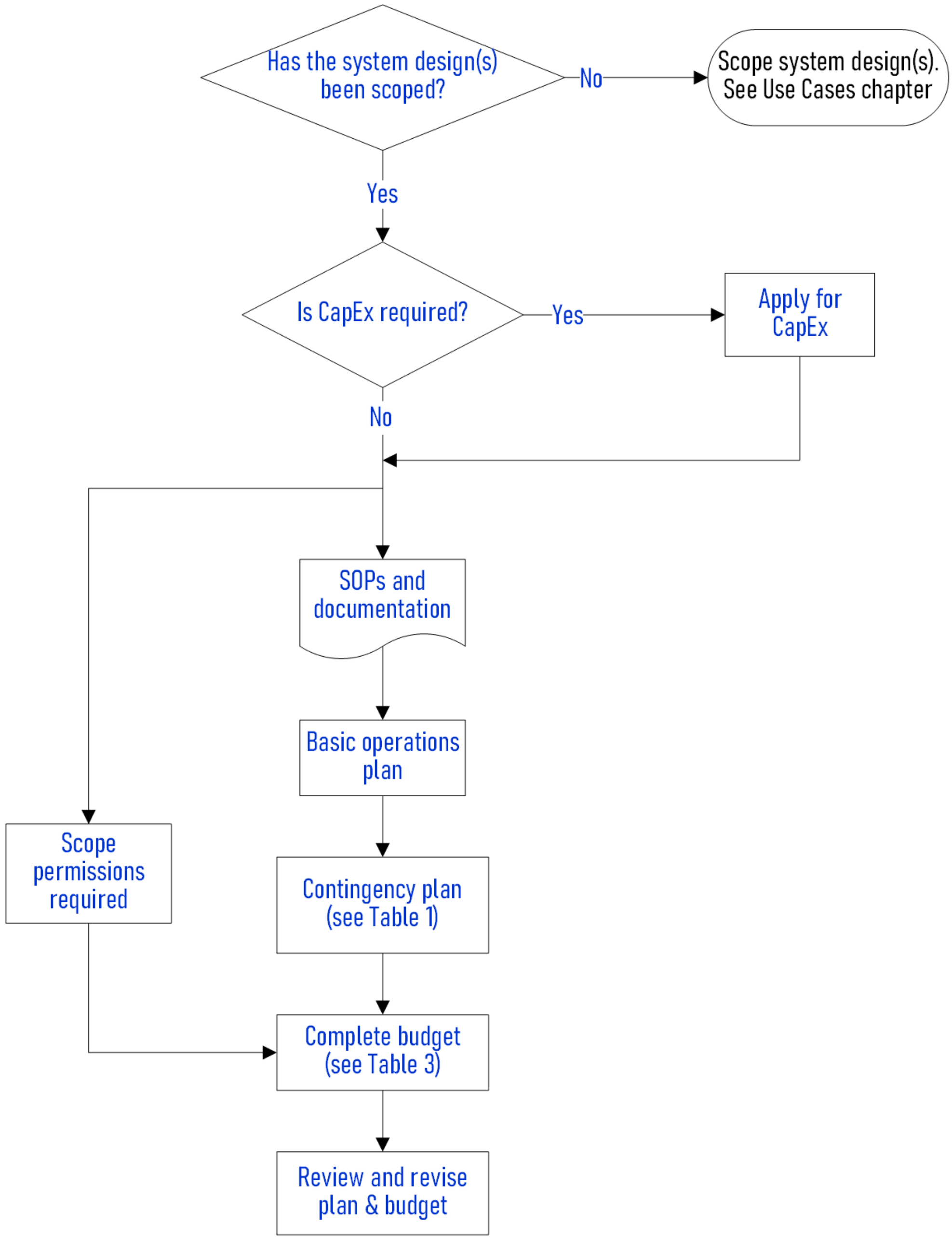


Figure 1. Suggested sequence of steps to guide resourcing.

RESOURCING OVERVIEW

To gather information for this chapter, a HFWQ monitoring, resourcing workshop, was held. The participants all had extensive experience with implementing and operating HFWQ monitoring programmes. The workshop identified that resourcing overspends are common due to a variety of challenges. This chapter will pass on lessons that have been learnt to others who are planning HFWQ projects. It focuses on the operational resourcing required for HFWQ, which includes planning, deployment, field operations and data processing.

Resourcing HFWQ can be challenging because there tend to be multiple objectives and stakeholders (Figure 2), many components, complex sensors, and unknown difficulties ahead. Our experienced project managers noted that almost without fail, the resourcing needed for HFWQ projects in their organisation was underestimated. This was largely because it took much longer to operate a site than predicted. That was due to unforeseen challenges and a lack of understanding of all the steps involved to undertake reliable HFWQ monitoring. It is unwise to use water level monitoring costs as a first estimate for resourcing, because the similarities are limited (e.g., site, logger, power).

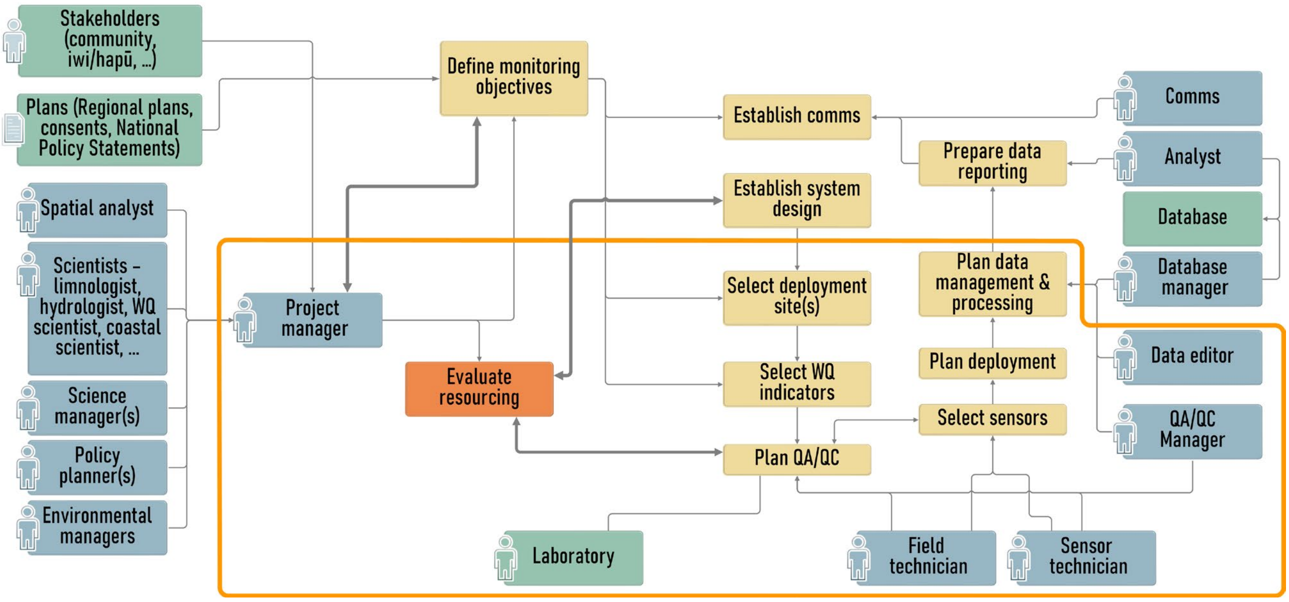


Figure 2. People and components in HFWQ deployment planning, with all tasks considered in this resourcing guidance inside the orange area (after Behmel et al. 2021).

Adequate resourcing tends to be one of the key constraints on HFWQ project system design. Several iterations and compromises are often required to ensure the final system design is possible within available resourcing. Resourcing costs for discrete sampling and field measurements taken on a regular schedule are comparatively simple to budget and to deliver as budgeted. However, for HFWQ sensing, factors such as fouling, extreme weather events and sensor failure increase the complexity, technical skill required and project resourcing costs (Figure 3).

