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Chapter 4

Designs of monitoring locations and case studies

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SUMMARY

This chapter presents a practical, top-down three-level framework (L1–L3) for selecting representative nitrous oxide monitoring locations in uncovered wastewater treatment plants. The approach systematically distinguishes sludge systems (L1), parallel versus non-parallel bioreactors (L2), and spatial heterogeneity within reactors (L3), supported by a decision-making tree and equations for plant-wide emission aggregation. The methodology is demonstrated using 19 full-scale international case studies, covering 12 typical configurations applied in practice: conventional activated sludge, step-feed, modified Ludzack Ettinger, Bardenpho, oxidation ditch, sequencing batch reactors (including aerobic granular sludge), membrane bioreactors/membrane aerated biofilm reactors, Modified University of Cape Town (MUCT), integrated fixed-film activated sludge, biofilters (biological aerated filter/Biostyr®), side-stream treatment systems, and other hybrid or site-specific designs. These cases illustrate how process configuration, aeration control, and spatial variability govern monitoring requirements and data representativeness. Practical lessons learned during implementation of monitoring campaigns are also highlighted across multiple case studies.

Keywords: monitoring location selection, total emission calculation, top-down three-level framework, typical configurations

4.1 PRINCIPLES OF MONITORING LOCATION SELECTION AND TOTAL EMISSIONS CALCULATION

The site selection described below focuses primarily on the aerated zones of the bioreactors. Although non-aerated zones – such as anaerobic/anoxic zones and primary or secondary clarifiers – do generate nitrous oxide (N_2O), they are not considered 'hotspots' for emissions due to the lower liquid-to-gas volumetric transfer rates.

4.1.1 Design of monitoring locations

The following three levels (L1, L2, and L3) are to be evaluated for a water resource recovery facility (WRRF) to select the number of necessary sampling points for N_2O monitoring for uncovered WRRFs:

L1: Number of Sludge Systems:
For one plant with different biological processes/configurations being used, or the biological reactors receiving different wastewater (e.g., mainstream and side-stream), each of these processes/configurations should be monitored individually. These biological processes/configurations are considered different sludge systems, each sludge system should be monitored separately.

L2: Number of Parallel Bioreactors:
Bioreactors that are fed simultaneously and operated under comparable process conditions can be regarded as parallel bioreactors and assumed to exhibit comparable N_2O emission dynamics, unless demonstrated otherwise. In such cases, monitoring may be conducted on one representative bioreactor. However, before selecting a representative monitoring bioreactor (may also be called 'lane' later on), equivalence between parallel bioreactors should be verified using available operational and performance indicators, such as dissolved oxygen (DO) profiles, air flow rate, ammonia and nitrite concentration trends, effluent nutrient concentrations, oxygen uptake rates, sludge age, mixed liquor suspended solids concentration, internal recycle configuration, and historical treatment performance data.

Separate monitoring is recommended where significant differences between lanes are observed or expected, including cases with intermittent or asynchronous feeding, uneven distribution of the daily incoming load, different internal recycle arrangements, incomplete mixing of influent wastewater, different aeration control strategies, different DO setpoints, different sludge retention times (SRTs), or other operational differences that may influence N_2O production and stripping. Once the equivalence of parallel or identical bioreactors has been confirmed, one representative bioreactor can be selected for monitoring. Bioreactors that cannot be regarded as operating equivalently in parallel should be monitored individually to ensure representative plant-wide N_2O emission estimation.

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L3: Number of monitoring locations within one bioreactor:
Bioreactors that are assumed completely mixed during aeration can be monitored with only one representative sampling point. Bioreactors with spatial concentration gradients are ideally equipped with multiple measuring points. For bioreactors designed in multi-stage processes (e.g., A–B process) or with step-feed, since process conditions can vary substantially between the stages or steps, it is recommended to select at least one monitoring location per process stage or per step. Then within each process stage or each step, depending on the number of aeration zones, the monitoring locations can be determined based on the number of aeration zones. In general, along with the flow direction, each aeration zone (i.e., either controlled with different DO set-points or control strategies or designed with different diffuser density) should be monitored as one monitoring location (with one hood or one liquid sensor placed). For long lanes (e.g., over 50 m) without subdivision into cascades, even when diffusers are evenly distributed, multiple measuring points (e.g., after 1/6 of the reactor length, in the middle and at 5/6) are also recommended to cover spatial variation of emission along the flow direction.

