

AN IWA WHITE PAPER ON

Good Practice In Nitrous Oxide Monitoring



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Executive Summary

This nitrous oxide (N_2O) monitoring guidance was developed by the IWA Climate Smart Utilities GHG monitoring sub-group. It is intended to support utilities in moving beyond using fixed emission factors (EFs) for approximating process N_2O emission factors to better establish their water resource recovery facility (WRRF) N_2O emissions. It provides simplified guidance for Utilities to support monitoring. It also summarises utility-relevant information and industry experience to date regarding measurement, modelling and mitigation of emissions.

Understanding N_2O production

Ongoing research continues to shed light on mechanisms and pathways for N_2O production and emissions. Simplified pathways and potential influencing factors are shown in Figure 6. It is recognised that N_2O production and emissions form a majority of Utility greenhouse gas emissions and that action to monitor and mitigate these is possible, and necessary, today.

Given understood pathways and potential N_2O risk factors in Figure (i), secondary biological treatment processes should remain the focus for Utility monitoring.

Significant seasonal and spatial variability in N_2O production and emissions within and across WRRFs is evident. Current models (whether mechanistic, data driven or hybrid) are limited in their ability to predict or account for N_2O emissions or to yet support lower N_2O design or sustained mitigation.

Intensification and sidestream treatment configurations and nutrient removal processes that target intentional nitrite production (e.g. nitrite short cut/shunt processes) or that are conducive to nitrite accumulation, carry elevated N_2O risks and warrant particular attention.

Risk factors for N_2O production and may differ across seasons and treatment configurations. Continuous monitoring across seasonal variation is required for Utilities to understand and mitigate emissions.

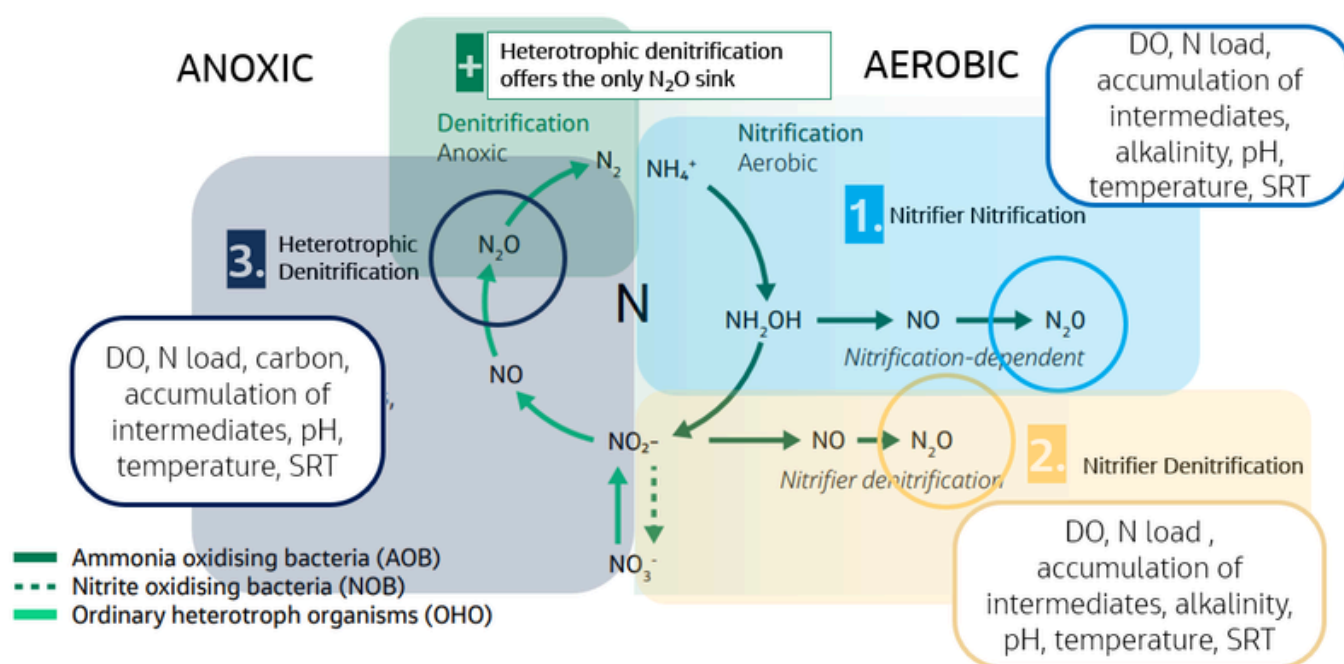


Figure (i) Potential influencing factors on N_2O production with simplified pathways

Monitoring methods and locations

N₂O monitoring can be undertaken with liquid or off-gas methods and have both been shown to offer comparative data when accurate air flow data and correctly modelled liquid to gas calculations are undertaken. Air flow data is required for mass emissions quantification for the zone monitored. Accurate air flow measurement representative of the tank or zone with N₂O monitoring is important. Liquid phase monitoring can also shed light on N₂O mechanisms within anoxic treatment tanks.

Site-wide methods (which can for example be possible in physically closed systems) may support site-level emissions understanding but not mechanisms of production for individual treatment processes.

Figure (ii)(overleaf) shows suggested monitoring locations for mainstream and sidestream WRRF process configurations. In plug flow configurations, N₂O production will vary along lanes, and it is suggested that each tapered and/or controlled aeration zone is monitored.

Duration of N₂O monitoring

Given seasonal variability in emissions, long term, continuous monitoring (e.g. minimum 12 months) at representative location(s) at process unit level is required in order to understand and mitigate N₂O emissions.

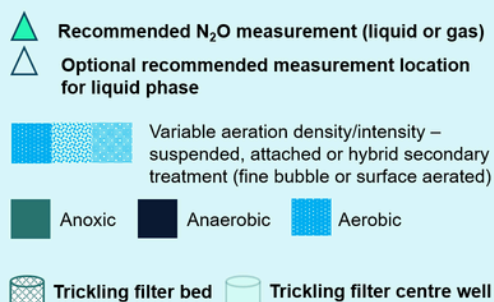
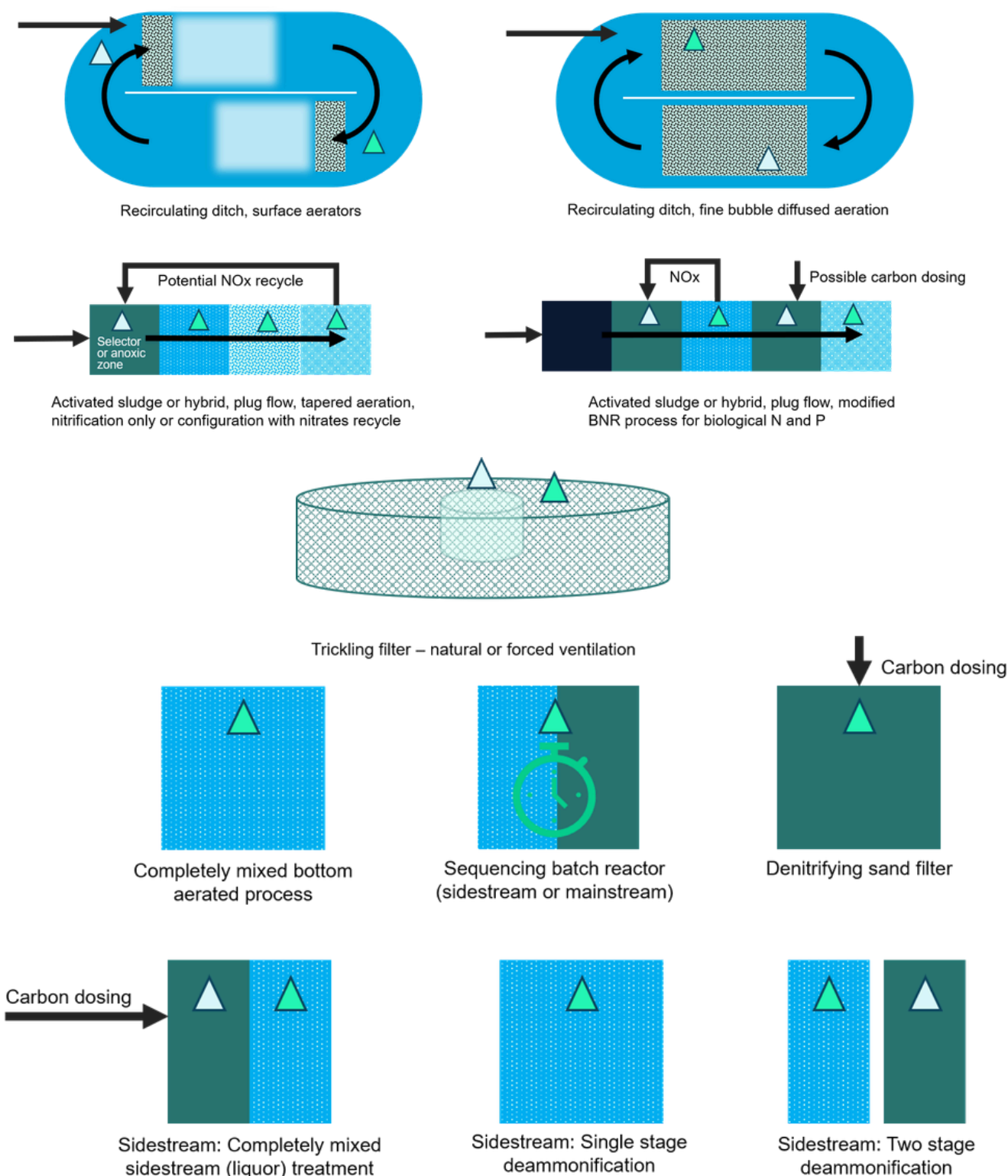
Short term monitoring may offer some information, however, these may miss key N₂O production periods, which may be a few months of a year only. This risks inaccurate extrapolation of emissions to an annual basis.

Given practical considerations, monitoring of all WRRFs and all processes within WRRFs will not be possible. Facility selection should prioritise medium to large facilities as these will represent significant overall nitrogen loads. The locations for monitoring points requires on-site assessment and an understanding of seasonal variation that might occur in parallel treatment streams (e.g. where streams are operated at different capacities seasonally). Representative points within tanks should be considered in context of flow and load, in-tank mixing and hydraulic characteristics and recycles, flow split/imbalances and differences in aeration efficacy or condition across tanks.

From data to information

A large volume of data can be generated directly from the N₂O monitoring but also other data necessary for emissions analysis and to enable an understanding of site-specific mitigation measures.

Data can be gathered at anything from 1-minute intervals to less frequently. However, more frequent data gathering is important, particularly where there is aeration control via set-points or in systems that attempt to match supplied air to in-tank demand. The data needs to be stored and analysed in a systematic way which requires additional resource and skillsets.



Accurate air flow data is required for mass emissions estimation for bottom aerated tanks. Gas phase measurement cannot be used in surface aerated plants.

All tapered aeration zones require (gas or liquid based) measurement in plug flow system to best estimate system emissions.

Anoxic zone measurement provides additional process insights but is possible only with liquid phase measurement.

Same locations apply for hybrid and granular sludge processes.

Multiple lanes should be measured where resources allow, particularly where flow or aeration conditions are known to differ or where multiple sludge systems are present.

Trickling filter measurement with natural ventilation is difficult to quantify mass emissions from.

Measurement (gas or liquid) in systems with carrier or sand media may require special consideration to protect N_2O instrumentation.

Figure (ii) N_2O monitoring locations for typical WRRF treatment configurations

Calculating Emission Factors

Calculation of facility mass emissions and Emission Factors (EFs) requires normalisation and these are typically calculated relative to incoming total nitrogen data. However, EFs calculated relative to influent ammonia or nitrogen removed are also used to support utility understanding within and across facilities.

Nitrogen data used to calculate EFs must also be sufficiently granular. Capturing the potential impact of sludge or wastewater import facilities and nitrogen in recycled streams may require consideration.

Data processing should include pre-processing and data quality checks prior to calculation of emissions, EFs and resulting process analysis. Graphical techniques, univariate statistics and correlation analyses are often applied for initial data inspection.

As N₂O can be highly dynamic, careful selection of data series from which to consider correlations and/or multi-variate analysis is important to derive actionable insights into potential causes of N₂O and thus mitigation strategies. Missing, imputed or extrapolated data (including across time and tanks on WRRF sites) should be clearly identified. Additional process data such as other influent and effluent data, in-process measurement (e.g. pH, ORP, nitrate nitrite, ammonium etc.) will enable development of mitigation strategies.

Mitigation

Following successful initiation of long term N₂O monitoring, utilities should consider the mitigation hierarchy, seeking to avoid the nitrogen which is converted to N₂O, reduce the extent of N₂O production and recover or destroy produced N₂O. Full scale examples, whilst limited, are emerging in each category of the hierarchy - and are summarised in this guidance document.

The potential positive or negative impacts of mitigation measures on energy consumption, regulatory compliance and other operational targets must also be considered. Low N₂O design considerations are also included. In all cases, N₂O mitigation must be also considered in broader future direction of sustainable nutrient removal and recovery for benefit of society, within planetary boundaries.

An imperative for action now

Deploying even one continuous N₂O measuring point at a priority process unit delivers site-specific understanding and the ability to move beyond emission factors. This is critical for the water sector to build the foundation for long-term monitoring and mitigation and to refine measurement protocols. We hope this guidance will inspire you to move beyond global N₂O emission factors and to start measuring N₂O today. You will gain meaningful process insights and establish pathways to reduction of your treatment CO₂ footprint. We encourage you to share your learnings with the global community; thank you for your climate action today!

**IWA Climate Smart Utilities
GHG Monitoring working group, 2026**

1. Introduction

Significant global evidence supports the need to address process emissions from wastewater treatment plants or water resource recovery facilities (WRRFs)^[1]. Greenhouse gas (GHG) emissions from water and wastewater treatment water utilities may account for 5% of global emissions. Wastewater treatment accounts for 70% of these emissions. In particular, the monitoring, quantification and mitigation of nitrous oxide (N₂O) emissions from WRRFs is key. Wastewater treatment is considered the most significant non-agricultural emitter of anthropogenic N₂O emissions (between 3% and 7% of overall N₂O emissions) (Song et al., 2024), and N₂O is a significant source of GHG emissions from WRRFs. The specific operational conditions and requirements of the WRRF and also the degree to which its electricity supply is decarbonised have a significant impact on the relative contribution of N₂O emissions, reported in terms of emission factors^[2] (IWA, 2023).

For example, Ranieri et al., (2024), using emission factors from IPCC and other literature sources, estimated N₂O emissions comprised 30% - 33% of emissions from 183 WRRFs in Italy (this analysis included N₂O, methane, biogenic carbon and fossil carbon emissions due to electricity consumption). Maktabifard et al (2022a) analysed a number of WRRFs in Finland and Poland and found an average of 55% of operational carbon footprint resulted from N₂O emissions. At the upper end, N₂O emissions can constitute up to 80% of the carbon footprint of a WRRF (Daelman et al., 2013). With a 100-year global warming potential which is 273 times greater than CO₂, N₂O contributes substantially to climate change and to stratospheric ozone depletion.

Globally, regulatory drivers are growing for N₂O - for example, the Danish Environment Ministry recently published a report on a proposal for N₂O Regulation to address their commitment to regulate emissions and in December 2024, the English and Welsh economic regulator, Ofwat, funded some £411 million of N₂O measurement and abatement which water companies will now deliver by 2030 - achieving an N₂O reduction of 163ktCO_{2eq} (Ofwat, 2025)^[3]. The revised Urban Wastewater Treatment Directive (Directive 2024/3019 st, 2025, within the EU has an increased emphasis on GHG reduction of treatment plants.

In the (more common) absence of regulatory drivers, many Utilities have adopted Net Zero targets - e.g. Water UK roadmap to net zero by 2030 (currently under revision for 2050), Water Services Association of Australia by 2050, Uisce Éireann (Ireland) by 2040 and the Beijing Drainage Group (China) by 2050. The Nordic water sector (Denmark, Sweden, Finland and Norway) has developed a roadmap to net zero. In taking action to baseline current emissions and develop pathways to Net Zero Utilities are seeking to go beyond existing IPCC Guidelines to quantify N₂O emissions at a facility level and to mitigate these.

Established WRRF design and process optimisation has generally focused on enabling WRRFs to meet regulation and reduce resource consumption. Design and operation of WRRFs must now include mitigation of GHG emissions - but utility guidance on this is lacking.

The Intergovernmental Panel on Climate Change (IPCC) provides global guidance for national inventory reporting of GHG from all sectors, including wastewater treatment (reported by countries in Section 5D1). The IPCC recommend a Tier 3 facility-level approach for establishing N₂O emissions quantification, given the high degree of variability of N₂O emissions from WRRFs – and thus the inadequacy of emission factor-based approaches.

For utilities establishing their baseline N₂O emissions, there is significant uncertainty in the methods available to quantify their emissions, particularly as these are often not directly measured in individual WRRFs but are estimated using emission factors.

The 2019 Refinement to the 2006 IPCC Guidelines for GHG accounting introduced a Tiered approach (discussed in Section 3) to support national GHG accounting of wastewater treatment emissions, which highlights the importance of 'Tier 3' facility level monitoring.

N₂O emissions vary widely diurnally, seasonally and across individual WRRFs (Sieranen et al., 2024), which contributes to the uncertainty in emissions estimating using default emission factors and therefore facility-level monitoring is key to understand and mitigate N₂O emissions.

This white paper builds on recent publications by Ye et al., (2022) and a previous white paper (IWA, 2023) developed by this IWA Climate Smart Utilities GHG subgroup. It seeks to provide good practice in N₂O emissions monitoring for Utilities.

It compiles and summarises the latest guidance in relation to the sources, measurement and mitigation of N₂O emissions at the WRRF level.

The white paper also provides guidance to support utilities in starting their journey or continuing their journey in monitoring and mitigation of N₂O.

[1] Water resource recovery facilities (WRRFs) are the selected language in this guidance, recognising the role of wastewater treatment plants in the necessary transition to a circular economy.

[2] Emission Factors (EFs) as defined by the IPCC seek to estimate N₂O emissions in terms of N₂O-N by calculating them as a percentage of incoming total nitrogen (TN) in units N₂O-N/TN_{in} and may be derived using generic assumptions or (most accurately) by facility level measurement (the subject of this guidance).