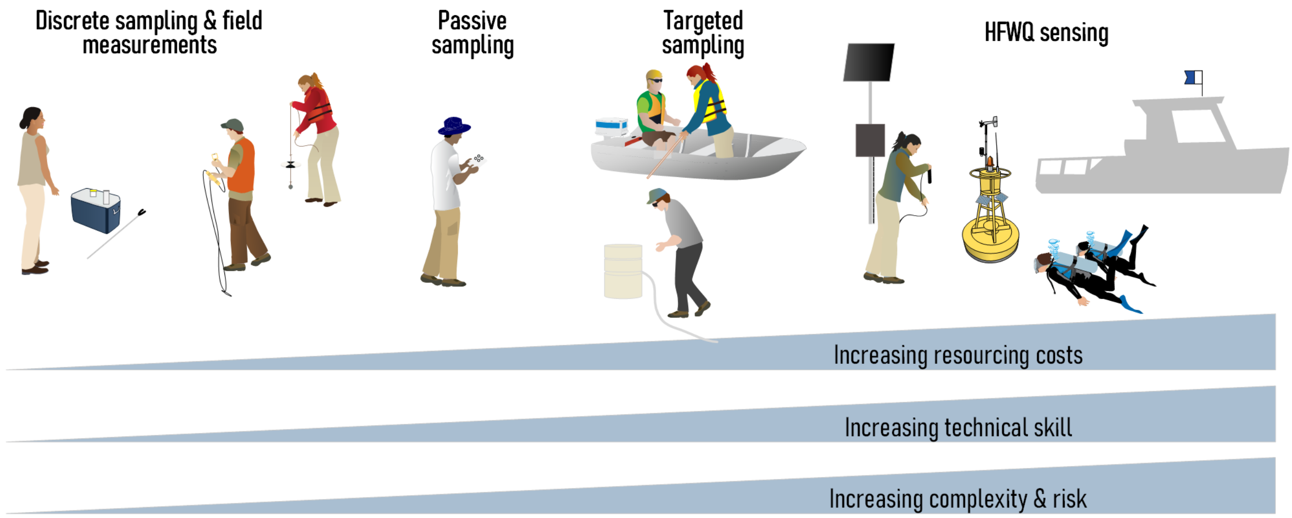


Figure 3. Summary of monitoring strategies and the increasing cost, technical skill and complexity to deliver data for decision-making (IAN symbols [ian.umces.edu/media-library], licensed under Attribution-ShareAlike 4.0 International (CC BY-SA 4.0))

ADVICE FOR NOVICES BUDGETING HFWQ

Here our experienced HFWQ project planners share advice for those who are new to budgeting projects and highlight one thing they wish they'd known earlier.

Be realistic about the cost; one planner commented "go big or go home!" There are significant operational costs associated with collecting fit-for-purpose HFWQ data of known quality. Securing CapEx is often seen as the big expense, but unless complex moorings are required (see Case study 2 – ORC Lake monitoring buoys), routine operations are what tend to dominate project budgets.

- Resource planning is important and time consuming. All the steps involved need to be planned and considered. Having good Standard Operating Procedures (SOPs) will assist with budgeting.
- Spare equipment is essential to simplify lab and field procedures and to support rapid troubleshooting.
- Don't underestimate the time required to ensure good quality data is collected and processed.
- Sensor selection is a key factor – consider how the sensor will operate at the site and as part of your sensor fleet.
- Fouling is a major sensor performance issue, so proactive fouling management is required. Refer to the Sensor Selection Guidance chapters for more details.
- Fieldwork will always take longer than you first think. Find shortcuts (for example consider using cable ties rather than hose clamps if you need to remove sensors frequently) and ensure you have good documentation (e.g., field operations SOPs) to support staff.
- Resourcing needs to consider all costs, right through to the end of data processing. Raw data of unknown quality is of limited value.
- Data processing is one of the most overlooked steps. Data processing is a significant task and should be resourced well. Good quality control data are essential. Staff skills should also factor into resourcing estimates for data processing.
- If quality assurance processes and procedures are not clear and implemented, then data processing will be more challenging.
- Compared to a standard hydrometric site, sites with HFWQ installations/operations use an estimated 2–3 x more resources. Everything will take longer than expected, and consistency in data collection and data processing is critical for data quality.
- HFWQ monitoring tends to require more resources than initially planned. Therefore, careful consideration of all the possible components of HFWQ monitoring and an understanding of the things that may go wrong is important (see Table 1).
- Spread the risk – don't put all your eggs in one basket. Consider using more smaller sensor deployments which can be maintained in-house, over large "showcase" deployments which rely on subcontractors.
- Fixing logger and telemetry faults can be difficult.
- Some sensors will need to be accompanied by targeted sampling, such as autosampling in river high flow events. For example, SSC samples may need collecting to develop a turbidity-SSC relationship, or high flow

event samples may need collecting when nitrate sensor performance is likely to be compromised (see Optical Nitrate Sensor Selection chapter). This additional sampling can be time consuming and needs to be well planned.

WAYS TO REDUCE COSTS

Our experienced planner team suggested several ways to find efficiencies, save time, reduce operating costs and reduce risk. Their advice included:

- It is important for HFWQ programme managers to know how to do all the steps involved in HFWQ monitoring so they are realistic about challenges, expectations and the required resources.
- Some recommend outsourcing complex sensor operations to external contractors.
    - For deep lake and large estuary monitoring buoys which have complex installation and maintenance requirements, outsourcing can be a good approach (see Case study 2 – ORC Lake monitoring buoys).
    - A key advantage is that extra equipment (e.g., boats, skippers, divers) are not required to be purchased or maintained.
    - Research contractors may also be able to supply and service research-grade sensors (for example, see the HFWQ Use Cases chapter, Case Study 2 – Integrated coastal monitoring in the Firth of Thames).
- Others recommend using sensors and deployment methods that can be maintained in-house.
    - This approach is reasonable when available in-house resources include equipment such as kayaks, boats and skippers, and is possibly more suitable for shallower waters (e.g., coastal lagoons, shallow lakes).
    - Some regional councils have tried to use their Harbourmaster’s boats to reduce costs, but there are often scheduling challenges.
    - Local knowledge of in-house staff capabilities is critical for efficient running of sites.
    - For more commonly used instruments with less complex deployments, it is typically more cost-effective to use in-house staff.
- Using a small number of sensor models for an indicator is simpler. Brands differ in download and servicing (including validation/calibration) requirements, and having a small number of sensor models will help with spares management, reduce project complexity and reduce the need to upskill staff in the use of different sensors.
- A common approach is to have the technician who collects the data process it. Technicians who visit the sites are familiar with the equipment and over time become familiar with the specific challenges of the site (e.g., seasonal weed growth, seasonal fouling).

TECHNICAL EXPERTISE

Some councils lack adequate experience and technical expertise for HFWQ monitoring. Technical expertise is essential to delivering high quality HFWQ data. Planning deployments and operating most HFWQ sensors require a high level of technical skill and familiarity with a wide range of equipment (e.g., sensors, autosamplers, loggers, solar power systems, field meters, etc.). A methodical approach and attention to detail are useful personal characteristics for HFWQ technical staff.

A lack of accessible training was identified as a major barrier to project success, particularly given the technical skill level required. Currently, most skills are learnt on the job.

Training should cover all aspects of quality assurance, deployment, calibration, verification, maintenance, troubleshooting and data processing. For example, the decision on where to place the sensor and how to secure it can make or break a project. These skills often come from experience, including learning from failures.

For more complex sensors, each sensor has unique challenges and requirements for maintenance and deployment. Understanding how a make/model of sensor works is critical to operating it correctly.

It can take several years for new staff to become confident operating a new type of sensor. Some new users currently learn how to operate complex sensors from manuals. This is not always ideal as some manuals are very general and lack adequate technical detail (see user experiences in the Sensor Comparison Tables in the six Sensor Selection chapters). This disadvantages users when they are taking their first steps into HFWQ sensing or are asked to operate a sensor they have not used before.

In councils, staff mostly learn from those who have already built their expertise. However, it is risky to depend too much on one expert staff member to do everything and train everyone. The loss of these expert staff can have a big impact on a monitoring programme and the delivery of staff training. Instead their experience needs to be converted into SOPs that define the routine operations and QC processes at a site. It's better to develop good documentation, divide tasks associated with managing a particular sensor type, and ensure multiple staff members receive training.

Field practice is simpler to teach than data processing practice, especially when looking at data of variable quality from a WQ sensor. At TRC, for example, new staff members such as recent university graduates shadow experienced staff for 1 year, and it takes between 18 months and two years for them to work independently. The new staff learn the lab and field practices rapidly, but data processing can be more challenging to learn and do independently. See Case study 1 - TRC Dissolved oxygen monitoring for more details.

To compare the outcomes of HFWQ data processing by a group of novices and experienced technicians, Jones et al. (2018) asked them to process the same water temperature, DO and specific conductivity dataset with the same software. The novices were undergraduate students and their mentors who were participating in a summer research program and had limited field experience. By comparison, the experienced technicians performed HFWQ data checking as part of their job or research. The study highlights the challenges which novices have, particularly around sensor drift correction. It also demonstrates the importance of providing clear data processing guidelines, and the value of ongoing resourcing and training to resolve any different decisions made by experienced technicians.

DOCUMENTATION

Good documentation outlining clear procedures (e.g., SOPs and NEMS) are essential for ensuring resourcing will cover all steps from planning through to data processing. Data quality and record completeness often suffer if good documentation is not available.

