Global Water Research Coalition

Companion Guide to

A Practical Protocol to Monitor and Quantify Nitrous Oxide Emissions



The race is on to reduce greenhouse gas emissions and meet net zero targets.

Internationally, as of September 2025, 137 of 198 national governments and self-governing territories have set net zero targets, covering at least 74% of global greenhouse gas emissions, and 79% of the world's population.

Water resource recovery facilities (WRRFs) are a major source of methane (CH_4) and nitrous oxide (N_2O), which are particularly difficult to measure and mitigate. These emissions are gaining relative importance as energy-related emissions decrease. N_2O comes with unique challenges, and utilities, technology providers and regulators need to understand what's driving them, and how to reduce them.

A Practical Protocol to Monitor and Quantify Nitrous Oxide Emissions will support WRRFs on this journey.

An international initiative of the Global Water Research Coalition (GWRC), it represents a collaborative effort involving utilities, research institutions, and industry experts from across the global water community, to address one of the industry's most important climate challenges.

The protocol is designed as a tool to assist utilities to better monitor and quantify N_2O emissions. More broadly, it also lays the foundations for a comparable global N_2O database to support more accurate assessment of emissions from the wastewater sector, the development of a globally-accepted standard for N_2O monitoring, and the identification of effective mitigation strategies.

Why prioritise this now?

You can't truly know how much you're emitting unless you measure it

Fixed emission factors don't reliably reflect real-world emissions: monitoring will give you a more accurate picture. The wastewater sector has a critical role to play in achieving emission reductions.

If you don't understand your nitrous oxide emissions, you can't reliably mitigate them

Having an accurate picture of your emissions helps you gain insights into your plant's dynamics, find mitigation options, and show they work.

By better understanding your facility, you can operate better, and be better positioned for the future

Monitoring and mitigation are complex: you need the right data and modelling, and obtaining results requires time and effort, so it is better to start sooner than later. Each WRRF is unique and monitoring will provide a site-specific understanding.

Be proactive, rather than reactive

Reporting requirements and regulatory environments evolve. With better information, utilities can be better prepared to meet future requirements, and be part of shaping positive change.

Offsets alone are not sufficient

The cost of offsets is significant, it increases over time, and offsets do not reduce emissions. A lasting reduction of emissions at the source lowers the need for offsets and associated costs.

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Top tips from utilities that have taken the journey

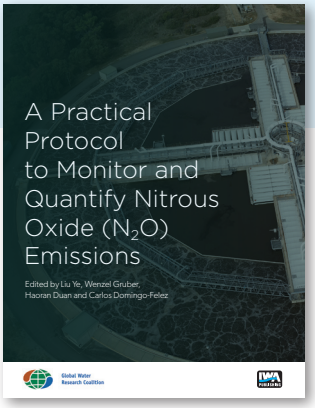
- Monitoring may take longer and need more resources than expected – don't expect a ready-made solution
- Different types of measurement suit different purposes – define your monitoring objectives first
- N_2O emissions and their drivers change over time, so short campaigns and one-off model calibrations may not represent long-term plant behaviour
- Operational changes and maintenance can have a significant impact on emissions: include the right stakeholders early, including operations staff.
- Use monitoring results to inform mitigation planning and long-lived asset decisions

Quick facts

- N_2O is the dominant human-influenced source of stratospheric ozone depletion
- Even small quantities of N_2O emitted from WRRFs can disproportionately contribute to overall greenhouse gas footprints
- It is a long-lived greenhouse gas with a 100-year global warming potential 273 times higher than CO_2
- Just 1% of nitrogen loading converted to N_2O could increase the total greenhouse gas footprint of WRRFs by 30%
- N_2O emissions from WRRFs are one of the most significant and uncertain contributors to the water sector's greenhouse gas footprint
- Accurate quantification of N_2O emissions is a crucial step for the water industry to reduce Scope 1 greenhouse gas emissions

The challenge

Monitoring N_2O emissions at WRRFs is technically challenging. Emissions can vary dramatically over short and long time periods, and differ spatially across treatment processes and within a treatment system. They are influenced by plant configuration, operational factors, microbial communities, and environmental conditions, and results differ based on the monitoring methodology used.