[3] Figures extracted from <https://www.ofwat.gov.uk/wp-content/uploads/2024/12/9.-PR24-final-determinations-Expenditure-allowances.pdf>

2. Emissions of nitrous oxide from wastewater treatment

2.1 The importance of Scope 1 N₂O emissions

The sources of key Scope 1, 2 and 3 GHG emissions from WRRFs are shown in **Figure 1**. Scope 1 emissions are a key priority for the water industry as they are solely responsible for producing and reducing these. This is unlike, for example, electricity related 'Scope 2' emissions which can be decarbonised by the energy sector – though of course water utilities can help by reducing energy consumption. Scope 3 emissions such as chemical/building materials are being tackled in industrial sectors – though again water utilities can reduce consumption of such materials and specify lower carbon options. Typical sources of process emissions at WRRFs are shown in **Figure 2**. Key sources of N₂O emissions are secondary biological treatment processes and effluent discharge

Additionally, less understood N₂O sources can include biosolids management, thermal sludge treatment (e.g. incineration), the sewer system, and combined storm overflows. The relative contribution of N₂O emissions to overall emissions from individual WRRFs will vary based on a variety of factors which are discussed later. However, as noted in Section 1 N₂O emissions are likely to be highly significant for most WRRFs. **Figure 3** shows an example of the estimated mass flow of emissions for an Austrian WRRF in 2016. This [web based tool](#) requires details of WRRF influent composition, energy consumption, effluent requirements and geographical energy grid details.

Figure 1 GHG emissions from WRRFs – from IWA Climate Smart Utilities GHG monitoring sub-group White Paper (2023)

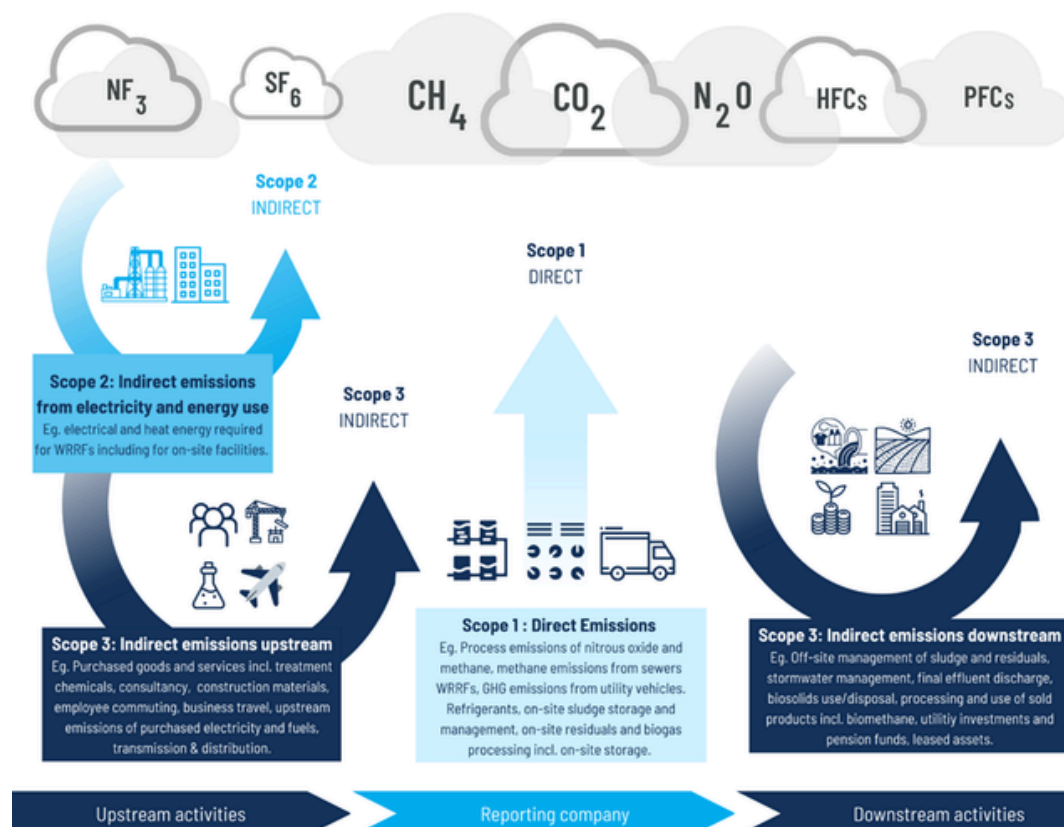


Figure 2 Key sources of N_2O and other GHG emissions from a typical WRRF

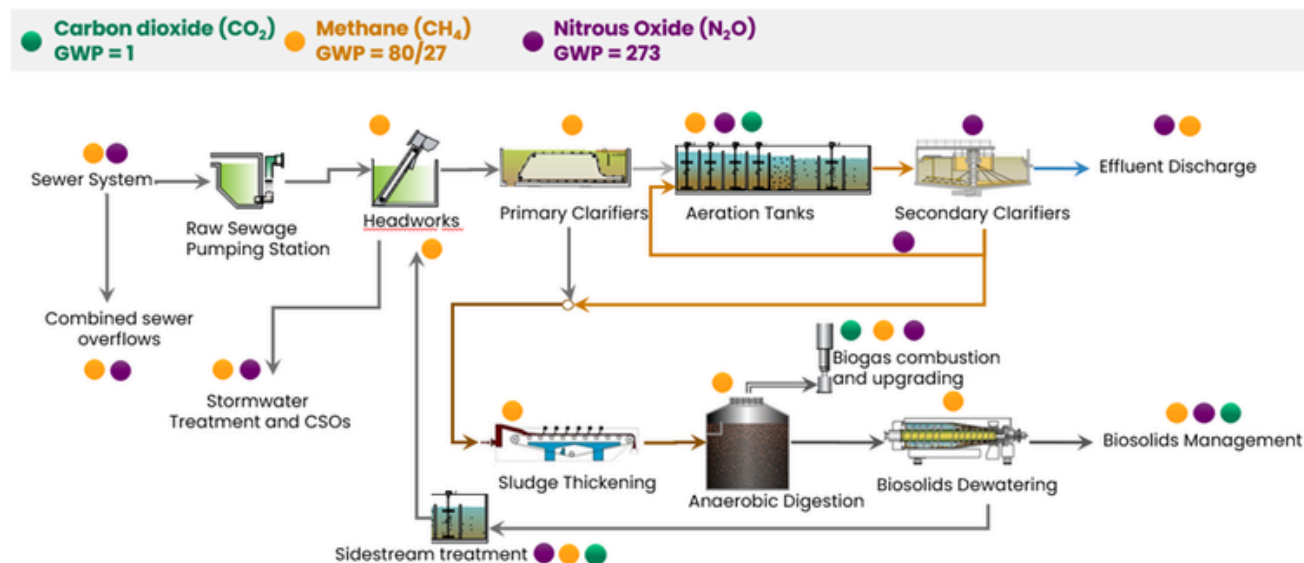
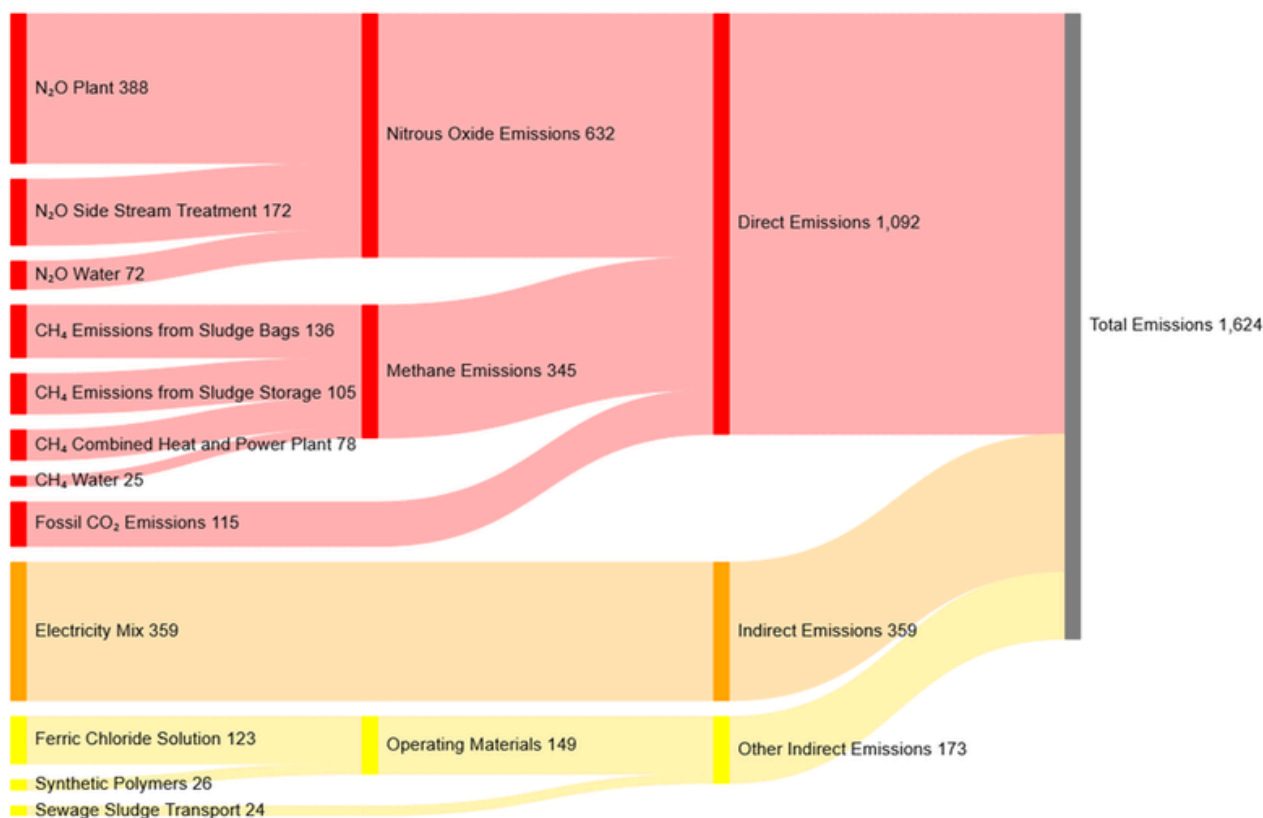


Figure 3 Sankey diagram showing operational (Scope 1, 2 and some 3) GHG emissions mass for a 50,000 PE WRRF in Vienna

Example WRRF (50000 Res) / greenhouse gas emissions [t CO_2 Equivalents/Year] - Scenario TU Vienna 2016 (N_2O -EF=0.45)



2.2 How is N₂O produced and emitted in biological liquid wastewater treatment?

N₂O emissions originate from the biological transformation of nitrogen in WRRF influent. This is from dietary protein intake, with excess protein excreted, primarily in urine. This results in ammoniacal nitrogen in raw sewage. Hydrolysis of organic nitrogen to ammoniacal N may also occur, in particular in liquor returns from sludge digestion. Production may occur in both anoxic and aerobic zones, but emission of N₂O to the atmosphere occurs mainly from stripping of gases due to forced aeration in aerobic treatment zones and/or in locations of hydraulic turbulence (e.g. due to mixing etc).

Figure 4 illustrates potential pathways for N₂O in a typical WRRF.

Hot spots for N₂O emissions include secondary biological treatment where nitrification, denitrification (including partial) is taking place, and potentially in aerobic sludge and biosolids process (though full-scale WRRF evidence remains limited).

Evidence is continuing to build regarding N₂O production pathways in WRRFs and these are not fully understood, with intermediates such as nitric oxide (NO) and hydroxylamine (NH₂OH) not typically able to be measured and the continued discovery of new organisms which play a role in nitrogen conversions in WRRFs.

However, N₂O simplified pathways have been developed to describe observed production and removal. In general, high ammonium and O₂ concentrations may stimulate N₂O production through hydroxylamine (NH₂OH) oxidation by ammonia-oxidising bacteria (AOB), while high nitrite and low O₂ concentrations may enhance the nitrifier denitrification pathway, where AOB can, under oxygen-limited conditions, reduce nitrite to N₂O.

Under anoxic conditions, N₂O accumulates when denitrification is unbalanced – typically at low COD/N ratios, under nitrite accumulation, or when trace dissolved oxygen carries over into the anoxic zone.

Here, N₂O can be the end-product during denitrification if there is a lack of bioavailable carbon to drive the complete denitrification. Abiotic (non-biological) pathways are also recognised as a contributor to N₂O production, but their significance remains poorly understood. Under typical WRRF operating conditions, the abiotic N₂O production pathway is thought to be limited (e.g. contributing to about 3% of N₂O) in its contribution to N₂O production (Su et al. 2019).

At many WRRFs, the likely production and removal pathways can be identified with a good degree of confidence through continuous assessment of N₂O emissions monitoring data and other plant operational conditions. However, specific analysis is required to confirm the validity of production and removal pathways.

As an example, omics methods including N₂O isotope analysis, sequencing and proteomics can assist in understanding N₂O production and removal pathways (e.g., Gruber et al., 2022; Strubbe et al. 2026, Roothans et al., 2025). While these may help in better understanding, such analysis is not required for utilities wishing to monitor and mitigate N₂O.

N₂O emissions can vary seasonally and spatially - due to loading rates, changes in biomass activity due to temperature and operational conditions. **Figure 5** shows examples of variation and the importance of continuous monitoring across seasons.

Figure 4 Fate of N₂O in a model WRRF treatment tank

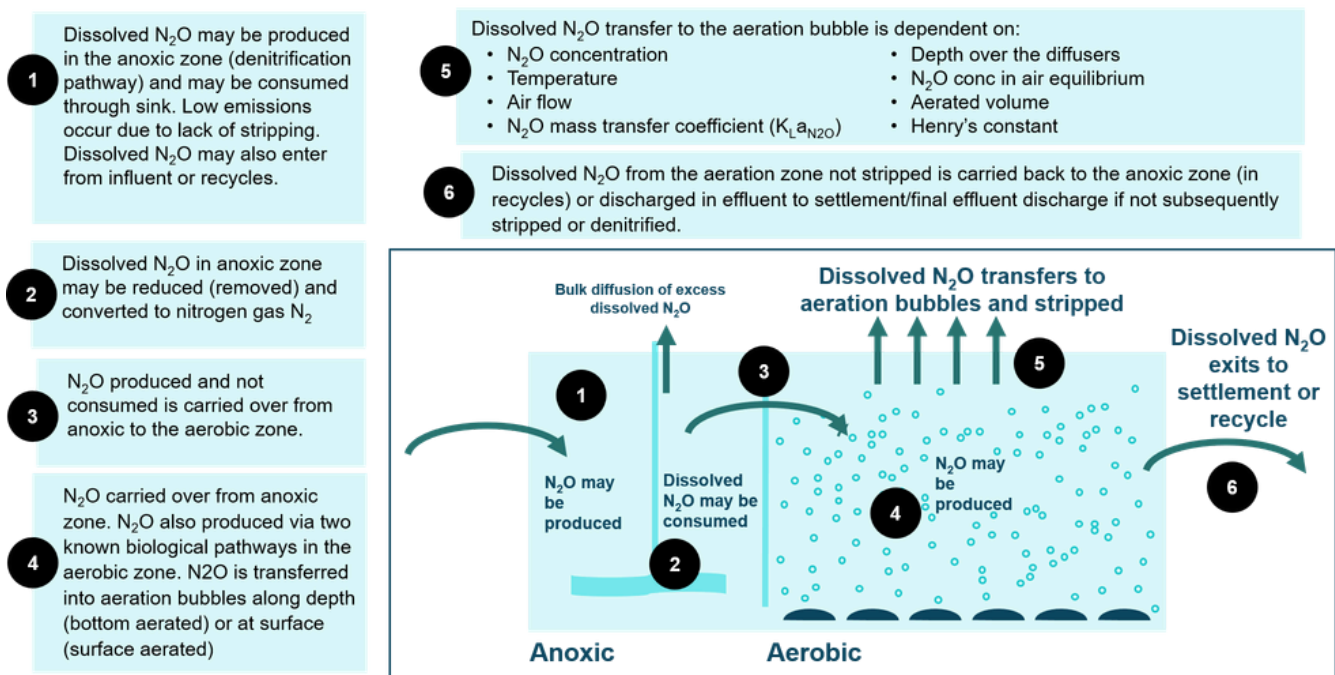
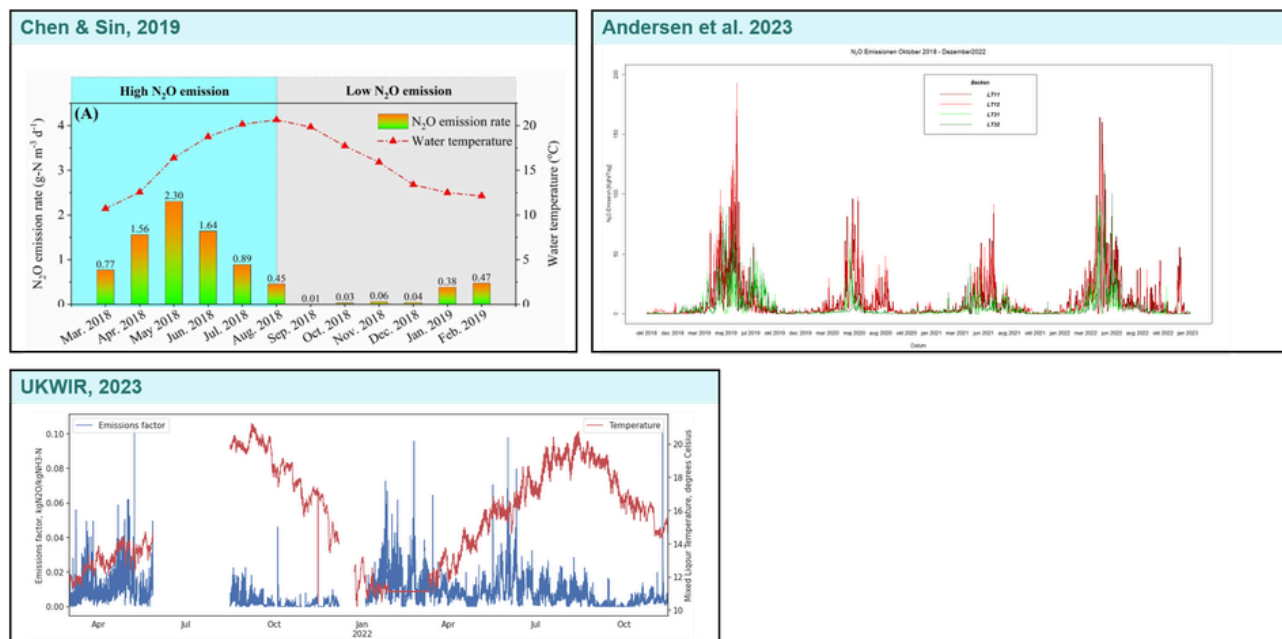


Figure 5 Single and multi-year N_2O datasets showing seasonal variability



Some WRRFs can emit the vast majority of their N_2O over just a few months of the year. To date, metabolic mechanisms controlling seasonal N_2O emissions remain largely unknown, hindering effective mitigation (Roothans et al., 2024).

These areas remain topics of academic research with significant fundamental research still required but sufficient progress has been made to support substantive mitigation of N_2O by utilities today.