In New Zealand, there are National Environmental Monitoring Standards (NEMS) for discrete measurements, three for HFWQ indicators (revised during 2025) and one for data processing (see Related resources). While the NEMS are designed for long-term monitoring programmes, they are also a valuable resource for guiding short-term deployments. They cover measurements, instruments, time and measurement timing, calibration, validation, maintenance, verification, supplementary measurements (e.g., correction factors), metadata and archiving.

NEMS cover the "what and why" but they do not aim to provide the detailed practical "how to" guidance which technical staff require. Good SOPs should outline the "how to" in sufficient detail to guide a less experienced staff member. Inexperienced staff are often good at finding missing or vague instructions in SOPs.

Metadata quality and completeness will impact on data processing and decision making. Collection and archiving of metadata should be included in any resourcing estimate. Metadata should cover site and equipment details, instrument calibration and validation checks, all site visit records (including sensor verification, sensor operating changes, site maintenance), and supporting information for data processors and end users. NEMS (2023) has more details on collecting and recording metadata.

Supplementary and complementary measurements may also be required. Depending on the indicator, supplementary time series may be required for corrections and unit conversions. For example, DO unit conversion in freshwater requires concurrent water temperature and barometric pressure time series. An on-site barometer may also be required if one is not available within 30 km (see NEMS 2025a). Complementary measurements are those which are required for understanding the sensor data. For example, flow measurement is required for load estimation in rivers, and currents, tides and wind speeds may be required in estuaries. If a surrogate relationship is needed (e.g., turbidity-SSC, algal fluorescence-algal biomass), then additional resources will be required to collect and analyse discrete WQ samples.

SUBCONTRACTING

Many councils engage subcontractors when in-house expertise is not readily available or staff do not have capacity to complete tasks within the desired timeframe. These contracts are typically for components such as deployments, servicing and data processing. A variety of contracts are used: supply and install; supply, install and service; service; and data processing.

For complex deployments needing specialist resources, such as deep lake and estuary monitoring buoys, multiple external subcontractors may be required to assist with project delivery. Engineering specialists are often required to design and install moorings, and other expert subcontractors may build, deploy and service equipment, and process data.

For example, Otago Regional Council operates four lake buoys using a mixed model of subcontractors supported by in-house experts (refer to Case study 2 – ORC Lake monitoring buoys). Similarly, Waikato Regional Council operates estuarine moorings in the Firth of Thames using a mixed model with two research organisations (refer to the Use Cases chapter: Case Study 2 – Integrated coastal monitoring in the Firth of Thames).

There can be several disadvantages with using subcontractors, including: (1) lack of opportunities for staff to build expertise in operating bespoke monitoring equipment, and (2) subcontracting data processing can be challenging as the contractors do not know the sites well, and data delivery can be time consuming.

NEW SITES

It helps to be familiar with the relevant lake, river or estuary when planning resourcing for new deployments. Existing data (e.g., river flow, discrete WQ, lake water level, consent data, satellite images) and advice (e.g., people who have worked in your organisation for a long time) may help with assessing variability and extremes. It can be more challenging to plan the resourcing without existing data or information.

Good field reconnaissance of rivers and their catchments may help to assess risks like flood damage and bed sediment mobility, but it can be more challenging to estimate sensor fouling rates. Nutrient concentrations and warm water temperatures will likely increase fouling. Periphyton data may be useful for estimating how fouling rates might vary seasonally.

Commissioning a new site and resolving technical glitches can take many months. Regular site visits (e.g., daily to weekly) will help resolve issues early and shorten the time to getting high quality data. Telemetry can help identify issues and may help shorten the commissioning period. For some sites it will take longer to gain a reasonable understanding of the site-specific challenges and risks.

NEW SENSORS

Budgeting field deployment and operations for unfamiliar sensors requires sound SOPs, resourcing for training, and careful contingency planning. Good sensor selection is crucial, and detailed information is available in the six Sensor Selection Guidance chapters (McKergow 2025a, McKergow 2025d, McKergow 2025c, McKergow 2025b, McKergow 2025e, McKergow and Vincent 2025). A robust sensor with an effective anti-fouling system will help with the collection of high-quality data.

INSURANCE

The issue of insuring high-frequency sensors (and ancillary equipment), which can be expensive, was discussed by workshop participants. The approach to insurance varied:

- Some councils carry insurance that allows lost or damaged monitoring equipment to be replaced. But there can be considerable delay between lodging a claim and receiving funding for replacement sensors (and ancillary equipment such as loggers, moorings, etc.). Delays can be internal and external.
- Some councils carry their own risk and do not insure their sensors because of the cost.
- Some insurance policies have high excess values, so sometimes it is not worthwhile insuring the equipment.
- Where claims have been made, they are often unsuccessful.
- It can be prohibitively expensive to insure all equipment. The risk of losing sensors can be reduced by installing extra measures to secure instruments at monitoring sites (e.g., securing sondes with chains attached to a bridge).
- Another approach is to use smaller, lower-cost sensors and loggers so that any instrument loss/damage is not expensive. This may, however, affect data quality.

CONTINGENCY PLANNING

Resourcing HFWQ monitoring projects is made difficult by many potential challenges and risks. Contingency planning is a key component to ensure adequate resources are secured (Table 1).

Table 1. Contingency planning – challenges and possible solutions.

Challenge	Consequence	Possible solutions
Shortage of trained staff	HFWQ objectives are not achieved	- Ensure resources are specifically allocated to HFWQ objectives. - Hire staff into specific HFWQ roles. - Ensure staff have training objectives in their key performance indicators. - Allocate staff training time, including opportunities to attend technical workshops. - Develop and maintain effective SOPs for end-to-end site operations.
Insufficient understanding by managers of resourcing and training requirements	Failure of project to meet objectives	- Provide detailed monitoring plans that document the expected outcomes and the daily, weekly and longer-term tasks that will be required. - Better communication with managers around the multifaceted nature of the HFWQ monitoring, the challenges and staff training requirements. - Complete a risk assessment and actively mitigate risks to data collection and delivery.
Poor deployment design	- Sensor loss - Poor quality data	- Ensure staff understand the ideal site selection criteria for each parameter (e.g. backwaters, eddies, representative flow, extremes) and locations for sensor verification (discrete sampling or field meter measurements). - Ensure staff have time to test and design good deployment methods. This can be particularly challenging for new sites and new staff. - Bench-test sensors and loggers prior to deployment.
Sensor calibration	- Inaccurate readings	- Calibrations can be difficult to carry out well in the field. Consider adopting a sensor exchange method, with the in-situ sensor exchanged with a freshly lab-calibrated sensor (of the same make and model). This requires more than one sensor and good scheduling but will ensure high quality calibrations are carried out. - Ensure reliable reference readings or samples are collected during site visits to qualify data reliability.
Sensor fouling	- Inaccurate values, poor data quality - No data for decision-making	- In freshwater, use mechanical wipers and physical barriers (e.g., copper, tapes). In estuaries also consider adding a biocide. Check the Fouling Management sections in the DO, EC, nitrate, turbidity and algal fluorescence Sensor Selection Guidance chapters for additional advice.
Hidden costs of data loss	- No data	- Using internal logging sensors (no telemetry) can and does result in data loss. Sometimes the failure is late in the deployment, sometimes all data is lost. It's hard to quantify how much it costs to lose data.
Sensor buried or covered with flood debris in rivers	- Sensor loss (temporary or permanent)	- Budget for a site visit immediately after a high flow event at river sites – the site might have changed. Replacement sensors may be required. - In small streams and rivers install steel fence posts (waratahs, star pickets, Y posts) upstream of the sensor to catch any flood debris.
Different sensor models to measure the same indicator	- Different setup and servicing requirements - Different file types - Different faults	- Recognise that not all sensor models use the same sensing principles and/or sensor design. This is particularly important for EC, turbidity and algal fluorescence sensors (refer to relevant Sensor Selection Guidance chapters). Changing sensor models can result in data and surrogate discontinuities. - Sensors with internal logging might have different battery lifespans, so scheduling downloads and managing instruments can be problematic. - Wherever possible, use a small number of sensor models/types within your organisation. This will simplify technicians' work, help reduce time costs (e.g., calibration and validation procedures), and spare sensors might be more readily available. If this is not possible, try to use same sensor model in a particular project. - If using different sensors, check for different response times and specifications.