The protocol supports utilities at three different stages:

Starting up

What to consider before starting a monitoring campaign, including what to measure, how, when, where and for how long

Setting up

For your own configuration and monitoring objectives, including equipment design and location, and number of sampling points. Case studies are provided to show you how it has been done by others, and how to overcome challenges

Summing up

Transforming the data collected into useful information

The protocol focuses on two real-time quantification approaches that are feasible at full-scale, and provides:

- guidance for sensor/equipment selection, installation, data processing, and emission calculation
- frameworks for designing representative monitoring locations, along with tailored approaches for covered systems and surface-aerated configurations
- guidance for planning monitoring campaigns, calculating emission factors, and collecting supporting operational data
- practical considerations and a structured decision-making tool to help to set-up an N_2O quantification project at an organisation level and select appropriate monitoring strategies based on plant conditions and objectives.

Starting up

Key steps

- deciding program duration and permanence
- defining monitoring objectives
- selecting priority sites for monitoring
- assigning roles, resources and continuity
- engaging operators and technical staff early

Understanding emissions sources and variability

Biological N_2O production pathways are the main contributor to the N_2O emitted at WRRFs, with the biological nutrient removal process being the main contributor. It is estimated to account for 81–99.9% of plant-wide N_2O emissions.

N_2O is influenced by a range of factors such as process conditions, environmental conditions, operational parameters, and control settings. As a result, spatial variations can exist within one reactor, between parallel treatment trains, between WRRFs with the same technology, or across WRRFs.

N_2O also varies across time: variations are observed across various time scales, from the time of the day to seasons, and more recently, it has been found that emission patterns vary across years.

When you are starting out on your monitoring journey, expect uncertainty, and communicate that. The team will have a lot to work through, to understand your facility's unique context. It will help to review how other utilities have set up monitoring, particularly before choosing equipment: take a look at the case studies in the protocol for some examples and lessons learned.

Monitoring technique and duration can both strongly affect estimated emission factors, and a single emission factor cannot represent the diverse and dynamic N_2O behaviour of WRRFs. Short-term, intermittent sampling can underestimate emissions by up to seven-fold compared with year-long continuous measurements.

To get the best results, you will need to take a long-term view: plan for a multi-year or continuous program, not a one-year project. If you are starting with temporary equipment, plan for a longer-term setup.

Continuous, robust monitoring is essential to capture real emission patterns, and guide process-specific mitigation, such as optimised aeration control, balanced carbon–nitrogen loading, and avoidance of nitrite accumulation.

Also, set clear objectives before designing the system. A successful N_2O monitoring campaign depends not only on robust measurement techniques but also on a representative monitoring design and a clear definition of the monitoring objectives.

To get a more informed picture, you'll need a range of input. Involve operators, operations engineers and instrumentation staff early, and also bring experienced practitioners in early, where needed. Bear in mind, there may not be local expertise to suit your requirements – you may need to bring in help from further afield, even internationally.

Starting up

Early involvement from operators and others will also help to determine what supporting processes and data will need to be captured – by recording and timestamping operational events, for example, you will gain a clearer understanding of possible reasons for variation.

Making data accessible for surveillance and computation is key. For example, quality airflow data is required for any method of N_2O quantification. Time spent on developing data management and data quality protocols will lead to more meaningful insights. It is also important to make instruments accessible for safe calibration and maintenance.

Ensure you define roles, responsibilities and succession arrangements, and budget for capability building, calibration, maintenance and contract management. If the complexity of monitoring presents a barrier, begin with a simple start-up and scale up as knowledge, experience, and resources develop.

The protocol provides practical examples of what to measure, where and when to take measurements, and guidance on how to report the resulting emission factor. Real world case studies from Australia, New Zealand, Denmark and the United Kingdom showcase globally leading utility monitoring work, providing helpful examples and lessons learned (chapter 8).

The protocol also provides guidance to help you design a sampling campaign that supports the collection of representative and reliable emissions data (chapter 7). The best time to start is now.

