

# Low N<sub>2</sub>O Design Guidance to Minimise N<sub>2</sub>O Risks

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## Authors

Daniel Adeoye – RVT Group  
Amber Bullen – AtkinsRéalis  
Alex Harrison – Severn Trent Water  
Amanda Lake – Jacobs  
Kenny McGibbon – Mott MacDonald  
Ellie Russell – Mott MacDonald  
Bharani Sri – Mott MacDonald  
Andrew Thompson – Fingleton White

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## Glossary

**AOB** – *Ammonia-Oxidising Bacteria*

Microorganisms that oxidise ammonia to nitrite during nitrification.

**AGS** – *Aerobic Granular Sludge*

Biological treatment process using dense microbial granules that support nutrient removal and good settlement.

**ASP** – *Activated Sludge Process*

Suspended-growth biological process used for organic and nutrient removal.

**BNR** – *Biological Nutrient Removal*

Combined biological removal of nitrogen and phosphorus.

**BOD** – *Biochemical Oxygen Demand*

Measure of biodegradable organic matter, expressed as the oxygen required for microbial oxidation of organics.

**COD** – *Chemical Oxygen Demand*

Measure of total oxidisable organic matter (biodegradable and non-biodegradable), determined by chemical oxidation.

**DO** – *Dissolved Oxygen*

Concentration of oxygen available to microorganisms in the mixed liquor.

**FBDA** – *Fine Bubble Diffused Aeration*

Aeration system using submerged diffusers to supply oxygen through fine bubbles for diffusion into the liquid, with high efficiency.

**FNA** – *Free Nitrous Acid*

Nitrous acid ( $\text{HNO}_2$ ) is an unstable acidic compound, that through stabilisation reactions drive formation of protonated (uncharged) forms of nitrite; FNA is thus a key inhibitor of nitrifying and denitrifying bacteria and a recognised driver of nitrous oxide ( $\text{N}_2\text{O}$ ) production under low pH and elevated nitrite conditions.

**GHG** – *Greenhouse Gas*

Greenhouse gases that contribute to global heating.

**GWP** – *Global Warming Potential*

Relative measure of a greenhouse gas's climate impact compared with  $\text{CO}_2$ .

**IFAS** – *Integrated Fixed-Film Activated Sludge*

Hybrid biological process combining suspended activated sludge with attached biofilm media to biomass retention and thus increase treatment capacity and robustness.

**IoT** – *Internet of Things*

Connected sensors and devices enabling real-time data collection and automated control.

**MABR** – *Membrane Aerated Biofilm Reactor*

Biofilm process where oxygen is delivered through gas-permeable membranes directly to attached biomass, enabling high oxygen transfer efficiency and low bulk DO operation.

**MLSS** – *Mixed Liquor Suspended Solid*

Wastewater operational parameter, representing the concentration of biomass in activated sludge reactors.

**NOB** – *Nitrite-Oxidising Bacteria*

Microorganisms that oxidise nitrite to nitrate during nitrification.

**N<sub>2</sub>O** – *Nitrous Oxide*

Potent greenhouse gas produced as an unintended by-product of biological nitrogen transformations.

**ORP** – *Oxidation-Reduction Potential*

Indicator or measure of the oxidative (electron donors) or reducing (electron acceptors) conditions within or ability of a solution.

**PST** – *Primary Settlement Tank*

Tank used to remove settleable solids prior to biological treatment.

**RAS** – *Return Activated Sludge*

Settled biomass returned from secondary clarification to the biological reactor to maintain a suitable biomass population for effective biological treatment.

**RTC** – *Real-Time Control*

Automated control based on live process data to dynamically adjust operation.

**SAS** – *Surplus Activated Sludge*

Excess biomass removed to maintain suitable food-to-microorganism (F/M) ratio, control sludge age, MLSS and thereby suitable biomass population in the ASP.

**SCADA** – *Supervisory Control and Data Acquisition*

System for monitoring, controlling and logging treatment processes performance and assets data.

**SRT** – *Solids Retention Time (Sludge Age)*

Average time biomass remains in the biological treatment system, typically measured in days.

**Water Recycling Centre (WRC)**

May be termed Water Resource Recovery Facility (WRRF), Water Recycling Centre (WRC), Wastewater Treatment Plant (WWTP) or Wastewater Treatment Works (WWTW). We use WRF throughout this document.