Challenge	Consequence	Possible solutions
Drift of sensor readings	- Inaccurate values, poor data quality	- Where possible, regularly review (eyeball) data to characterise the extent of possible drift.
Sensor failure	- No data - Frustrated users	- Bench-test sensors (and loggers) prior to deployment. - Wherever possible, routinely "eyeball" data for operational continuity and quality. - Keep adequate spare sensors to enable quick replacement. - Where possible, always carry a spare sensor when visiting a site. - If resources allow, deploy a backup sensor to ensure data continuity should the primary sensor fail, is buried or not submerged (see Water Temperature Sensor Selection Guidance for a case study). - Track sensor firmware updates. For complex sensors, falling behind on updates means the sensor may need to be sent overseas for servicing.
Communications failure	- Data not transmitted	- Use power control relays to restart sensors and loggers remotely. - Ensure easy access to spare loggers and modem equipment so you don't have to wait for delivery of replacements. - While communications are down, visit the site more regularly to download and secure the data. - If backups are used, establish two methods of communication with loggers (can be expensive).
Power supply issues	- No data - Intermittent data (solar)	- At solar-powered sites, design for at least 5 days' battery capacity without charging. - Sensor internal batteries can fail due to manufacturing faults (avoid using those battery brands again). - Use larger batteries and solar panels. - Use equipment with low power requirements. - Use methanol fuel cells at remote sites with poor solar charging (e.g., forests).
Scheduling issues with boats and skippers	- Loss of data continuity	- For sensors with internal logging, try to ensure data capacity far exceeds the worst-case visit frequency. - Ensure more than one vessel is available to access the site. - Train more skippers. - Enlist Harbourmaster support. - Plan for weather to disrupt plans. - Prioritise specific works.
Vandalism	- Loss of data and complete loss of equipment	- Use proven secure housings – many use steel boxes for river sites. - Locate equipment on private land with approval. - Locate sites away from public places where possible (e.g., roads, parks, walkways). - Sometimes a "less is more" approach may work – the more secure something looks, the more likely it is to be vandalised. - A sticker saying "high voltage'" or "danger" may be an adequate deterrent. - If solar panels & batteries continue to be stolen, consider operating a different power source. Is mains power possible? Is there space for a methanol fuel cell in the housing? - Remove site locations from your organisation's website. - If possible, obtain insurance for equipment.

Challenge	Consequence	Possible solutions
Equipment loss during extreme weather events	- Loss of data - Loss of equipment	- Equipment loss is unavoidable, so budget for it. - Carry out frequent downloads or use telemetry to secure data. - Use a double anchoring system in rivers, such as chaining the sensor to something solid (e.g., bridge pier) in addition to normal deployment methods. - Use lower cost sensors, rather than expensive sensors (such as multiparameter sondes) in high-risk environments. - In large rivers, consider using flow-through systems and pumping water to the sensors on the riverbank. This will cost more to set up, but for long-term sites it can be cost-effective. Horizons RC use this approach on large rivers.
Unfavourable weather conditions	- Data objectives not fulfilled - Site cannot be serviced	- Take care budgeting projects which target particular conditions (e.g., low flows, high flow events). Unfavourable weather (i.e., the opposite of what you require) can affect resourcing. Budget for extra site visits and a longer project duration. - Site visits for lake and estuary monitoring buoys often require calm weather. Budget additional resources to cover postponements or paying subcontractors.
Short-term deployment timing	- Data not representative	- The current NPS-FM Action Plan attribute for river metabolism requires at least 2 weeks of data collection over the summer period, with at least 7 days of consecutive data. This specification means that values collected one summer cannot be statistically compared with values from other years. In addition, sometimes the minimum DO period does not fall within summer (Nov–end Apr); see examples in Young et al. (2025). - Be aware that short-term deployments may not adequately represent variability in water quality conditions.
Short-term site becomes a long-term site.	- Inappropriate deployment approach (e.g., use of internal logging sensor)	- Additional resourcing may be required to transition a site to a more durable long-term set up. This might include redesigning the sensor mounting, using dual attachment methods, using a different wiper, changing to a telemetry-capable sensor.
Delays in data processing	- Data not available for analysis	- Allocate staff time for QC processing and include training time for new staff or new procedures (e.g., NEMS updates). - Automate data processing (see Automated Anomaly Detection chapter).
Uncertainty with QA/QC procedures	- Incorrect data - Incorrectly quality coded data	- Refer to NEMS for guidance (NEMS 2023, NEMS 2025b, NEMS 2025a, NEMS 2025c). - If a NEMS is not currently available decide on your team's approach (the simplest approach might be to remove spikes, code missing data, ensure metadata is archived, and leave the data grade as QC0 – non verified). - Learn from other councils and adopt common approaches for what to do with data in given situations.
Delays in manually loading data from sensors with internal loggers	- Delayed data processing	- Set up automated procedures for syncing offline files to databases. - Ensure users of sensors with internal logging realise that data on a memory stick or laptop may as well not exist – it must be transferred into the database.
Delays in entering field visits & discrete samples into databases	- Delayed data processing	- Use electronic field sheets. - If possible, receive lab analysis results in an electronic format that can be imported directly into the database. Receiving pdf results and manually entering them into a database is time consuming and prone to errors.
Inadequate resourcing to maintain HFWQ sites and data processing	- Poorly maintained sites - Poor quality data	- Ensure all resourcing needs are identified at the beginning so budget is available to maintain sites. - Share resourcing/costs between organisations that have common interests in monitoring.

ESTIMATING RESOURCING COSTS

Estimating HFWQ operational costs is particularly difficult. One useful resource is a summary of cost estimates compiled by the Our Land and Water National Science Challenge for discrete sampling and some HFWQ monitoring in a series of fact sheets (see Related resources). A difficulty in costing staff time is that regional council staff operate multiple sensor networks, and staff often work across several environmental monitoring domains and sites. In many cases staff are not required to record which site or project they spend their time on.

HFWQ data typically cost more than discrete sampling and field measurements, but the cost per data value may be smaller. HFWQ quality assurance requires regular sensor calibration (and/or validation) and verification procedures to ensure sensor values are of known quality. It's always necessary to verify sensor values, with discrete samples or field measurements. These procedures can be time consuming, particularly if verification is required for conditions not checked during routine site visits. For example, operating an optical nitrate sensor requires collecting discrete samples for sensor verification, and extra effort may be required to verify sensor values during high flow events. Likewise, turbidity data is meaningless without concurrent values for the surrogate of interest (e.g., SSC, visual clarity).

The case studies below aim to set some of these challenges in real-life contexts. The first case study compares the labour resourcing required for two different approaches to river DO monitoring in Taranaki. Case study 2 explores the resourcing of Otago Regional Council's HFWQ lake monitoring programme.

CASE STUDY 1 - TRC DISSOLVED OXYGEN MONITORING

Dissolved oxygen (DO) is critical for aquatic biota to live and thrive in water. DO is an attribute in the National Objectives Framework (NOF) of the National Policy Statement – Freshwater Management (New Zealand Government 2024). Regional councils are required to monitor DO to determine the attribute state for rivers in different waterbody management units and downstream of point source discharges. Taranaki Regional Council (TRC) monitors high-frequency DO in streams and rivers year-round at seven permanent sites and at additional sites over the peak summer months (~8 weeks).

Multi-parameter sondes (YSI EXO or In-Situ Aqua TROLL) are operated at the permanent stream and river sites. The sondes are equipped with automatic wiper brushes to clean any fouling from the sensor face before measurements are taken. The sonde sites are all telemetered and have associated site infrastructure (e.g., logger housing and power supply). Provisional data for some of the permanent sites is available in near real-time on the TRC website (Environmental data / Taranaki Regional Council).

The summer-only sites are generally operated with ZebraTech D-Opto Loggers, which store the data in their internal memory. Wipers cannot be used on the soft foils of the D-Opto Loggers (see DO Sensor Selection chapter for details), so these sensors require fortnightly site visits to ensure fouling does not impact data quality. While these short-term summer site deployments are simpler and cheap to establish, they are more labour intensive. The deployments can also be less visible to potential vandals, often requiring only the sensor, a steel fence post (i.e., waratah, star picket, Y-post) and some cable ties.

TRC keeps a detailed database of the time commitments required for each HFWQ indicator they measure. The information builds on information the council compiled to determine resourcing requirements for operating a river flow monitoring site. The database has expanded over time and now includes estimated time requirements for numerous indicators and different deployment scenarios.

At TRC's permanent sites, the DO sensor is one of several measured on the multi-parameter sondes (4–5 sensors measuring 5–6 indicators). It is not always necessary to use all available sonde sensors at all sites, so TRC has assigned time resources required to operate each sonde sensor. In the case of DO, TRC have estimated that 33 hours per site per year are required for an experienced technician. A breakdown of the time allocation for each task related to continuous DO measurement is given in Table 2. To process DO data, supplementary measurements of water temperature and on-site barometric pressure are required for unit conversions. TRC operate YSI EXO sondes for this purpose, and an additional 16.5 hours of resourcing is required to collect and process the conductivity/temperature and 11 hours to collect and process the on-site barometric pressure data.

