Nitrous Oxide Emissions Reduction Strategy

Watercare

Disclaimers

Watercare Innovation Centre – Prototype gas collection hood

Acknowledgements

This strategy document has been prepared by members of the Watercare Process Emissions Specialist Panel (PESP). Watercare wishes to acknowledge each of the panel members for their passion, skills, and contributions to this strategy. To our knowledge, this is the first international panel of its type specifically targeted at helping a water utility develop a strategy for tackling nitrous oxide emissions.

Meet the panel

Panel member		Organisation	Expertise
	Dr Nerea Uri Carreno	N118 Consulting – Denmark	Innovation, process modelling, nitrous oxide measurement, quantification and mitigation
	Professor Liu Ye	University of Queensland – Australia	Nitrous Oxide quantification, production pathways, modelling and mitigation strategies
	Professor Kartik Chandran	Columbia University – New York	Research into fundamentals of N_2O production, process modelling, measurement
	Dr Wim Audenaert	AM-Team – Belgium	Advanced process and CFD modelling, digital twins, model aided N2O quantification and mitigation
	Amanda Lake	Jacobs – Edinburgh Scotland	Nitrogen, Carbon and Circular economy, nitrous oxide quantification and mitigation measurement
	Chris Thurston	Sustainability specialist – Golden Bay, New Zealand	Sustainability, GHG accounting, project management and facilitation
	Kevan Brian	Watercare – Auckland, New Zealand	Innovation, measurement of N_2O, process modelling and project management

Contents

Summary

This process emissions strategy is a first of its kind in the wastewater sector worldwide. It provides Watercare with a tool to guide its actions towards the reduction of process emissions from its wastewater treatment plants, both immediately, and in the long term. It builds on the work already done in 2021 as part the Watercare Decarbonisation Roadmap that identified N_2O emission mitigation as key to achieve a 50 per cent reduction in emissions by 2030.

This strategy uses state-of-the-art knowledge accumulated over the years by academics and practitioners in the field, and provides new methodologies to convert this knowledge into practical and coherent full-scale implementation. A novel mitigation hierarchy classifies actions into different categories to help prioritise implementation actions: avoidance, reduction, and technology replacement.

The strategy also proposes a novel implementation method that combines the simultaneous monitoring of N_2O with process modelling in a synergetic manner. This would speed up the understanding of the causes and mitigation actions to avoid lengthy monitoring campaigns that would delay mitigation.

A comprehensive assessment of the existing technologies and processes at Watercare's four largest wastewater treatment plants was carried out along with identification of potential N_2O emissions risks. This assessment provided detailed potential actions that can be carried out both in the short and long term, including both operational and design changes. These will help Watercare start implementing mitigation while measurements and modelling provide further understanding into the causes and potential pathways for nitrous oxide mitigation.

The first action from this strategy is to implement the proposed measurement campaigns at Māngere and Rosedale wastewater treatment plants, set up data and data processing systems, and establish quality controls to ensure measured data is reliable and as accurate as possible.

Once data starts to flow, some initial understanding of possible pathways and nitrous oxide hot spots will be gained. It is expected from this point that some academic or more advanced work will be needed to better understand cause and effect of the emissions and potential pathways to mitigation. In addition, work is required to understand how or if some of the new processes we are planning, such as InDENSE, may affect emissions.

In addition to measurement, innovation/research and development work, progress on integrating emissions-related capital investment and renewals is required. Given that upgrades of significant assets will take a long period of time, these must be started very soon so that tools are available to realise mitigation options in the future.

Background work and studies

As background to this strategy, Watercare conducted a monitoring trial at the Rosedale Wastewater Treatment Plant. In this trial, liquid and gas phase nitrous oxide measurements from the activated sludge reactors were taken and compared to the predictions of simulation models. In addition, combined computational fluid dynamics modelling (CFD) and mechanistic modelling of the activated sludge reactors at Rosedale was used to identify potential nitrous oxide hotspots and to inform and optimise future monitoring locations.

Extensive work on the pilot scale has been undertaken on a hybrid membrane aerated biofilm reactor (MABR) to establish emissions factors and to study and quantify mitigation strategies. This work will be published separate to this strategy. Based on these two initial studies, Watercare has installed New Zealand's first full-scale hybrid MABR for the Waikato District Council at Te Kauwhata and this is the first wastewater plant in New Zealand to install full nitrous oxide monitoring.

Improving our understanding of a complex issue

Currently Watercare uses fixed factors to assess the emissions associated with wastewater. This shows us that most of the emissions occur within large, activated sludge processes, dominated by the reactor clarifiers at Māngere followed by the MLE (Modified Ludzack-Ettinger) reactors at Rosedale and the disposal of wastewater sludge from these sites. Using fixed factors to assess emissions has significant limitations that this strategy addresses, namely:

- The factors are essentially based on population and the more nitrogen treated, the higher the emissions are assumed to be. This approach means that as Auckland's population grows, so do emissions.
- The factors may over or underestimate actual emissions and this may affect their contribution to Watercare's emissions profile.
- Fixed emission factors do not take into account spatial and temporal heterogeneity or variability in emissions from different treatment operations.
- To quantify any improvements that are made to reduce emissions, Watercare will need to establish site-specific factors as published factors do not have the flexibility to incorporate improvements without a site-specific factor for each plant being established first.

Measuring emissions

A critical step in this strategy is direct emissions measurement through gas hoods and liquid probes over a relatively long period (e.g. 12 months). This step will inform the scale of emissions, where they occur, and start to inform our understanding of why they occur. Understanding why the emissions occur is key to mitigation. Measurement will also allow Watercare to establish its own specific baseline that can then be used to benchmark our progress against the 50 per cent reduction target.

At Māngere and Rosedale, a project to install direct N_2O monitoring equipment is scheduled to start in August 2024. Once this equipment is installed, resources are required to maintain, calibrate, and troubleshoot this instrumentation to ensure the best possible data is gathered. In addition, resources will be required to convert field measurements into emissions rates to help establish the emissions baseline.

Use of modelling

Direct measurement of emissions will not occur over all process reactors, and measurements will not be able to be taken everywhere in the processes simultaneously and at high data resolution. This is due to the significant cost and complexity of direct measurement. Mechanistic modelling will be used to supplement direct monitoring and aid understanding of the fundamental pathways and causes of emissions and identify the most relevant monitoring locations. Modelling also allows virtual mitigation strategy testing and integrating minimal N_2O emissions into planning exercises (i.e. 'minimal N_2O by design').

An approach to modelling that is benchmarked or standardised or recognised and accepted by the scientific community is critical to success. Challenges remain in calibration and validation of models that predict long-term nitrous oxide emissions in both academic and industry-led work, hence they cannot be used "out of the box" without significant investment in calibration and validation that must come from measured data.

Actions and steps to reduce emissions

There are several potential actions that could reduce emissions. Many of these have not been proven at full scale and there is not a recipe book for managing N_2O.

This strategy splits mitigation into a proposed mitigation hierarchy: avoid, reduce and replace. In this context, avoid refers to actions intended to modify the load pattern of nitrogen into the wastewater treatment plant, reduce refers to actions intended to reduce the production and emissions of N_2O within the existing technology/infrastructure, and replace refers to the replacement of the processes/technologies with lower-emission ones. The strategy does not attempt to quantify the percentage reduction that each action may provide; rather, based on our current knowledge, we have ranked options as high, medium, or low impact.

Implementing the strategy

A critical part of the strategy is how it will be implemented. For this strategy to succeed, actions must be integrated into how infrastructure is planned. In addition, the findings from detailed measurement and experimentation work needs to be integrated into new facilities. This strategy should not stand alone; it should be part of an overall plan for each site to reach Watercare's level of service, growth and climate goals.

Historically, our operations teams have focused on maintaining compliance with our discharge consents for water and for the environment. These have not required consideration of the discharge of greenhouse gases. A change in approach to consider how the operation of our plants affects emissions will likely become commonplace in the future but is currently in its earliest stages.

The operations teams at the wastewater facilities will need to monitor mitigation and help to report and record improvements over time. It is important to note that long-term, even permanent changes may need to be made to how our plants are run. This must be achieved while maintaining compliance and keeping operational costs low.

Suggested responsibilities are as follows:

- **Responsibility for delivery:** The project requires an executive sponsor who will provide leadership, guidance and governance to maintain momentum and progress. It is recommended that this be the chief strategy and planning officer. Given the complexity of the issues, the scope of the projects within the strategy, the uncertainty, and urgency to take action on climate-related issues, it is recommended that dedicated resources be allocated to deliver this strategy. These resources would need to be supported by teams across the business.
- **Programme management and capital upgrades:** This strategy must be integrated with programme delivery at major treatment sites so that asset upgrades and renewals, as well as major projects, are considered holistically.
- **Research and development funding:** To build understanding and accelerate mitigation, it is critical to maintain and enhance relationships with the academic world and with other utilities.

Watercare must drive the needs of this research, and given the skills needed to understand these issues, this may include further education for employees such as Masters-level study.

- **Monitoring:** Funding for monitoring equipment has already been secured, and instrumentation will be installed in the second half of 2024. This programme needs to be supported after installation and commissioning.

Delivery programme

Measurement of emissions, cause-and-effect studies, and replacement or upgrade of significant assets is required to meet 2030 goals. This strategy proposes that several workstreams need to occur at the same time and planning of asset renewals and upgrades needs to run simultaneously with research and innovation.