→ Chapter 1 → Chapter 7 → Chapter 8



Setting up

Key steps

- choosing gas-based or liquid-based monitoring
- equipment suppliers and specialist expertise
- equipment design and sensor placement
- achieving representative measurement
- planning supporting data collection

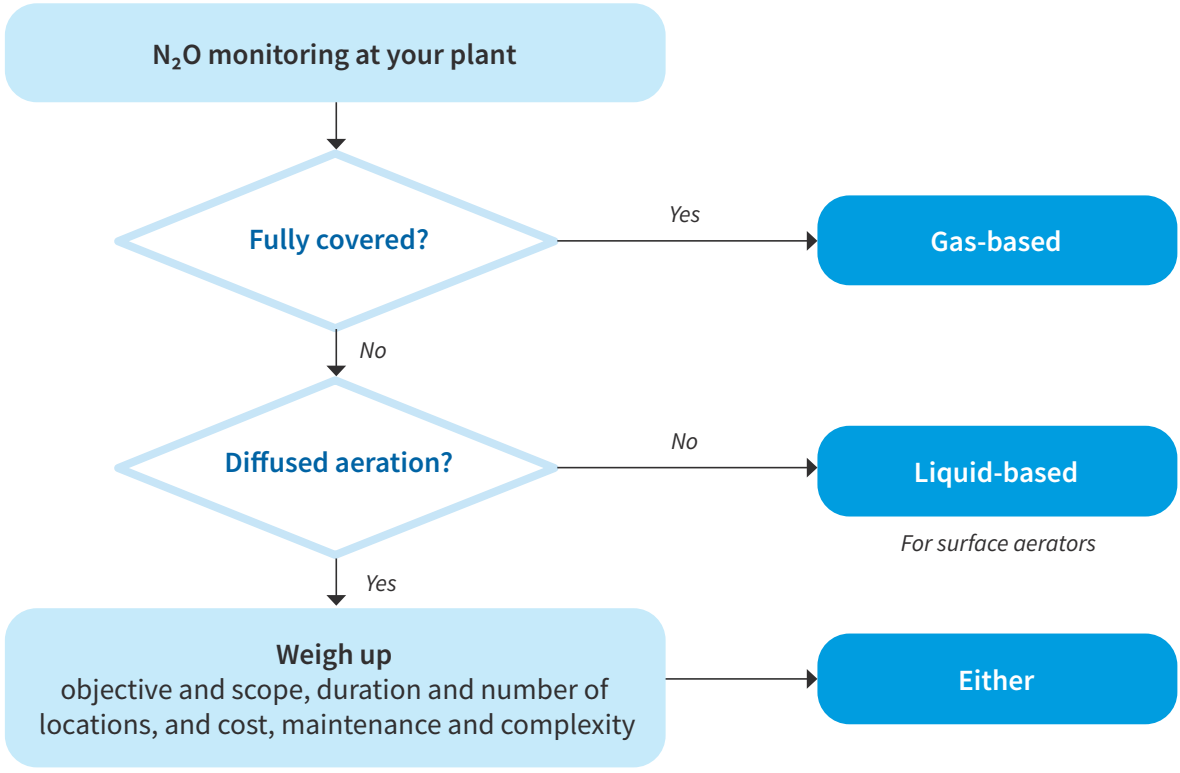
Selecting a monitoring approach

Before monitoring can begin, a suitable monitoring approach needs to be selected. This decision requires consideration of your plant configuration, including whether your plant is fully or partially covered, or open to the atmosphere, and the aeration system used. Another important consideration is market availability, as being able to readily access equipment and specialist expertise can have an impact on the effort and time required to obtain usable data.

The protocol provides some decision-making support in the form of decision-trees, web-based tools and case studies, so you can learn from others' experiences.

Chapter 7 will help you design a long-term sampling campaign, including what, where and when to measure, and select the right monitoring approach for your configuration and monitoring objectives.

→ Chapter 7 → Chapter 8



A simplified decision tree for method selection - more detail in the Protocol

Setting up

Gas-based monitoring

N_2O quantification in wastewater treatment has traditionally relied on gas-based monitoring (gas-based quantification). This method is highly automatable, with straightforward calculation. N_2O fluxes are determined by capturing off-gas with hoods, conveying the gas to a sensor system and then quantifying gas concentrations. This method requires a range of auxiliary equipment, including hoods (which may be closed or open), a switching device, gas conditioning unit, data logger system, and gas analyser. Designing and maintaining hoods, and measuring airflow, are key steps for this process.