For budgeting purposes, staff training requires additional resourcing. It is challenging to outline these resourcing requirements as they depend on the technician's experience, but some general guidance is possible. At TRC, recent graduate technicians with less than 2 years' experience are paired with experienced technicians for all field work for at least 12 months. They do not process data for at least 18 months (someone with more experience would typically pick this up). After 18 months' experience they start to process data, but their work is reviewed thoroughly for at least 6 months until sufficient experience is gained.

Table 2. Time allocated by TRC for DO collection at permanent sites (sonde with telemetry and conductivity & temperature sensor, and barometric pressure) versus summer-only sites (internal logging sensor). The resourcing hours are indicative of a fully competent field & data officer with at least 2 years' experience.

Task	Permanent site staff time allocation (hours)	Summer-only site staff time allocation (hours)
Site visits (including verification, maintenance and upgrades)	12	16
Data processing	12	
Travel	3	
Administration	3	
Unscheduled repairs	3	
DO total	**33**	
Conductivity/Temperature total	**16.5**	
Barometric pressure total	**11**	
TOTAL	**60.5/12 months**	**~20-30 hours/2 months**

Obtaining high-quality data from peak summer DO monitoring sites was estimated by TRC to require approximate 20–30 hours per site per year (Table 2). Additional staff time is required for extra site visits (approximately fortnightly) to ensure the sensors are operating, the DO sensor foils are clean, and to download and secure the data.

Using sensors with internal logging does not require any complex infrastructure (e.g., telemetered loggers, housings, power). Their installation cost might be only a third of that of installing a sensor with telemetered logging plus its solar power supply and data logger. However, with internal logging there is the risk that some or all data is lost between sensor deployment and retrieval. Consequently, internal logging sensors need regular site visits to check the sensor and the data it is collecting because there is no way to check in near real-time for spurious data and respond rapidly.

TRC are looking to phase out sensors with internal logging and install telemetered sensors at the summer-only sites. This will allow staff to identify data quality issues early and respond to them, improving data quality. It will reduce resourcing by lengthening the period between site visits and cut staff time spent downloading and managing data from the internally logging sensors.

CASE STUDY 2 – ORC LAKE MONITORING BUOYS

Otago Regional Council (ORC) currently operates three lake water quality buoys for their State of the Environment (SoE) monitoring programme in lakes Hayes, Wānaka and Whakatipu. As of December 2024, a fourth buoy was being prepared for Lake Hāwea. The buoys all have weather sensors. The HFWQ sensors on the buoys measure temperature, dissolved oxygen, turbidity, chlorophyll, conductivity and pH at high frequency. The Lake Hayes buoy also has an extra algal fluorescence sensor (phycocyanin) to detect new algal blooms. The buoys are solar-powered and use an electric winch and armoured data cable to lower and raise the sensors through the water column to a maximum depth of 80 m (Figure 4 B & C). Additional internal logging DO sensors are deployed near the lake bed and in the deep lakes at ~120 m depth.

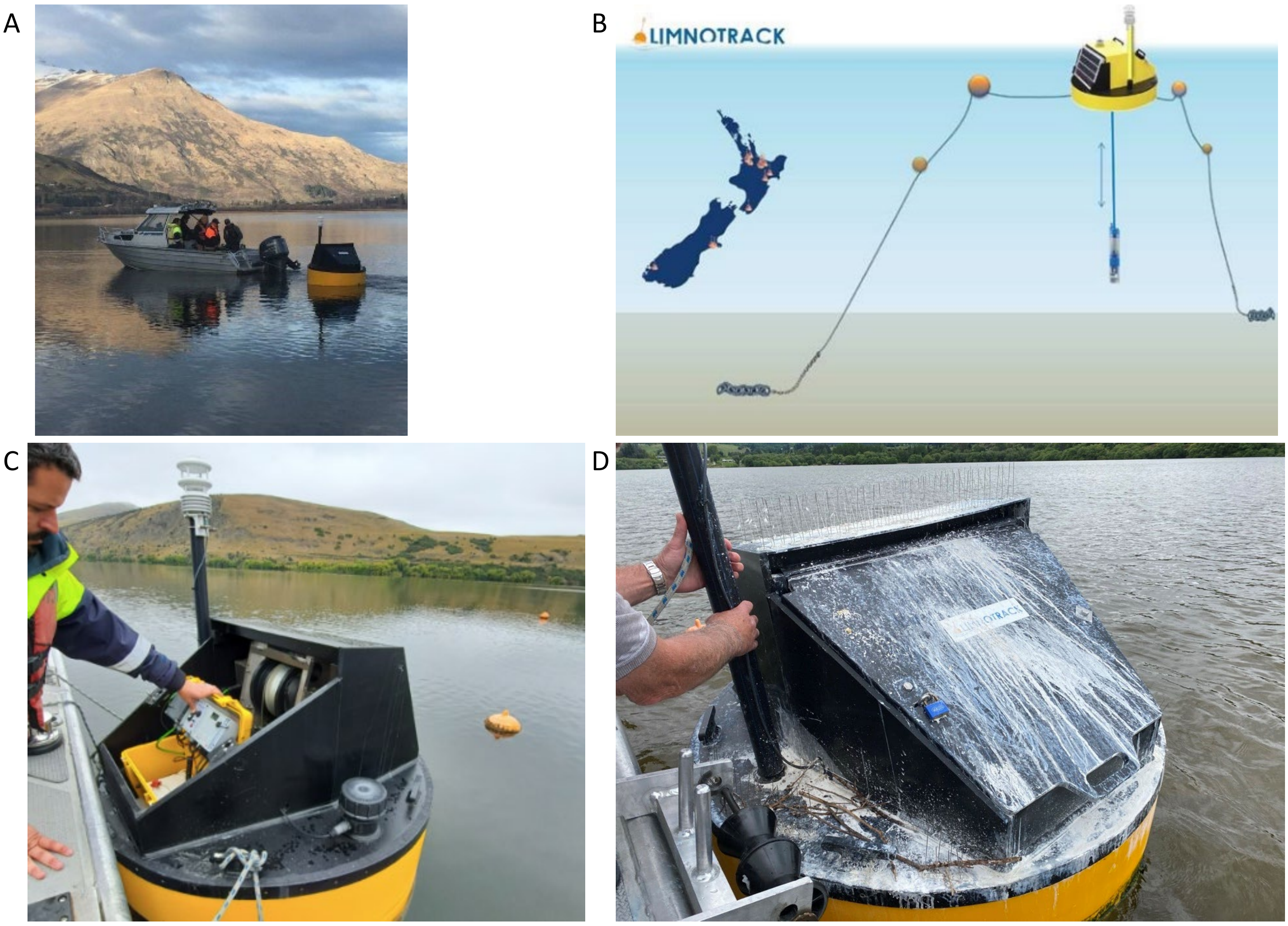


Figure 4. Lake Hayes monitoring buoy installation in July 2019. (A) Buoy being towed to the site [ORC]. (B) Diagram of the mooring [provided to ORC by Limnotrack]. (C) Buoy installed [ORC]. (D) Fouled buoy despite bird spikes [ORC].

ORC originally planned to purchase monitoring buoys and use in-house skills to operate the sensors and process the large volume of data. However, it became apparent that this would be a complex and potentially risky project for a small regional council. So ORC manages each monitoring buoy project in-house and subcontracts different components, such as consent applications, mooring design and installation, monitoring buoy design and installation, monitoring buoy servicing and data processing.

ORC contracts Limnotrack, a North Island-based commercial provider of lake monitoring buoy services, to design and supply fully operational lake WQ monitoring buoys. The buoys have a custom-built hull fitted with a LUFT weather station, a custom HFWQ sensor array, a solar panel, a winch, and a control system (Kisters iRIS logger). ORC leases the buoys from this commercial provider. A mixed-model servicing arrangement is in place for buoy servicing; the commercial provider carries out on-site servicing around twice a year, and ORC staff complete additional servicing if required.

Servicing the buoys is a complex logistical exercise; the ORC boat is in Cromwell and the only trained ORC skipper is in Dunedin. A Central Otago-based ORC staff member is training to be a skipper, which should ease the logistical challenge. It is a large time commitment to train as a boat skipper, requiring a lot of logged training time on the water and large assessments. The training can be completed over the course of a year or as a short 5-week block course (with some providers). It would be hard for a skipper to complete this training at ORC without the support of the Harbourmaster's team.

Data from the buoys are telemetered directly to the commercial provider, who completes the data processing. The data are then uploaded to the ORC's website (see https://envdata.orc.govt.nz/AQWebPortal/Data/ Dashboard/1676). So ORC essentially purchases water quality data from the commercial provider.