**VFA – Volatile Fatty Acids**

Short chain fatty acids that are water soluble (e.g. acetic, propionic and butyric acid), In this context it represents the readily biodegradable organic carbon compounds that support denitrification.

**WRC – Water Recycling Centre**

Wastewater treatment facility with an emphasis on recycling, recovery and resource efficiency.

**WwTW – Wastewater Treatment Works**

Facility designed to treat wastewater to meet environmental and discharge standards.

# Introduction

Nitrous oxide (N<sub>2</sub>O) is a potent greenhouse gas and ozone-depleting substance generated as an unintended by-product of biological nitrogen removal. In wastewater treatment, N<sub>2</sub>O can form under both aerobic and anoxic conditions through several microbial pathways. For greenhouse gas inventories, the IPCC 2019 Refinement (IPCC, 2019) provides a Tier-1 default emission factor for direct N<sub>2</sub>O from full-scale domestic wastewater treatment plants of 0.016 kg N<sub>2</sub>O-N per kg influent total nitrogen (1.6%N<sub>2</sub>O-N/TN<sub>in</sub>), but reported full-scale emission factors span a very wide range (orders of magnitude) depending on process configuration and operation.

The Tier-1 factor should be treated as an inventory default rather than a 'typical' plant performance value. Although typically a small fraction of the total nitrogen transformed, its high global warming potential of 273 times that of carbon dioxide means even low emission rates can significantly increase the operational carbon footprint of full-scale Water Recycling Centres (WRCs).

This guidance has been developed by the Process Emissions Action Community (PEAC), a collaboration of industry practitioners committed to practical, evidence-based reduction of process emissions, working in the UK and Irish Water Utilities Sector. It aims to provide design-focused actions and considerations for engineers involved in new-build WRCs, upgrades, and optimisation projects, helping to reduce N<sub>2</sub>O formation risk through informed design decisions. These recommendations represent the latest insights and current best practice to minimise N<sub>2</sub>O risk in wastewater treatment assets.

The suggested interventions may improve process performance and therefore reduce the operating cost of assets over time. However some of these interventions could incur additional capital or operational costs, and so a whole life carbon and cost assessment is important.

This design guidance for low N<sub>2</sub>O WRCs aims to empower designers to challenge design standards, and utilities to develop their own design guidance and standards that can result in low(er) N<sub>2</sub>O production. Considerations for optimising WRCs for low(er) N<sub>2</sub>O and design of intentional N<sub>2</sub>O mitigation - for example destruction of off-gases - are outside the scope of this design guidance.

It is not intended to be categoric or comprehensive but a starting point to offer support and motivation for low(er) N<sub>2</sub>O WRC design today. As long-term, coordinated monitoring and research improves, our understanding of the N<sub>2</sub>O generation process and the effectiveness of mitigation strategies will continue to develop; therefore this guidance is expected to evolve as the global evidence base grows.

[PAS 2080](#) highlights that many of the most impactful carbon-reduction opportunities occur during the design and construction stages. This applies especially to N<sub>2</sub>O: early design choices, such as process selection, reactor configuration, load balancing, and process monitoring and control provision, can strongly influence whether a plant is predisposed to high or low N<sub>2</sub>O emissions. Designers therefore play a crucial role in embedding low-emission principles from the outset and ensuring systems are future-ready for optimisation.