2.3 Key drivers for nitrous oxide production in biological wastewater treatment

Work over the past two decades has highlighted potential risk factors or drivers for N_2O production. A summary of these is shown in **Figure 6** for the simplified biological pathways and include DO control, pH, temperature, accumulation of intermediates and SRT which can be a factor across all pathways, carbon limitations (e.g. pathway 3), ammonium (NH_4) load and alkalinity (pathway 1).

Risk factors may differ across seasons, with WRRF influent quality, treatment configurations etc. Where a known risk factor doesn't correlate with emissions, it may indicate that an alternative pathway for N_2O production is more dominant.

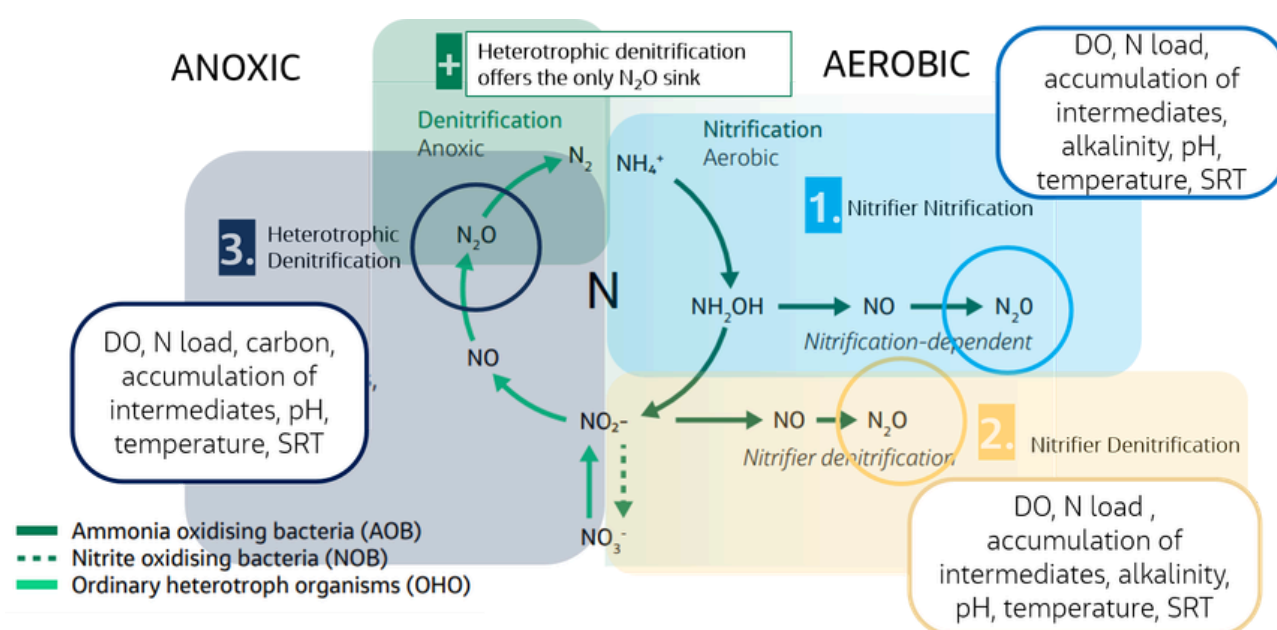
- **For Pathway 1 Nitrifier nitrification:** high ammonium and O_2 concentrations stimulate N_2O production through hydroxylamine (NH_2OH) oxidation by ammonia-oxidising bacteria (AOB). Alkalinity limitations can result in N_2O production (and addition of dosing of additional alkalinity can support N_2O mitigation)(Kosonen et al., 2016).

- **For Pathway 2 Nitrifier denitrification:** high nitrite and low O_2 concentrations enhance the nitrifier denitrification pathway, where AOB can, under oxygen-limited conditions, reduce nitrite to N_2O .
- **For Pathway 3 Heterotrophic denitrification:** Under anoxic conditions, high N_2O and high O_2 concentrations can result in N_2O accumulation from imbalanced denitrification by heterotrophic denitrifying bacteria. N_2O can be the end-product during denitrification if there is a lack of bioavailable carbon to drive complete denitrification.
- **A sink for N_2O** exists under anoxic conditions, where heterotrophic denitrifying bacteria can denitrify oxidised species through N_2O to dinitrogen gas. This allows for reduction of N_2O and potential mitigation measure, if this sink can be enhanced.

Where acclimated microbial populations are living in conditions of 'stability' and/or 'sufficiency', N_2O risks may be lower. Process stability may include, for example, stable ranges of system operation, stable process conditions and good process control. Sufficiency includes for example, sufficient dissolved oxygen (DO), alkalinity, carbon and biomass for treatment. Sufficiency will differ between biological systems which themselves may change in time and space in terms of microbial community and activity.

An acclimated, adapted or transitioned biomass operated in consistently low DO conditions may find low DO conditions 'sufficient' for treatment, whereas a biomass which is used to higher DO conditions sufficient and increased risk of N_2O production may be present. An acclimated or transitioned 'low(er) DO' biomass may not produce as much N_2O ; a non-acclimated or alternative biomass used to other conditions may have increased risks of N_2O production.

Figure 6 Potential influencing factors on N_2O production with simplified pathways



This remains an area of emerging understanding with limited publications, with N₂O beginning to be considered in low DO research work – e.g. Jimenez et al., 2026. Insights from long term, full scale data including N₂O remain work in progress.

Seasonal process changes may also play a role in influencing microbial communities which exhibit variable N₂O responses. This is an emerging area of understanding, complemented by microbial analysis and meta-omics approaches seeking to resolve microbial N₂O conversions, participating communities and underlying factors (Roothans et al., 2024).

Process configuration can impact certain risk factors that may influence N₂O production and emission. For example, plug flow activated sludge treatment configurations can have higher ammonia to active biomass loading rates than completely mixed systems which is a known risk factor. Sidestream^[4] treatment, including deammonification and full nitrification/denitrification processes, has been associated with relatively high N₂O production and emissions both in academic review work (Vasilaki et al., 2019; Song et al. 2024) and full-scale utility work in Denmark and Switzerland (Dieziger et al., 2023, MUDP, 2020).

Partially nitrifying systems (either suspended growth or biofilm systems) can operate under conditions where dissolved oxygen concentrations are relatively low and can require a higher degree of control to mitigate N₂O emissions. N₂O emissions from biofilm systems are not yet sufficiently studied at full scale and their use of mechanical aeration or passive (natural) aeration can influence N₂O emission risk and the ability to mitigate that risk.

Identifying potential risk factors or drivers of N₂O production may be useful in prioritisation and identification of WRRFs that utilities should focus on for N₂O monitoring. For example, work by VCS Denmark showed that modifying deammonification plant aeration was able to significantly reduce N₂O emissions (Uri Carreño et al., 2017). Results from the NACAT project in Denmark trialled N₂O destruction across sidestream and mainstream WRRFs and in Switzerland, sidestream treatment is prioritised for funded N₂O abatement schemes through regenerative thermal oxidation (RTO) (MUDP, 2025, CIWEM, 2025).

In the UK, Anglian Water has received project funding to prioritise tackling N₂O emissions from four sidestream treatment facilities through nitrogen recovery and N₂O destruction. It is important to recognise that further research is necessary to improve understanding of the conditions which can result in higher N₂O emissions. On-site measurement across a wider range of regions, operating conditions, WRRF sizes and configurations will improve understanding of the magnitude of N₂O emissions from treatment processes under a range of operating conditions. This guide seeks to support good practice in this area.

[4] Sidestreams refer to return streams from sludge treatment which may also be termed supernatant, returns, liquor, concentrates.

2.4 N₂O production in wastewater sludge treatment processes

N₂O emissions from solids stream (sludge treatment) treatment processes, which are likely to produce N₂O such as drying, incineration, and thermal processes, are under-explored. IPCC guidelines include emission factors for composting, incineration and pyrolysis of waste and commentary on N₂O emissions from landfilling (IPCC, 2006; IPCC, 2019). The biosolids GHG accounting tool BEAM (NEBRA and Northwest Biosolids, available <https://www.biosolidsghgs.org/>) includes available references and may support utility assessments in the absence of measured data.

Emissions can be expected from sludge storage tanks, aerobic digestion and biosolids management processes, including biosolids incineration, advanced thermal conversion, composting and storage Galfalk et al. 2025 found anaerobic digestion a major source of N₂O.

Where solids stream processes result in hydrolysis of sludge and release of additional ammonia, it should be recognised that these liquors may be a significant N₂O risk of emissions - whether due to production in side stream treatment or when recycled back to main wastewater stream processes.

3. Current approaches to N₂O estimation

3.1 IPCC Tiered reporting framework

N₂O and other GHG emissions are quantified for national inventory assessments in accordance with IPCC Guidelines. In the 2019 Refinement to the 2006 Guidelines for National GHG Inventories (referred to as 'The 2019 Refinement'), the IPCC recommended that national accounting for N₂O emissions include N₂O emissions from municipal WRRFs (within reporting sector 5D1 GHG inventory reporting).

The 2019 Refinement recommended that countries adopt a 3-tiered assessment framework for N₂O reporting and a new EF for N₂O emissions from biological treatment, which was approximately 30-fold higher compared to the earlier and optional 2006 Guideline value for WRRF N₂O.

For a detailed description of the 2019 Refinement tiered approach, please refer to the 2022 IWA publication Quantification and Modelling of Fugitive Greenhouse Gas Emissions from Urban Water Systems, Chapter 4.

3.2 Other applicable standards

Utilities should consider the ISO14064 (Parts 1 – 3) GHG monitoring, mitigation and reporting standard principles of Completeness, Consistency, Accuracy, Transparency and Conservativeness in their GHG monitoring projects. These standard principles have been considered in the development of this guidance document.

Given the dynamic nature and variability of these emissions across existing WRRFs, facility-level monitoring is critical for sufficiently understanding mitigation strategies. The IPCC recognised this may not be immediately possible and provided a 3-tiered assessment framework for calculating N₂O emissions with a view to all reporting moving towards Tier 3 – facility level monitoring (**Table 1**).

Some countries (e.g. Austria, Denmark, Switzerland, Germany) have introduced national EFs (Tier 2, as described in Appendix B). These are either based on in-country long-term measured N₂O data across multiple WRRFs, which are then applied to other WRRFs. The accuracy of Tier 2 EFs will also benefit from in-country refined data (e.g. measured nitrogen loads).

Table 1. The Intergovernmental Panel on Climate Change (IPCC) 3-tiered assessment framework and considerations for relevance to utilities in the water sector

Tier	Method	Application and relevance
1	Applies default values for the EFs as per Table 6.8a (new) in the 2019 refinement for wastewater treatment and effluent and country specific activity factors where possible.	Considered good practice for countries with limited data. <i>Currently applied in some national and sector level accounting approaches for water sector.</i>
2	Applies country-specific EFs and country-specific activity data. Such factors should be based on field measurements undertaken in the same region or climate area. Methods should account for amount of sludge removed for incineration, biogas production, landfilling or agriculture.	Good practice where direct measurements are not available, but where country or regional specific emission factors have been developed. There is no guidance from IPCC or other sources on how Tier 2 EFs should be developed from measured data or otherwise. <i>May support improved accounting but cannot support mitigation. Utilities should consider IPCC Tier 2 guidance for different receiving water effluent EFs for nutrient impacted waterbodies.</i>
3	Use of EFs based on plant-specific emissions data from larger WRRFs. Country-specific measurements of N discharged to the aquatic environment should be used.	Advanced practice, where direct measurement will provide a more accurate measurement of N ₂ O production from each WRRF. <i>Most relevant for utility and sector climate action.</i>

3.2 The importance of facility level quantification of N₂O for utilities

The recommended Tier 1 EF (good practice) of 1.6%N₂O-N incoming total influent nitrogen load being emitted as N₂O emissions, is considered a top-down assessment approach and applied where data, resources, methodologies are not available at country-level for more detailed approaches. Whenever possible, the use of Tier 2 (good practice) or Tier 3 (advanced practice) as bottom-up approaches is preferable.

These approaches, to varying degrees, consist of measurements of the actual N₂O emissions at the facility level and other supporting data.

Bottom-up approaches can include measurement at a site-level of N₂O emissions and source-level or process-unit level measurement for WRRF N₂O quantification in priority areas of the WRRF.

Site-wide measurement methods for N₂O currently do not provide enough detail on N₂O production and emission to support mitigation; conversely, source-level N₂O measurement methods can provide a quantification of some of the WRRF N₂O but must be extrapolated to the facility level through assumptions to give a full site-wide quantification. Thus, a pragmatic approach to facility-level monitoring will need to balance these factors.

Section 4 provides details about these measurement methods and discusses key considerations when designing a monitoring campaign.

3.3 N₂O quantification method approaches for utilities

The following key points should be considered by utilities for accurate quantification and mitigation of their N₂O emissions. These are in line with the intention of IPCC Tier 3 for plant-specific quantification.

1. Accurate estimation of N₂O emissions requires continuous facility-level measurement of recognised major N₂O sources (this white paper supports utility efforts in undertaking this bottom-up approach to quantification of their N₂O emissions).

2. Bottom-up source/process unit level measurement is required to demonstrably mitigate N₂O emissions.

3. Where facility-level monitoring is not possible, the 2019 Refinement recommends the application of EFs in a top-down approach to N₂O quantification. This approach is detailed in Chapter 6.3 (for domestic / municipal wastewater) and Chapter 6.4 (for industrial wastewater) of the 2019 Refinement document and is not considered further in this document.

4. A *bottom-up* approach at Tier 3 (WRRF level) can support improved Tier 2 approaches. For example, by developing process-type specific EFs which can be applied at country-level in an improved Tier 2 quantification; Switzerland, has used national monitoring results across 14 WRRFs to develop different EFs for nitrifying, nitrifying/denitrifying and carbonaceous WRRFs in new national EFs (Gruber et al., 2021). Appendix B provides case studies for where facility-level emission monitoring has led to recommendations at national level, although few countries have yet adopted such nationally derived factors.

5. *Bottom-up* measurement work for N₂O typically only involves a sub-set of WRRF assets, for instance, measurement in some zones or lanes only. Nevertheless, such data can be used to derive a site-specific EF. Section 5 discusses how data from such measurement campaigns can be extrapolated to site level.

6. Utilities should consider the ISO14064 GHG monitoring, mitigation and reporting standard principles of *Completeness, Consistency, Accuracy, Transparency and Conservativeness* in their GHG monitoring projects.

Common methodologies for monitoring and reporting in line with Tiers, 2 and 3 using facility level data are currently lacking though facility level monitoring protocols are emerging.

Developing guidance will not only support comparative benchmarking across sites to inform transparent annual reporting by utilities and companies in their sustainability/integrated reports, but will also enable strategic action to reduce N₂O emissions.

Monitoring programmes will also be central to developing national EFs, thus informing sector emissions and reduction trajectories and actual mitigation.

4. Proven approaches for measurement of N₂O

Facility-level monitoring is critical for the quantification and mitigation of N₂O emissions. This section sets out key monitoring approaches for N₂O with a focus on the currently used gas and liquid phase measurement methods. This section is framed around questions a utility may have in developing an N₂O measurement approach, including:

- What are my objectives for monitoring N₂O?
- Which monitoring methods should I employ?
- Where should I monitor?
- How do I monitor different WRRF configurations?
- How many process trains should I monitor?
- What are the key resource requirements?

4.1. What are my objectives for monitoring N₂O?

Monitoring of N₂O may be undertaken to meet all or some of the following goals: (a) direct measurement of N₂O emissions to report these annually, (b) to support mitigation efforts and/or (c) to enable prioritisation of N₂O measurement and mitigation across multiple WRRFs. In general, long-term, continuous N₂O measurement is key to understanding N₂O emission variability and to developing and sustaining effective mitigation strategies. Such long-term monitoring should be conducted over a continuous period to capture recognised seasonal variation. This should consider a minimum of 12 months where possible.

Continuous long-term monitoring has highlighted significant variability in N₂O production and emissions.

Long-term campaigns typically report larger EFs than short-term campaigns (Vasilaki et al., 2019). Short-term campaigns may also risk overestimating or underestimating emissions if the monitoring period coincides with a period of process disturbance or unusual process stability. For example, during a period where unwanted nitrification-denitrification was observed at the Viikinmäki WRRF (Finland), a spike was observed in measured N₂O emissions (Kuokkanen et al., 2021).

At Avedøre WRRF in Denmark, some 80% of emissions are generated during a 3 – 4-month period of the year (Andersen et al., 2023). Similarly, Seshan et al. (2024), highlight the challenges of biokinetic N₂O modelling to predict seasonal variation, which was evident for just 2 months of the year. A short-term campaign, if not capturing this period, may entirely miss the N₂O risks at such a facility.

Long-term continuous monitoring is not a prerequisite for taking action to mitigate N₂O emissions. Given recognised uncertainty of N₂O emissions, short term WRRF measurement campaigns are likely to support more informed action by Utilities than no measurement. They may identify sites which may have higher emissions than others (at the time of measurement). This may support where to prioritise long term measurement and mitigation work to maximise impact. However, misleading conclusions can be drawn if the campaign coincides, for example, with a low or high-emission period.

4.2 Which monitoring methods?

Figure 7 shows various approaches which are currently applied for site-wide and process unit-level N_2O measurement. Other methods (for example, Eddy Covariance) remain emerging and under evaluation (MUDP, 2025).

Process unit level measurement methods, shown with red borders in Figure 7, are required to support N_2O understanding and sustained mitigation and include N_2O measurement options in the liquid and gas phase. This section provides a detailed description of these and key considerations for utilities in deciding which measurement method to utilise.