A significant resourcing cost for lake monitoring buoys is the design, construction and installation of the mooring system. Mooring designs are specific to the site and sensor package, and lake depth and water level variability are key design factors. The ORC WQ buoys use profiling sensors, which move vertically through the water column taking measurements at multiple depths. Using a profiler system means that the mooring must be located distant from the WQ buoy (see Figure 5 D). The deep lake monitoring buoys are held in place by a three-point spread mooring anchored to the lakebed with three large suction cup anchors (suitable for the muddy bed conditions) that are tethered to spar buoys (tall, thin buoys) at the surface (see Figure 5 A, C & D & Figure 6). This allows for dynamic horizontal loading of the WQ buoy in the centre, some limited horizontal movement during windy conditions and for changing lake levels.

Dynamic lake water levels hugely increase the resourcing costs. For Lake Hāwea, a complex mooring system is required as the water beneath the monitoring buoy is 375 metres deep and the water level can vary by 8 metres as the lake is used for hydro-electric power water storage. A marine engineer was engaged in the design process and the mooring system will cost ~$100,000 to design and install. Lake Wānaka (265 metres deep) and Lake Whakatipu (375 metres) have more stable water levels, and the combined cost for their moorings was ~$80,000. Lake Hayes is shallow (~30 metres deep), so a basic mooring was feasible and cost less than $5000. The deep lake moorings were designed and installed by deep water engineering contractors.

In addition to the mooring and WQ buoy servicing costs there are also unanticipated challenges which require contingency planning. For example, when components of the mooring and WQ buoy were damaged by a boat, the WQ monitoring buoy required towing to shore and patching, and the services of the mooring contractors were also required to repair the mooring lines. In addition, birds sit on the WQ buoys despite bird spikes (Figure 4 D). Their droppings have damaged equipment (e.g., sensor cable corrosion) and fouled the buoys and solar panels.

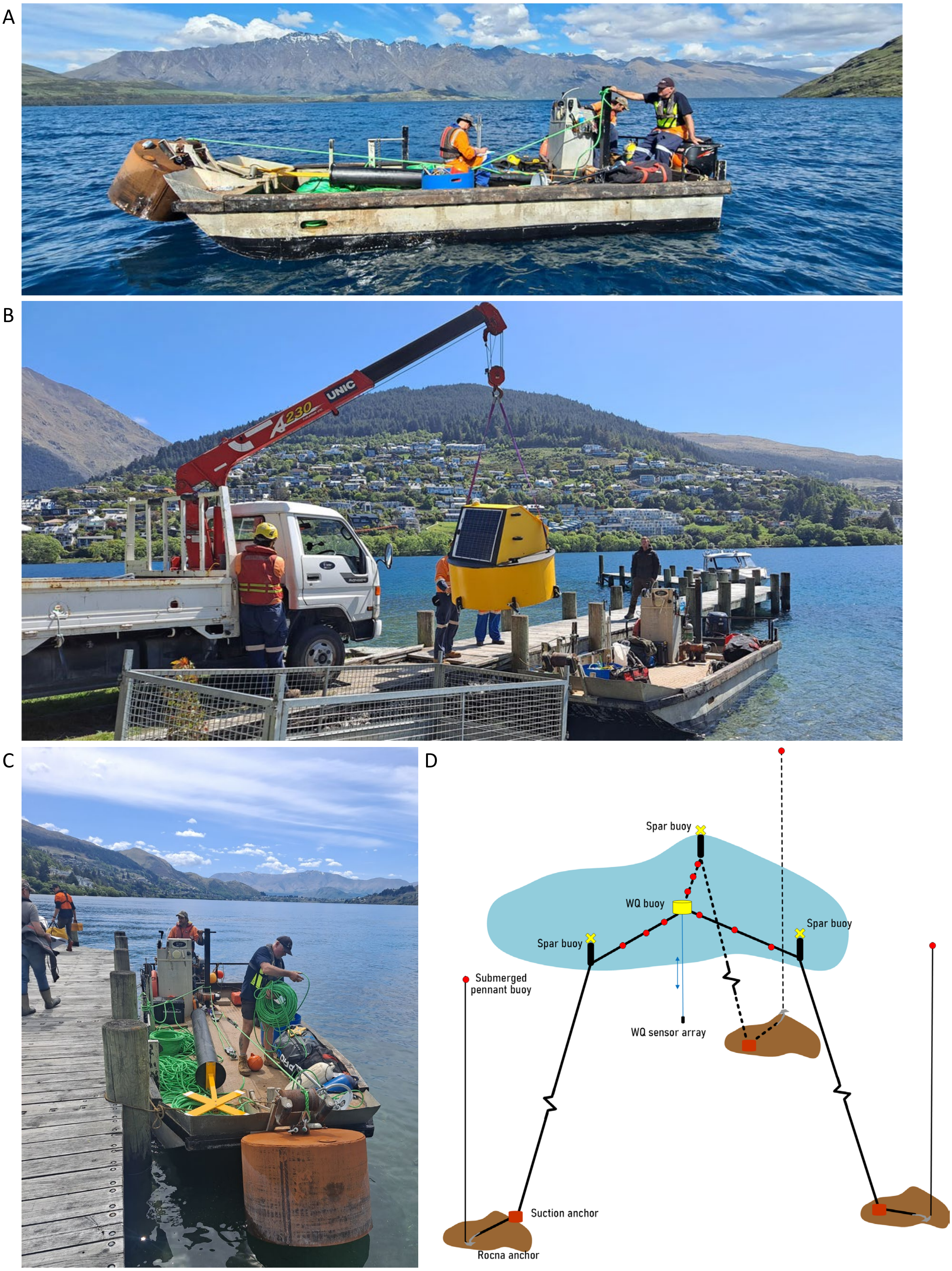


Figure 5. Lake Whakatipu buoy installation in November 2022. (A) Mooring components being transported to the site [ORC]. (B) Monitoring buoy being loaded for transport to the site [ORC]. (C) Spar buoy and anchor loaded to transport to site [ORC]. (D) Simplified diagram of the key mooring components [from drawings provided to ORC by Offshore and Coastal Engineering Ltd].