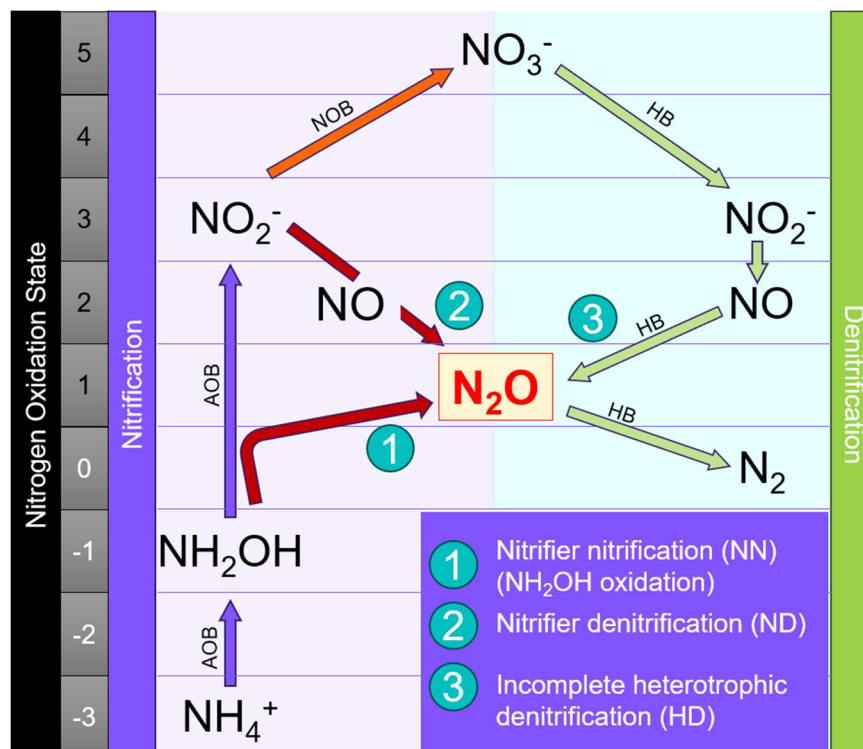
This document focuses on activated sludge processes (ASPs) which is the treatment technology implemented from the majority of the population in centralised facilities. This includes hybrid processes and those involving biofilms (such as IFAS - Integrated Fixed Film Activated Sludge, AGS - Aerobic Granular Sludge, MABR - Membrane Aerated Biofilm Reactor), however the underlying low N<sub>2</sub>O design principles apply across other WRC process types dealing with nitrogen removal (including side stream liquor treatment).

# Pathways and potential triggers for N<sub>2</sub>O generation

Figure 1 provides a simplified overview of the key pathways and triggers associated with N<sub>2</sub>O generation during biological nitrogen removal. This is intended to outline the production pathway to help identify risk factors and consider appropriate mitigation measures. While useful as a working model, it represents a simplified view of a process that is highly dynamic, site-specific, and not yet fully explained in the current science base.

Current understanding recognises three main biological pathways, two autotrophic and one heterotrophic, and a less common abiotic pathway (Lui, 2017). These pathways can be activated under different circumstances, with their relative contribution dependant on factors such as environmental (site temperature, pressure, etc.), substrate (concentration, presence of various pollutants, pH, variations, etc.) and operating conditions (e.g. aeration, mixing, return and recycle streams and their intersection with main treatment, etc.).

This simplified description provides a practical foundation for identifying conditions that may elevate N<sub>2</sub>O risk in design, while acknowledging that actual N<sub>2</sub>O formation results from complex microbial interactions and environmental drivers. The sections that follow build on this working model to highlight specific design considerations that can help minimise N<sub>2</sub>O generation potential. For more information on N<sub>2</sub>O triggers and pathways, please refer to [IWA, 2022](#).



**Figure 1: Simplified nitrous oxide pathways** AOB = Ammonia oxidising bacteria, NOB = Nitrite oxidising bacteria, HB = Heterotrophic bacteria

The simplified pathways are described below along with potential risk factors. Academic research remains ongoing to better understand pathways and causal factors for N<sub>2</sub>O.

1. **Nitrifier nitrification (NN):**  $N_2O$  can be produced as a side-product of hydroxylamine ( $NH_2OH$ ) oxidation during nitrification. Under potential stress conditions, ammonia-oxidising bacteria (AOB) may divert the oxidation of the  $NH_2OH$  intermediate towards  $N_2O$ .

Risk factors = high(er) ammonia loading, (high(er) DO, high(er)  $NH_4^+$  loading, low(er) pH), alkalinity limitations, temperature (high or low).

2. **Nitrifier denitrification (ND):** Nitrite ( $NO_2^-$ ) formed during ammonia nitrification can be reduced to  $N_2O$  when oxygen becomes limiting. Under low-DO conditions, AOB may continue oxidising ammonia to nitrite while NOB activity is suppressed, promoting nitrite accumulation and risk of  $N_2O$  formation.