The protocol discusses currently applied methods for gas-based monitoring and recommendations for best practice. It reviews key design principles for hoods and associated gas collection equipment, assesses their impact on measurement accuracy, and provides examples of suitable designs and their implementation. It also discusses limitations for this method, and how uncertainties can be reduced.

→ Chapter 2

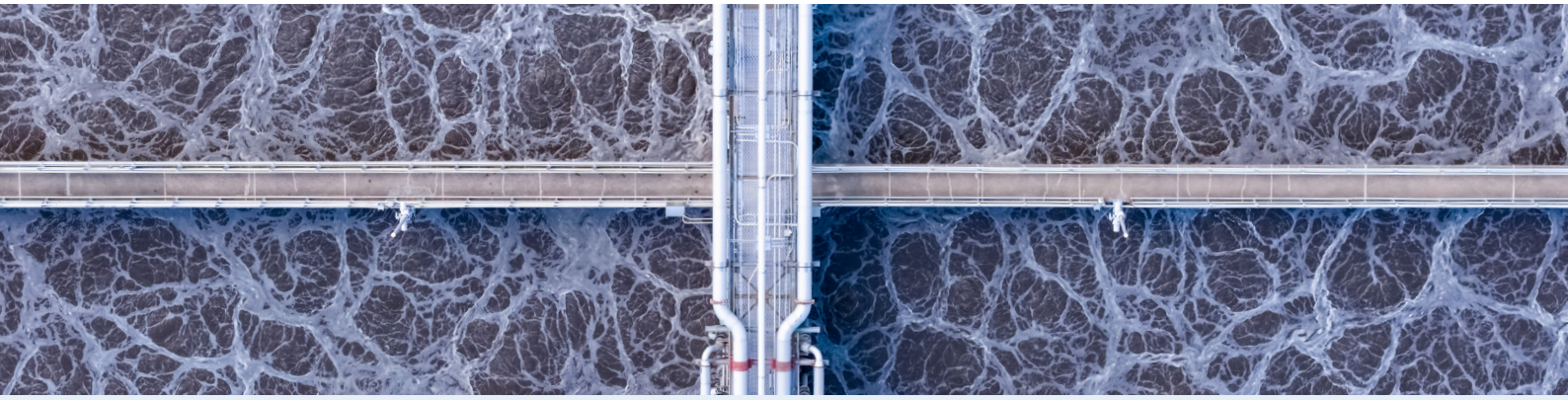
Liquid-based monitoring

The other common approach is liquid-based monitoring, which can be applied to virtually all types of treatment systems. In this method, dissolved N_2O sensors provide real-time measurements at the site of production. Compared with the traditional gas-based monitoring method, dissolved N_2O sensors offer a potentially more convenient alternative by measuring N_2O concentrations directly in the liquid phase and allowing flexible monitoring across different bioreactor zones.

Since these sensors only measure concentration in the liquid phase, emission quantification requires linking these N_2O concentrations to emissions to the atmosphere. Also, as the N_2O emissions are estimated from dissolved N_2O concentrations, not directly, the estimated emissions also depend not only on the liquid sensor measurements, but also the availability and quality of supporting data (e.g. gas flow rate and temperature).

The protocol provides practical guidance on dissolved N_2O sensor usage, as well as calculation tools (in Python and Excel). It outlines a standardised protocol for dissolved N_2O monitoring in fine-bubble aeration systems, including sensor principles and deployment, volumetric mass-transfer coefficient (kLa) and N_2O emission calculation approaches. It also provides procedures for sensor calibration, maintenance, and troubleshooting to ensure reliable and comparable N_2O emission estimates.