Note that the duration and content of these detailed tasks/projects may be subject to change based on the ongoing work and evolving knowledge

Strategy background and targets

Watercare has a target to reduce scope 1 and 2 operational GHG emissions by 50 per cent by 2030 and to have net zero emissions by 2050. In 2021, the Watercare Decarbonisation Roadmap (the roadmap) identified Nitrous Oxide (N_2O) optimisation as one of the leading strategies to meet the 2030 target, however the details of how to deliver this were not developed. One of the four key priority actions in the roadmap is to create a process emissions strategy. The hierarchy of the climate strategy and roadmap are shown in figure 2.

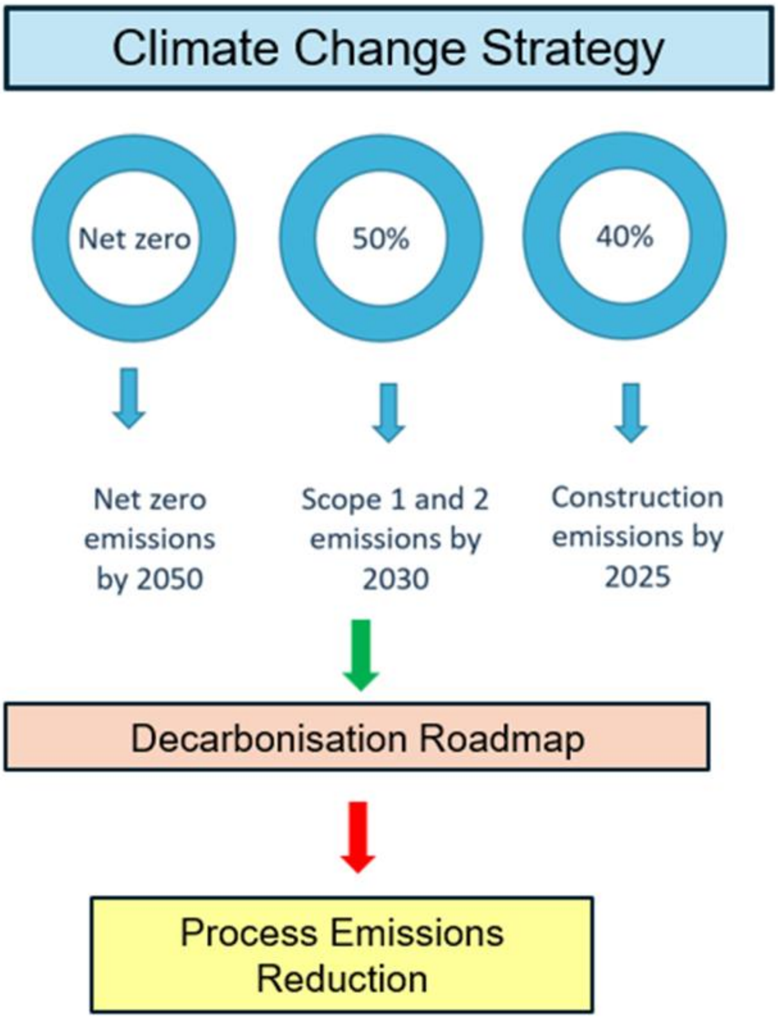


Figure 1:– Strategy hierarchy

N_2O is a potent greenhouse gas with a global warming potential 273 times that of carbon dioxide. Using the Intergovernmental Panel on Climate Change (IPCC) emissions factors, wastewater process emissions account for 79 per cent of Watercare's current scope one and two operational emissions. N_2O emissions make up 46 per cent of the wastewater emissions and are a bigger contributor to emissions than all of Watercare's energy consumption. Therefore, reduction goals cannot be achieved without substantial progress in reducing nitrous oxide at our major treatment facilities.

This N_2O process emissions strategy provides the specific actions to reduce N_2O emissions at our four major wastewater treatment plants (Māngere, Rosedale, Pukekohe and Army Bay) and contributes to Watercare's overall decarbonisation strategy. Methane emissions from wastewater, predominantly sludge, are also a significant contributor to Watercare's GHG profile, however they are not covered in this strategy.

The overarching ambition is to achieve net zero no later than 2050 and to report to Auckland Council on a 50 per cent reduction in operational emissions by 2030.

Strategy outcomes

- Establish a baseline for N_2O emissions that will be used to quantify future mitigations. For reporting purposes this baseline must include the 2018/2019 reporting period.
- Establish an action plan to reduce process emissions by no less than 50 per cent against the 2018/2019 baseline by 2030.
- Consider what are the long-term actions required to achieve net zero.

Principles

The following high-level principles were used to develop the strategy:

- **Impact and action-oriented mitigation hierarchy**: Focus on the largest emission contributors and, within these, where most significant progress is possible. Simultaneous quantification and mitigation will be aimed for. A multi-tiered approach will be used whereby near-real time simulation of performance and emissions, generated through modelling and adjustments through real-time measurements, will be undertaken. Concurrently, real-time mitigation will proceed based on combining modelling (mechanisms or trends) and measurements.
- **Progress over perfection:** We will not wait to complete baselining our emissions; mitigation must start in parallel to meet our goals.
- **Holistic process optimisation approach:** Cost-effective solutions are sought which will allow Watercare to maintain or improve effluent quality and process efficiency whilst acting on N_2O emissions at the pace required.
- **Optimisation for asset health and co-benefits:** For example, a focus on solutions that reduce energy consumption, improve effluent quality, or provide any other quantifiable benefits besides emission reduction.
- **Leveraging capital upgrades:** Ensuring capital upgrades are completed in a way that reduces emissions, or at least does not increase them.
- **Building further on international experiences:** Globally, template solutions don't yet exist; aim to create those, iterating and improving along the way. Aim to develop tomorrow's solutions whilst implementing those most viable for today.
- **Science-based and data driven**
- **Knowledge share**: Within New Zealand and with the global community

How emissions are reported

Watercare has been reporting its emissions since 2014 using factors provided by the New Zealand Ministry for the Environment, peer-reviewed literature and specific applications and assumptions based on local conditions.

N_2O has a global warming equivalent of 273 times that of carbon dioxide. It is considered to have a long life in the atmosphere of around 120 years (IPCC, 2018). This high carbon dioxide equivalence means that even if very small amounts of this gas are emitted to the atmosphere, they can make a significant contribution to our equivalent carbon dioxide inventory. From measurements we have already undertaken, N_2O can vary between a fraction of a percent to several percent of the influent nitrogen in our treatment plants.

Nitrous oxide is soluble in water and is mostly emitted to the atmosphere where aeration is applied to a process. This aeration "strips" the dissolved N_2O into the air bubbles that are travelling through the water. In our treatment facilities, we pump very large quantities of air through the process reactors to provide oxygen for the microbial breakdown of the pollutants in the wastewater. Nitrous oxide is only emitted in statistically significant quantities where a process is aerated, due to this stripping effect. It can be formed in aerated and non-aerated parts of a plant, but it is mostly discharged to the atmosphere where there is aeration.

There are many challenges associated with measuring and reporting N_2O, and until recently (the last one to 10 years), little or no attention was paid to N_2O emissions. Due to lack of data, the complexity of measurement and the development of knowledge in N_2O, and where to measure it, the IPCC has issued factors that organisations such as Watercare can use to try and quantify how much may be discharged. These factors can then be used to calculate an organisation's carbon footprint.

The IPCC has three levels of factors for assessing N_2O:

- Level 1: Factor-based (global) guidelines.
- Level 2: Country-specific factors (Carbon accounting guidelines for wastewater treatment: CH4 and N_2O produced by Water New Zealand is our country-specific factor)
- Level 3: Site-specific factors based on facility-level measurement.

The measurement and reporting of GHG emissions have evolved in recent years and in 2021 an additional focus was put on wastewater process emissions. The methodology to assess emissions was updated following the Carbon accounting guidelines for wastewater treatment: CH4 and N_2O produced by Water New Zealand[1]. These are a local refinement of the 2019 updates to the IPCC guidelines (level 1) on reporting waste-related emissions and are 'Level 2' reporting.

The Level 2 factor for New Zealand is a N_2O emission rate of 1per cent of the nitrogen load treated at each facility. The work we have already done at a pilot scale and the testing programme conducted at Rosedale in 2022, both show that this factor is highly variable; however, studies have shown that measured emissions and the level 2 factor are in the same order of magnitude over time. Whilst we expect the measured factors to be different from the level 2 factor, we do not expect to see a significant difference, although the rate of N_2O emission may vary to this extent over short periods of time.

[1] Carbon accounting guidelines for wastewater treatment. https://www.waternz.org.nz/Article?Action=View&Article_id=2078

To achieve this strategy, it is critical that Watercare moves to 'Tier 3' direct measurement alongside integration with modelling efforts on a site-by-site basis to establish our own specific emissions rates/factors. It is recognised that the GHG footprint will evolve as measurement data becomes available and it is likely that the factors used from the IPCC will not represent what is measured at each site. Each site that we measure may have its own emissions factor or rate that is specific to how a particular plant is configured, operated and the load that it receives, hence monitoring across multiple sites is necessary.

Figure 3 shows a projection of scope 1 emissions with mitigation applied from 2024. Note that because we use factors to estimate our emissions, these will increase with population. This is expected to occur in the future even once we have site specific factors if there are no mitigation actions implemented as these will also be based on percentages of load treated.