Risk factors = high(er) ammonia conversion, DO limitation, high(er)  $NO_2^-$ -N/free nitrous acid (FNA) accumulation, unstable aeration/DO control (frequent or poorly controlled transitions), and conditions that suppress NOB activity (e.g., transient toxicity or process upsets), low(er) pH, alkalinity limitations, temperature.

3. **Heterotrophic denitrification (HD):**  $N_2O$  is an intermediate in the denitrification sequence ( $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$ ). Under stable anoxic conditions with sufficiently readily biodegradable carbon, HD can be a sink for  $N_2O$  (via reduction to  $N_2$ ).  $N_2O$  may accumulate when the final reduction step is inhibited.

Risk factors = Oxygen carryover into anoxic zones, carbon limitations and carbon type, low(er) temperature, low(er) pH and high(er)  $NO_2^-$ -N/free nitrous acid (FNA) inhibiting  $N_2O$  reduction, temperature.

## Process selection and considerations

Long-term, full-scale assessments of nitrous oxide emissions remain limited, and current evidence is still insufficient to conclude that any single biological treatment process consistently achieves lower  $N_2O$  emissions than others. Processes which provide nitrification as well as denitrification capacity provide an  $N_2O$  reduction sink which does not exist in nitrifying only processes, based on current scientific understanding. Processes which partially nitrify may result in higher  $N_2O$  risk factors – an example here being carbonaceous plants which nitrify seasonally and can result in very high  $N_2O$  risks.

To determine which technologies reliably minimise emissions, more standardised, long-duration monitoring campaigns across all major process configurations are needed.

Nevertheless, systems that employ good aeration control, good distribution of nitrogen and carbon loads, appropriate recirculation flows, and maintaining biomass at utilisation rates that support nitrification–denitrification balance, offer greater operational energy savings, flexibility during loading peaks and tend to demonstrate lower  $N_2O$  emissions.

Biological wastewater treatment processes transforming nitrogen will produce nitrous oxide. Circular treatment processes where ammonia is recovered, or which rely on alternative (e.g. abiotic) processes, or technologies implementing potential microbial selection with less net  $N_2O$  all offer opportunities for resource recovery. These technologies are emerging with some practical examples – for example sidestream Nitrogen recovery rather than sidestream deammonification treatment by a Swedish Utility.

# Key Design Principles for lower N<sub>2</sub>O emissions risk

Nitrous oxide (N<sub>2</sub>O) emissions from biological wastewater treatment are strongly influenced by how treatment processes are designed, integrated and controlled.

The following eight design principles and interventions set out practical considerations to support design of plants which may support lower risk of N<sub>2</sub>O generation and emissions. They are not intended to provide a hierarchy but a list of potential low N<sub>2</sub>O design considerations for practitioners to consider in every day design work even where N<sub>2</sub>O is not a specific focus. They are focused on activated sludge processes which make up the majority of our largest wastewater treatment facilities and where Utilities should start their measurement and mitigation focus. Low N<sub>2</sub>O operation is another topic for PEAC to address in further work and not covered in these design principles.

**Figure 2: Summary of lower N<sub>2</sub>O design principles**

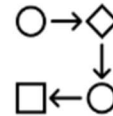
**Consistent feed flows & loads**



**Even flow & load distribution**



**Maximise process levers & flexibility**



**Effective aeration**



**Sufficient alkalinity**



**Denitrification capacity**



**Smart instrumentation systems**



**Design for N<sub>2</sub>O monitoring**



## Principle 1: Consistent feed flows and loads

**Reasoning:** Avoids stress conditions, stabilises microbial activity, and allows for less reactive process control. N<sub>2</sub>O emission trends tend to follow ammonia loading.

### Design considerations:

- Investigate options to control incoming flows and loads. First look for opportunities for flow balancing or pollution reduction in the catchment and network, then internal flow recirculation and use of existing tanks for flow balancing.
- Consider smart control systems to consider weather forecasting to prepare the plant for changes in flow and load conditions.
- Install controls to manage liquor return flows to balance incoming load, e.g. avoid returning liquors during times of high system loading. This could also require balancing capacity.
- Develop control strategies to mitigate the impacts of incoming flow extremes (see process control levers).
- Provide sufficient PST capacity to remove peak organics up front (reduces heterotrophic oxygen demand in the ASP, helping maintain stable DO profiles and supporting nitrifier activity). Balancing this ensures enough carbon remains available for downstream denitrification where included (for compliance or this may be a mitigation measure for N<sub>2</sub>O reduction).