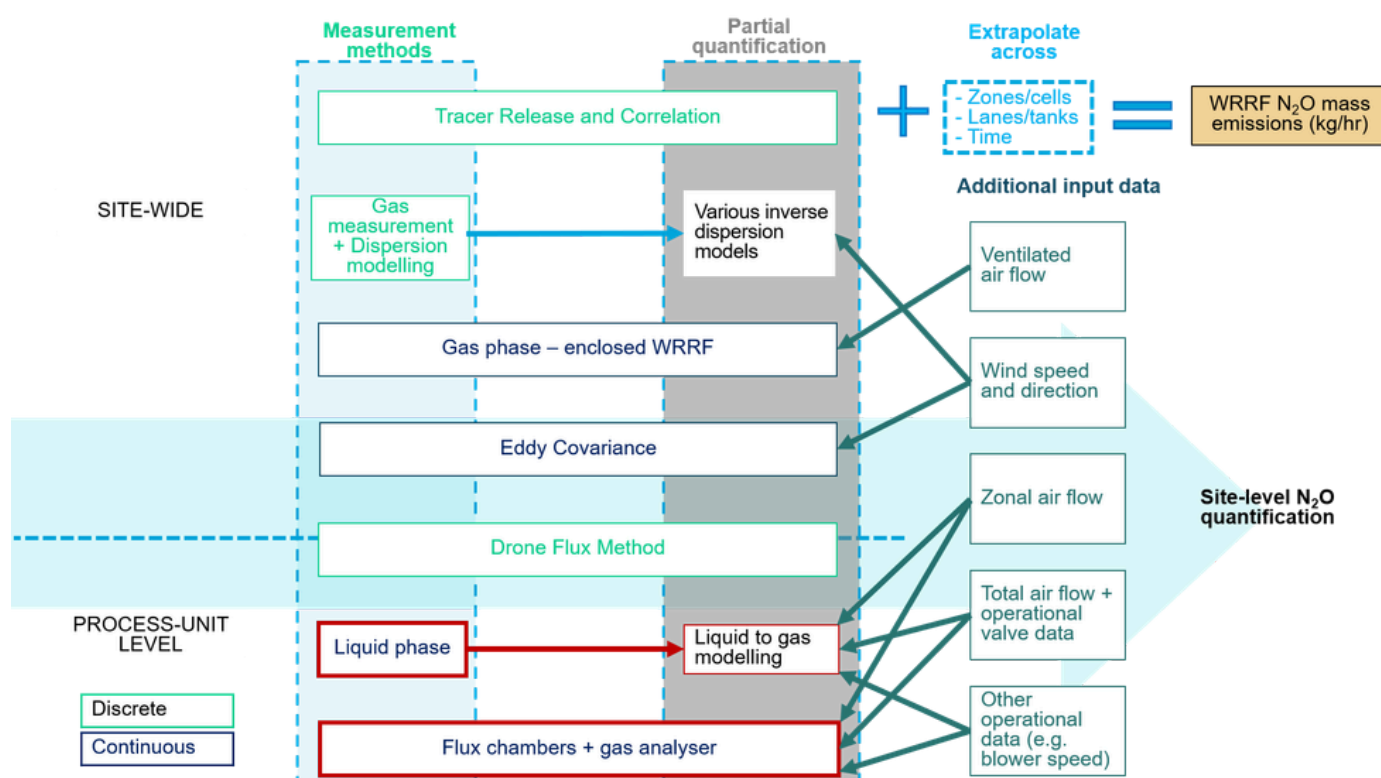
Liquid phase measurements use Clark-type electrochemical sensors whilst infra-red or mass spectrometry-based gas techniques are used for gas phase N_2O analysis.

There are numerous gas phase analysers for N_2O but a limited number of commercially available gas phase systems which include gas hoods, gas conditioning and analysis (see the Danish EPA proposal for N_2O regulation which includes details of available N_2O monitoring systems available to utilities).

The following sections provide attributes of commercially available N_2O measurement systems which are available for utilities to install to support their N_2O quantification and mitigation work.

Costs for systems, where available, may be comparable when capital purchase of equipment, maintenance and consumables costs are considered; utilities should consider these in combination with their asset types and intention of monitoring. **Figure 7** shows various approaches which are currently applied for site wide and process unit-level N_2O measurement.

Figure 7 Demonstrated methods for N_2O quantification at facility level



4.3 A note on the importance of air flow data

Liquid and gas phase analysis provides a concentration of N_2O in the liquid or gas phase in mg/l or parts per million. Air flow data in each zone of measurement (for example, in each zone of a plug flow tapered aeration activated sludge plant) is critical to quantify mass emissions of N_2O .

Where air flow data is not available, estimates may be made based on valve positions and type, diffuser density, pressure conditions and/or blower operating parameters.

Commercially available gas monitoring systems can incorporate air flow measurement with thermal mass meters; however, given the relatively low percentage of the tank being monitored and typical heterogeneity in air flow distribution in WRRF aeration tanks, individual hood-based air flow may be less accurate than zone and/or tank air flow data.

Where aerated processes (whether passive or forced) are not used in the WRRF configuration (for example anaerobic or facultative lagoons or treatment wetlands which do not rely on aerobic processes), the above considerations do not apply.

4.4 Continuous liquid phase N_2O measurement

To date most utility-led efforts to monitor N_2O emissions at process level use liquid phase sensors. There is a single liquid phase continuous N_2O sensor on the market (**Figure 8**, Unisense Environment A/S, Denmark).

This comprises a controller which can be stand alone or connected to a site SCADA system and multiple N_2O sensor bodies to which sensor heads are connected. Cabling requirements between sensor bodies and the controller will be dependent on WRRF layout, and required distances between measurement locations should be assessed, including the potential requirement for sensor heads to be moved around to understand spatial variation in N_2O .

The full sensor body must remain submerged as it relies on the temperature sensor on top of the sensor for accurate N_2O quantification. Metal fixings must be avoided as they will corrode the sensor body.

Mounting should facilitate easy removal for 2 monthly calibration and sensor head replacement without damage to sensor or risk of vibration or colliding with objects in treatment tanks.

The N_2O measurement undergoes temperature correction and requires regular temperature-dependent calibration. Liquid phase measurement of N_2O records a dissolved reading – often ranging from 0 – 2 mg/l N_2O -N (0 – 2500ppm) for mainstream plants and significantly higher (up to 9 mg/l N_2O -N) for facilities treating sidestreams (e.g. from sludge treatment processes). The limit of detection is 0.0002 – 0.0005mgN/L or 2 – 7ppm. For higher temperature effluents or higher concentrations of N_2O and/or O_2 , different sensor heads are required.

Figure 8 Liquid phase N_2O Wastewater System sensor body, head and panel and in-situ (Unisense Environment).



The measurement principle uses electrodes which are consumed upon exposure to N_2O and O_2 .

While the glass sensor tip generally remains free of biofilm, where installed in free-flowing liquids, cleaning of the submerged sensor body and head is required and will depend on the degree of fouling and ragging.

Calibration is required every 2 months or if there are significant changes in wastewater temperature (refer to system manuals here <https://unisense-environment.com/manuals/>).

Two-point calibration takes place in tap water and a N_2O calibration solution at operating temperature and is temperature compensated $\pm 3^\circ C$ by the sensor controller.

A 6-monthly replacement of the electrodes is recommended by the vendor, but this will depend on exposure to both N_2O and O_2 . Adherence to recommended replacement intervals and evidence of correct calibration and sensor head replacement are important to consider as part of reporting protocols. The sensor body must remain dry when sensor heads are being replaced as water will damage the unit.

4.5 From liquid to gas phase N₂O emission

The liquid phase N₂O measurement yields a concentration of N₂O, and this must be input to the gas-liquid transfer calculation to estimate N₂O emissions to air. Calculations differ depending on whether the measured WRRF is bottom fine bubble aerated^[5], coarse bubble aerated or surfaced aerated^[6].

These calculations result in a modelled, not measured N₂O mass emission – however work by utilities and academics has shown good alignment of this for conventional fine bubble diffused aeration activated sludge WRRFs where side-by-side liquid and direct gas phase measurement have been undertaken (e.g., academic study by Baresel et al., 2016, and utility study by Watercare – see vendor summary).

Multiple mass transfer models exist for fine bubble diffused aeration systems based on film theory, Henry's law and differing assumptions about gas solubilities, properties of bubbles and in-tank pressure gradient and composition of bubbles at bottom and top of the tank (see Vasileios et al., 2023 for further detail).

The current guidance for the commercially available liquid phase sensor recommends use of a mass transfer model which applies an empirically derived N₂O mass transfer coefficient $k_L a_{N_2O}$ from liquid to gas for reactor depths up to 6 m (Foley et al., 2010).

This is corrected for tank depth and temperature and can be applied in tanks up to 6 m in depth, with an alternative method (Baeten et al., 2020) shown to be valid in tanks up to 11 m. It should be noted that in applying the mass transfer model of Foley et al., 2010, there is an error in the original paper formula – the correct formula is explained in a summary paper.^[7]

Commercially available wastewater process simulation software models which utilise two-film theory-based mass transfer and not the above methods may over-estimate stripping from measured liquid phase N₂O data.

This can occur where they assume similar solubilities of N₂O and O₂ in water and constant mole fraction and pressure which does not align with the observed near complete saturation of the gas phase N₂O at the top of the reactor (Baeten et al., 2020).

[5] Refer to guidance from vendor here <https://unisense-environment.com/wp-content/uploads/2024/02/N2O-Sensor-based-Emission-Calculation-Ver-3.pdf>

[6] Refer to guidance from vendor here <https://unisense-environment.com/wp-content/uploads/2024/09/N2O-Emission-calculation-surface-aerator-Ver-4.pdf>

[7] Formula (9) in Foley et al. 2010 accidentally applies a 0.86 power to (34,500 x vg) (superficial gas velocity of the field reactor), the correct formula is 34,500 x (vg)^{0.86}, refer to Appendix 8 in document here <https://unisense-environment.com/wp-content/uploads/2024/08/2024.06-N2O-Wastewater-System.pdf>

4.6 Laboratory N₂O determination – not continuous

There are laboratory methods available for N₂O measurement in liquid samples. These initially require reagents to be added to the same to prevent further biological activity before transport to the laboratory – see A best practice guide for dissolved CH₄ and N₂O (de la Paz et al., 2021).

However, great care to prevent N₂O conversion or loss during sampling is needed, and there should be validation of such methods to the extent possible. Even when handled carefully, such analyses will only provide periodic “snapshots” of N₂O production in the liquid phase, and the importance of continuous N₂O measurement to provide more than a snapshot of information on emissions is stressed in this white paper.

4.7 Continuous Gas phase N₂O measurement

To-date, most academic research on full scale WRRF N₂O measurement over the past two decades has utilised gas hood systems. Typically, off-gas N₂O and commercial analysers are integrated into multi-hood and gas phase measurement systems. A range of suitable analysers exist, based on infrared and mass spectrometry technology, with ongoing research to reduce costs and improve measurement capability.

To date, gas phase monitoring was primarily carried out by research groups with self-built rigs (with reference to and building upon the work of Chandran, 2011).

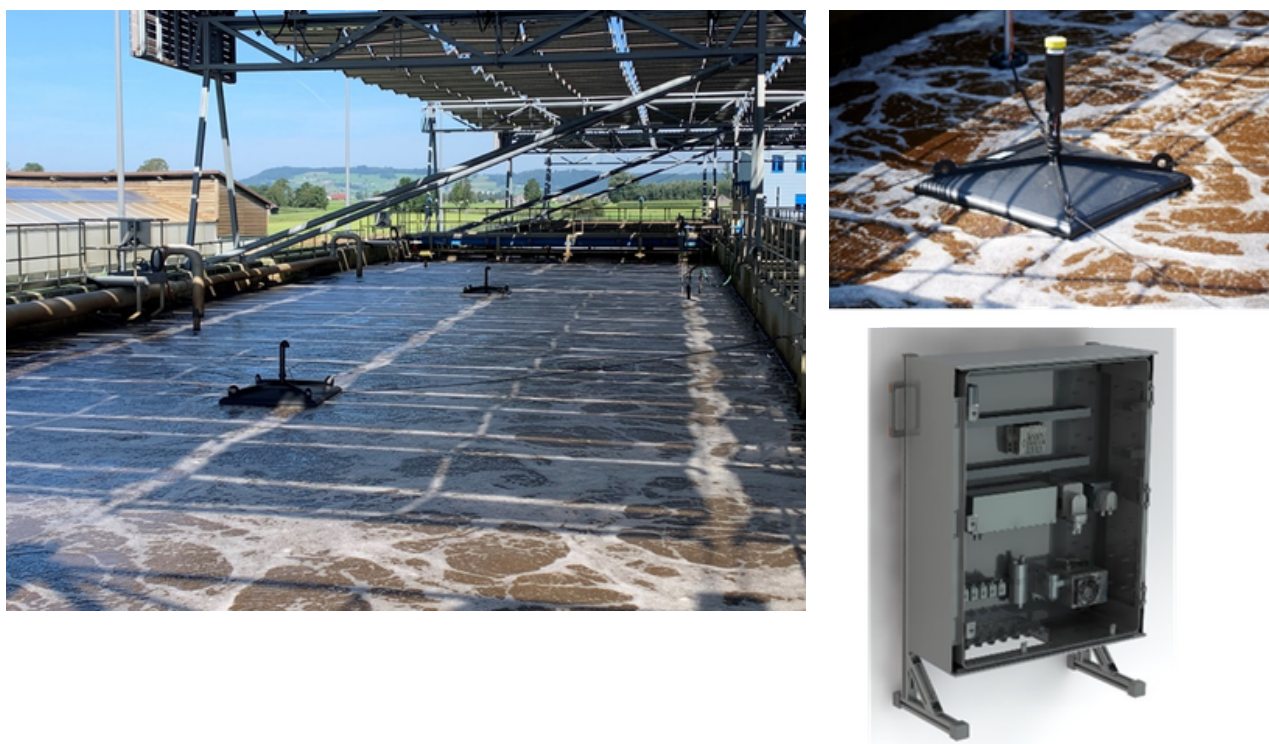
In Europe, a few vendors of commercial gas hood systems now exist for utility purchase (for example, see **Figure 8**). Full systems will include gas hoods, gas conditioning and analysis (see the Danish EPA proposal for N₂O regulation^[8], which includes details of some available N₂O monitoring systems relevant for to utilities in Europe).

During operation, gas hoods should remain free of gas buildup, and WRRFs with significant foaming and scum issues may have challenges. Gas tubing must be free of moisture and condensate and gas preparation prior to analysis to remove humidity is achieved by heating or cooling. Tubing distances should be discussed with system providers and may require design considerations to prevent moisture, damage and freezing. Gas analysers require regular calibration with prepared gases, which are required to be brought to the site or provided as part of the sensor set-up. Autocalibration is part of some commercial system designs that include pressurised storage calibration gases and a biannual or annual visit for maintenance and analyser calibration. Utilities should clarify limits of detection and any issues with interference (e.g. foam, moisture) and gas conditioning which may be required for their installation.

The technology chosen may depend on the measurement range required (typically such systems can have a range of between 0 and 1,500 ppm), potential measurement interference, cost, usability and other factors.

[8] See proposal for regulation in Denmark available <https://www2.mst.dk/Udgiv/publikationer/2025/02/978-87-7038-708-8.pdf>

Figure 9 Flux hood monitoring



In research applications, gas phase measurement of N_2O (and other gases) has been applied to aerated and non-aerated zones. The currently available commercial systems offer utilities the ability to measure in aerated zones only. Given this is where most N_2O emissions are stripped, this may be sufficient for N_2O quantification.

However, to fully understand N_2O production and apply mitigation in process control, it is useful for utilities to be able to measure (with liquid phase sensor) in non-aerated (anoxic) zones where both N_2O production and reduction may be occurring.

Table 2 summarises the various elements in a typical gas phase measurement system, including gas collection, transport, analysis and gas flow measurement.

Commercial multi-hood and gas analyser systems for WRRFs are limited, larger hoods which cover a larger area of the aeration tank are more desirable than smaller surface areas (original SEIFIC US EPA design was for a 0.13 m^2 hood but commercial systems typically use larger hood designs of $\sim 1 \text{ m}^2$ or more). Size, weight, buoyancy, portability and accessibility around the tanks in question are all practical considerations that can influence equipment choice.

Multi-hood systems are available that can support multiple measurement points and include including hood(s), multiplexing system and integrated gas conditioning, moisture traps and analyser. Data upload, visualisation and supporting N_2O quantification and mitigation may also be included.

Table 2 Typical elements of floating hoods and off-gas monitoring system

System element	Equipment	Purpose
Gas collection	Hood	Sits on the tank surface and collects off gas from processes with forced air flow. May include air flow measurement.
Gas transportation to sampling and flow measurement	Tubing	Transports collected gas from hood to analyser and may include pumped or passive gas transport.
Gas analysis	Analyzer – typically Infrared (IR) based	Measures concentration of N ₂ O (and other gases). Includes gas preparation to avoid moisture and correct for humidity.
Gas flow measurement – on hood or within panel	Gas flow sensor	Hot-wire anemometer can be included to measure gas flow in commercially available solutions on actual hoods., This may be additional cost. Measured flow may be undertaken at hood or locally in equipment housing.

Delivery of gas to the analyser requires consideration of tubing type and length, condensation, risk of damage, unintentional gas loss/exchange, prevention of biological growth and freezing.

For example, moving gas over longer distances can be challenging and continuous moisture removal is required to dry the gas prior. Measurement time (retention of gas in hood, transit in air piping) for off-gas systems should be considered if building N₂O measurement into process control, where a reaction time in minutes may be desirable for process optimisation.

As previously discussed, air flow measurement is critical for N₂O quantification and whilst off-gas vendors may include air flow measurement from individual hoods, this may not give as accurate a quantification when compared with using measured zone/tank air flow from (calibrated) air flow meters on aeration manifolds and header pipes- data from these should always be used where available.

Hoods are typically open through vent to atmosphere to avoid pressure build-up which differs from soil system flux chamber sampling which may be used in treatment wetlands, where a finite volume of gas is accumulated and then purged between sampling – with air flow estimated over time.

Where photosynthetic activity takes place (e.g. treatment wetlands), additional elements may be required – for example a light source. Off-gas analysis in non-aerated biological treatment process (e.g., wetlands, ponds, high-rate algal ponds) requires estimation of diffusion based on the ideal gas law and in addition to Table 2 components, also requires temperature measurements.

4.8 Gas versus liquid N₂O measurement – Utility considerations

Table 3 highlights challenges and opportunities for liquid and gas phase N₂O measurement and considerations for Utilities in determining which approach to adopt (or if both are preferred).

Continuous liquid phase measurement has been shown to offer control opportunities for N₂O mitigation at scale and may be used in both aerobic and anoxic zones for this purpose. As discussed previously, the liquid to gas mass transfer model used in deriving mass emissions from liquid phase N₂O measurement has been shown (e.g. by Baresel et al., 2016) to give reliable estimations considering uncertainties in gas phase measurement, which can include spatial variation, air flow measurement accuracy and assumptions. However, utilities could consider mobile short-term gas phase N₂O measurement to support validation of the liquid to gas estimate. This may be a consideration where such N₂O data is being used in reporting of emissions for regulators. .

4.9 Where should I monitor?

In an ideal world, N₂O monitoring would be provided throughout the WRRF, wherever biological nitrogen transformation is being undertaken – e.g. in each aeration zone/lane and in other parts of the WRRF such as biosolids processing and biological odour control, which may also be sources of N₂O.

In practice, utilities are limited in terms of the number of measurement locations and systems that can be deployed. Thus, a fully comprehensive bottom-up measurement is not possible, and treatment tank(s) and lane(s) where most biological nitrogen transformation occurs can be prioritised. Measurement in several locations within the same tank is ideal and particularly necessary where aeration conditions vary (e.g. tapered aeration) or where mixing is not uniform. This can ensure more accuracy when extrapolating emissions. **Figure 10** provides guidance for Utilities designing a monitoring programme.