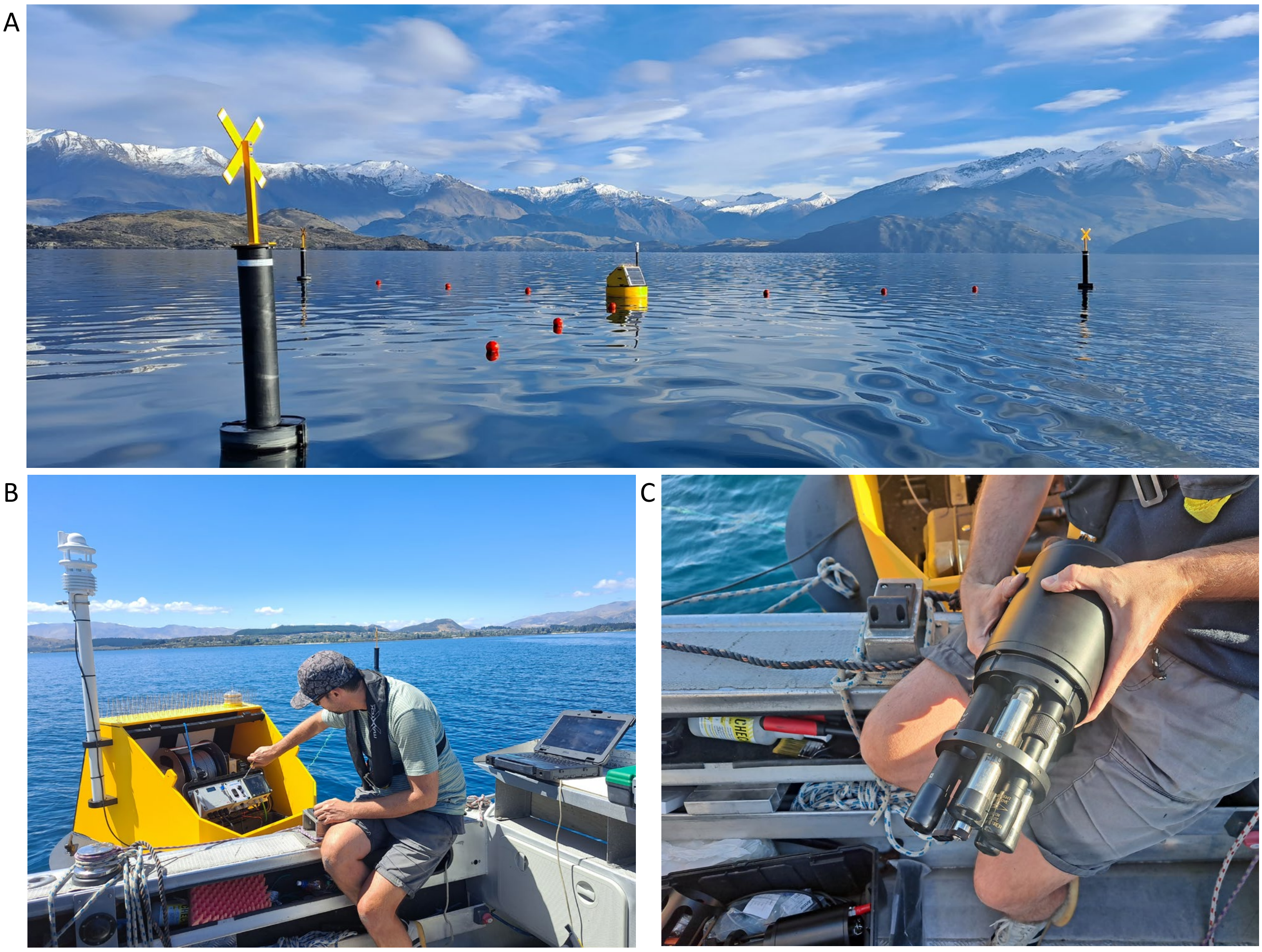


Figure 6. Lake Wānaka monitoring buoy. (A) Monitoring buoy with three spar buoys on the mooring [ORC]. (B) Servicing the monitoring buoy [ORC]. (C) HFWQ sensor package deployed on the profiling winch [ORC].

Securing approvals and authorisations for the moorings are an additional resourcing cost. For example, the ORC project manager for the Lake Hāwea buoy spent around 2.5 weeks collating the information required. An environmental consultant prepared the consent application at a cost of around $5000. ORC has 35-year resource consents with Queenstown Lakes District Council for the Wānaka and Whakatipu buoys and moorings. Licences are also held for use of the lake beds. The licenses are issue by LINZ and while the cost is low, the processing time is around 3 months.

Exact information on the time required to service these buoys is difficult to assess because of the mixed-model servicing agreement. Furthermore, as a commercial provider is involved, there is commercial sensitivity around cost and staff time components. However, in the same way that more complex moorings are more costly than simple ones, operating a monitoring buoy on a large, exposed lake will be more challenging and require more resourcing. Scheduled servicing of buoys in large lakes also requires calm weather conditions, and organising the fieldwork logistics (and rescheduling) can be time consuming.

BUDGET TEMPLATE

This template is for annual operating costs. The basic unit of the budget is hours, which can be totalled and converted to FTE if required. The direct costs (sensor repairs, consumables, accommodation, fees, etc.) should also be estimated and contingencies resourced (refer to Table 3 for examples to consider). Justifications are important to include in budgets to ensure managers and administrators reviewing the budget can see the details of each item. For example, time taken to travel to the site should be included in the budget justification along with the estimated number of site visits.

It's important to understand how your organisation defines Capital Expenditure (CapEx). The CapEx limits and definitions vary between councils ($1,000–$20,000 limits in 2024). Be aware these limits can and do change, so it's important to check current limits and definitions. Many HFWQ sensors will be CapEx items (see costs in Sensor Selection Guidance chapters), but some low-cost sensors or those with short lifespans tend to be classified as consumables (e.g., HOBO Pro V2 and Campbell Scientific 109 temperature sensors). In some organisations, labour to commission and install equipment can be included in a CapEx project, while for other organisations no time component is allowed.

Operational expenditure is the day-to-day operational cost. In addition, many items, depending on cost and cost limits, may be consumables. For example, a wiper unit may be classified as CapEx, but a new wiper brush is a consumable under OpEx. Costs associated with operating time series software and databases are often managed by IT departments. Time for data processing is an operational expense and needs to be resourced appropriately.

Commissioning may take several months, especially if the site and type of sensor are new. Being realistic about expectations (e.g., data gaps, comms issues, training) helps to ensure time is allocated to deal with these teething issues. Adding sensors to existing sites which technicians are familiar with tends to require fewer hours for commissioning.

Table 3. An example budget template. The template serves as a starting point for detailed budgeting. Items with a (Tel) relate to telemetry systems.

Budget item	No. of items	Unit (hours)	Cost per unit	Cost ($)	Justification	Some things to consider
Labour costs						
Preparation						
Project management						- Include staff hires, managing subcontractors, writing proposals.
Approvals and permissions						- Permissions: landowner, iwi/hapū consents. For moorings Harbourmaster, LINZ (when required).
Travel to locate suitable site						- Can take a considerable amount of time and expertise.
Design sensor deployment						- Can take a considerable amount of time and expertise. If the site is an existing hydrometric site, consider whether need a separate logger for HFWQ sensors.
Staff training to operate new sensor/site						
Monitoring system testing						- May require external assistance/guidance. - Consider contracting out to an experienced supplier.
QA procedures						- Write/update SOPs or procedures prior to deployment so they can be correctly resourced.
Establish data pipeline						- Set up a new site in database and link telemetry/establish data ingest procedures.
Request up-to-date lab analysis quote						- Ensure original planning lab analysis costs are still valid.
Pre-deployment tasks						
Update site workplace safety plans						- H&S risk assessment needed for project design, site selection and sensor deployment/maintenance. - New site may have different hazards and risks. - Budget an additional staff member if solo workers not permitted.
Check site representativeness						- In rivers, check for mixing by checking the deployment cross-section.
Fabricate sensor mounting/housing						- Reuse a housing if possible.
Assemble field gear						- Create a checklist to ensure you have all equipment required.
Calibrate/validate sensors						- Check sensors output high quality data. - Consult NEMS where available, plus sensor manual and technical notes. - Check Sensor Selection chapters for notes on user experiences of calibration.
Test fouling management tools						- Test wiper. Establish wiper operating interval.
Deployment						
Travel to and from site						- If long travel distances, include breaks and possibly a contingency for accommodation & meals.
Deployment						- Estimate with a good contingency. Sometimes installs are straightforward, others do not go to plan.
Support crew (e.g., skipper)						- Consider availability of support crew. If multiple staff members are required, check how often are they not available at the same time.
Set up data pipeline from logger to time series archive						- Sometimes the data flow is best completed after deployment in case any changes in the logger program are required.

Budget item	No. of items	Unit (hours)	Cost per unit	Cost ($)	Justification	Some things to consider
						- Ensure metadata useful for data processing is archived (e.g., wiper metadata).
Staff training on deployment						
Commissioning						
Travel to site						- Include extra site visits while the new sensors are being commissioned (min. 3 months).
Troubleshooting						- When on site it helps to have technical support available via phone/messaging. - For telemetered sites, use relays to allow logger and sensor restarts remotely. This can save you a site visit.
Field operation						
Staff training on field operations						
Prep – calibrate field sensor						
Prep – lab purchase order (if required)						
Travel to and from site						
Onsite tasks						- Check SOPs, likely to include cleaning housing, cleaning sensor, taking field measurements & discrete samples for sensor verification, wiper maintenance, etc.
Daily check on data (Tel)						
Troubleshooting						
Post-visit tasks						- Unpacking, repairs, biosecurity treatment of gear.
Data entry & metadata						
Field visit notes & readings						- Use electronic field forms to save data entry time.
Manual download data import						- Data import can be tricky with some sensors with internal loggers. Check Sensor Selection Guidance chapters for user experiences.
Load discrete sample data						- If possible, receive data directly into a database or as csv files for import.
Data processing						
Staff training to process data						
Edit data						
Verification & grading						
Data audit (annual)						
LABOUR TOTAL						

Costs						
Accommodation & meals						- May be needed for site selection, deployment, and field operations.
Consumables – install						- For rivers: timber, pipe, bolts, housing, batteries. - For simple buoys: buoys, chain, rope, navigation lights, etc.
Consumables – ops						- Consider replacement DO caps, cables, batteries.