→ Chapter 3



Setting up

Selecting monitoring locations for uncovered plants

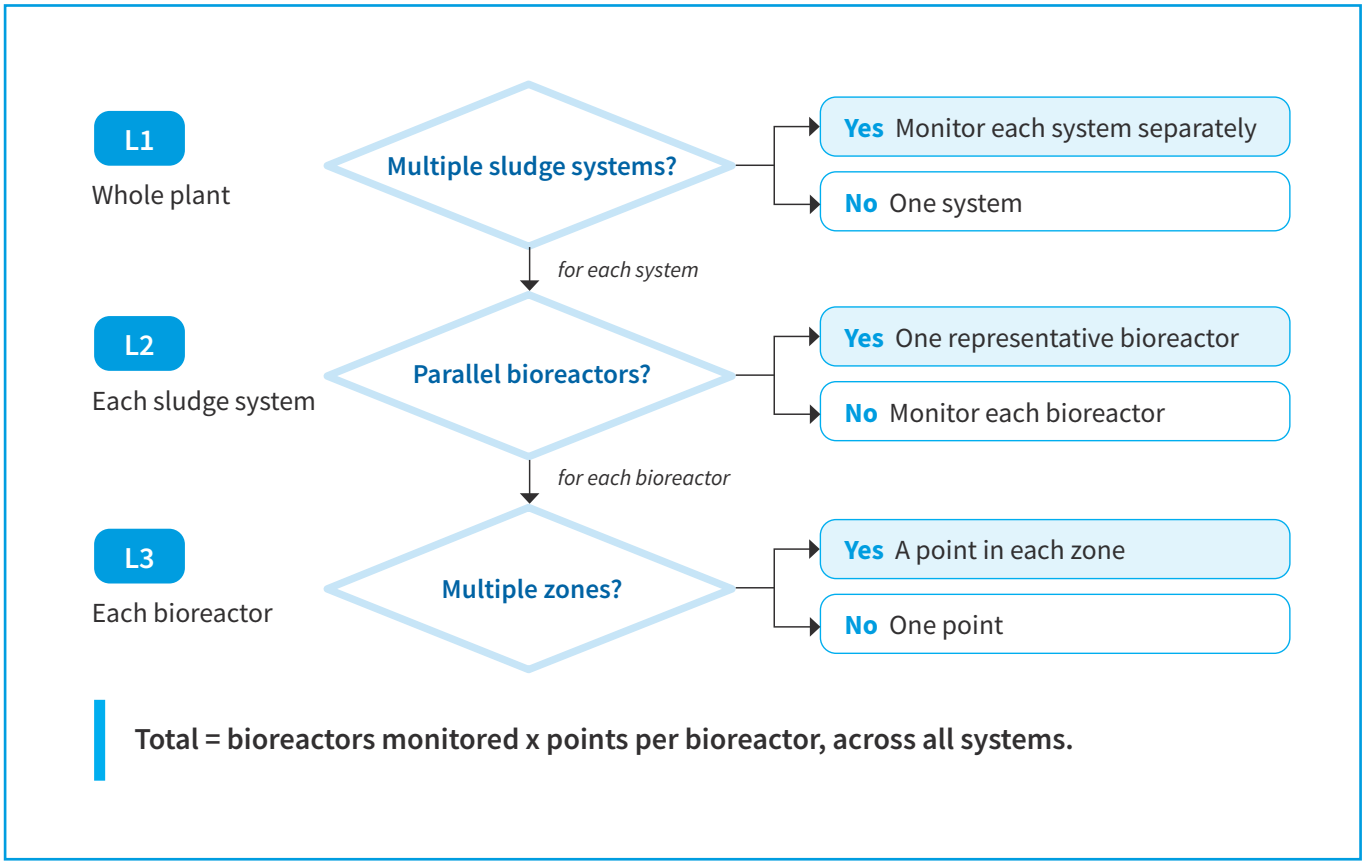
The protocol provides a top-down three-level framework for selecting representative monitoring locations for N_2O quantification at uncovered plants with diffused aeration systems.

The framework systematically distinguishes sludge systems (Level 1), parallel versus non-parallel bioreactors (Level 2), and spatial heterogeneity within reactors (Level 3), and is supported by a decision tree and equations for plant-wide emission aggregation.

The methodology is demonstrated using 19 full-scale international case studies that illustrate how process configuration, aeration control, and spatial variability govern monitoring requirements and data representativeness. The case studies cover 12 typical configurations applied in practice: conventional activated sludge, step-feed, MLE, Bardenpho, oxidation ditch, sequencing batch reactors (including AGS), membrane bioreactors (MBR/MABR), MUCT, IFAS, biofilters (BAF/Biostyr®), side-stream treatment systems, and other hybrid or site-specific designs.

The protocol provides a structured guiding framework; the case studies presented are useful for demonstrating how the framework can be applied in real plants, and provide practical lessons learned during the implementation of monitoring campaigns. The three-level location-selection principle offers a transparent, scalable path from plant complexity to a defensible, minimal set of N_2O monitoring points.