Measurement in parallel lanes should be measured where resources allow, particularly where flow or aeration conditions are known to differ. Systems with natural ventilation or some biofilm-based systems may require additional considerations:

- Measurement (gas or liquid) in systems with carrier or sand media will require special consideration to protect instrumentation
- Measurements in trickling filters are possible only with off-gas methods or site-wide methods. With off-gas methods, systems with natural ventilation provide challenges for quantification of mass emissions, and very limited examples exist globally where filter-specific N₂O assessment has been undertaken.

Figure 10 Suggested approach for site selection for N₂O monitoring

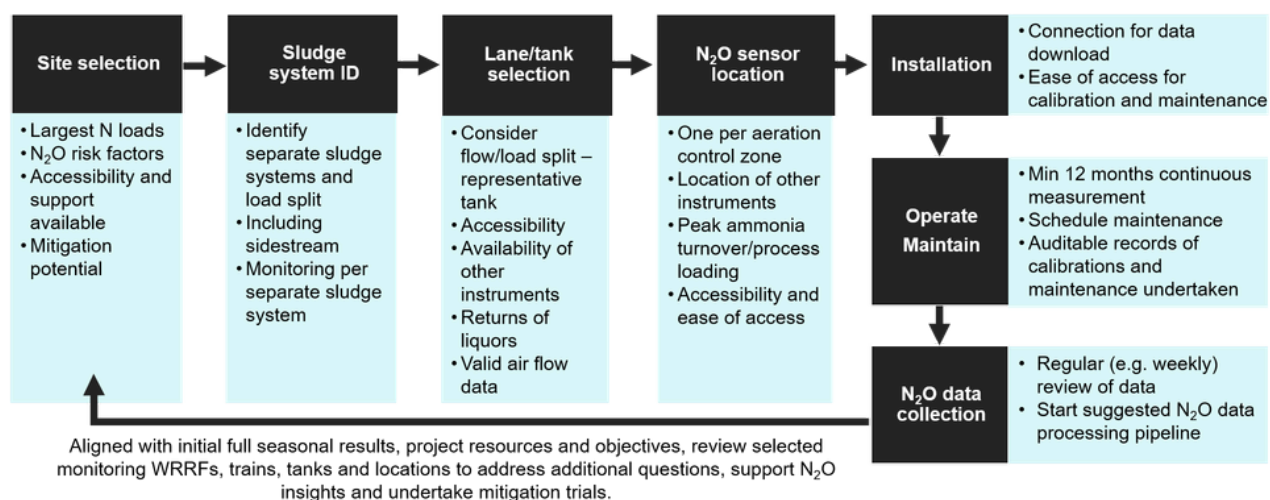


Table 3 Gas versus liquid phase considerations for Utilities

Liquid phase N ₂ O measurement	Gas phase N ₂ O measurement
Requires accurate process (zone) air flow data in aerated systems	Requires accurate process (zone) air flow data. Hood air flow alone may not be sufficiently representative
Requires calculation and liquid-gas transfer assumptions to calculate mass emissions. Captures emissions in concentration by volume (e.g. mgN/l), requires calculation of mass emissions (e.g. kg/hr), possible in actively aerated zones only	Requires calculation and liquid-gas transfer assumptions to calculate mass emissions Captures emissions in concentration by volume, requires calculation of mass emissions (in actively aerated zones only)
Currently supports utility real time N ₂ O mitigation through direct control or monitoring (limited case studies from Netherlands , Denmark)	Potential to support real time N ₂ O control approaches (limited applications to date see Gruber et al., 2021)
Allows monitoring of non-aerated anoxic zones to understand N ₂ O production and support mitigation (e.g. through carbon dosing)	Supports measurement of other gases – CH ₄ , CO ₂ , O ₂ – and wider system analysis including aeration system efficiency
Requires monthly calibration approximately every 2 months. Gas phase analysis typically requires less calibration	May be used for full WRRF analysis for enclosed reactor systems (though does not allow for key production and emissions to be understood unless coupled with process unit measurement)
Requires approximately 6 monthly sensor head replacement depending on use	Issues with monitoring can occur if the site has scum / foaming
May be moved between zones/tanks relatively easily with sufficient cabling	May require more effort to move between tanks; limitations in length of tubing exists to convey off-gas sample to analyser

4.10 How do I monitor different WRRFs?

It is important to prioritise N₂O measurement locations to generate best possible data that supports the objective of monitoring and mitigation priorities. For mitigation, understanding where the highest N₂O production occurs and can be mitigated may be the priority; for baseline reporting, understanding what the average N₂O production and emission is may be preferable.

Figures 11a and **11b** provide examples of recommended N₂O measurement locations for different process configurations. For treatment wetlands, approaches remain emerging; see Appendix D for example locations for measurement – noting that measurement devices may not be the same as those currently employed in the WRRF configurations below.

Figure 11a N₂O monitoring locations for typical WRRF treatment typologies. See Appendix D for example treatment wetland measurement locations.

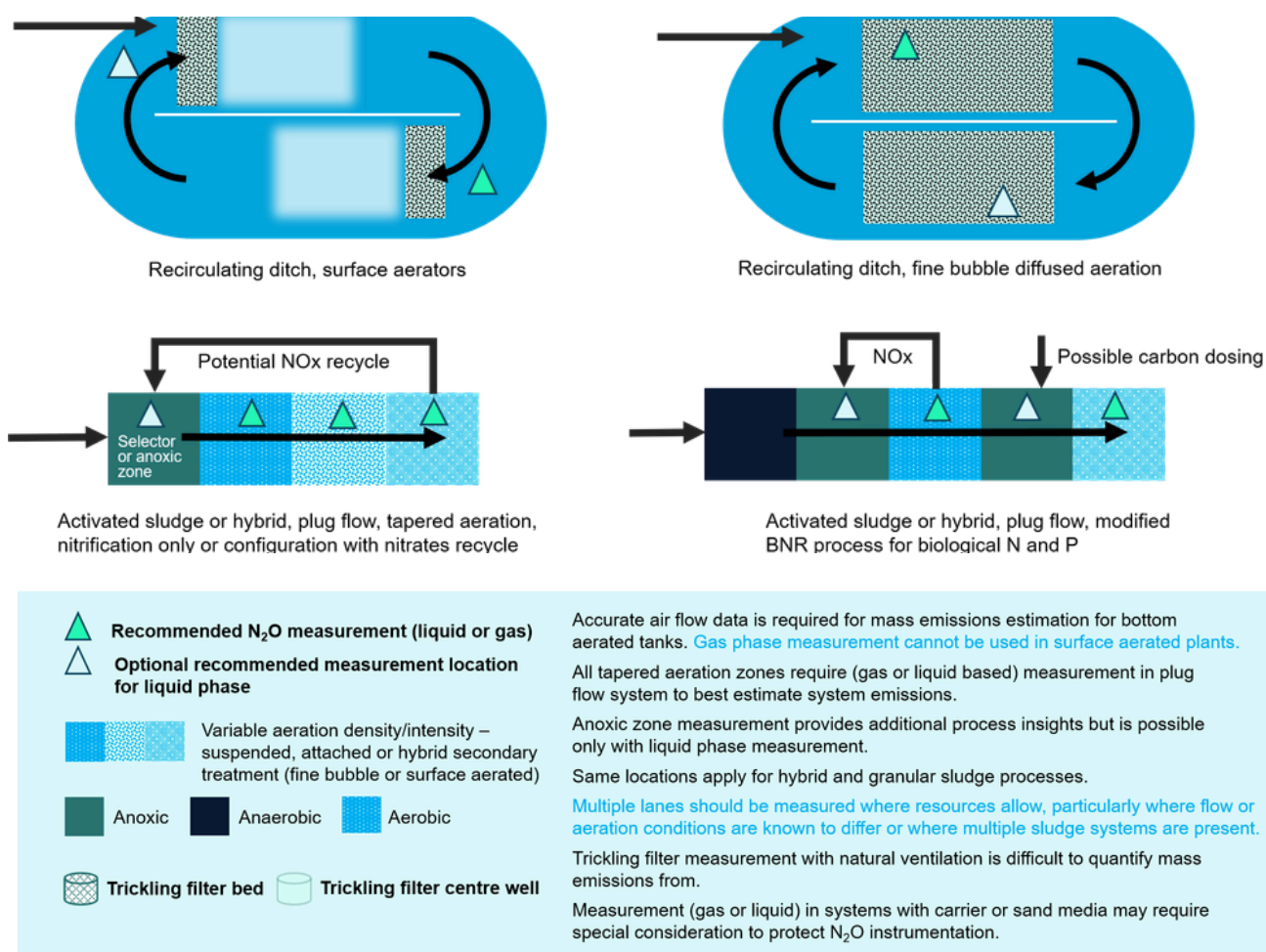
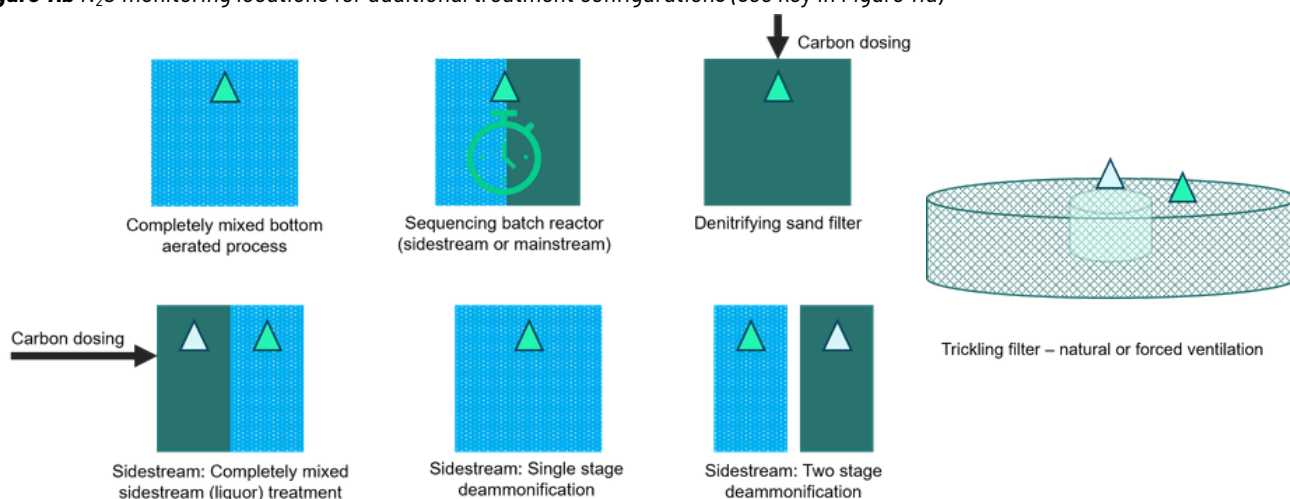


Figure 11b N_2O monitoring locations for additional treatment configurations (see key in Figure 11a)



4.11 How many lanes to monitor?

Measurement in multiple reactors/treatment trains may be important particularly where flow and load distribution or aeration/control efficacy is known to differ between treatment tanks/lanes.

Where mitigation can be trialled in parallel treatment trains/lanes, these should both be monitored.

Gruber et al., 2019, provide a decision tree and refined monitoring strategy for measurement location across multi-lane facilities. An example of such decision-making when applied to plug flow systems might prioritise monitoring in all aeration zones in one lane over measurement in one or two zones only across multiple lanes.

A representative magnitude of N_2O , including seasonal variability, may be missed if only some zones are measured.

4.12 Monitoring in plug flow versus completely mixed tanks

When measuring N_2O in plug flow (PF) systems, providing measurement in each sequential aeration zone is recommended to give an accurate estimation of the emission due to changes in N_2O formation and the stripping coefficient (KL_a) for N_2O and to enable mitigation strategies to be deployed.

4.13 Monitoring in Biological Nitrogen Removal Plants (EPBR)

Typical WRRF configurations include a pre-denitrification zone utilizing the carbon in the wastewater or external carbon. Nitrate is recirculated back from the nitrification tank to the denitrification tank to allow denitrification; Measurement of N_2O in anoxic (liquid phase measurement) and aerobic zones is required to fully understand production and emissions and to support mitigation measures. This applies to suspended growth, hybrid or granular configurations. Where carrier media is included, protection of measurement instruments may be required.

4.14 Monitoring in Sequencing Batch Reactor (SBR) processes

In an SBR reactor, the processing of wastewater is done sequentially in the same tank. Often several reactors work together in parallel with their cycles staggered to limit the need for influent storage and ensure steadier effluent flow rates.

Cycles can be altered for different operational applications. Mixing and aeration can be varied during the fill phase to create a denitrification or nitrification environment.

N₂O can normally be monitored by one N₂O sensor in each SBR-reactor assuming completely mixed conditions. This applies to suspended growth or granular SBR configurations. Where carrier media is included, protection of measurement instruments may be required.

4.15 Monitoring in sidestream processes

Sidestream treatment for ammonia treatment, including nitrifying, denitrifying and deammonification processes, has been associated with relatively high N₂O production and resulting emissions as reviewed in previous studies (Vasilaki et al., 2019, Song et al., 2024) and in full-scale utility work in Switzerland and Denmark (Dieziger et al. 2023, MUDP, 2020).

Liquid and gas approaches can both work for these typically open, bottom-aerated systems. However, sensors that operate in higher temperature environments and N₂O ranges may be required depending on the nature of these side-streams.

4.16 Monitoring covered WRRF processes

Covered WRRFs may offer unique opportunities or whole-plant N₂O quantification through gas phase analyser and known system ventilation rates. However, for an understanding of production and emission characteristics and resulting mitigation opportunities, process-level measurement through gas or liquid phase analysis is required.

4.17 Monitoring surface aerated systems

Surface aerated systems provide a challenge in measuring N₂O emissions from because both liquid and gas phase approaches are not practical where surface (e.g. brush or rotor type) aeration exists. It can be challenging to properly locate gas hoods or liquid phase sensors due to mechanical parts and turbulence. As there can be rapid stripping of N₂O in highly turbulent areas and measurements taken too close to the aerator or too far away may not be representative of the overall emissions.

Liquid phase sensors may still be employed to help develop mitigation measures to minimise N₂O levels through aeration control, rotor submergence, speed – however accurate N₂O emissions remain challenging. The quantify and site-level (e.g. drone flux or tracer correlation) methods may best support quantification or support liquid N₂O measurement.

4.18 Monitoring biofilm and hybrid WRRF processes

Biofilm processes require particular N₂O measurement considerations; some of the key issues and considerations are summarised below:

- For biological trickling filters with no forced aeration rate, mass emissions from the process stage cannot yet be accurately determined using existing methods. Site-level methods such as tracer correlation or drone flux methods can enable site-wide N₂O quantification.

- For biological trickling filters with forced aeration, and where the air flow rate is known or can be measured, gas phase concentration measurement using a hood can enable measurement, or it may be possible to measure via a ventilation system where the system is enclosed.
- For membrane aerated biofilm reactors (MABRs), downstream diffused aeration system zones require measurement as per normal activated sludge plant configurations with liquid or gas systems. Within the anoxic zone(s) where the MABR is generally installed, liquid and gas phase measurements are required to understand system emissions. Ideally, measurement would be installed on lumen (hollow tube) off-gas (from MABR), surface off gas (from anoxic tank where MABR is installed in order to capture intermittent but often frequent scouring which may be with air or N₂O rich exhaust gas) and liquid measurement in anoxic zone (to support understanding of N₂O carryover into downstream aeration zones, N₂O production pathways and potential mitigation strategies like carbon dosing). Liquid phase measurement cannot be used to estimate scouring system emissions with existing mass transfer calculations, and off-gas measurement is required for this.
- For moving bed biofilm processes (MBBRs) and biological aerated filter processes (BAFs) (including pure film and hybrid approaches), coarse or medium bubble aeration is common, and existing validated mass transfer models cannot be used for liquid phase measurement. Accordingly, gas phase measurement is required. For accurate mass emissions quantification, liquid phase monitoring would require validation of the gas transfer (e.g. with temporary gas hood monitoring). The risk of blockage or damage to both gas hood and liquid phase sensor systems should be considered where media can damage the measurement system and protective cages or zones may be required.
- For hybrid systems with activated sludge such as integrated fixed film activated sludge (IFAS), N₂O mass emissions can be estimated from liquid phase measurement (if the system has fine bubble diffused aeration) or from other modelled liquid to gas calculation or with a direct gas hood measurement system. Liquid phase measurement may support direct N₂O control for mitigation in aerobic or anoxic zones; gas phase measurement may support direct N₂O control for mitigation, but only in aerobic zones. As with moving bed processes, the potential for sensor damage due to media should be considered.

4.19 Monitoring treatment wetlands and ponds as biological treatment systems

Engineered wetlands have been used for wastewater treatment worldwide for over four decades. Whilst many names and classifications exist, the basic typology is based on the location of the water table (i.e., visible on the surface or subsurface) and the direction of flow (vertical or horizontal). The systems can operate free draining (akin to trickling filters; vertical flow), with forced aeration (akin to SAFs and BAFs; aerated wetlands), saturated and anoxic (anoxic tanks in ASPs; horizontal flow), and saturated and facultative (horizontal flow). As such, the types of sensors and methods for monitoring can be similar to those described in this guidance. To date, limited wetland monitoring has been undertaken by Utilities.

Monitoring of emissions from treatment wetlands will vary depending on objective and, equally important, the size of the treatment system. For large systems (>1ha land cover), “site wide” methods including drones and eddy towers provide better quality of information for carbon accounting than point-source monitoring (“process unit level”) due to the large heterogeneity of conditions that can impact on N₂O production and emissions.

As any other biological treatment process, disturbances to process conditions (e.g., oxygen in anoxic zones due to fluctuations in water levels), bioavailable carbon limitations (e.g., in tertiary systems), and shock loads (e.g., due to upstream treatment processes failures) can result in high-intensity temporal emissions (Mander et al., 2014).

Short-term, multiple-point discrete campaigns may enable profiling and targeting of “hot spots” (Kasak et al., 2022). Management strategies on site should be recorded, as harvesting is known to cause temporary peaks in process emissions (Okiti et al., 2025). As with any other biological system, full understanding will only be achieved with long term (full year) monitoring given seasonal variability.

Discrete measurement campaigns at process unit-level in systems without surface water flow employ methods from natural wetlands and soil/agricultural science. These involve installing pre-made rings within the substrate down to a 5-10 cm depth, which will then allow for a chamber to be attached and form a seal to capture emissions during a specific time period.

For wetlands, additional considerations include decisions around covering/not covering plants (which can sequester carbon during the day) and using a clear vs an opaque chamber (to block or include photosynthetic activity).

For surface flow systems, anchoring of the monitoring hood is also important, with boardwalks recommended to avoid disturbing the sediment during placement of a floating hood. See Appendix D for suggested locations

4.20 What are the key resource requirements for N₂O campaigns?

Below are key resourcing considerations for Utilities undertaking N₂O measurements at WRRFs.