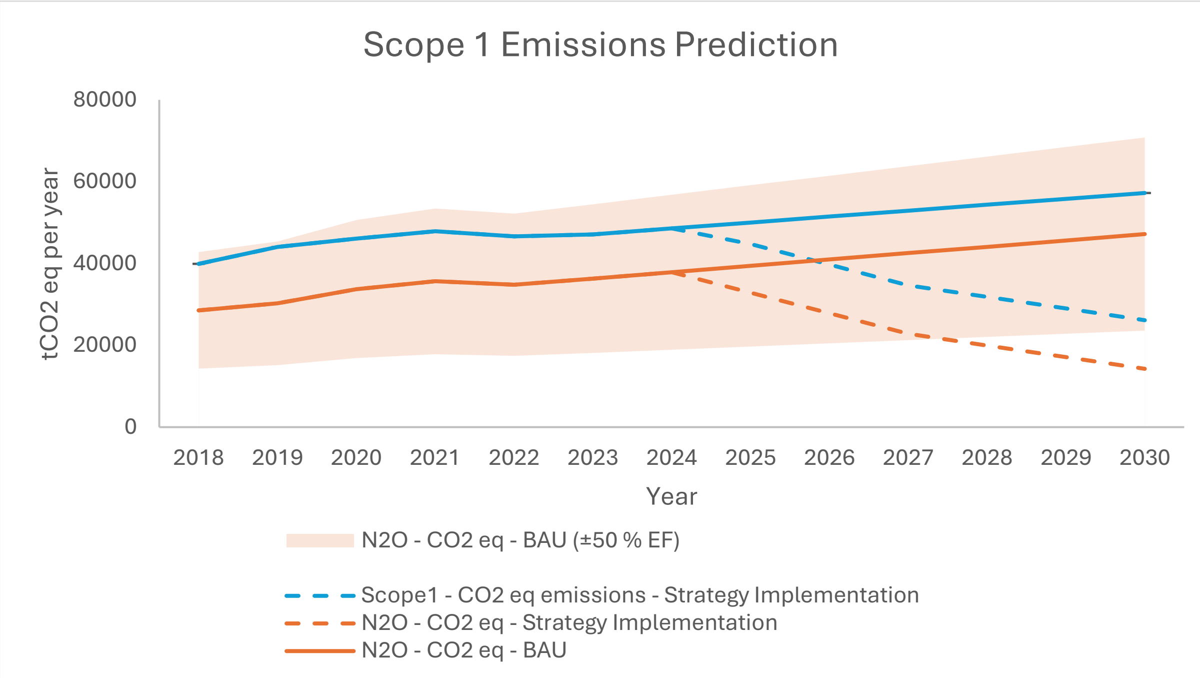


Figure 2: Projected Scope 1 Emissions

Scope one and two emissions

When this report was prepared, the most recent data – from financial year 2022/2023 – indicated scope 1 and 2 emissions were 107,285 tCO2e, which can be broken down into the key sources shown in figure 4.

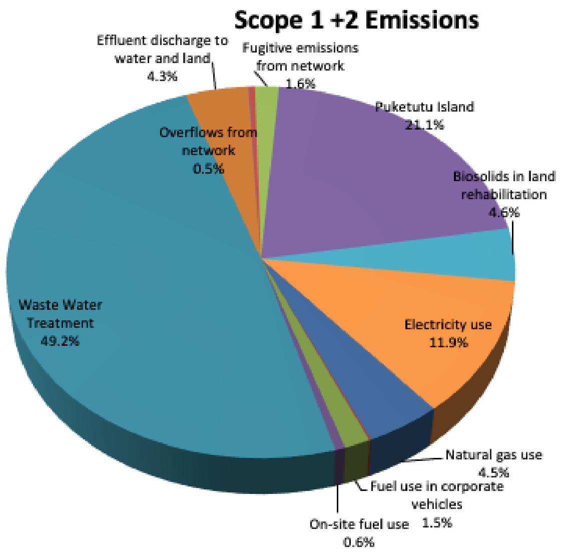


Figure 3: Scope 1 and 2 Breakdown

The emissions from the wastewater treatment plants correlate closely with the size of the plants and the population that they serve. The four largest sites, Māngere, Rosedale, Army Bay and Pukekohe have the most emissions as shown in figure 5.

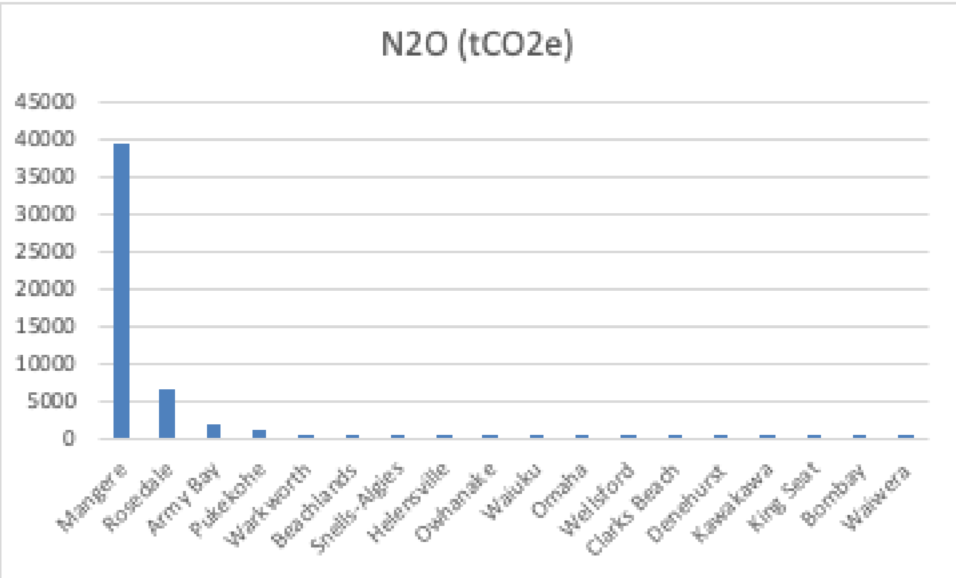


Figure 4: Relative contribution of nitrous oxide emission per facility, 2023

It is expected that with 'Tier 3' data collection, analysis and use of modelling methods (which are discussed further below), the process emissions baseline for N_2O will change from the 2018/19 baseline. This is a critical step to get a better handle on the 'real' baseline and more granularity on where and how the N_2O emissions are occurring.

The usefulness of collected and analysed data and validity of modelling methods will also evolve over time. The level of data sufficiency will support an acceptable model, and this will support quantification of mitigation efforts across Watercare's major assets.

How nitrous oxide is formed

Nitrous oxide is an undesired byproduct of both nitrification and denitrification processes in biological nutrient removal processes. Process conditions determine which fraction of the nitrogen treated will result in N_2O, or other nitrogen compounds (N_2, NO_x, NH_x, etc...). Despite decades of scientific research in this area and due to the complexity of the biochemical nitrogen cycle, there still exist gaps and controversies in our understanding of how N_2O is produced and under which conditions.

Scientific literature reports three main N_2O biological production pathways and one abiotic one (Domingo-Félez and Smets, 2016). Two of the biological processes are related to ammonia-oxidising organisms (AOO) activity: the nitrifier-nitrification (NN) and nitrifier-denitrification (ND) pathway, while the third biological production pathway, heterotrophic denitrification (HD), is related to ordinary heterotrophic organisms (OHO). The last pathway, abiotic production (AP), is related to the two chemical reactions driven by hydroxylamine (Heil et al., 2014).

Nitrifying organisms are responsible for the two first pathways, NN and ND. The first one under high substrate (ammonia and oxygen) conditions, and therefore high substrate utilisation rates, and the second one under substrate limiting conditions. Denitrifying organisms can be responsible for either the overall net production or reduction of N_2O, depending on substrate availability.

Mitigation strategies (avoid, reduce and replace) aim to ensure that substrate availability and substrate utilisation rates are such that N_2O-inducing intermediates are not accumulated in the process so that N_2O production is reduced and N_2O reduction is enhanced. This is done by ensuring optimal aeration control (substrate: dissolved oxygen), optimal load distribution and recirculation rates (substrate: nitrogen and carbon), and optimal biomass inventory (utilisation rates).