Budget item	No. of items	Unit (hours)	Cost per unit	Cost ($)	Justification	Some things to consider
Consumables – fouling						- Consider wiper brushes, biocides, duct tape to wrap sensors, tape, etc.
Calibration workstation						- Costs associated with dedicated calibration workstation (computer, cables, space, stands).
Software license						- Most software is free, some requires a license (see Sensor Selection chapters).
Calibration solutions						- Standard solutions have short shelf lives.
Health and safety costs						- PPE, working at heights training, etc.
Insurance costs						- Refer to Insurance section and Contingencies table.
Biosecurity costs						- Extra set of field gear if drying of gear is required to meet biosecurity requirements.
Telemetry costs (Tel)						- Consider mobile and satellite service fees.
Lab analysis						- Consider sensor verification methods (e.g. optical nitrate sensors verified by discrete samples) & surrogate relationships (e.g., SSC analysis for turbidity-SSC relationship).
Vehicle costs						
Miscellaneous costs						- Include miscellaneous costs such as boat ramp fees.
Sensor servicing						- Include freight, particularly if a sensor requires servicing overseas.
COSTS TOTAL						
Contingency planning						
Sensor or equipment repairs						
CONTINGENCY LABOUR TOTAL						
CONTINGENCY COSTS TOTAL						
CONTINGENCY TOTAL						
TOTAL						

REFERENCES

Ausseil, O. (2023a) Cost estimates for monitoring indicators of water quality and ecological health in rivers and lakes. Our Land and Water National Science Challenge. https://www.monitoringfreshwater.co.nz/factsheets

Ausseil, O. (2023b) Monitoring chlorophyll a in lakes. Our Land and Water National Science Challenge. https://www.monitoringfreshwater.co.nz/factsheets

Ausseil, O. (2023c) Monitoring nitrogen in rivers. Our Land and Water National Science Challenge. https://www.monitoringfreshwater.co.nz/factsheets

Ausseil, O. (2023d) Monitoring water clarity and turbidity in rivers. Our Land and Water National Science Challenge. https://www.monitoringfreshwater.co.nz/factsheets

Jones, A.S., Aanderud, Z.T., Horsburgh, J.S., Eiriksson, D.P., Dastrup, D., Cox, C., Jones, S.B., Bowling, D.R., Carlisle, J., Carling, G.T., Baker, M.A. (2017) Designing and Implementing a Network for Sensing Water Quality and Hydrology across Mountain to Urban Transitions. *JAWRA Journal of the American Water Resources Association*, 53(5): 1095–1120. http://dx.doi.org/10.1111/1752-1688.12557

Jones, A.S., Horsburgh, J.S., Eiriksson, D.P. (2018) Assessing subjectivity in environmental sensor data post processing via a controlled experiment. *Ecological Informatics*, 46: 86–96. https://doi.org/10.1016/j.ecoinf.2018.05.001

McKergow, L. (2025a) Algal fluorescence sensor selection. *High Frequency Water Quality Monitoring Guidance. An Envirolink Tool prepared by NIWA*, NIWA Client Report 2025313HN. https://www.envirolink.govt.nz/

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

McKergow, L. (2025c) Electrical conductivity sensor selection. *High Frequency Water Quality Monitoring Guidance. An Envirolink Tool prepared by NIWA*, NIWA Client Report 2025311HN. https://www.envirolink.govt.nz/

McKergow, L. (2025d) Optical scattering (Turbidity and backscatter) sensor selection. *High Frequency Water Quality Monitoring Guidance. An Envirolink Tool prepared by NIWA*, NIWA Client Report 2025312HN. https://www.envirolink.govt.nz/

McKergow, L. (2025e) Water temperature sensor selection. *High Frequency Water Quality Monitoring Guidance. An Envirolink Tool prepared by NIWA*, NIWA Client Report 2025309HN. https://www.envirolink.govt.nz/

McKergow, L., Vincent, A. (2025) Optical nitrate sensor selection. *High Frequency Water Quality Monitoring Guidance. An Envirolink Tool prepared by NIWA*, NIWA Client Report 2025308HN. https://www.envirolink.govt.nz/

NEMS (2023) Processing of Environmental Time-series Data. Version 1.1.0. https://www.nems.org.nz/documents/data-processing/

NEMS (2025a) Dissolved oxygen: Measuring, processing and archiving of dissolved oxygen data. V 3.0. https://www.nems.org.nz/documents

NEMS (2025b) Turbidity recording: Continuous in situ measurement of turbidity data. V 2.0. https://www.nems.org.nz/documents

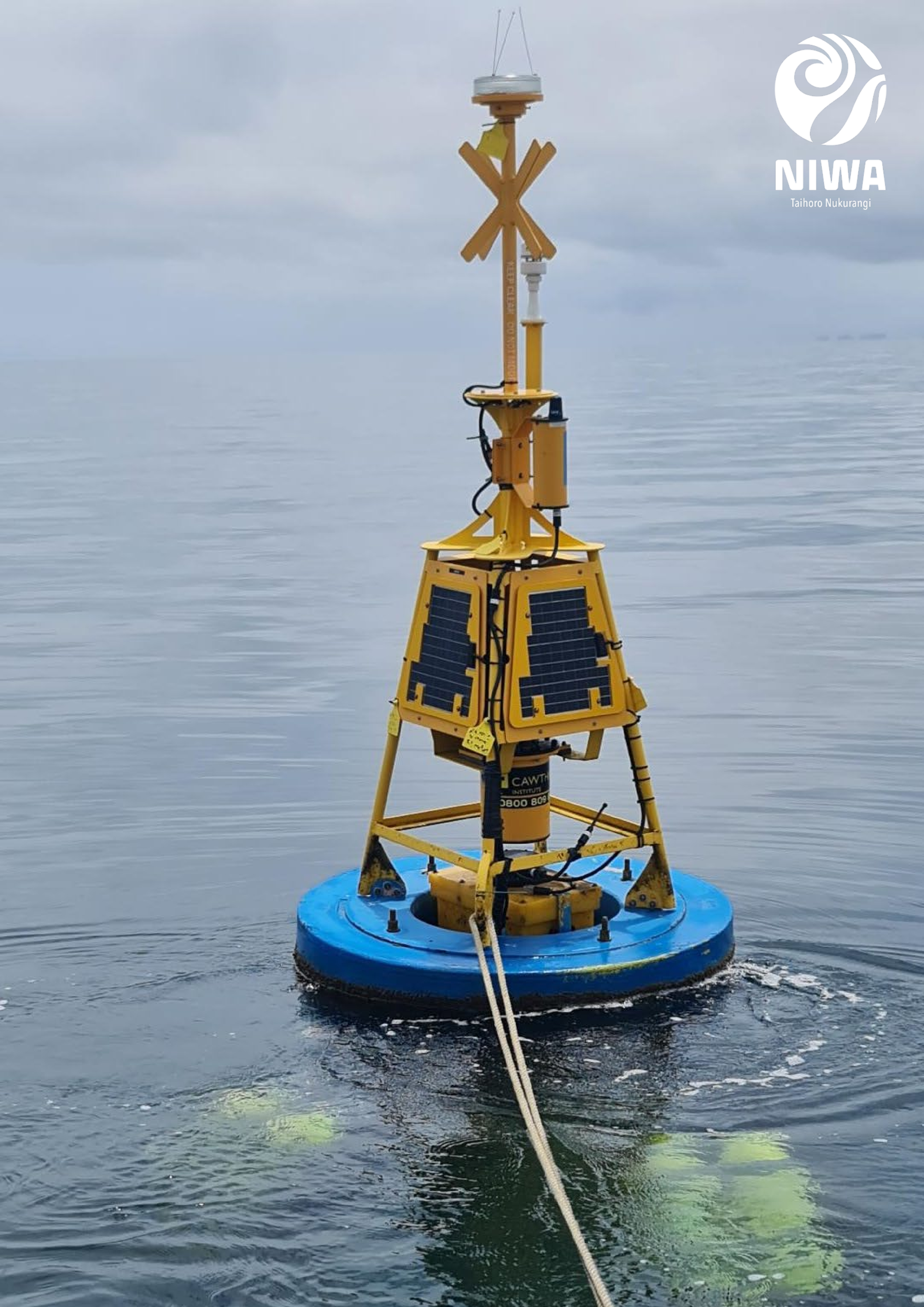
NEMS (2025c) Water temperature: Measuring, processing and archiving of water temperature data. V 3.0. https://www.nems.org.nz/documents/water-temperature-recording

New Zealand Government (2024) National Policy Statement for Freshwater Management 2020: 70.

Schroeder, K., Borghini, M. (2024) An example of a field service plan for oceanographic submerged moorings. *Frontiers in Marine Science*, 11. https://www.frontiersin.org/journals/marine-science/articles/10.3389/fmars.2024.1380914

Seifert-Dähnn, I., Furuseth, I.S., Vondolia, G.K., Gal, G., de Eyto, E., Jennings, E., Pierson, D. (2021) Costs and benefits of automated high-frequency environmental monitoring - The case of lake water management. *Journal of Environmental Management*, 285: 112108. https://www.ncbi.nlm.nih.gov/pubmed/33561731

Young, R., Casanovas, P., Cervantes Loreto, A., Kamke, J., Fraser, S. (2025) Dissolved oxygen and ecosystem metabolism in Auckland rivers: 2020–24. *Cawthron Report prepared for Auckland Council*, 4111. https://www.knowledgeauckland.org.nz/publications/dissolved-oxygen-and-ecosystem-metabolism-in-auckland-rivers-2020-24/



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