## Principle 2: Balanced liquid flow & load distribution

**Reasoning:** Avoids short-circuiting and dead-spots, promotes more consistent and controllable flow and load distribution within and across lanes.

### Design considerations:

- Consider pre-mixing of RAS, return flows and influent streams, where the design allows, to ensure homogeneous load distribution.
- Consider using low-rate mixers in anoxic zones to prevent dead zones and encourage a uniform load distribution.
- Consider internal baffles, and design with a length to width ratio that promotes plug flow to prevent short circuiting.

## Principle 3: Maximise process control levers & flexibility

**Reasoning:** The more control levers available, the more opportunities there are to support lower N<sub>2</sub>O operation through stable process operation. Design should consider maximum flexibility in process parameters that impact N<sub>2</sub>O production. This should allow for good monitoring and control of DO, sludge age, pH, liquor return flow and loads, alkalinity and carbon availability.

**Design considerations:**

- Provide spare power supply, telemetry and Internet of Things (IoT) capacity to allow for future collection of online data and automation.
- Sludge age or solid retention time (SRT) control - good SRT maintains a robust nitrifier population promoting complete ammonia oxidation and helps prevent partial nitrification pathways. For nitrifying sites, longer aerobic sludge age improves microbial stability which avoids accumulation of nitrite leading to higher N<sub>2</sub>O emissions, however this needs to be balanced with higher endogenous respiration and energy use.
- For carbonaceous sites, design that supports maintaining a lower sludge age is favourable to prevent unintentional nitrification. This requires careful design of SRT and DO control.
- Provide online MLSS and SAS concentration instrumentation. Design control philosophy to use on-line data to dynamically calculate and trend sludge age data on SCADA to support better control. Consider MLVSS versus MLSS given presence of chemical addition.
- Provide pumping systems capable of accommodating a wide range of RAS and SAS flow rates, enabling greater flexibility in sludge age and MLSS control across the full range of influent flows.
- Consider hydraulic sludge age control (i.e. wasting from reactor) for simpler control of sludge age – though this impacts downstream thickening hydraulic loading.
- Ensure final tanks are adequately sized for seasonal adjustment of sludge age. Consider adjustable or modular tanks (e.g. swing zones) to change aeration volume if needed.

**Aeration control**

*See Principle 4 for effective aeration which is critical for good aeration control.*

- Design aeration systems on a solid understanding of the range of flows, loads and peaking factors throughout the project lifecycle from commissioning through to the design horizon (through catchment and network modelling, including climate change and growth forecasts). Design manuals typically state that the plant should be designed on average operating conditions at the design horizon.
- Install variable-speed blowers to maximise turnup/-down flexibility and adaptability to incoming flow and load profile.
- Install high-quality DO sensors along the length of the aeration lanes, which can be easily accessed for maintenance.
- Include in operating philosophies and site manuals for weekly DO probe cleaning and calibration.
- Advanced aeration control strategies could support N<sub>2</sub>O mitigation, adjusting aeration dynamically based on real time flow and load information.
- Install high resolution modulating valves to allow for finer aeration adjustments.
- Provide defined tank zones that can be aerated and controlled independently.
- Design internal recycle streams to avoid DO carryover into anoxic zones.

## Principle 4: Design for effective aeration

**Reasoning:** Maintains defined, controllable aeration zones where airflow is evenly and efficiently distributed across each zone to support maintaining desirable biological activity and has sufficient turn down as well as turn up for current actual loads and future design horizons.