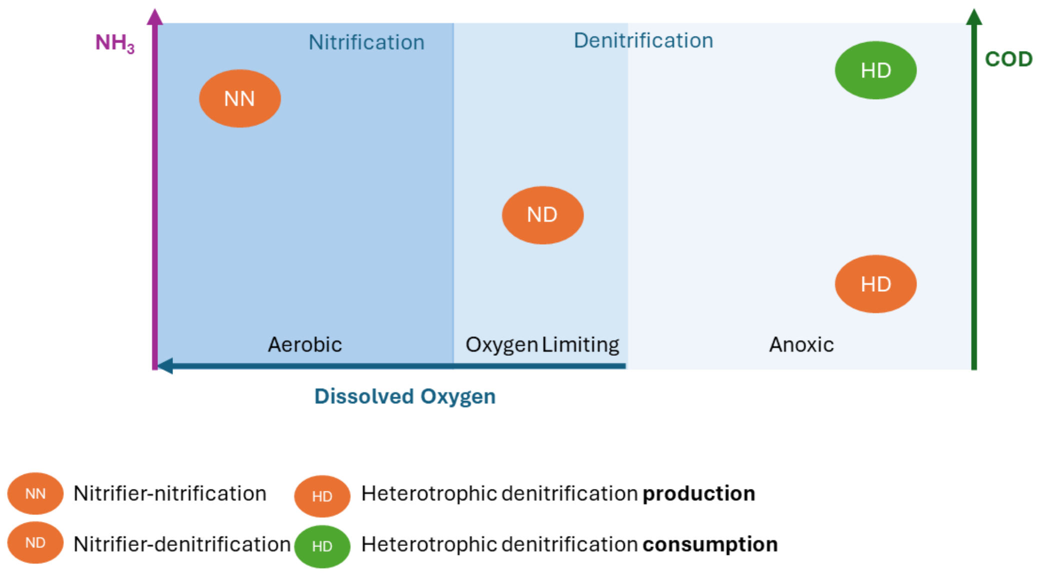


Figure 5: Nitrous oxide pathways

Mitigation options

There are several ways that N_2O can be reduced or eliminated in wastewater treatment plants. Following a typical GHG mitigation framework, the following hierarchy for mitigation of N_2O emissions at wastewater treatment plants is proposed: Avoid, Reduce, Replace and Offset. Generally, in this strategy, mitigation has been approached with a focus on avoidance of N_2O and reduction of N_2O. Offsets do not address the cause of the emissions nor the need to quantify the emissions over time and are not considered further in this strategy. Offsets may need to be used to achieve net zero as it is unlikely that zero nitrous oxide can be achieved while meeting nutrient targets that are typically in our discharge consents.

The hierarchy applied for each site strategy depends on site specifics including the planned capital programme(s). Options that have the greatest expected impact on emissions and the greatest chance of being implemented should be prioritised. This is shown diagrammatically in Figure 7. Short-term solutions are proposed within constraints of current site operation/controls and longer-term solutions are proposed aligned with capital programmes and upgrades/enhancements.

It is important to note that the source of nitrogen in the wastewater catchments is largely the result of the amount of protein consumed and discharged to the sewer network. While not covered directly by this strategy, limiting the influx of proteinaceous matter in domestic wastewater may be a key factor in the future.

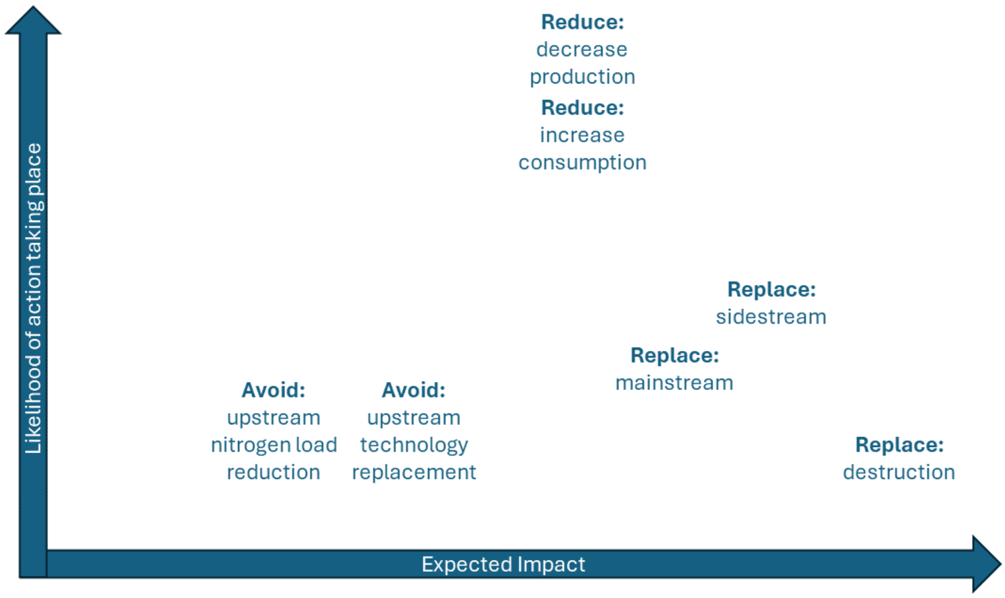


Figure 6: Reduction options and impact

Technology replacement – Design-based solutions

For mainstream nitrogen removal, which means the treatment of wastewater other than centrate (flow after the dewatering of anaerobically digested sludge), the small amount of data from treatment processes around the world means we cannot suggest definitively that any process will emit more or less than any other. Due to a lack of data, there currently does not appear to be any clear justification for design-based mitigation solutions apart from improving or replacing assets such as aeration equipment.

Another potential option for mitigating or removing N_2O is to cover a process and extract the air for further treatment to decompose N_2O. One of the difficulties of this approach, apart from expense, is the very high gas flow and very low N_2O concentrations. Where trials have been run with covering of an entire facility, the amount of airflow appears to dilute the N_2O, making it very difficult to measure influent and effluent gaseous concentrations, likely limiting the success of this approach. Given the likely expense and operating complexity of covering a site such as Māngere, this option does not appear to be justifiable to meet 2030 targets.

On the other hand, side-stream nitrogen removal of digested liquids, which consists of a smaller volume of flow with much higher concentrations of ammonia and higher temperatures, has been shown to have considerably different N_2O emissions factors depending on the technology employed to treat it. Two-stage deammonification reactors typically incur larger emissions than single stage anammox or alternative technology solutions. While the recovery of ammonia or the destruction of N_2O from covered treatment tanks have the potential to minimise N_2O emissions, technology readiness is not currently high enough for them to be practical solutions. Digested liquors at Māngere are treated together with the rest of the wastewater as part of the mainstream biological nitrogen removal.

Avoid: Reducing and balancing nitrogen loads

Nitrous oxide emissions are produced during the biological removal of nitrogen, therefore, actions upstream of the nitrogen removal processes aimed at reducing or equalising these nitrogen loads can be expected to have a positive impact on the fraction of nitrogen ultimately emitted as N_2O.

In the context of this strategy, a possible option available is the use of the new interceptor at the Māngere Wastewater Treatment Plant to optimise the nitrogen load into the plant and therefore avoid loading peaks that can lead to N_2O peaks downstream in the process.

Reduce: Optimisation-based mitigation

Mitigation via optimisation involves manipulating the biological environment within the activated sludge processes at three of the four targeted plants, to promote conditions that produce less N_2O and/or consume N_2O. Given the uncertainty with design-based solutions or abatement, it is likely that mitigation via optimisation of process operating conditions will give the biggest return on investment. The disadvantage of this approach is that it requires a detailed understanding of why the N_2O is being formed, identification of potential biological pathways and trial and error for mitigation. These will all take time and have uncertain outcomes. The approach also requires enough flexibility in the existing treatment assets at the four plants to accommodate any operational changes identified.

Based on current knowledge, it is unlikely that optimisation itself will be able to reduce N_2O to zero, and it is not possible at this time to quantify what percentage reduction may be achieved through optimisation only. The other uncertainty is the effectiveness of the process optimisation strategy over time. There is also a lack of case studies on this. The panel is confident that at least a 50 per cent reduction can be achieved and, as we progress with measurement and modelling and develop our understanding further, we may have more certainty around what magnitude of mitigation can be achieved.

Optimisation approach

The approach to optimisation of process conditions, and the ultimate mitigation and reduction of N_2O in Watercare's wastewater treatment plants, will be an iterative process. Key to success will be identifying patterns of N_2O behaviours over the different reactors, across treatment zones on a diurnal and seasonal basis and confirming these over a period of time. This approach will use several concurrent points of investigation that move together to provide an understanding of where the N_2O is generated or consumed, what conditions are present when these patterns occur and how they might be manipulated to reduce how much N_2O is produced. This concept is illustrated in Figure 8

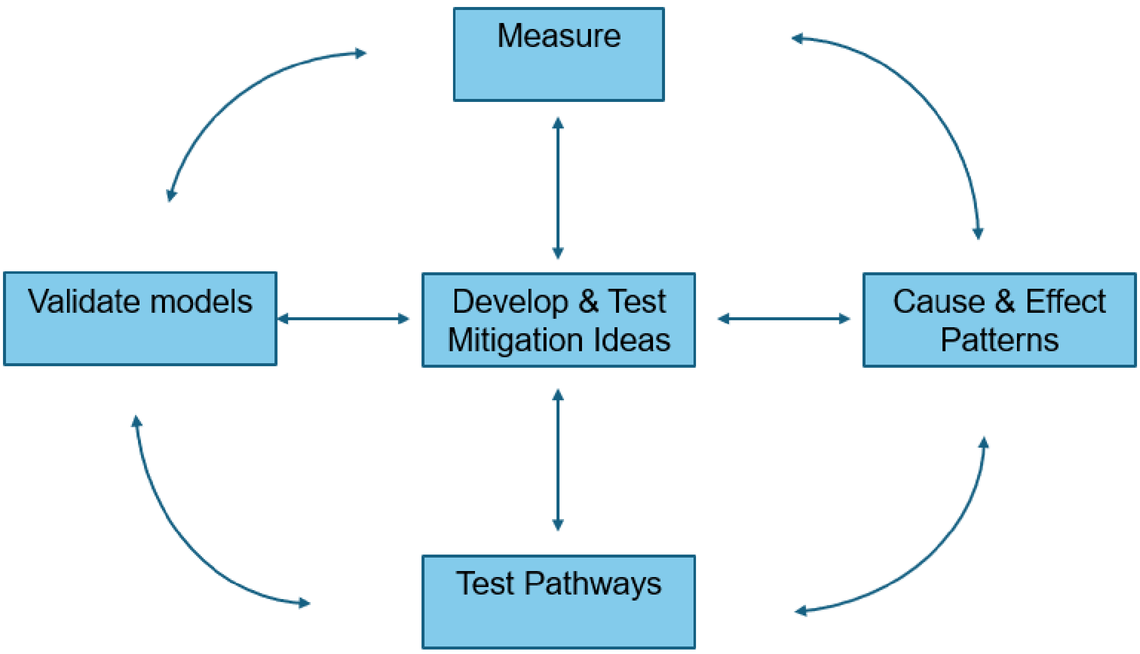


Figure 7: Iterative approach to mitigation

This approach will require detailed investigations, laboratory and pilot-scale tests and validation at full scale within the constraints of the existing process.