- The required maintenance and calibration will vary between technologies, but resources should be made available for regular maintenance and calibration. This might vary from every 2 months to twice per year and will require trained staff.
- Integration into the site Supervisory Control and Data Acquisition (SCADA) system is not necessary but can be beneficial as it allows for a common data pool for N₂O and associated process data and provides for the potential to integrate N₂O monitoring into real-time control algorithms. Where this is not possible, data may need to be downloaded locally.
- Resources and expertise to regularly collate, review and analyse extensive datasets which will be developed. The expertise to convert such data into mitigation strategies that can be implemented and tested on-site should not be underestimated.
- To use the data for developing mitigation strategies, supporting process data (e.g. air flow, DO, pH, ammonium, nitrite, nitrate, etc.) as well as laboratory data is required to quantify N₂O emissions and understand production mechanisms.
- A large volume of data can be generated – for example, continuously logged N₂O data in 1 min intervals from a liquid or gas phase monitoring system can require SCADA air flow data at 1 min to 15 min intervals to estimate N₂O mass emissions and understand N₂O production. The data needs to be stored and analysed in a systematic way, which requires additional resource and skillsets.

5. Analysing data from N₂O monitoring campaigns

5.1 Using monitoring data to calculate N₂O emissions

For both gas and liquid phase measurements the air flow rate through the reactor data is required. For gas concentration, this provides a mass quantification; when liquid phase N₂O concentration data is used, a N₂O mass transfer coefficient calculation is utilised (as previously discussed).

5.2 Using monitoring data to calculate emission factors

Typically, N₂O emission factors are calculated by normalising the emissions with a functional unit to facilitate the interpretation of the emission level and comparison with other treatment plants. Typical functional units are influent total nitrogen load (kg N/time unit) – which is used by the IPCC – or total nitrogen load removed in the treatment process (kg N removed/time unit), or using other nitrogen species like ammonia, which may be measured continuously.

It should be noted that the time lag between influent and effluent data should be considered, which is influenced by the overall hydraulic residence time. The basis for incoming nitrogen should be clear – e.g. whether this is TN in influent sewage from catchment or TN in influent sewage PLUS additional TN which may come from imported sludge-derived liquors. Even for a WRRF which receives no sludge imports, the change in nitrogen due to hydrolysis in anaerobic digestion may contribute to additional N₂O production, and whether a WRRF has high-strength return

liquors is an important consideration in attempting to compare and contrast EFs. For comparison with IPCC Tier 1 EF, influent TN should be used but utilities can consider also calculating based on nitrogen removed to enable further comparisons and understanding of underlying processes that may increase emissions.

Whilst N₂O data is highly granular (e.g. 1-2 minute data), many facilities may have limited TN data. Where TN is not routinely measured – for example, because discharge regulations focus only on NH₄ limits, utilities may consider alternative data to normalise their emissions. Nitrogen from sludge imports or the digestion process should also be measured and considered where this is not already captured in the total influent load – i.e. the functional unit of influent total N load should encompass all influent sources.

5.3 Using data to compare and put N₂O in context

Comparing N₂O emissions across different WRRFs and understanding the reasons behind N₂O production and emission requires more than just N₂O data. The following additional context and data should be considered to maximise the effect of any mitigation measures developed and to enable better comparison between WRRFs (a detailed example is given in Appendix A):

1. Plant typology – plant description (alternating, recirculating, or plug flow process).
2. N₂O measurement sensor type and location of measurement point(s) (aerobic, anoxic) across lane(s) or tank(s).

3. Process design and operational conditions
 - MLSS, MLVSS, SRT, COD:N ratio, recycle flowrates, capacity WRRF utilised (e.g. hydraulic or organic loading capacity utilised).
4. Process aeration data – air flow data, aeration system characteristics (tapered, number of zones, measured air flow or assumptions made in deriving air flow).
5. Additional process instrumentation, location and calibration data (for example, online DO, ORP, NH_4 , NO_3 or NO_2).
6. Periods of abnormality or known operational issues.
7. Calibration details for all installed N_2O measurement equipment and other instruments that are relied upon in calculation of N_2O emissions and analysis of N_2O production (e.g. air flow).

5.4 Data quality and integrity

Data analysis is the process of inspecting, cleaning, transforming, and quality assuring data so it can support decision-making and to draw informed cause conclusions. Multiple data analysis techniques have been used for different applications in the wastewater sector (e.g. see Corominas et al., 2018). More recently, Baarimah et al., (2024), presented some of the key trends in relation to the use of artificial intelligence in wastewater treatment and the challenges in its practical implementation.

Meta-data, i.e. descriptive information of the collected data, such as information about the measurement ranges of applied process instruments, their locations in the process and their maintenance and calibration history (Alferes et al., 2024), is also valuable for data analysis.

For example, meta-data that enables labelling acquired data associated with process and instrument maintenance periods is very useful. However, data sets collected from municipal WRRFs often do not include meta-data. Hansen et al. (2024) found lack of meta-data a significant challenge in their study, where collected N_2O and process data of four plants were used for data-driven modelling purposes.

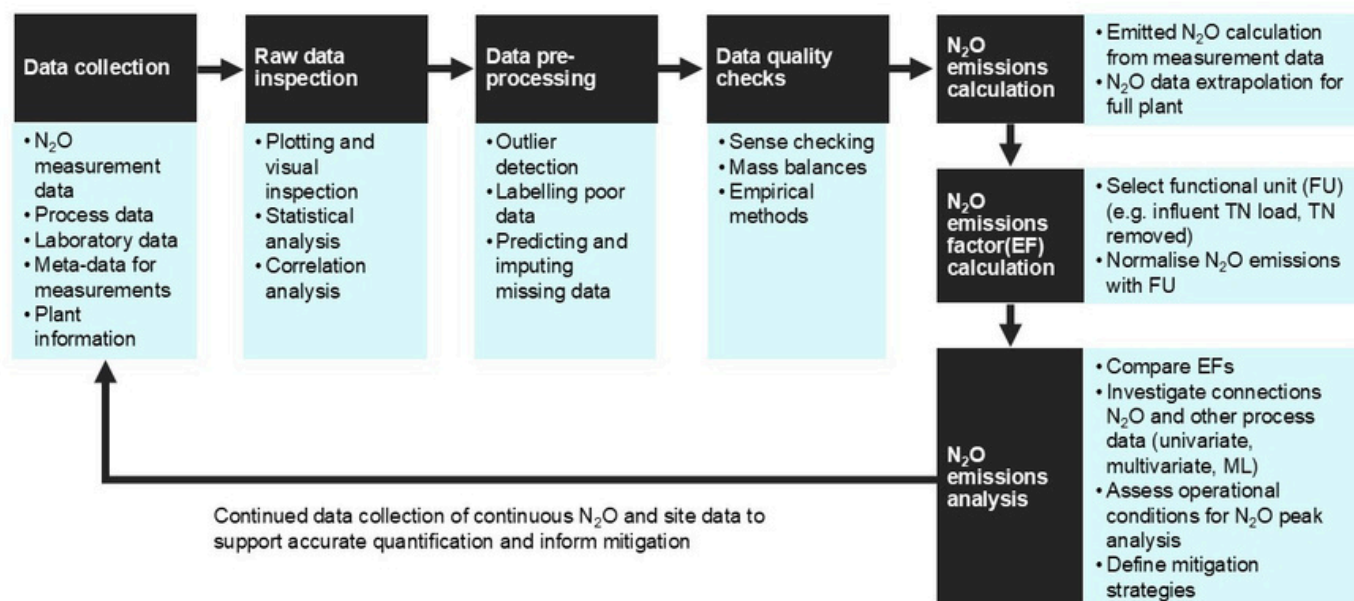
5.5 Data processing techniques

In the water sector, there have been various approaches taken to automate data cleaning and to provide fault detection for detecting anomalous data (e.g. Baarimah et al., 2024, and Hashim et al., 2022). A typical data processing pipeline and common data quality assessment techniques applied in wastewater treatment are presented in Aguado et al. (2024) – adapted below in **Figure 12**. This approach is applicable for N_2O monitoring campaigns that involve long periods of emission and process data to be analysed.

Collected N_2O data and the associated process and laboratory data should first be inspected, and presence of obvious problems with the data should be identified. Such problems with data can concern, for example, missing data, drifting data, constant values, obvious outliers, and data outside of the instrument measurement range (Haimi et al., 2013).

Graphical techniques, univariate statistics and correlation analyses are often applied for initial data inspection. As N_2O can be highly dynamic, careful selection of data series from which to consider correlations and/or multi-variate analysis is important to derive actionable insights into potential causes of N_2O and thus mitigation strategies.

Figure 12 Data processing stages for N₂O quantification and analysis



5.6 Data visualisation

The first step of any data inspection is plotting and visual inspection. Graphical inspection can be done for each variable separately and for multiple variables simultaneously. Typical methods for graphical inspection of single variables include time series plots, box plots and histograms, and of multiple variables are pairwise scatterplots and cross-correlation function plots (Newhart et al., 2019).

5.7 Statistical analysis

Manual graphical data inspection is usually supported by statistical analysis as an additional step of the exploratory data analysis. Experience and knowledge of the treatment processes and the instrumentation is necessary to draw meaningful conclusions from this data analysis step.

Interpreting basic univariate statistics such as averages, medians, standard deviations, minimums, and maximums can also provide insight into any potential challenges with the acquired data sets.

Practitioners should be aware that highly granular N₂O data is not normally distributed and analysis of skew is necessary and the most relevant statistical methods should be applied (Domingo-Felez et al., 2024). Removal of “outliers” or “extreme” values should only be done after careful consideration (e.g. where the data aligns with a calibration or maintenance event).

5.8 Analysis to identify potential causes of N₂O production

Correlation methods study the statistical relationship between two variables. Different correlation analysis techniques have been applied to study the degree of association between N₂O emission and process variables (e.g. Daelman et al, 2015; Kosonen et al., 2016; Chen et al., 2019).

Furthermore, statistical multivariate techniques such as principal component analysis (applied appropriately - i.e., highly correlated variables and redundant parameters are removed) have been used to investigate relationships among multiple variables, including N₂O, simultaneously (Ahn et al., 2010; Vasilaki et al., 2018).

5.9 Dealing with data gaps

One purpose of exploratory data analysis is to enable labelling data points that are clearly associated with problems and remove those from the data set. The data sets of long-term monitoring campaigns will likely include periods of missing and incomplete data. For instance, the share of missing data in a N₂O study ranged between 1.9 – 15% for four case sites (Hansen et al., 2024, data sampled during COVID). These should be explicitly identified, including in visualisations.

There are number of techniques available for predicting and inputting the missing data (Aguado et. al, 2024). Obviously, the need for inputting missing data depends on the objective of the data use and is not always required.

The use of an imputation technique is case-specific and depends on many factors such as purpose of the data use, lengths of the breaks and available data of other variables.

Given the dynamic nature of N₂O emissions, backfilling long periods (e.g. greater than multi-week periods) of data should be approached carefully. Any imputation method used to fill data gaps should be explicitly mentioned. Where data gaps are present utilities should also examine means by which such gaps can be reduced in future (e.g. operator training, maintenance resources etc).

5.10 Data extrapolation

A key data gap, given limited resources for N₂O measurement, is often a lack of N₂O data across multiple treatment zones or across parallel treatment lanes. For unmeasured zones in plug flow reactors, assumptions that N₂O production or emissions are the same as prior or following zones are risky, given seasonal and spatial variation in biochemical transformations that occur along the lane, which can influence N₂O production.

For assumptions across multiple parallel treatment tanks or reactors, assumptions of equal flow, biomass concentration and compositions, load and biomass distribution, as well as aeration system operation are required to extrapolate data from a single lane(s) to others. A mass balance can be carried out on each parallel reactor to identify if there are significant differences in reactor operation; where reactors are significantly different data extrapolation is likely to be inaccurate.

6. Lessons learned – design of measurement campaigns and associated data analysis

This section provides a summary of some key lessons from utility measurement campaigns and practitioners to date and what Utilities should consider as intended outcome (overleaf).

Long-term measurement is required, given seasonable variability. A campaign should strive for the collection of robust and comparable data in a consistent manner over all seasons (one year) and given year on year variation, measurement should remain in place – particularly if mitigation is desired.

Multiple, clear and reproducible monitoring locations are important. Measurement in multiple locations, particularly for plug flow systems, is important (see Section 4). Where measurement locations are shifted or out of service, time-stamped records recording these events are important. The ability to move measurement locations may be required depending on campaign objectives (e.g. to determine peak N₂O for mitigation purposes versus an ‘average’ WRRF baseline).

Accurate air flow data is key – as discussed in Section 4.

Incoming and returned nitrogen loads are required to calculate EFs which help to put N₂O emissions in context across time horizons (e.g. year on year) and across WRRFs.

Macro considerations – sufficient time and resource allowance for measurement equipment care and maintenance (Section 4), data analysis (Section 5) are critical.

Explaining N₂O may require additional sensors or sampling and associated cost/resource.

Data beyond what utilities routinely collect may be required to understand N₂O production and emissions. Important factors can include diurnal ammonia loads onto secondary treatment, the influence of return liquors or identifying where incomplete nitrification is occurring within reactors through additional nitrogen species (NH₄, NO₃, NO₂) measurement. Discrete sampling and laboratory analysis are better than no data, but given the dynamic nature of N₂O, continuous analysis will offer more insights. However, any additional sampling point or sensor installation should come with resources to ensure sensor, analyser or sampler calibration and maintenance as required.

The importance of meta data. Information such as WRRF type, size, hydraulic and organic loading and operating conditions is required to put N₂O production in context and allow comparison of N₂O emissions across multiple sites. Appendix A provides an example Data Collection Matrix for measurement campaigns. Utilities should record equipment maintenance and calibration events as part of data quality protocols.

Sharing data is critical for sector learning. Collectively sharing and comparing campaign results will lead to more in-depth and comparable data globally. This can enable the use of context-specific N₂O emission and wider WRRF data to inform the selection of appropriate emission factors (where direct measurement is not available) and also enable potential mitigation measures to be deployed in other (appropriate) locations.

6.1 Key outputs from N₂O monitoring campaigns

The following are desirable key outputs from Utility N₂O monitoring campaigns.

- High quality, long term N₂O data and associated process data with which to investigate N₂O production drivers through a defined and sustainable data management process which resources can maintain
- A clear basis for regional, national and global comparison which considers the context of WRRF plant type and operation
- Ability to calculate N₂O emissions based on reference units such as incoming nitrogen as well, the mass of nitrogen removed and relevant process loading rates.
- Where utilities publish how measurement campaigns were conducted and the key lessons learned, this can contribute to ISO14064 GHG monitoring, reporting and verification principles for both internal utility use and external benefit. This supports regional efforts by other utilities, national efforts and international discourse and if shared can be used to support the IPCC EF database.

7. Role of modelling for N₂O quantification and mitigation

This section discusses the modelling of N₂O – considering the status of mechanistic, data driven and hybrid approaches and their function to support Utilities.

Extrapolation from single lane to site and gas to liquid calculations are two applications of N₂O modelling which are commonly applied to N₂O measurement datasets.

Mathematical models have been widely utilized to study wastewater treatment and are increasingly applied to study the production and emission of N₂O (Spérandio et al., 2022).

However, modelling N₂O remains challenging – as highlighted in the 2024 IWA WRRMod workshop and associated publication which concluded that advancements are needed to enhance N₂O model predictive capabilities and real world application (Uri-Carreno et al. 2026). Good Modelling Practice (GMP) is lacking for N₂O specifically in terms of mechanistic models and more generally GMP is lacking for data driven and hybrid models – though these model types may be required for N₂O given mechanistic understanding remains challenged and elusive for utility application.

Biokinetic N₂O mechanisms are not fully understood and models rely on simplified pathways. Increasing long term measurement data combined with complimentary omics and isotopic analysis is beginning to unravel this understanding (Roothans et al. 2025). However, such omics approaches remain within leading academic work and to date are less accessible to the majority of Utilities or practitioners.

Simplified N₂O pathway models are a struggle to calibrate given the challenges of accounting for sub-mg/l levels of N₂O, the lack of GMP in terms of modelling approach and lack of understanding and measurement of key intermediates such as nitric oxide and hydroxylamine.

As a result of these challenges, there is currently no published evidence (yet) of the practical application of mechanistic, data driven or hybrid N₂O models by utilities to support an auditable baseline quantification of N₂O or to support successful sustained mitigation.

However, a variety of mechanistic, data driven and hybrid modelling approaches for N₂O are evolving and offer promise (Uri-Carreno et al. 2026). As N₂O production pathways are further studied and seasonal N₂O characteristics able to be explained, and as data and hybrid approaches evolve (all supported by robust N₂O data and GMP), it is likely that models will become increasingly useful.

Plant-wide models without N₂O data may support simulation of process scenarios and resulting effluent and energy compliance given changes in control (e.g. aeration, alkalinity, carbon dosing) which may be suspected to have an impact on N₂O. However, for N₂O modelling itself, continuous N₂O measurement data is required at ‘sufficient’ locations to support understanding – with sufficiency discussed previously. Models of any sort do not (yet) offer a science-based substitute for continuous N₂O measurement.

7.1 Mechanistic modelling approaches

Mechanistic models are the most common approach in wastewater treatment process modelling. One type of mechanistic models is the Activated Sludge Models (ASMs) which have been developed to study conventional activated sludge processes (Henze et al., 2000). The production and emission of N_2O can be integrated into existing ASMs by extending the nitrification and denitrification reactions (Massara et al., 2017).

Several ASM-based mechanistic models have been proposed to describe the N_2O production pathways (introduced in Section 2) related to nitrification and heterotrophic denitrification (e.g. ASM for Nitrogen (ASMN) and ASM with Indirect Coupling of Electrons (ASM-ICE) (Zhao et al., 2024). Commercial software providers have incorporated these or other models to enable attempts to model of N_2O production. The assumed stripping models vary across software.

It is important the user understands the limitations of the applied models.

Principally, the models can be divided into four categories, according to the modelled pathways: 1) single-pathway models of the nitrifier denitrification pathway (e.g. by Mampaey et al. (2013) and Guo and Vanrolleghem (2014)), 2) single-pathway models of the NH_2OH oxidation pathway (e.g. by Law et al. (2012) and Ni et al. (2013)), 3) two-pathway models including both nitrifier denitrification and NH_2OH oxidation pathways (e.g. by Peng et al. (2016) and Pocquet et al. (2016)), and 4) heterotrophic denitrification related models (e.g. by Hiatt and Grady (2008) and Domingo-Félez and Smets (2020)).

It is also possible to implement a model combining a nitrification (categories 1-3) and denitrification (category 4) related N_2O production pathways.