For anoxic zones, although there is no active stripping of N_2O, normally it is very useful to monitor them with liquid sensor to inform the level of dissolved N_2O generation by denitrification and also its contribution to the total N_2O emissions (some of the later full-scale case studies have anoxic zones being monitored for this purpose). The suggested monitoring location in the anoxic zone is toward the end of the anoxic zone. Monitoring dissolved N_2O in anoxic zones improves interpretation of downstream stripping-driven emissions during subsequent aeration.

After the monitoring locations have been selected, the measurement apparatus should be installed following the method-specific guidance provided in chapters 2 and 3. In brief, gas-phase hoods should be positioned to capture representative off-gas from the selected aerated zone, avoiding obvious local disturbances from walls, baffles, mixers, or uneven turbulence. Dissolved N_2O sensors should be fully submerged at a representative mixed-liquor depth and positioned away from walls, diffusers, mixers, or stagnant regions (Figure 4.1).

To summarize, determining the number of the monitoring locations should start from the plant level, then to the bioreactor level and to the zones level. The total number of monitoring locations can be calculated using Equation (4.1):

$$Total\,Number\,of\,Monitoring\,Locations = \sum_{1}^{L1=i} L2_j \cdot L3_k \tag{4.1}$$

where i represents the number of sludge systems within a plant (level 1), j represents the number of nonparallel bioreactors (i.e., different bioreactors) within one sludge system, while k represents the number of separate zones that should be monitored within one bioreactor.

4.1.2 Total emission calculation from multiple locations

In this section, we suggest the following three steps to calculate total emissions from a plant, assuming the N_2O fluxes (gN/m^2) from each of the monitoring location are known using the methods introduced in chapters 2 and 3:

Step 1: Calculate emission from different monitoring locations in one bioreactor (level 3).

The emission area for one bioreactor (L3) corresponds to one monitoring location ($k = 1$), or more than one location ($k > 1$).

$$Emissions_{L3,Total} = \sum_{1}^{k} Flux_k \cdot Area_k \tag{4.2}$$

where k represents the number of separate zones that should be monitored within one bioreactor, $Flux_k$ represents the N_2O flux (gN/m^2) from the monitored location, while $Area_k$ is the corresponding

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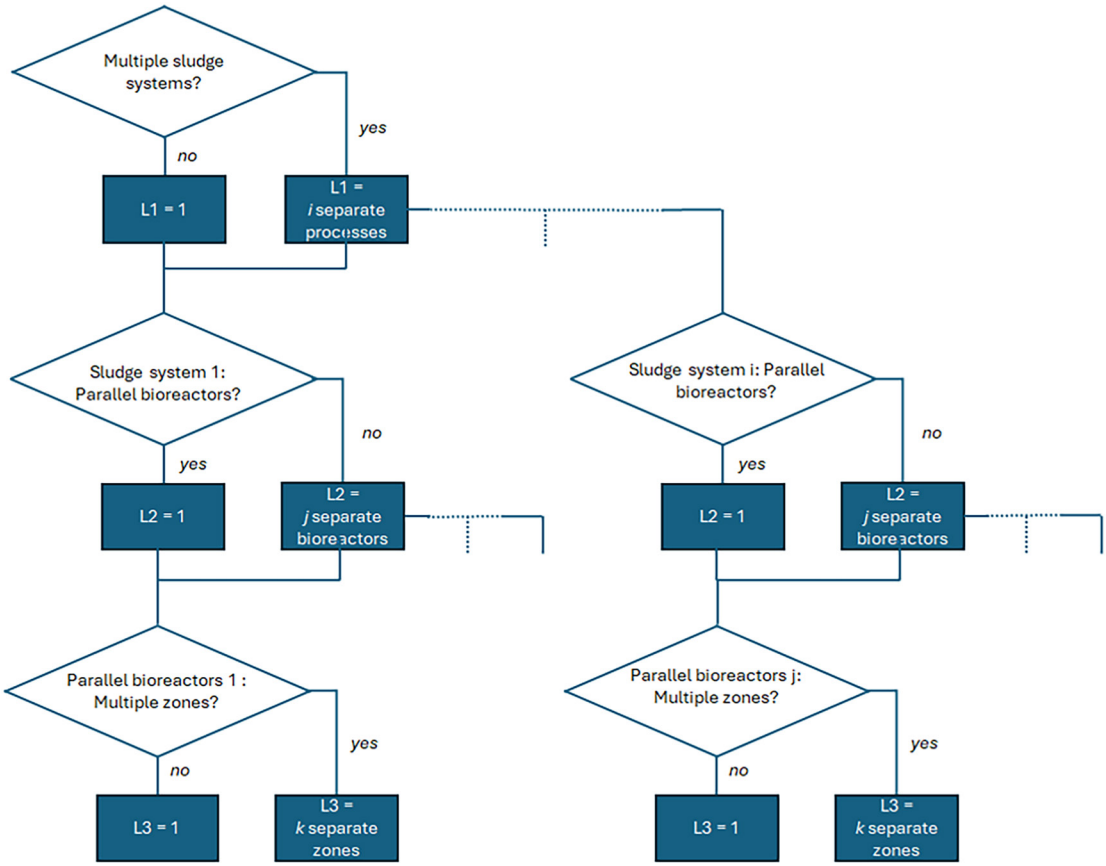