Back casting and extrapolation

Given that investigations will only be undertaken in certain reactors where monitoring equipment is installed, there will be a need to extrapolate results to different reactors and perhaps to different plants. Extrapolation of results will be required for the setting of the baseline, which is the 2018/2019 reporting year. It is unlikely that a comprehensive dataset will be available that would allow a detailed mathematical model of historic conditions; hence a simplified approach is recommended where conditions such as current nitrogen loading, aeration control etc are first compared to historic data, then to calibrated and validated models of existing conditions. A high enough level of detail is required to make valid comparisons, however a balance between detail and uncertainty will need to be made.

***Action**: Establish site-wide emissions factors based on key parameters alongside the N_2O monitoring equipment. Use this to back cast to 2018/19 to create an updated baseline.*

Mathematical modelling

Mathematical modelling plays a key role in the design, operation and quantification of effluent quality from wastewater treatment plants.

It is expected that modelling will also play a key role in mitigation of N_2O, but is yet to be demonstrated by practical, utility-led approaches globally. Challenges remain in calibration and validation of models using readily available process data in both academic and industry-led work.

Mechanistic models (i.e those that describe the mechanism of reactions within a wastewater treatment process) are the most commonly-used tool for design and optimisation of wastewater treatment plants, particularly activated sludge systems. These models rely on the ability of the predictions made to be validated against real plant measurements obtained through instrumentation or by taking samples and analysing these in a laboratory. The key assumption with this data is that it is reliable and accurate, and the model can be calibrated and validated with some degree of confidence.

Measurement of nitrous oxide in liquid, and in the gas discharge from wastewater facilities, is evolving and is currently subject to a high degree of uncertainty. This makes it difficult to establish where errors are occurring – i.e are these in the measurement of N_2O or from inaccuracies in the model formulation? We propose in this strategy that during the initial phases of the project, models and measured data are used together to inform the quantum of emissions from Watercare's treatment plants, rather than a sole reliance on either approach. As both measurement certainty and model accuracy improve over time, it may be possible to use models to replace measurement or enhance understanding of the source of emissions. In addition, models may be used to develop "soft sensors" that can be used to predict where and how N_2O will be produced.

One of the key steps in the strategy is the validation of results. This will give more confidence to investigate possible scenarios for mitigation and direct some of the investigation and testing that will be required. At this time, it is difficult to predict the level of detail the models will need to capture with respect to predicting measured/observed patterns in N_2O generation and consumption. It is recommended that the complexity of the modelling used is only that required to answer the questions or hypothesises that are proposed. i.e. the models do not necessarily need to include the whole plant or all reactors

Modelling approach

Process modelling has the potential to provide the advantages shown in figure 9:

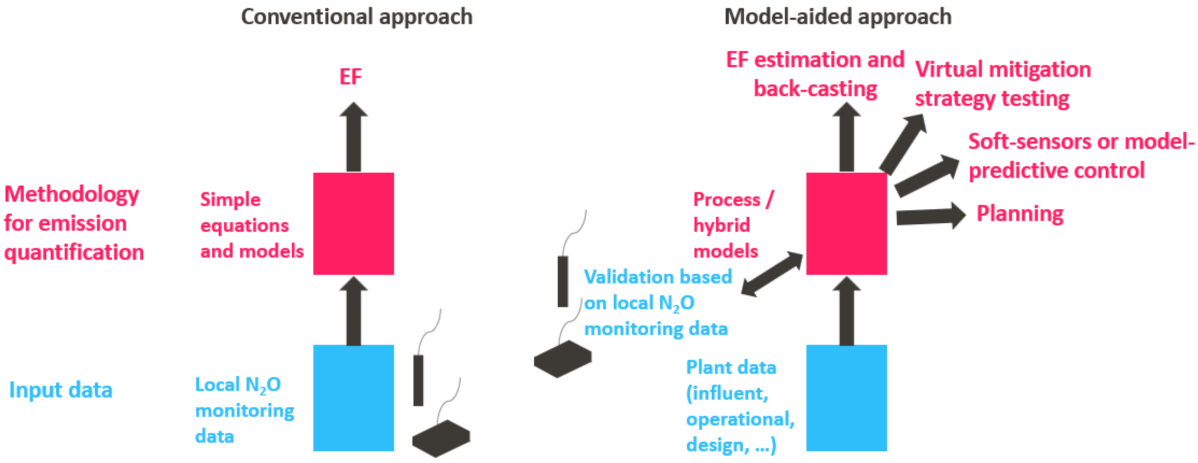


Figure 8: Modelling approach

Each approach has uncertainty at the level of the input data and the methodology. The main differences between the conventional approach and an integrated approach are:

- The input data for emission quantification shifts from local N_2O monitoring data to (pre-existing) plant data. In the integrated approach, local N_2O monitoring data takes up a dual role as 'validation/verification' of the models and as the measurement of actual emissions.
- Given this change in input data, the integrated approach uses long-term N_2O monitoring, unlocking the opportunity of 'retrospective baselining', in which historical plant data is being used to back-cast N_2O emissions.
- The models can also be used as virtual mitigation strategy testing tools. The implemented mitigation strategies can be verified using onsite N_2O monitoring data if desired.
- In very advanced applications where the models are used in real-time, they can be used for real-time emission monitoring (soft-sensoring) or advanced process control. Note that these "models" do not have to be applied at a plant level and do not have to include all biological processes. They may be simplified model elements used to help describe or measure parameters within the reactors.

The role of modelling will change over time as more data becomes available and methods improve.

In addition to mechanistic (knowledge-driven) models, machine learning approaches to predict and mitigate N_2O are being developed in trial work by utilities, practitioners and in emerging real-time control proprietary solutions globally. However, the ability and effectiveness of such approaches to support improved quantification and sustained mitigation remains to be seen.

Measurement framework

Direct N_2O monitoring is a critical component of this strategy and the overall understanding of actual N_2O emissions. This section provides an overview of the methodology for developing the facility baselines and references the plans for installing advanced direct monitoring equipment.

Baseline assessment methodology

Watercare currently accounts for N_2O emissions using industry-adopted emissions factors based on total nitrogen coming into the respective treatment plant. As N_2O data becomes available, improved baseline assessment will be possible.

This section summarises how these improved baselines will be developed as N_2O data becomes available in parallel with mitigation.

This will involve the following general approach:

- Maximise installed continuous monitoring systems to allow a minimum of one representative bioreactor in the secondary treatment process per site and ideally more.
- For each bioreactor, monitor emissions from multiple locations to cover spatial variation, augmented by model predictions.
- Estimate emissions in treatment zones/lanes not monitored using best available evidence from zones that are monitored using methods outlined below.
- Use continuous data from calibrated, online sensors to calculate mass emissions from the monitored bioreactor and then multiply the number of the bioreactors running in parallel at the site.
- Cross-reference liquid phase measurement with gas hood-based measurement; if gas hood-based measurement is adopted, using the direct measured gas emission data for calculation; Obtain a site-wide emission baseline for the secondary treatment process, to be reported on using actual data on an annual basis.
- Obtain improved emission factors through ensuring sufficient incoming TN measurement to contribute to Watercare and global understanding.

Where long-term monitoring is not undertaken in zones/lanes/reactors, estimation of emissions will be undertaken using the following approach:

1. Temporary monitoring of zone/lane/(s) where possible through structured monitoring programme
2. Estimation of data in zones/lanes not monitored using a calibrated, validated dynamic N_2O modelling approach (mechanistic or emerging hybrid/data driven methods)
3. Estimation of data in zones not monitored using data from monitored zones by expert judgement and assumption where valid models are not available to aggregate emissions at lane, reactor and site level.

An additional project to establish an industry methodology for measuring wastewater process emissions is being completed by the University of Queensland alongside other Australasian water utilities, including Watercare.