### Design considerations:

- Fine bubble diffused aeration (FBDA) is preferred over surface aeration. FBDA provides a higher oxygen transfer efficiency (OTE), longer contact time, better mixing and control opportunities, as well as being more efficient if well maintained. Surface aerators also create turbulent environments which will likely promote the mass transfer or 'stripping' of N<sub>2</sub>O from liquid to gas phase. Surface aeration should only be considered at existing works with shallow tanks where FBDA could be problematic to install or inefficient.
- Consider pipework design to include tapping points for pressure monitoring, facilities for in-situ chemical cleaning of diffusers, and control valves in the aeration grid system.
- All valves and instruments (e.g. diffuser grids and aeration control valves) should be designed for easy access for cleaning and maintenance.
- Diffuser grids should be designed in consideration of hydraulics so that flow and air is evenly distributed.
- For a new FBDA ASP, standards often suggest tank depths of 4 - 7m deep. Deep(er) tanks should be considered where possible (if compatible with other considerations such as head, cost, and planning permission and risks of degassing) to increase OTE, allowing gas bubbles more time to dissolve, improve mixing, and to potentially reduce the amount of N<sub>2</sub>O that escapes directly to the atmosphere through stripping.
- Aeration and mixing systems should aim for discrete control in individual aeration zones. This may require provision of mechanical mixers to keep the liquid well mixed under low aeration conditions.

## Principle 5: Provide sufficient alkalinity

**Reasoning:** Sufficient alkalinity is required to support nitrification. Alkalinity dosing has been shown to support N<sub>2</sub>O mitigation in some cases.

### Design considerations:

- Design with a sufficient alkalinity balance to consider nitrification and consumption and alkalinity balance across the site, taking into consideration alkalinity consumers e.g. chemical dosing for P removal and stripping of CO<sub>2</sub> from aeration. In addition to rule of thumb effluent bicarbonate alkalinity requirements, assess site specific alkalinity needs from measured data. These will differ site to site and resulting 'sufficiency' for N<sub>2</sub>O and impacts on N<sub>2</sub>O production, where evident, are also likely to vary for a given alkalinity level.
- Review dosing locations to support those which mitigate N<sub>2</sub>O risks.
- Consider the differing alkalinity impacts of chemicals used for phosphorus removal.
- Consider emerging evidence in support of additional alkalinity dosing as a potential mitigation measure for N<sub>2</sub>O formation including from work in Finland by HSY. This may include alkalinity dosing beyond levels required for nitrification.
- Include, or allow space for, alkalinity dosing to maintain a stable pH and inorganic carbon availability under varying load conditions.

See Principle 6 - consider provision of anoxic treatment which both supports the alkalinity balance as well as providing the only available sink for N<sub>2</sub>O reduction based on current knowledge

## Principle 6: Provide denitrification capacity

**Reasoning:** Denitrification is a potential N<sub>2</sub>O sink. Anoxic capacity and carbon availability are required for denitrification. Dedicated anoxic tanks and/or swing zones can support this though carbon addition may be necessary.

### Design considerations

- For nitrifying ASPs, consider adding denitrification capacity by providing adequately sized anoxic zones (and potentially carbon dosing), even when there is no total nitrogen consent. The denitrification pathway offers an N<sub>2</sub>O sink, however insufficient carbon for denitrification may create risk of N<sub>2</sub>O. Designing for anoxic capacity, carbon dosing and future internal nitrates recycles may support mitigation.
- Where denitrification is planned, include or provide infrastructure for future carbon dosing to maintain carbon availability for denitrification.
- Consider control of carbon dosing in design of control philosophy – this may include nitrate sensors in anoxic zone(s) controlling dosing and/or recirculation.
- Consider the impact of chemical phosphorus removal on the availability of degradable COD for denitrification post primary settlement, as chemical dosing increases the removal of organic material in primary settlement tanks.
- Consider impact of dosing upstream of PST. Reducing dosing helps retain particulate and colloidal BOD that would otherwise be removed. These organics can undergo hydrolysis in the ASP, increasing the availability of biodegradable carbon to support denitrification. Conversely, the additional organic load also requires more aeration downstream and may contribute negatively to N<sub>2</sub>O production if this results in a more highly loaded ASP. Flexible designs will allow these aspects to be optimised given knowledge remains incomplete.
- Where there is a risk that influent degradable COD is insufficient, consider implementing primary sludge fermentation for volatile fatty acids (VFAs), or chemical carbon dosing (e.g., acetate, glycerol) and real-time COD/BOD monitoring. The carbon type has been showing to impact on N<sub>2</sub>O emissions as well as embodied chemical (e.g. Scope 3) carbon footprint.