Mechanistic models have advantages that they offer interpretability for most of the nitrogen flows (though less so for N_2O given understanding is not complete), they support process understanding (though not for N_2O) and offer direct relation to operational parameters and ability to extrapolate in some circumstances. Disadvantages include relative over-parameterisation for N_2O , the lack of understanding of N_2O pathways, population dynamics and seasonal variability.

At the start of N_2O modelling (as with any attempt to model WRRF processes), attention should be paid to model selection and to the quality and quantity of the data available. As mentioned above, several mechanistic models exist to simulate N_2O production in wastewater treatment processes, however, any given model will not model all currently understood N_2O production pathways.

Thus, a good consideration of the potential N_2O production pathways behind the emissions in the treatment process is important so that the chosen modelling approach incorporates these pathways. It should be noted that mechanistic models can also be used to help identify dominant N_2O production pathways (e.g. Maktabifard et al., 2022) though unless molecular or isotopic analysis is undertaken, pathways cannot be validated.

Including several pathways in the model can result in overparameterization and the need for heavy calibration efforts (Vasilaki et al., 2018), and key challenges such as where intermediate species such as hydroxylamine, nitric oxide and nitrite are not available to calibrate with.

Good quality influent fractionation data from dry and wet weather conditions form the basis for the input data for any mechanistic model (Rieger et al., 2012). In addition, good-quality in-process data is required for the model as input data and for model validation. Furthermore, the process data should be supported by meta data, the importance of which is highlighted in Section 5.

On-site N_2O monitoring data, measured either from the off-gas or the soluble phase is critical. Preferably, the input data should cover the seasonality in N_2O emissions in different operational and environmental conditions. In addition, all models require that the mixing and aeration are appropriately simulated and reflect on-site conditions, and this might require the adaption of existing models to improve prediction of nitrification, nitrous oxide emissions etc (e.g. Fiat et al 2019).

7.2 Data driven and hybrid modelling approaches

Another increasingly relevant approach is data-driven modelling techniques, such as multivariate statistics and machine learning algorithms, which can be applied on their own (Khalil et al., 2023) to model WWTPs or in hybrid modelling by integrating them with mechanistic, typically ASM-based, models (Vasilaki et al., 2019; Hwangbo et al., 2021).

By learning their own model structure and by potentially integrating novel data sources, ML-based approaches may reveal and capture hidden relationships (Uri-Carreno et al. 2026, Vasilaki et al., 2020) Both statistical (Vasilaki et al., 2020) and machine learning (Hwangbo et al., 2021; Khalil et al., 2023; Szelag et al., 2023) regression models have been applied to estimate soluble or gaseous N_2O in WWTPs.

Limitations of data-driven approaches are the ability to interpret them, relate them to operational dependences and challenges in addressing seasonal N_2O peaks (as with mechanistic models). Further, data driven models have requirements for sufficient data quality and large data sets that are often not available (Li et al., 2022). Approaches for outlier removal and error assessment require careful approach to avoid excluding potentially valid data and operational conditions which may be responsible for higher N_2O periods.

Hybrid models can be used where there are more limited data for purely data driven prediction (Li et al., 2022; Mehrani et al., 2022). Though these can suffer from similar limitations of mechanistic and data driven approaches, they also offer opportunities to tackle these though remain highly limited in application with respect to N_2O . GMP approaches are required for N_2O modelling to support quantification and mitigation.

7.3 Modelling for mitigation

Modelling can be utilized in N₂O mitigation to support full site N₂O emission quantification (from a single lane measurement), liquid to gas calculations and multi-zone and multi-lane mass emission calculations. Models (both those that include N₂O production and those that don't) may also be used to generate data streams for data driven mechanistic and hybrid approaches.

While the application of models for N₂O mitigation by utilities remain limited given the limitations of N₂O modelling, the aspiration is that modelling could be used to help develop and simulate potential mitigation strategies or identify operational strategies that might result in lower or higher emissions.

Duan et al., (2021) reviewed nitrous oxide mitigation strategies in wastewater treatment which included the use of modelling to develop proposed strategies which were subsequently implemented at full-scale (see also Zabrowska et al., 2019; Duan et al., 2020; Wen et al., Chen et al., 2015). However, the extent of data that the models are based upon, robustness of calibration and validation approaches in the absence of GMP for N₂O and the time window for which (i) models were valid and (ii) any mitigation was sustained all remain limited.

Whilst N₂O modelling is not yet proven to support either baselining of emissions or sustained mitigation for full scale utility application, the use of well calibrated process models can be useful to show how an N₂O mitigation strategy may impact wide WRRF goals such as energy use and the capacity to meet discharge limits.

8. Mitigating N₂O

This section outlines strategies for mitigating N₂O emissions at existing treatment works and guidance for designers when considering new treatment assets. Appendix B provides case studies for full scale and pilot scale N₂O mitigation of relevance to Utilities.

8.1 Mitigating N₂O emissions at existing treatment sites

Site selection for mitigation activities

Where multiple WRRFs are operated, a first step in the N₂O mitigation strategy is WRRF site selection and prioritisation. Sites with the highest potential for N₂O mass emissions should be targeted and continuous measurement installed using liquid or gas-based methods, or a combination of these. Consideration of known N₂O risk factors identified in Section 2 could be used to identify sites with potentially higher N₂O risk (for example, those with sidestream treatment of reject water or those with particularly high ammonia loading rates, plug flow configurations and limitations in aeration system capacity). However, until WRRF level measurement is initiated, which accounts for seasonal variability, the actual magnitude of N₂O cannot be estimated in any reliable quantitative manner (e.g. through risk factors or modelling).

Selected sites should have the capacity to implement operational changes, such as dissolved oxygen set points, sludge age changes, and mixed liquor concentrations to target N₂O generation pathways. These changes should ideally be implemented on one train (or lane) with other train(s) being used as controls to assess the impact of mitigation actions.

The importance of emissions measurement for mitigation

N₂O emissions should be measured using liquid phase sensors or gas hoods (or both) to baseline emissions prior to and during mitigation trials.

Emissions must be measured throughout trial periods to benchmark the impact of mitigation actions.

It may be possible to combine baselining and evaluation of mitigation strategies if multiple trains can be monitored simultaneously. It is also important to confirm that proposed mitigation actions do not cause intentional consequences for effluent quality and that potential changes in energy or chemical requirements are explored; mitigating N₂O may, in some cases, require more aeration energy.

8.2 An N₂O mitigation hierarchy

The following hierarchy for the mitigation of N₂O emissions should be considered:

1. **Avoid:** This can include interventions upstream of the nitrogen removal processes to reduce or balance nitrogen loads
2. **Reduce:** This can include strategies that manipulate the biochemical environment within the process, promoting conditions that produce less, or consume more N₂O.
3. **Remove:** This can include actions that remove residual N₂O gas for destruction or valorisation.

These are summarised in **Figure 13** and full-scale mitigation examples for each of “avoid”, “reduce” and “remove” are outlined in **Tables 4, 5 and 6**. Despite the various full-scale approaches presented below, there is a need for more full-scale and long-term studies globally so more context-specific guidance can be developed and to demonstrate the long-term sustainability of various mitigation approaches.

It is important to note that these mitigation measures are designed to help reduce N₂O emissions. These need to be evaluated with regard to other WRRF priorities and the available personnel and operational resources available to implement them.

Ideally an analysis would consider the potential impacts of any mitigation measure which might result in increased emissions (e.g. Blomberg et al., 2024).

Figure 13 Hierarchy of strategies - Avoid N₂O, Reduce N₂O, Remove N₂O

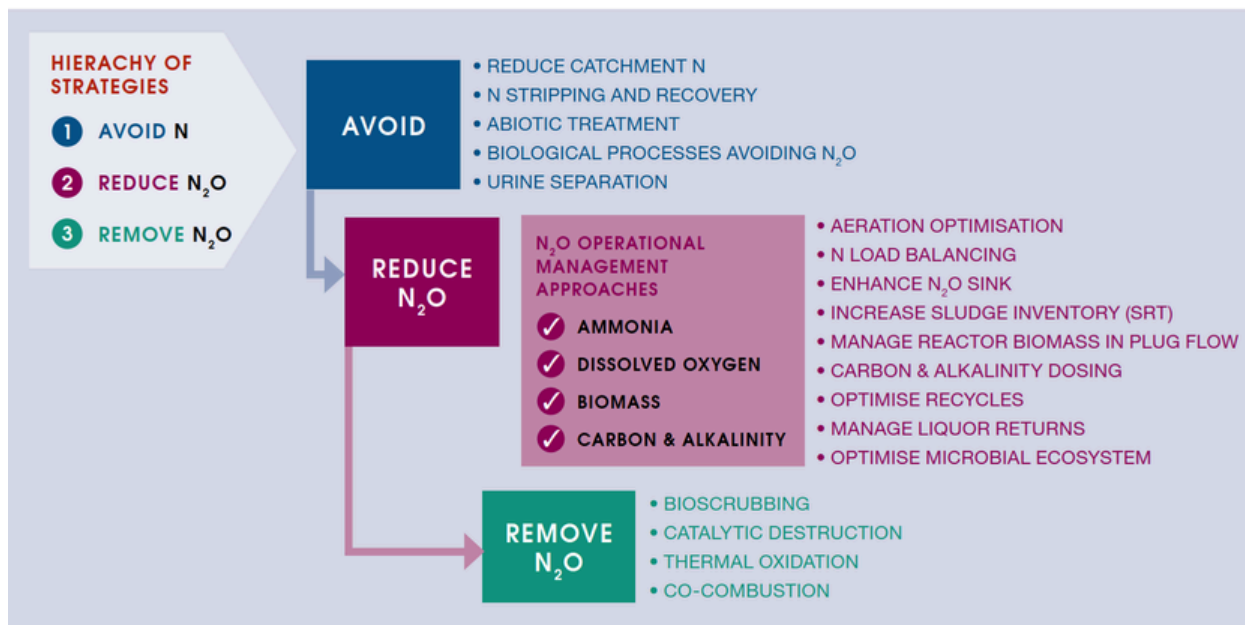


Table 4. Mitigation - Avoid N₂O emissions

Nitrous oxide trigger	Mitigation action	Possible interventions
Ammonia peaks and overloading	• Reduce ammonia peaks by balancing influent loads where possible. • Avoid shock loading (e.g. high ammonium loading rates) where possible	• Balancing of supernatant or high-strength liquors return to reduce ammonia loading (Work by Belgian utility Fenu et al. 2019, as referenced by Unisense A/S). • Providing adequate sludge liquor balancing tank capacity and associated control system so return flows can be balanced or controlled based on incoming ammonia concentrations. • Influent forecasting to inform preparation for incoming peaks through weather impact modelling and forecasting systems. This can inform both infrastructure upgrades and/or operational changes
	Ammonia stripping and recovery	Install ammonia recovery processes, particularly for high concentration liquor treatment processes at sludge treatment centres.

Table 5 Mitigation – Reduce N₂O emissions

Nitrous oxide trigger	Mitigation action	Possible interventions
Oxygen management: insufficient or excessive for process requirements	Improve DO control and range	• Increase available air flow range through ensuring blowers are sized for peak demand and turndown. • Provide air flow control valves so that air flow can be locally controlled. • Provide flexibility in blower output through variable speed drives connected to a real time control system. • Ensure DO probes are cleaned and calibrated in line with the standards. • Reducing DO set points where these may be excessive for nitrification or impeding denitrification. • DO set point adjustment to increase anoxic treatment time and reduce aeration time (e.g. Duan et al., 2020; Rodriguez-Caballero et al., 2015).
Oxygen management: Denitrification limited by excess oxygen	Simultaneous nitrification and denitrification (SND) to enhance sink for reduction	Optimisation of process to achieve simultaneous nitrification and denitrification through low (<0.2-0.5mg/l DO) operation in aerobic zones (MUDP, 2022; Duan et al. 2020).
Inadequate process control	Install advanced process real time control systems	• Maximise process stability by changing operation (e.g. by matching aeration to incoming load). • Advanced process control systems with or without AI/ML incorporating N₂O monitoring • Real time control of RAS and SAS flow rates based on changes in influent characteristics and treatment performance metrics.
Biomass management: Insufficient sludge age or conditions leading to nitrite accumulation	Control sludge age Maximise solids retention time to encourage full nitrification	• Control (real-time or otherwise) of RAS and sludge wastage rates based on changes in influent characteristics and treatment performance metrics can enable longer sludge ages, encourage stable treatment and potentially reduce N₂O emissions. • Increase SRT by step change in MLSS operation to reduce specific biomass ammonia loading (Andersen et al., 2023). • Sludge age should not be too high as this can lead to other issues such as reduced biomass activity and sludge bulking which in turn may increase emissions

Table 5 Mitigation – Reduce N₂O emissions (continued)

Nitrous oxide trigger	Mitigation action	Possible interventions
Nitrification conditions: insufficient alkalinity, inadequate pH control.	Modified alkalinity dosing	Chemical dosing to increase alkalinity to reduce free nitrous acid and minimise N ₂ O emissions (see Blomberg et al., 2024 where embodied carbon from alkalinity dosing is also considered).
Carbon management: insufficient carbon in anoxic zones for denitrification	Carbon dosing to maintain COD:N ratio	- Carbon dosing to anoxic zone of an ASP can boost denitrification reduce N₂O emissions (Blomberg et al., 2024) - Avoid liquor returns containing high N₂O loads coinciding with relatively low incoming carbon load (carbon). This may require frequent measurement of incoming and return loads and load balancing capacity.
Insufficient denitrification capacity: Limits capacity transform produced N ₂ O to N ₂	Increase anoxic zone residence time	- Extending the anoxic zone to encourage denitrification, which can act as a nitrous oxide sink. - Requires sufficient carbon to avoid increasing N₂O risks from partial denitrification to N₂O.

Table 6 Destroy or Remove N₂O

Removal mechanism	Technology	Evidence to date
Thermal destruction (>900°C)	Regenerative Thermal Oxidation (RTO)	- Treatment of N₂O emissions is possible through thermal destruction from mainstream or sidestream processes where the emissions can be captured (these are demonstrated for sewage sludge incineration) (Diezeiger et al., 2023). - In Switzerland, to date, regenerative thermal oxidation has been applied at three WRRFs, one with covered mainstream and deammonification plant; the other 2 operating with incineration off-gas (CIWEM, 2025).

Table 6 Mitigation – Destroy or Remove N₂O continued

Removal mechanism	Technology	Evidence to date
Catalytic destruction (~450°C)	Catalytic N ₂ O destruction	- In Denmark the Danish ECO-Innovation Programme (MUDP) has supported the nitrous oxide abatement by catalytic treatment project (NACAT (MUDP report)). - This has demonstrated the viability of N₂O destruction though TRL remains low, catalyst longevity and interference key areas for further work.
Biological scrubbing	Denitrification or scrubbing of N ₂ O	- Use of biological removal - In biotrickling filters – see lab and site trial work in Korea from Han et al. 2023 - In scrubbing tower – see Austrian academic work Valipoor et al. (2025)

8.3 Designing WRRFs for low N₂O

Drawing on proven mitigation approaches, and existing knowledge, this section provides key considerations for good practice to incorporate low N₂O considerations into WRRF design and operational goals. When designed in from the outset, low(er) N₂O considerations can support N₂O mitigation and be more cost effective than upgrading the WRRF at a later date.

- Design for (future) N₂O measurement and good air flow quantification and control.
- Design sufficient balancing capacity for incoming nitrogen loads, which can include upstream storage, step-feeding or the use of recycling streams.
- Provide flexibility in treatment through the provision of swing zones to support N₂O sink in denitrification (if sufficient carbon)
- Ensure the adequate provision of mixing – reliance on some aeration technologies for mixing can reduce flexibility in anoxic systems/during anoxic periods.
- Design in the capacity for a high level of DO control including the ability to match aeration to incoming load.
- Consider use of mechanical rather than air based mixing to avoid introduction of air when not required, given it can contribute to N₂O formation.
- Install accurate air flow measurement in all aeration control zones.
- Design to enable longer SRT (but this may conflict with other treatment objectives).
- Side-stream treatment can result in relatively high emissions; treating liquors through mainstream processes may yield lower emissions where adequate capacity exists.
- Careful consideration of process intensification options – there remains a lack of data for full-scale and whole-system IFAS, mobile biofilm and MABR intensification options.
- Explore the potential for tank covering to enable the conveyancing of off-gas conversion/destruction technologies.

9. N₂O mitigation in context

Nitrous oxide mitigation must be seen in the broader context of the future direction of the wastewater treatment sector.

As wastewater treatment plants move towards the concept of WRRFs nitrous oxide mitigation will occur alongside other circular economy activities such as nutrient recovery, energy recovery and water reuse. Such goals are not mutually exclusive as has been shown in recent work such as by the IVL Swedish Environmental Research Institute, RISE and Mälardalen University. The transformation of conventional treatment plants into WRRFs will require the integration of advanced monitoring and control systems.

Real-time N₂O monitoring, coupled with process control strategies, will enable Utilities to identify hotspots and implement targeted mitigation measures. Given the significant differences between infrastructure capacity at small WRRFs and larger facilities, the initial focus, where resources are limited, should be on a smaller number of medium to large facilities where most nitrogen is removed.

These end goals will lead to a transformation in how the sector designs and operates WRRFs. It will be necessary to design systems with the capability for N₂O emissions mitigation, resource optimisation and nutrient/energy recovery as equal design criteria alongside or part of regulatory compliance. Facilities must be designed to have or enable the necessary technology and infrastructure to allow these objectives to be met, while maintaining operational flexibility to adapt to changing conditions and requirements.

For example, a core requirement at the design stage will be the ability to capture relevant data, process this data and have technology onsite that is amenable to control (e.g. during aerobic and anoxic treatment stages).

Systems may be designed to enable influent load balancing which can provide advantages in terms of emissions mitigation, overall system efficiency and control flexibility. How influent load balancing can occur in regions where storm and foul sewers are combined will be a related challenge. It will also be necessary to design for potential climate-related impacts over the life cycle of infrastructure, including temperature impacts and hydraulic load impacts.

The need to reduce N₂O emissions may also result in potential trade-offs between energy and resource optimisation, effluent quality and carbon re-direction. These trade-offs require a systematic decision-making framework that considers both immediate operational impacts and long-term sustainability goals.

For example, with nitrogen discharge limits generally decreasing to protect receiving waters, nutrient recovery may provide a means to reduce emissions and meet such limits. In other scenarios, there may be a trade-off between additional nitrogen removal and emissions reduction. Policy makers, utilities, regulators and designers will need to “build-in” these requirements and consider such trade-offs from the initial design stage, through planning, procurement and construction stages for new WRRFs or when upgrading WRRFs.

10. A vision for monitoring and mitigation of N₂O

Nitrous oxide emissions are a key challenge for utilities in meeting net-zero targets globally. However, it should be remembered that for many countries, regions and utilities, meeting discharge regulation or even improving the capture and basic treatment of wastewater is still a major challenge.