Mitigation strategies

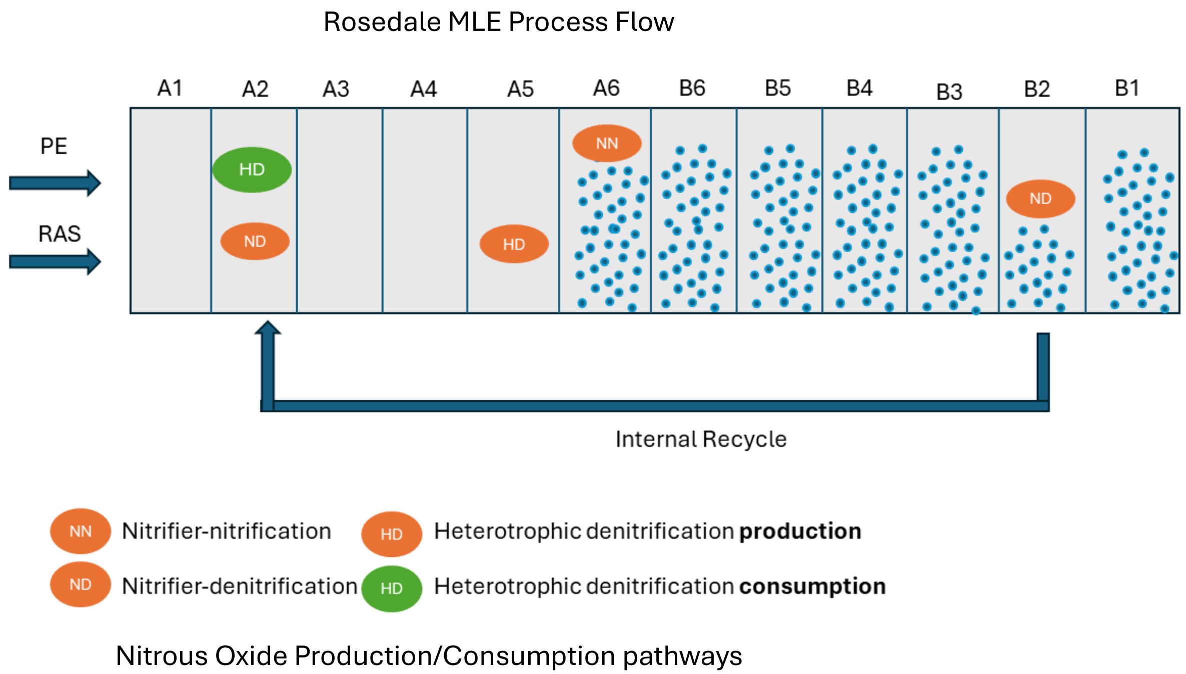
Mitigation strategies have been developed for three of Watercare's major wastewater plants.

Given that a significant upgrade is planned for the Army Bay Wastewater Treatment Plant, no mitigations have been proposed, however it is very likely that similar themes and strategies will be used here as at the other facilities. The strategies below have been developed with the relevant Watercare production teams and have considered upcoming or planned CAPEX upgrades and how these could be integrated or accelerated to deliver better emissions outcomes. These have been ranked in terms of potential to reduce emissions and be able to be implemented using expert guidance and experience from the process emissions strategy panel.

The strategies detailed for each plant below are ranked high, medium and low depending on their mitigation potential. Actions have not been prioritised beyond this level of detail at this time. The main reason for this is that measurement data and identification of trends and patterns in emission rates need to be identified first. This will give insight into which of the actions below have the most potential. A further analysis will be required at this point to determine the cost and risk of implementation of each of the identified actions.

This set of mitigation strategies has been identified as the most likely to achieve our goal. At this point in time, it is not possible to provide an estimate of the emission reduction or even the timeframe in which it would be achieved. Work will continue in this area so that the timing and quantum can be better understood.

Rosedale N_2O mitigation strategies



Oxygen management

Mitigation action	Objective	Application considerations	Potential	Short term foundational actions (12 months)	Desired outcome Long term (1-10 years)
Aeration control optimisation NN	Reduce both N_2O production and stripping in aerated zones by better adjusting aeration to oxygen requirements	Currently manual control for three MLEs MLE4 has zonal control 4 blowers, with outlet diffusers, ramp from 3 blowers down to 1 overnight. Operating at around 52kpa Headers A5 and 6, B6 to B2 Weighted average of Dissolved Oxygen probes across three points. DO set point at around 2.	High	• Like-for-like butterfly valves on replacement schedule. • Potential to push for vacumass valves for better control. • Better air flow meters. Move to hotwire to get more confidence.	
Enhance denitrification HD	Decrease N_2O production potential by nitrification and increase N_2O sinks	Effluent consent allows for flexibility in the ratio of ammonia versus nitrogen in the effluent. Consider driving ammonia higher, considering headroom in the TN consent. Keep an eye on downstream impacts – eg algae and odour in the ponds.	High	• Consider use of Ammonia vs Nitrate (AvN) control, which has not been currently utilised • Optimise internal recycle and RAS recycle flows • Reduce mixing in A1 to induce anaerobic conditions under high F:M ratio to promote internal carbon storage for denitrification	
Intentional, sustained low DO operation HD NN	Intentional operation in limiting DO in the nitrifying zones to either minimise N_2O production and/or promote N_2O consumption.	Could start in swing zones through manual weighting of probe so overall weighted DO is influenced more by others. Should support reduction in energy consumption. Potential to try on MLE4 as it has highest levers to pull. Then consider business case for roll out to others. Low DO could have an undesired opposite effect by promoting the ND N2O production pathway Bulking may be an issue to be considered. Not necessarily related directly to low DO. Potential for passing on N2O to next phase (e.g. effluent).	Medium	• Trial low DO operation by gradually operating at lower DO • Install ORP measurements for refinement of aeration control	

Ammonia management

Mitigation action	Objective	Application considerations	Potential	Short term (12 months)	Long term (5-10 years)
Optimisation of non-ideal flow splitting NN	Avoid unequal loading of MLEs	Loading is assumed to be equal	Low		
Plant-wide liquors balancing and flow distribution NN	Avoid nitrogen load peaks	20-24% of TKN load is from digested liquors	High		Automatic flow balancing
Sidestream anammox NN	Decrease nitrogen load to mainstream	Considered as part of upgrades with Thermal Hydrolysis post 2030 Sidestream anammox have been shown to be prone to risk of high N_2O emissions if not properly operated however could be better suited to covering and destruction of gas due to high intensity/low footprint	High	Consider in capital programme feasibility work and need/benefit of sidestream treatment.	N recovery and local liquid N recovery to remove significant post-digestion N load.
Load balancing via Central Interceptor NN		Smooth diurnal ammonia load profile through upstream balancing through pump station operation and/or upstream interventions in spines and CI dry weather operation	Medium-high	Consider short-term control options	Fundamental changes to operation of system.

Carbon management

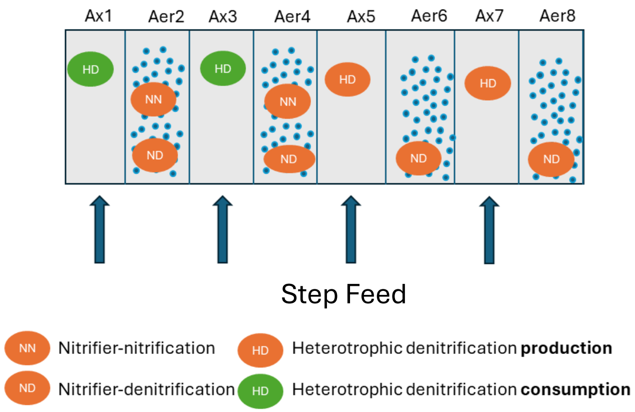
Mitigation action	Objective	Application considerations	Potential	Short term (12 months)	Long term (5-10 years)
Implementation / optimisation of carbon dosing HD HD	Increase N_2O reduction by heterotrophic denitrification HD	Additional C dosing in view of N_2O mitigation can be considered, including a trial dosing unit on one reactor. Additional carbon streams could be considered Smart C dosing based on advanced control to be assessed Carbon sources may impact N_2O emissions and life cycle footprint and swap a scope 1 emission to a scope 3 Consider cost benefit Influent and carbon mixing (if dosed) to be assessed; carbon limitation risk in some zones	High	Trial dosing unit on one reactor, supported by model-based dosing evaluation Evaluation of (future) dosing locations Temporary diversion Characterise biomass from time to time to determine the applicability of increased carbon dosing as a strategy for N_2O mitigation. Characterisation could be through batch assays	

Biomass management

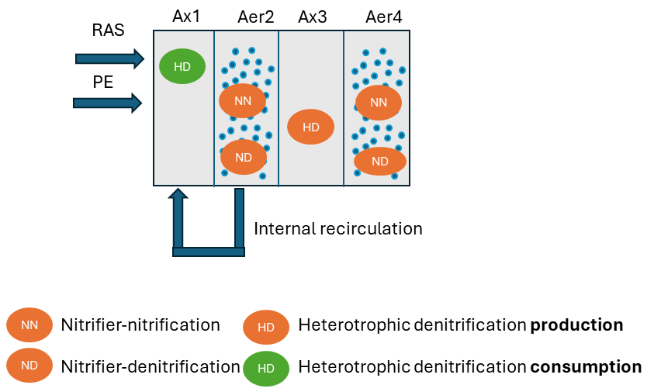
Mitigation action	Objective	Application considerations	Potential	Short term (12 months)	Long term (5-10 years)
Densification to increase sludge inventory HD	Decrease N_2O production by increasing biomass inventory and decreasing specific activity rates	InDENSE might be implemented, allowing higher hydraulic capacity, and therefore the potential to increase biomass inventory (longer SRTs) Insufficient/no evidence at present but potential to increase sludge inventory with (relatively small) granulation has potential and not same questions/challenges as with larger granulation (e.g. AGS).	Medium	Observe impact through N_2O monitoring	
Optimisation of SRT control for minimised specific ammonia loading NN	Decrease N_2O production by optimising nitrifier inventory and reducing specific activity rates	Dewatering capacity might limit wasting capacity	Medium	Implement dynamic SRT control Carry out batch activity test to determine nitrifying inventory and activity rates	