## Principle 7: Smart Instrumentation Systems

**Reasoning:** Real-time measurements, predictive control and automated decision making enable continuous adjustments of process levers to prepare for and respond to fluctuations in flows and loads, maintaining process stability.

### Design considerations:

Table 1 shows the instrumentation that is recommended to improve process understanding, provide insights to nitrous oxide generation and emissions pathways, and aid the development of process control and mitigation approaches.

Taking care of standard site instrumentation (i.e. DO, airflow, ammonia, and flow meters) should be prioritised and additional instrumentation (i.e. nitrate and/or nitrite probes), should be considered where budget allows. Site instrumentation should be calibrated and maintained to the manufacturer's instructions.

Consider walkway length and positioning so that access to sensors for maintenance and calibration is as convenient and safe as possible.

**Table 1: Instrumentation recommendations**

Parameter	Instrumentation location	Relevance to nitrous oxide
Dissolved Oxygen (DO)	Aeration tanks (multiple zones along plug-flow lanes), anoxic zones	DO is essential for microbial activity. DO levels must be controlled to provide sufficient operational conditions for stable nitrification, and to minimise N <sub>2</sub> O formation and stripping.
Ammonium (NH <sub>4</sub> <sup>+</sup> )	Influent, aeration tank inlet, mid-zone, liquor return flows	NH <sub>4</sub> <sup>+</sup> load and concentration is often aligned with N <sub>2</sub> O, supporting smoothing of these loads may support mitigation, including through process control.
Nitrite (NO <sub>2</sub> <sup>-</sup> )	Aeration zones (especially mid/end), anoxic zones	Intermediate strongly linked to N <sub>2</sub> O production; accumulation may indicate N <sub>2</sub> O risk and may support mitigation control measures.
Nitrate (NO <sub>3</sub> <sup>-</sup> )	Aeration zones, anoxic zone	Indicates nitrification/denitrification performance and nitrogen pathway balance.
Dissolved N <sub>2</sub> O	Aeration control zones, aeration tanks, anoxic tanks	Identifies where N <sub>2</sub> O is produced within the process. Ideally measurement campaigns should be a minimum of 12 months to capture seasonal variation.
Off-gas N <sub>2</sub> O concentration	Aeration tank hoods, off-gas ducts, flux chambers on open tanks	Identifies where N <sub>2</sub> O is produced within the aerobic part of treatment (cannot be used in anoxic zones). Ideally measurement campaigns should be a minimum of 12 months to capture seasonal variation.
Airflow / off-gas flow rate	Aeration system manifolds and zones, ventilation ducts, hood exhausts.	Required to convert measured N <sub>2</sub> O concentration (as mg/l N <sub>2</sub> O_N in liquid or ppm in gas) into emission rate (mass N <sub>2</sub> O).
Oxidation-Reduction Potential (ORP)	Anoxic and aerobic zones	Indicates redox conditions; may correlate with N <sub>2</sub> O processes and support understanding/mitigation.
pH	Influent, aeration tanks, final effluent	pH influences microbial pathways and is affected by biological processes; low or fluctuating pH may produce N <sub>2</sub> O.
Temperature	Aeration lanes and return flows	Affects microbial activity and gas solubility, influencing N <sub>2</sub> O production and stripping.
COD / BOD	Influent, anoxic zones, primary effluent	Low carbon during denitrification can lead to incomplete reduction and N <sub>2</sub> O release.
Total Nitrogen (TN), Total Kjeldahl Nitrogen (TKN)	Influent and settled sewage	Defines incoming nitrogen load, influencing downstream N <sub>2</sub> O formation potential. Require for calculation of N <sub>2</sub> O emission factors for benchmarking, comparison purposes.
MLSS	Aeration tanks	Biomass concentration affects oxygen transfer and treatment efficacy and is related to system SRT - control of which may support N <sub>2</sub> O mitigation.
Alkalinity	Influent, aeration tank	Low alkalinity impacts nitrification and can increase N <sub>2</sub> O production risk.

## Principle 8: Design for N<sub>2</sub>O monitoring

**Reasoning:** N<sub>2</sub>O sensor placement is essential for identifying emission sources and triggers. Accurate airflow monitoring is critical for reliable liquid phase N<sub>2</sub>O measurements and mass-emission calculations. Off-gas systems may include internal flow meters for flux measurements, but total plant airflow is still required to extrapolate emissions across the whole asset, since airflow is not uniform throughout the plant.