Figure 4.1 Illustrated simple decision-making tree for the monitoring location determination based on the three-level top-down method L = level.

surface area (m^2) of the monitored zone. Detailed calculations of the Level 3 N_2O emissions (g N/day) for each monitored zone are provided in chapter 2, section 2.3, and chapter 3, section 3.4.2.

Step 2: Calculate emissions from parallel bioreactors (level 2).
The emissions from parallel bioreactors (L2) are calculated based on the number of parallel bioreactors ($j = 1$) or separated bioreactors ($j > 1$), where j represents the number of non-parallel bioreactors L2:

If L2 = 1,

$$Emissions_{L2,total} = Emissions_{L3,total} \cdot n \tag{4.3}$$

where n represents the number of the parallel reactors.

If L2 > 1,

$$Emissions_{L2,total} = \sum_{1}^{j} Emission_{L3,total,j} \cdot n_j \tag{4.4}$$

where j represents the number of non-parallel bioreactors L2.

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Step 3: Calculate emissions for whole plant (different configuration) (level 1).
The emissions from multiple sludge systems (L1) are calculated based on the number of parallel sludge systems (L1 = 1) or separated sludge systems (L1 > 1), where i represents the number of different sludge systems in L1:

If L1 = 1,

$$Emissions_{L1,total} = Emissions_{L2,total} \tag{4.5}$$

If L1 > 1,

$$Emissions_{L1,total} = \sum_{1}^{i} Emission_{L2,total,i} \tag{4.6}$$

where i represents the number of different sludge systems in L1.

Two illustrated examples to determine the number of sampling locations and the calculation of total emissions are shown below. To calculate the emissions from multiple locations we need to consider the heterogeneity within one bioreactor (L3), within bioreactors (L2), and within sludge systems (L1).

Example 1
Determine monitoring location(s):

Level 1: In this plant, the secondary treatment is using a plug flow conventional sludge system. Therefore, there is only one sludge system, L1 = 1.

Level 2: The plant is designed with four bioreactors, fed the same influent load simultaneously and the bioreactors share the same sludge. The four bioreactors are also operated equally (same SRT, same DO set points). Therefore, the four bioreactors can be regarded as parallel and only one of the bioreactors needs to be monitored, L2 = 1 (Figure 4.2, left).

Level 3: There are four aeration zones in each bioreactor, controlled by different DO set points. Each aeration zone represents substantially different conditions and the emissions from each aeration zone cannot be assumed equal. Therefore, each of the aeration zones is considered as one monitoring location, L3 = 4 (Monitoring locations are also indicated in Figure 4.2, right).

Total N_2O emission calculation – Example 1:

Step 1: Since L3 = 4, so $k = 4$, based on Equation (4.2)

$$Emissions_{L3,total} = \sum_{k=1}^{4} Flux_k \cdot Area_k$$

Step 2: Since L2 = 1, but $n = 4$, based on Equation (4.4)

$$Emissions_{L2,total} = Emissions_{L3,total} \cdot 4$$

Step 3: Since L1 = 1, based on Equation (4.5)

$$Emissions_{L1,total} = Emissions_{L2,total}$$

Example 2
Figure 4.3 shows two other examples, which have non-parallel bioreactors.

Determine monitoring location(s):

Level 1: In both plant examples (plants A and B, Figure 4.3), the secondary treatment is a plug flow conventional sludge system. Therefore, in both cases, there is still only one sludge system and L1 = 1, same as Example 1.