Māngere N_2O mitigation strategies

Mangere Reactor Clarifier Process Flow



Mangere Bardenpho Process Flow



Nitrous Oxide Production/Consumption pathways

Oxygen management

Mitigation action	Objective	Application considerations	Potential	Short term foundational actions (12 months)	Desired outcome long term (1-10 years)
Aeration control optimisation NN	Reduce both N_2O production and stripping in aerated zones by better adjusting aeration to oxygen requirements	RCs: limited advanced aeration control possibilities (one combined long air header for all 9 RCs, this will be replaced with individual blowers by 2029) -RC 5 has process air flow meters + air T & P – potentially to be also installed at RC4 (currently on hold due to cost) -Bardenpho reactors (Reactor 10 & 11) have better aeration control flexibility (linear valves, airflow meters, cascade control) -RC 4&5 have multiple new ammonia sensors in aerated zones Ability to improve air distribution and timing through new blowers and control – both taper and blower system. Minimise the combination of high ammonia oxidation rate – high NH4 and high DO – through improved aeration control. Individual blower sets will be upgraded at each RC, rolling every year. Assume 2-3 blowers per RC and be completed by 2029. FBDA hasn't been replaced in 20 years and cleaning is problematic for operations. Diffusers could be replaced or repositioned individually now that the air flow will be per RC instead of centralised. -Some flexibility in airflow redistribution might exist (more of operational change) – more so in R10,R11 -When FBDA replaced, consider aeration taper. -Consider valve upgrades as part of this maintenance and redesign.	High	• Install additional airflow valves in RCs (if model shows effective) • If possible, can try ammonia-based aeration control in short term. • (immediate step is to measure and then see if control philosophy has positive impact) • RCs: model-based assessment of butterfly valve settings and manual readjustment of valves. • If possible, can try Ammonia-based aeration control in short-term. • Air flow estimation/validation using gas hoods. • Model-based evaluation of adjusted oxygen setpoints controls, targeting homogeneous DO across zones. Pay attention to sensor location in view of modelled gradients. • Oxygen transfer and energy efficiency evaluation	Install additional airflow valves in RCs (if model shows effective) Replacement (once blower rationalisation/optimisation improvements)

				• Evaluation for blowers' design and associated pipework/valve upgrades 20%	
Intentional, sustained low DO operation HD NN	Intentional operation in limiting DO in the nitrifying zones to either minimise N_2O production and/or promote N2O consumption.	Low DO could have an undesired opposite effect by promoting the ND N2O production pathway. Bulking may be an issue to be considered. Not necessarily related directly to low DO. Potential for passing on N2O to next phase (eg effluent).	Medium	Trial low DO operation by gradually operating at lower DO Install ORP measurements for refinement of aeration control	
Optimisation of mixing with respect to recycles and DO carryover – specifically for R10-11 ND	Minimise the consumption of RBCOD in anoxic zones to enhance potential for N2O consumption	Adjust and optimise internal recycles, minimise DO recycling	Med/low	R10-11: adjust internal recycles, and avoid DO recycling within constraints of existing system.	

Ammonia management

Mitigation action	Objective	Application considerations	Potential	Short term (12 months)	Long term (5-10 years)
Implementation / optimisation of step-feed NN	Apply an optimised ammonia load and mass of biomass in various zones	Limited RC step-feed optimisation potential (manual butterfly valves and no flow meters) -Risk – loading to clarifiers and difficulty in implementing.	High	RCs: Model-based assessment of effects on clarifiers of butterfly valve settings and/or flow changes and manual readjustment	Implement dynamic step-feed flow control. Note that this would potentially include using InDENSE to allow higher or different loads on existing clarifiers
Return loads NN	Decrease impact of nitrogen load on mainstream	20-24% of TKN load is from post-digestion cycle -R10 & 11 can potentially be used to take over some load from RCs (flat flow or load balancing possible and aeration	High	Model-based evaluation of load rebalancing options – increase load to R10-11 if beneficial for emissions	N recovery and local liquid N recovery to remove significant post-digestion N load.

		design might allow it) – only restriction is MLSS (additional thickening unit would be needed) -Given operational flexibility (more 'control handles to mitigate') in Bardenpho process, load rebalancing from RCs to R10 and R11 might be considered, while allowing for an appropriate F:M to be maintained, avoiding maximum specific growth rates. Centrate balancing - improve step feed of centrate to maximise biomass loading.			
Load balancing using CI to balance loads in dry weather NN		Smooth diurnal ammonia load profile through upstream balancing through pump station operation and/or upstream interventions in spines and CI dry weather operation	High	Consider short-term control options	Fundamental changes to operation of system.

Carbon management

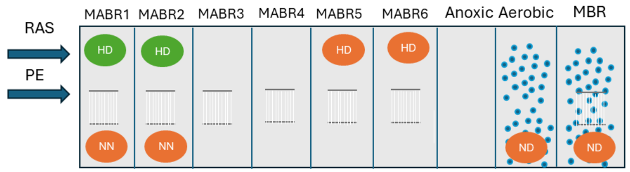
Mitigation action	Objective	Application considerations	Potential	Short term (12 months)	Long term (5-10 years)
Implementation / optimisation of carbon dosing HD HD	Increase N_2O reduction by heterotrophic denitrification HD	Additional C dosing in view of N_2O mitigation can be considered, including a trial dosing unit on one reactor. Additional carbon streams could be considered Smart C dosing based on advanced control to be assessed Carbon sources may impact N_2O emissions and life cycle footprint and swap a scope 1 emission to a scope 3 Consider cost benefit Influent and carbon mixing (if dosed) to be assessed; carbon limitation risk in some zones	High	Evaluate, based on measurement if N_2O is being produced in anoxic zones. If so, then investigate carbon dosing Evaluation of (future) dosing locations Temporary diversion Characterise biomass from time to time to determine the applicability of increased carbon dosing as a strategy for	

				N_2O mitigation. Characterisation could be through batch assays	

Biomass management

Mitigation action	Objective	Application considerations	Potential	Short term (12 months)	Long term (5-10 years)
Densification to increase sludge inventory HD	Decrease N_2O production by better managing inventory between zones and clarifiers and decreasing specific activity rates	InDENSE to be implemented, allowing higher hydraulic capacity, and therefore the potential to increase biomass inventory (longer SRTs) Insufficient/no evidence at present but potential to increase sludge inventory with (relatively small) granulation has potential and not same questions/challenges as with larger granulation (e.g. AGS).	Medium	Observe impact through N_2O monitoring. Further work needed on current RC8 InDENSE system to evaluate if rates are different and what impact InDENSE may have	Possible dynamic RAS control
Optimisation of SRT control for minimised specific ammonia loading NN	Decrease N_2O production by optimising nitrifier inventory and reducing specific activity rates	Dewatering capacity might limit wasting capacity	Medium	Implement dynamic SRT control Carry out batch activity test to determine nitrifying inventory and activity rates	

Pukekohe N_2O mitigation strategies



NN Nitrifier-nitrification
ND Nitrifier-denitrification
HD Heterotrophic denitrification **production**
HD Heterotrophic denitrification **consumption**

Oxygen management

Mitigation action	Objective	Application considerations	Potential	Short term foundational actions (12 months)	Desired outcome Long term (1-10 years)
Aeration Control Optimisation NN	To reduce or flatten ammonia gradients	Ammonia Feed Forward and feed back control can be implemented in the aeration zones, based on the Binder Flex Control system. This has the potential to lower the DO setpoint used in the aeration zones of the ASRs such that nitrification is occurring under limited substrate conditions. The plant already has Vacumass valves and zonal aeration control	High/Medium	Look to implement the Binder control system after a short period of N_2O measurement	After assessing the effect of ABAC control look to implement this permanently. Note that this system could also be used on the Māngere BNR as the valve setup and supplier are the same.

Ammonia management

Mitigation action	Objective	Application considerations	Potential	Short term (12 months)	Long term (5-10 years)
Minimise NN pathway in MBR reactors NN	Minimise the carryover of ammonia to MBR trains to minimise nitrification and stripping of N_2O.	Avoid the carryover of ammonia to the intensive aeration and stripping conditions within the MBR trains. This would involve making sure that the concentration of ammonia leaving the last aeration zone is minimised and is as close to zero as possible	Low/Medium	Verify ammonia concentration by offline or online measurement.	Look to ensure that, as the load to the facility increases over time, ammonia leakage to the MBR tanks is not occurring
Manage ammonia in returns NN	Minimise the return of high ammonia from pond 1	Potential to use pond 1 for load balancing to minimise ammonia peaks and return these flows at night or when loads are low	Medium	Investigate automation of return valve in pond 1 and monitoring the effect of ammonia spikes	
Manage ammonia Loads NN	Minimise ammonia load	Work with trade waste team to determine if industrial customers can decrease their discharge – particularly of protein to the WWTP or manage the time that these take place to avoid load surges or spikes	Low/Medium	Liaise with trade customers	

Carbon management

Mitigation action	Objective	Application considerations	Potential	Short term (12 months)	Long term (5-10 years)
Carbon Dosing HD	Use acetic acid to increase COD to N ratio to promote N_2O consumption	Carbon dosing is available - to boost denitrification. C/N ratio is already very good but could be improved. Potential to trial Carbon management directly from Unisense probes when these are installed.	Medium/high	Consider trial of tuning carbon dosing to residual N_2O concentration as measured via Unisense.	Long term OPEX evaluation needed as well as consideration of scope 3 emissions from the carbon source
Carbon Management HD	Alter Anoxic MF to maximise use of carbon available in wastewater to consume N_2O	Optimise the anoxic mass fraction by utilising swing zones. Possible to automate the "phasing" of the use of the swing zone with automatic valves to follow diurnal patterns etc.	High	Investigate the automation of the aeration system in the swing zone to either slow nitrification and/or to boost denitrification	