→ Chapter 4



Total = bioreactors monitored x points per bioreactor, across all systems.

Setting up

Enclosed and surface-covered plants

Globally, only a small proportion of WRRFs are covered, ranging from partially or fully structurally covered tanks to fully underground facilities. While not as widely spread as open-surface plants, covered plants provide a unique opportunity for accurate monitoring due to their controlled environment. Quantification can be undertaken directly from the collected off-gas, with continuous airflow and gas concentration measurement performed on centralised ventilation and exhaust systems.

The protocol provides a guideline for quantifying N_2O emissions from enclosed and surface covered WRRFs. It details methods for airflow and N_2O monitoring, and condensate management.

While fully enclosed plants simplify plant-wide monitoring as quantification can be achieved by measuring the captured air at the outlet, additional sampling (e.g. hoods, liquid probes) is needed to understand process-specific N_2O dynamics and therefore develop effective mitigation strategies.

A limitation is that continuous exhaust monitoring does not capture the strong spatial and temporal variability of N_2O production within bioreactors, requiring additional targeted measurements. Accurate quantification also depends heavily on reliable ventilation airflow measurements, which are prone to error. Sampling representativeness also remains a challenge.

The protocol discusses key design considerations, recommendations, and a range of case studies that demonstrate how different plant configurations affect monitoring setup and data interpretation. It illustrates practical monitoring setups, challenges, and insights.

→ Chapter 5

Surface aerator systems

Surface aerators use rotating impellers powered by motors to stir the wastewater, facilitating the dissolution of oxygen. Despite the shift towards diffused aeration systems, surface aeration remains increasingly necessary in small and medium-sized industrial, rural, decentralized wastewater treatment. In such cases, their affordability, simple setup, accessibility, and ease of maintenance make them particularly advantageous.

Quantification of gaseous N_2O emissions from plants equipped with surface aerator systems is challenging due to the high turbulence around the aerator. This results in larger uncertainties in emissions estimation than for bottom-diffused aeration systems, where both airflow rate and N_2O gaseous concentrations can be monitored.

To support with these challenges, the protocol reviews key mass transfer principles for dissolved gases, and provides methodologies to calculate gaseous emissions from dissolved N_2O concentrations and averaged stripping rates for the surface aerator, based on alternative measurements such as power input or dissolved oxygen.

It also provides examples and recommendations for monitoring campaigns, and discusses alternative methodologies, common pitfalls in measurement and practical solutions to address them.

→ Chapter 6



Summing up

Key steps

- using data to calculate emission factors
- benchmarking unusual results
- interpreting data with site knowledge
- using insights for further actions and next steps

Next steps

After you have 'started up' your monitoring journey, and moved through the 'setting up' process, the next steps are looking at your data and using it to calculate emission factors.

The protocol provides methodology to calculate an N_2O emission factor that is representative for the monitoring campaign for any WRRF performing biological nitrogen removal.

You will want to know you can rely on the monitoring data you have collected. As discussed earlier, an important part of that picture is the supporting data: contextual information such as maintenance activities, operational incidents, and relevant logbook data.

Accurate airflow measurement is particularly important, but can be challenging – for example, it may require calibration or replacement of existing airflow meters.

As well as discussing what to do to have the right information to support your calculations and avoid poor data quality, the protocol can also help you decide what processes should be targeted for short- or long-term monitoring. A consistent approach is particularly important to gaining insights from your results.

In considering your results and looking for insights from them, it will be important to both benchmark unusual results and account for variability over time – and communicate both on the results themselves, and uncertainties.

The protocol provides several calculation tools and strategies, and discusses common pitfalls for different methodologies, and configurations to help you generate data you trust and use it appropriately.

Read chapter 7 to understand how your data can be used for accurate reporting of site level emissions, and insights on how the plant's operational data can inform the development of mitigation strategies.

→ Chapter 7 → Chapter 9

About this Companion Guide

This Companion Guide provides an overview and introduction to *A Practical Protocol to Monitor and Quantify Nitrous Oxide Emissions* (IWA Publishing, 2026). See the Protocol for detailed information and references.

The Protocol is an open access book.

It can be found at:

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