Level 2: Plants A and B operate with four reactors, are fed with the same wastewater and share the same sludge. However, in plant A, reactor 2 has a de-aeration zone operated before the last aeration

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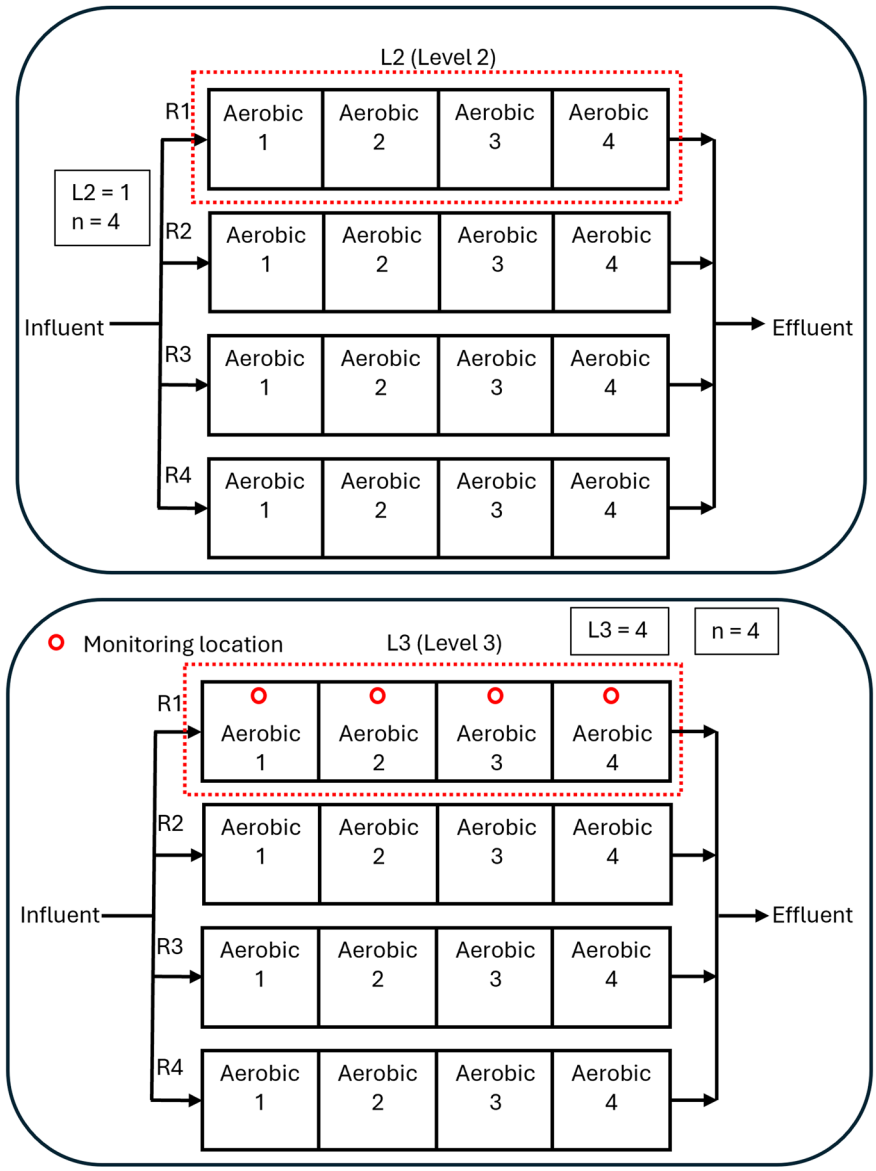


Figure 4.2 Example of L1 = 1, L2 = 1, and L3 = 4.

zone (e.g., long-maintenance or failure), while reactors 1, 3, and 4 are operated equally and can be considered parallel reactors. In plant *B*, reactor 3 has a higher loading compared to reactors 1, 2, and 4, which are fed similarly and can be considered parallel reactors. Therefore, bioreactors with different operations (i.e., reactor 2 in plant *A* and reactor 3 in plant *B*) also need to be monitored and L2 = 2.

Level 3: Level 3 monitoring locations are equal to those in Example 1, except reactor 2 in plant *A*. Since there is one anoxic zone, monitoring in this zone is optional as no active stripping of N_2O occurs in this zone. Therefore, for reactor 2, the monitoring location $k = 3$, but for the rest of the reactors, $k = 4$.