Biomass management

Mitigation action	Objective	Application considerations	Potential	Short term (12 months)	Long term (5-10 years)
Increase sludge inventory HD	Decrease N_2O production by better managing inventory and decreasing specific activity rates	Already running at high SRT (25-30 days) so could be used to assess if this has any effect. Could shut down a reactor if required to lower SRT if this was useful	Low/Medium	Look to design experiments or tests to determine if this approach has any effect. Consider if possible to take a reactor out or service to reduce SRT for same MLSS concentration	
Alter Internal Recycles NN	Increase or IMLR to flatten ammonia gradients	Alter the RAS ratio to increase or decrease, MLSS concentration in the ASR. Could also run higher recycle to flatten COD and ammonia gradients within the Plant. This would let the plant operate as more of a CSTR rather than plug flow. This has shown some promise in minimizing N_2O production. Caution with promoting carbon limited conditions	Medium/High	Measure ammonia and COD to determine gradients then look to trial higher IMLR	

Capital programme

A critical part of this strategy is how it will be delivered. For this strategy to succeed, the identified actions must be integrated into how we plan some of our infrastructure. In addition, the findings from our detailed work needs to be integrated into new facilities that are being planned. This strategy should not stand alone from the plant facility plans and should be part of an overall plan for each site to reach our level of service, growth and climate goals.

To deliver the reduction initiatives and to achieve 50 per cent reduction in nitrous oxide emission by 2030, changes in the operation of each plant, as well as assets, are required.

One of the major risks and potential roadblocks to progressing our emissions reduction is the ability of our existing plant assets to be operated in new ways that might be different to or even outside of their original design envelope. This is probably most significant at the Māngere Wastewater Treatment Plant, where many of the key assets are at least 20 years old. If these cannot be operated differently, then replacement over time with new assets as part of our renewals or upgrade programmes will need to be considered. The implementation of capital projects, given the scale of the Māngere site, is likely to be expensive and may take several years to complete. We therefore run a significant risk that we will understand how to mitigate our emissions, but not have the tools to make any progress.

Major capital projects

The following CAPEX projects are key to our success in mitigating N_2O and achieving Watercare's decarbonisation targets.

Decentralised blowers at Māngere

This project includes the replacement of the single blower room at Māngere with dedicated units for individual reactors or clusters of 2-3 reactor clarifiers. This project is considered critical to the success of the Māngere mitigation strategies. At this time the panel is sure that significant improvements in aeration control will be used for mitigation, although the abatement potential is not fully understood, therefore this project is considered a very significant enabler to ensure we have the tools we need to optimise aeration.

Centrate treatment

Centrate treatment is proposed for the Māngere and Rosedale treatment plants once the solids stream projects (thermal hydrolysis) are completed. These projects have the potential to reduce or remove significant ammonia loads (15-20%) from the liquid stream reactors. While side stream may have potential negative impacts on N_2O emissions, it is anticipated that a centrate treatment process would have a small surface area, meaning that it would be more suited to 'cover and destroy' type of mitigation. Significant additional work is required in the planning phases of these projects to understand the impact on the emissions and if it would be more cost effective to return these loads to the liquids stream and mitigate emissions there or to remove and mitigate these at source.

Capacity upgrades

In terms of N_2O emissions, the reconfiguration of the reactor clarifiers and expansion of the Rosedale MLEs could have significant mitigation potential. We are not yet able to definitively say what, if any, impact different configurations may have on emissions. There is no justification to alter the current configurations until we have more information.

Sludge Volume Index (SVI) improvements

Solids settling or Sludge Volume Index improvements are due to be implemented on four reactor clarifiers at Māngere between now and 2028. Rosedale may also be selected for SVI improvements.

At this time, we do not know if any improvements to emissions may be available with implementation of InDENSE, however granular sludge may provide further mitigation options in the future. Further academic study will need to be carried out on how N_2O and emissions and InDENSE interact as we implement these programmes of work.

Implementation

Our operational teams at our wastewater facilities will need to monitor mitigation and help to report and record improvements over time. It is important to note that long-term, potentially permanent changes will need to be made to how we run our plants. This must be achieved while at least maintaining compliance and operational cost at our facilities.

Suggested responsibilities are as follows:

- **Responsibility for delivery:** The project requires an executive sponsor who will provide leadership, guidance and governance to maintain momentum and progress. It is recommended that this is the chief strategy and planning officer. The delivery of the outcomes of the strategy must be viewed as part of our "day jobs" and not as an extra or addition to what we do. Given the complexity of the issues, the scope of the projects within the strategy, the uncertainty and urgency to take action on climate-related issues, a dedicated team needs to be allocated to deliver this strategy that sits within the overall strategy and planning team. These staff members would need to be supported by teams across the business.
- **Programme management and capital upgrades:** This strategy must be integrated with our programme delivery approach to our major treatment sites such that asset upgrades and renewals as well as major projects are considered holistically.
- **Research and development funding:** To progress our understanding, it is critical to maintain and enhance our relationships with the academic world and that we remain open to work with other utilities to build our knowledge. Watercare must drive the needs of our research, and given the skills needed to understand these issues, we must consider higher education for our employees such as Masters-level study.
- **Monitoring**: Funding for monitoring equipment has already been secured and instrumentation will be installed in the second half of 2024. For us to get quality information this programme needs to be supported, and equipment regularly maintained and calibrated after installation and commissioning.

Risks

Key risks

Misalignment with our Asset Management Plan

It is likely that, as our knowledge of N_2O emissions builds over time, asset upgrades or renewals not in our Asset Management Plan will be identified that are needed to progress mitigation. There is a risk of budget not being available to implement these or that implementation takes too long, resulting in Watercare not progressing mitigation or achieving our goals by 2030.

Resourcing

This strategy must be integrated into and become business as usual for our operations and delivery/planning teams. If this strategy sits to the side as an interesting but not essential set of projects, there is little chance of us meeting our 2030 goals.

Skills

Given the emerging nature of the science of understanding our emissions and the practical aspects of measuring our emissions, the level of skill required to deliver this strategy will be very high, at least in the initial stages. As there is no proven methodology or track record in the consulting market to help us deliver the strategy, this work cannot be packaged and given to the market to deliver in the same way as traditional optioneering or design. This means we may need to use internal Watercare skills and resources and specifically target individuals to help us deliver the strategy. At present there are no academics in New Zealand who have the skills we need to deliver aspects of this strategy. Therefore, much of this support will need to come from offshore.

Conclusion and future work

This process emissions strategy is the first of its kind in the wastewater sector worldwide. It provides Watercare with a tool to guide its actions in the reduction of process emissions from its wastewater treatment plants, both immediately, and in the long term. It builds on the work already done in 2021 as part the Watercare Decarbonisation Roadmap that identified N_2O emission mitigation as key to achieving its 2030 target.

The strategy uses state-of-the-art knowledge accumulated over the years by academics and practitioners in the field, but also provides new methodologies to convert this knowledge into practical and coherent full-scale implementation. A novel mitigation hierarchy that classifies actions into different categories to help prioritise implementation actions (avoidance, reduction and technology replacement) has been proposed.

It also proposes a novel implementation method that combines the simultaneous monitoring of N_2O with process modelling, in a synergetic manner, to speed up the understanding of the causes and implement mitigation actions, thereby avoiding lengthy monitoring campaigns that would delay mitigation actions.

A comprehensive assessment of the existing technologies and processes at Watercare's four largest wastewater treatment plants was carried out, along with the identification of potential N_2O emissions risks. This assessment has provided detailed potential actions to be carried out both in the short and long term, including both operational and design changes. These lists of potential actions will help Watercare start implementing mitigation measures while measurements and modelling provide further understanding into the causes and potential pathways for nitrous oxide mitigation.

The first action from this strategy is to implement the proposed measurement campaigns at Māngere and Rosedale wastewater treatment plants, set up data and data processing systems, and quality controls to ensure measured data is reliable and as accurate as possible.

Once data starts to flow from measurements, some initial understanding of possible pathways and nitrous oxide hot spots will be gained. It is expected from this point that some academic or more advanced work is needed to better understand cause and effect of the emissions and identify potential pathways to mitigation. In addition, work is required to understand if and how some of the new processes we are planning, such as InDENSE, may affect emissions.

In addition to measurement and innovation/research and development work, progress on integrating emissions-related capital and renewals programme is required. Given upgrades of significant assets will take a long period of time, they must begin soon to ensure we have the tools available to realise mitigation options in the near future.

Glossary of Terms

Term	Definition
NN	Nitrifier Nitrification pathway as it relates to nitrous oxide production
ND	Nitrifier Denitrification
HD	Heterotrophic Dentification (note this refers to both production and consumption of nitrous oxide)
DO	Dissolved Oxygen
Heterotrophic	Organism that uses organic carbon for growth
COD	Chemical Oxygen Demand
NH3	Ammonia Nitrogen
RAS	Return Activated Sludge
F:M Ratio	Food to micro organism Ratio
PE	Primary Effluent
InDENSE	Hydrocyclone Sludge Densification Technology