### Design considerations:

Both liquid-phase (dissolved) and off-gas monitoring systems have been successfully used for long-term N<sub>2</sub>O monitoring in activated sludge processes. Guidance on monitoring protocols should be referred to when looking to carry out an N<sub>2</sub>O monitoring campaign. Further information is available from industry working groups including STOWA (STOWA, 2025), the International Water Association (pending), the GWRC (Global Water Research Coalition - pending), and technology suppliers.

Liquid-phase monitoring can be carried out using standard-range (SR) wastewater liquid phase N<sub>2</sub>O sensors, which have a working range of 0-1.5 mg N<sub>2</sub>O-N/L, a temperature range of 0-27°C, and a detection limit of 0.005 mg N<sub>2</sub>O-N/L. For sidestream reactors with higher temperatures or processes with higher N<sub>2</sub>O ranges, higher range sensors are available.

Dissolved N<sub>2</sub>O measurements can be converted to an emission rate where the stripping (gas–liquid mass transfer) is quantified; this requires (i) dissolved N<sub>2</sub>O-N concentration, (ii) mixed-liquor temperature (for equilibrium partitioning/solubility via Henry’s law constant), (iii) airflow supplied to the monitored zone, and (iv) an estimate of the gas–liquid mass transfer coefficient (kLa) (Unisense Environment, 2025).

Off-gas hoods and gas analysers can also be used to monitor N<sub>2</sub>O emissions. These systems directly measure N<sub>2</sub>O gas flux. Off-gas units may include internal flow meters that measure flux and provide emission rates per unit area of the monitored section.

Because airflow across ASPs is not uniform, total plant airflow data key for both dissolved and off-gas N<sub>2</sub>O measurement. Data from lane(s) monitored then requires to be scaled up to tank level. Monitoring of ‘representative’ tanks should be considered through assessment of flow/load split and operational conditions/issues within individual process lanes.

The following considerations apply to both dissolved and off-gas measurement, unless noted.

1. Given the high spatial variability in N<sub>2</sub>O production and emissions, the preferred approach is to install measurement within each aeration control zone. This allows profiling of the aeration lane and tracking of shifts in peak emissions as loading and operating conditions change, providing a more representative view of emissions. Where monitoring of all aeration control zones in a single lane (typically numbering 2 – 4) is not practicable, two measurement points may be used as an initial arrangement, positioned at approximately one-third and two-thirds along the aerated length of the lane. Multiple mounting points and safe access can be provided to allow measurement point relocation during commissioning and hotspot identification but it is important to note that such profiling will only be relevant for the period during which it is done – emissions hotspots may move within a plug flow system.
2. The liquid phase N<sub>2</sub>O probe also contains a temperature sensor which is critical for the liquid phase N<sub>2</sub>O calculation. Ensure this is placed below the water level (to measure water temperature instead of air temperature). Note the N<sub>2</sub>O measurements are sensitive to the water temperature. Follow manufacturer’s instructions for recalibration if the water temperature exceeds +/-3°C.

3. Accurate localised air flow measurement is required to calculate mass emissions reliably for both dissolved and off-gas methods. Improved resolution and confidence in air flow data directly improve the quality of emission estimates, while also supporting tighter process control and faster identification of issues such as blocked or damaged diffusers. Air flow should be determined for the individual zone(s) with measurement sensors and can be undertaken using air flow meters (if available) or derived from valve position ratios and where possible including diffuser details.
4. Ensure liquid phase sensors are easily and safely accessible for ongoing calibration (2 monthly) and maintenance (sensor head replacement recommended every 6 months).

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**Disclaimer:**

This document provides high-level guidance only and is not intended to be used as a definitive or standalone reference for nitrous oxide (N<sub>2</sub>O) assessment, quantification or mitigation. It does not replace detailed process design, specialist advice, or project-specific analysis. Decisions relating to N<sub>2</sub>O emissions should be based on appropriate expertise, up-to-date standards, and site-specific data.

For further details about the Process Emissions Action Community (PEAC) please visit <https://aquaenviro.co.uk/PEAC>