Therefore, utilities and practitioners with the ability to contribute to N₂O measurement and mitigation should aim to do so. To support this, there is a need for more shared case-studies with sufficient context, demonstrating long-term full-scale N₂O mitigation measures and transferable opportunities. Building on the past two decades of research and in-practice learning, a vision for progress over the next decade should consider:

- Monitoring N₂O and the integration of N₂O mitigation strategies in WRRF design and operation as **business as usual**; N₂O emissions are seen as important to control as effluent compliance.
- **A N₂O mitigation hierarchy is adopted as best practice** – avoid, reduce, remove/destroy.
- **Liquid and gas N₂O monitoring methods** in secondary biological treatment are installed and matched with site-wide validation to ensure that the majority of N₂O emissions are being monitored and mitigated through bottom-up approach.
- All WRRFs over 25,000 population include **direct N₂O monitoring** for dominant secondary biological treatment sources and are operated for compliant effluent, low resource consumption energy and low N₂O emissions. Measured emissions support annual N₂O reporting for every utility, which supports country level GHG inventories.
- **Site-wide validation and liquid and off gas process unit** approaches remain complementary to each other.
- Evolution of monitoring methods to make these more **accessible and lower cost** to utilities who today cannot yet afford to consider N₂O.
- **Clear guidance for Utilities** is published for best available techniques (BAT) for N₂O mitigation and validation of N₂O measurements, including evidence for intensification and novel treatment processes and operational methods.
- **Sustainable nitrogen management** through the lowest N₂O generation options – considering recovery, optimised mainstream or side-stream treatment, and incorporating destruction or utilisation of N₂O-containing off gases in application of an N₂O mitigation hierarchy.

- **Evolution of N₂O modelling** to support optimisation of design and operation for low N₂O and best N₂O quantification; realised potential in soft-sensors. Development of GMP.
- **Refined Tier 1, 2 and 3 methods** – with clear practical guidance for countries to move towards Tier 2 EFs and for Utilities to develop comprehensive Tier 3 N₂O monitoring approaches that support their national efforts and regional development of meaningful EFs. Tier 3 site N₂O measurement results are continuously shared in open source databases and fed back into the IPCC via the IPCC Emission Factor database.
- **Green product, procurement and operation practices** which highlight GHG savings in every aspect of WRRF design, construction and operation – from N₂O sensor system consumables to the proactive maintenance of plant and equipment.
- **Engagement between utilities and broader stakeholders** (including the public) to reduce per capita nitrogen loads to WRRFs, thus extending the ability of existing infrastructure to meet societal needs.

10.1 Towards shared measurement and mitigation practices

For all Utilities, the ultimate aim to move towards net-zero emissions, while maintaining service, regulatory compliance and cost efficiency, will likely require the adoption of a variety of approaches to N₂O monitoring and mitigation.

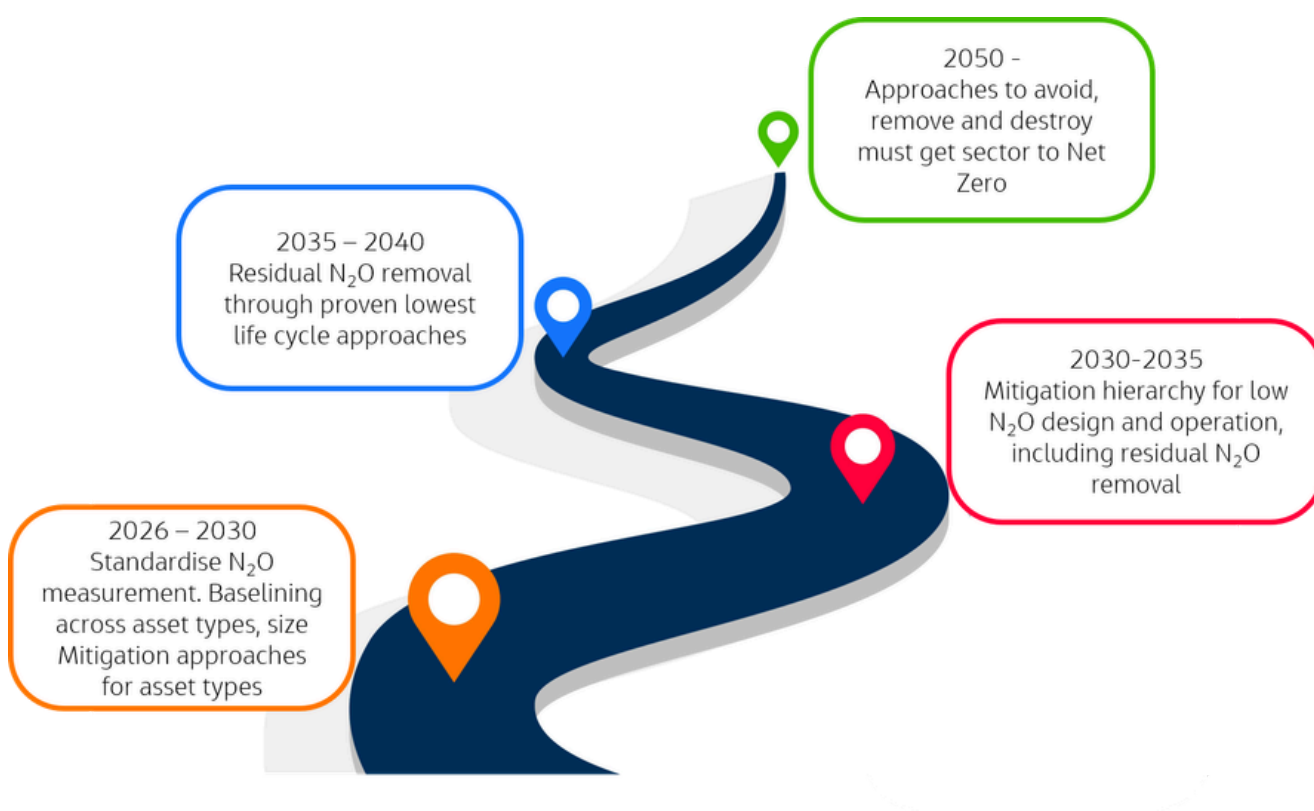
The development of common approaches and a toolbox for N₂O emissions monitoring and mitigation is key, as is sharing context and relevance to other utilities and country efforts.

Figure 14 provides considerations towards a shared route map for the water sector.

As a working group, this will be our next focus, and we hope you will start compiling your emissions monitoring campaign data and metadata (see Appendix A) and join us in demonstrating good practice, contributing to global learning and taking action for urgent mitigation.

Mitigating emissions, through shared knowledge, will benefit utilities and society at large and ensure new opportunities present themselves for innovation in this sector.

Figure 14 Towards shared nitrous oxide measurement and mitigation practices



Appendix A – Suggested data collection for high quality N₂O campaigns

MACRO DATA FROM WWTP	
Data required	Detail
Dates of monitoring campaign(s)	
Aim of the campaign	<i>e.g. To detect N₂O emissions per kgTN/m³ WW Treated in WWTP</i>
Responsibility for campaign	
General process information	
Size of WRRF	· Population equivalent (PE) · Flow rate (m³/day)
WRRF, storm and liquors treatment processes	
WRRF loading Total of site/technology being tested.	· Total N kg / day · COD kg /day · BOD kg/day · Sludge Retention Time *Loading rates outlined with a) overall; b) seasonally; c) diurnal flow-rate.
Type of biological process	<i>Specific to all Technologies on WWTP. Define Nitrogen removal type</i>
Operational (aerobic/total) SRT or MLSS/MLVSS	Total & across seasons a) Days SRT b) MLSS; MLVSS
Define P removal	1) Chemical usage 2) Biological systems
Type of aeration system	E.g. FBDA, surface aerated, coarse bubble aeration
Aeration control and set points	<i>e.g. Basic aeration control (DO= e.g., 1.5/2.0), advanced ABAC etc. Logged SP changes where possible</i>

Instrumentation in secondary treatment	<i>E.g. Dissolved oxygen (DO), NH₄⁺ and nitrate monitoring locations</i>
Number of lanes/ zones/ zone size	<i>Aeration system set up – drawing including diffuser details and density, location of air flow measurement.</i>
Process data	In-tank DO, temperature, pH, dosing, nitrogen species at appropriate time intervals – TN, NH ₄ ⁺ , TKN, nitrite (NO ₂ ⁻), NO ₃ ⁻
Sludge treatment details for WRRF	
Sludge treatment – process	<i>Diagram with loading rates.</i>
Biogas treatment and utilization (if any)	<i>Report the flows (m³) with the energetic values (% Methane and kWh)</i>
Liquors management	<i>e.g. Partial nitrification-anammox, nitrification-denitrification, balancing tank etc., monitoring data available, source of air flow, chemical dosing data</i>
Return N load to secondary process	Kg TN/day
NITROUS OXIDE CAMPAIGN MONITORING DATA	
Monitoring campaign Duration and frequency (12 months minimum recommended)	· Time (Months) · Frequency · Seasonal Impacts Noted (diurnal)
Type of monitoring	Process unit level locations, site-level quantification
Monitoring details – N₂O (more information in Section 3)	<i>Type: off-gas or liquid phase; remote methods, location</i>
Plan of monitoring locations	<i>Location: in anoxic/off-gas/aerated zones in one or more points, consider access, power, maintenance.</i> <i>*Include Diagram/photos</i>
Record of details and events during the campaign	<i>e.g. Site weather station/local weather</i> <i>Tank stirring/emptying; issues with incoming loading, returns, process upsets.</i>

Appendix B – Tier 2 country-level N₂O emissions estimation examples

Table B1. Example of facility-level monitoring resulting at national level EFs (Tier 2).

Country	Methodology	EF
Austria (BMLFUW, 2015)	The estimation of a country-specific EF was developed based on a national measuring program conducted in 2012–2014 with 20 field measurements at 8 representative activated sludge WRRFs. The monitoring campaigns were carried out with long-term online measurements of several weeks, with both off-gas measurement (flux chamber) and liquid measurement (Unisense microsensor).	43 g N₂O/PE/year. EF derived from linear regression of N₂O emissions and nitrogen removal for 18 of the 20 campaigns and extrapolated to include nitrogen removal consideration for WRRFs with an organic design capacity larger than 5 000 PE (94%) and less than 2 000 PE (~6%). The authors note that the wider applicability of the regression model considering extent of TN reduction requires to be further assessed.
Denmark (MUDP Rapport, 2020)	Denmark completed a national survey between 2018–2020 funded by the Danish Environmental Protection Agency (EPA). The monitoring campaigns were carried based on long-term liquid-phase measurements (Unisense microsensor) across 9 WRRFs covering a range of plant size, nitrogen load, aeration technology, sludge treatment, and reject water handling. The results were used to derive a national EF and to apply mitigation strategies to reduce N₂O emissions across the sector.	0.84% N₂O-N/TN influent. EF derived from the weighted average in relation to the WRRF's TN load, excluding outliers. Therefore, the results from the largest WwTWs affect the average EF to a greater extent, compared to the results from the smaller WwTWs. Note that an additional sidestream treatment process was excluded for the purposes of the EF, as the study found an EF of 5–6% N₂O-N/Total-N influent, which is significantly higher than the average emission factor found for mainstream processes. Additionally, results from a surface aerated WRRF was not considered reliable enough to be included in the overall EF calculation for N₂O emissions.

Country	Methodology	EF
Germany (Umweltbundesamt)	National study (not published yet). New factor since 2024 (reporting year 2022)	35 g N ₂ O/PE/year (real inhabitants. Additional 30% for industrial emissions of N ₂ O)
Switzerland (Gruber et al., 2020)	National monitoring study commissioned by the Federal Office for the Environment (FOEN) Climate Division, and the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) to develop improved national reporting for Switzerland. The monitoring campaigns covered long-term emissions from continuous gas phase across 14 WRRFs from 2024-2019 using a multi-flux hood approach to cover spatial variation (at least three chambers per lane across all lanes, recognising differences in loading and air flow across lanes).	Carbon removal WRRF = 4.3% N₂O-N/TN influent) Nitrifying WRRF = 1.8% N₂O-N/TN effluent Denitrifying WRRF = 0.9% N₂O-N/TN effluent The original recommendations took average values but the revised recommendations to Swiss Federal agency were for median values given recognised challenges with the dataset.

Appendix C – Demonstrated N₂O Mitigation table

	Reference	Mitigation Measure
Mitigation strategies demonstrated at full scale at Water Utility Site	MUDP, 2022; Duan et al., 2020	Optimisation of process to achieve simultaneous nitrification and denitrification through low DO (<0.2-0.5 mg/l) operation in aerobic zones.
	Andersen et al., 2023	Increased Solids Retention Time (SRT) by step change in MLSS operation to reduce ammonia loading.
	Duan et al., 2020; Rodriguez-Caballero et al., 2015	DO SP adjustment in SBR system to increase anoxic treatment time and reduce aeration time.
	Böhler et al., 2012	Nitrogen recovery to recover N load from system from reject water/liquors.
	Blomberg et al., 2024	Carbon dosing to the anoxic zone of an ASP to boost denitrification and reduce N ₂ O emissions.
	Blomberg et al., 2024	Chemical dosing to increase alkalinity in an ASP to promote nitrification and avoid N ₂ O emissions.
	Chen et al., 2019	Extending denitrifying volume (i.e. anoxic phase).
	Diezeiger et al., 2023 Utility practice Switzerland	Capture and treatment of N ₂ O emissions through thermal or catalytic destruction from mainstream and sidestream processes.

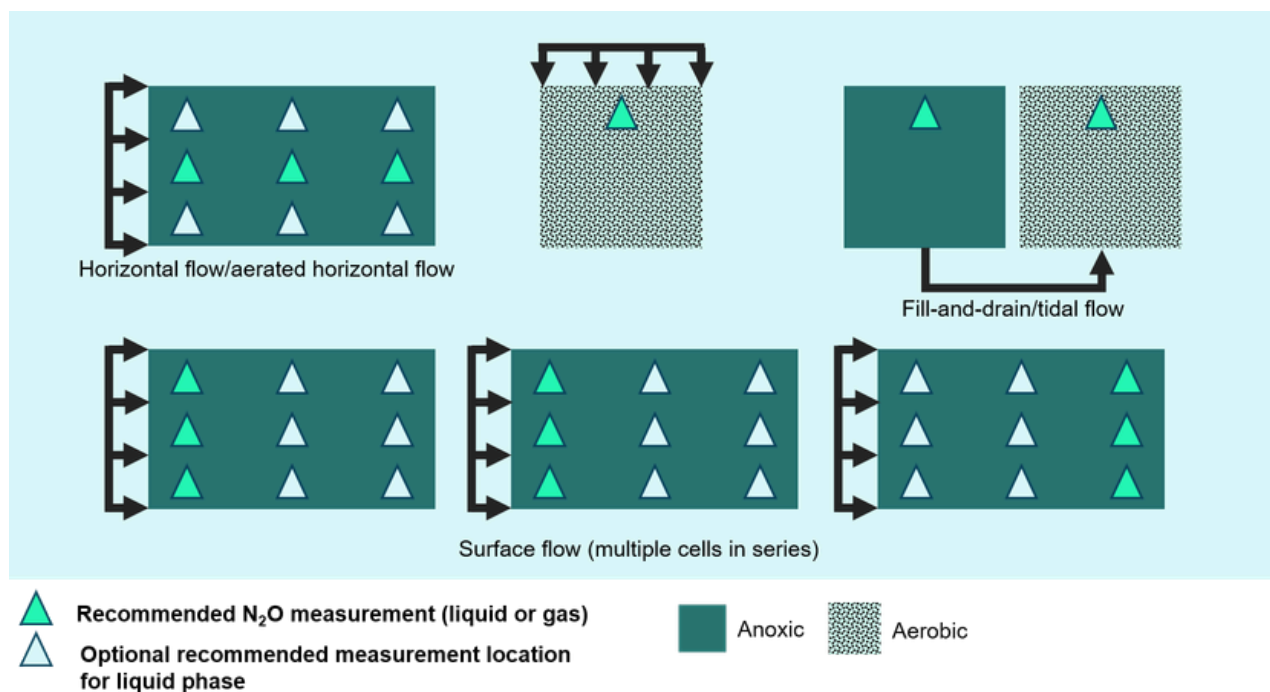
Appendix C – Demonstrated N₂O Mitigation table (continue)

	Reference	Mitigation Measure
Mitigation strategies proposed but not demonstrated at scale or yet in sustained manner	Debel et al.2025	Model Predictive Control systems with AI/ML incorporating N ₂ O monitoring and active control through optimisation.
	Porro et al., 2017; Sun et al., 2017	DO set point (SP) optimisation – reducing SPs where these may be excessive for nitrification or impeding denitrification or changing SPs to avoid conditions which promote more N ₂ O.
	Hu et al., 2013 Khalil, M., 2026	Optimisation of liquor returns or perhaps (yet to be proven) RAS to reduce ammonia loading. Use of step feed to reduce (dilute) ammonia loading or increase biomass – e.g. step feed of influent and RAS (limited evidence exists).
	Fenu et al. 2019, referenced by Unisense A/S	Alteration of aeration cycle for high strength liquors sidestream treatment to minimise emissions – required additional energy (aeration) input. Balancing of supernatant or high strength liquors return to reduce peaks in ammonia loading. Use of pH adjustment for control of free nitrous acid.
	Drastrup and Fink, 2022	Three control strategies proposed for specific observations for cyclic ASP plants in Denmark: Control of carbon dosing, modification of aeration cycles, enhance denitrification, increase or decrease aeration SPs, equalise load if possible.

Appendix C – Demonstrated N₂O Mitigation table (continue)

	Reference	Mitigation Measure
Emerging mitigation strategies in stages of R&D or trial – as yet not demonstrated in practical water industry use for mitigation of N ₂ O	Utility practice	Real time control systems including nitrite and/or solely N ₂ O monitoring with objectives for example to minimise nitrite production and accumulation.
	IWA, 2022	Mechanistic, data-driven or hybrid models to predict emissions and define mitigation actions which are then implemented and validated.
		Use of digital twins or soft sensors or surrogate (e.g. nitrite) monitoring.
		Use of CFD modelling with mechanistic process models for N ₂ O prediction and modelling of mixing/aeration throughout reactor.
	Diezeiger et al., 2023 MUDP, 2026	Capture and treatment of N ₂ O emissions through thermal catalytic destruction from mainstream and sidestream processes.
	Kinh et al., 2017, Nemeth et al., 2025	Implementation of alternative treatment solutions including Membrane Aerated Biofilm Reactors (MABR) as proven lower-N ₂ O technology options.
	Kinnunen et al., 2025	Activated sludge microbiome monitoring, analysing connections between microbiome and N ₂ O, and developing mitigation strategies relying on community optimisation.

Appendix D – Suggested measurement locations for GHGs from treatment wetlands



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