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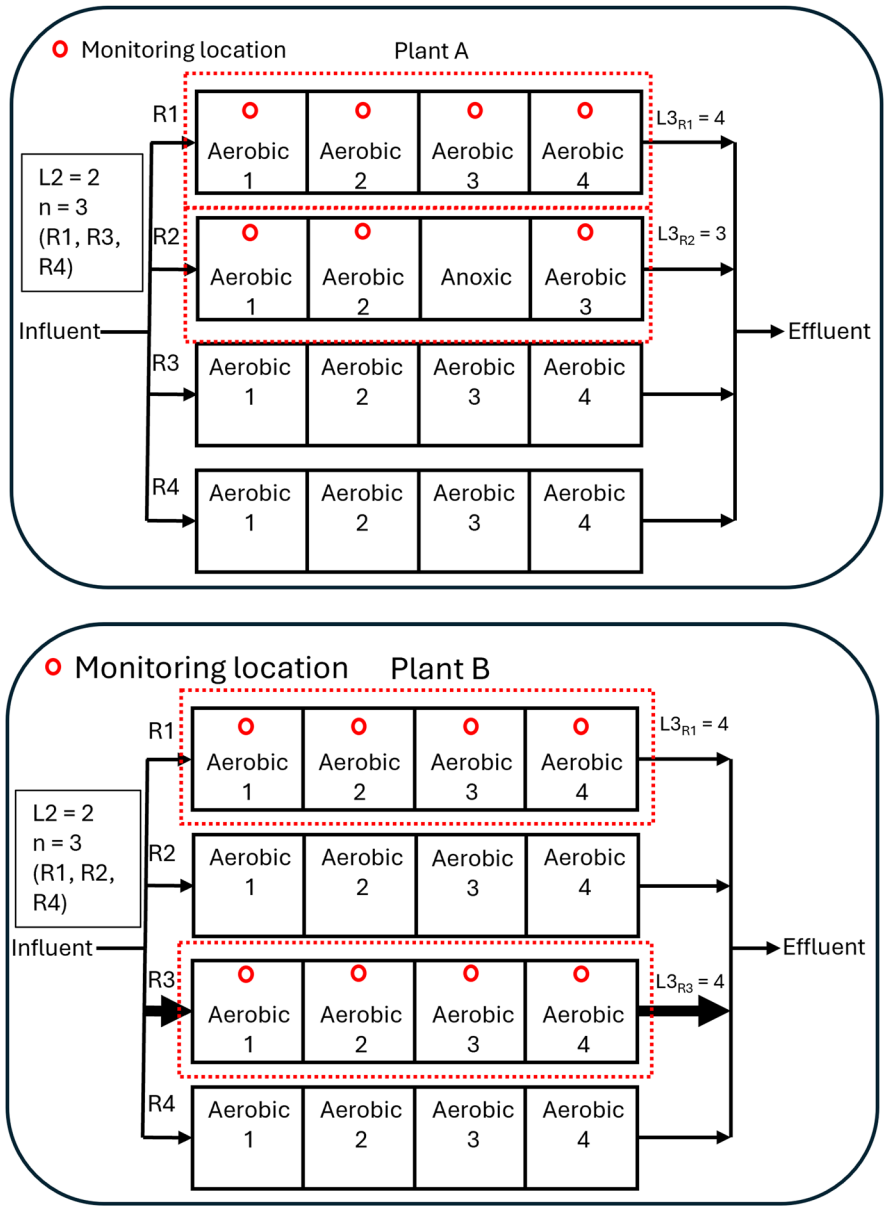


Figure 4.3 Example of L1 = 1, L2 = 2 for different operational (left) and feeding (right) strategies.

Total N_2O emission calculation – plant A:

Step 1: For reactor 1, $k = 4$, based on Equation (4.2),

$$Emissions_{L3,R1} = \sum_{k=1}^{4} Flux_k \cdot Area_k$$

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For reactor 2, $k = 3$, based on Equation (4.2),

$$Emissions_{L3,R2} = \sum_{k=1}^{3} Flux_k \cdot Area_k$$

Step 2: Since L2 = 2, and for parallel reactor (reactor 1, 3, and 4) $n = 3$, based on Equation (4.4)

$$Emissions_{L2,total} = Emissions_{L3,R1} \cdot 3 + Emissions_{L3,R2}$$

Step 3: Since L1 = 1, based on Equation (4.5)

$$Emissions_{L1,total} = Emissions_{L2,total}$$

Total N_2O emission calculation – plant B:

Step 1: For Reactor 1, $k = 4$, based on Equation (4.2),

$$Emissions_{L3,R1} = \sum_{k=1}^{4} Flux_k \cdot Area_k$$

For Reactor 3, $k = 4$, based on Equation (4.2),

$$Emissions_{L3,R3} = \sum_{k=1}^{4} Flux_k \cdot Area_k$$

Step 2: Since L2 = 2, and for parallel reactor (reactors 1, 2, and 4) $n = 3$, based on Equation (4.4)

$$Emissions_{L2,total} = Emissions_{L3,R1} \cdot 3 + Emissions_{L3,R3}$$

Step 3: Since L1 = 1, based on Equation (4.5)

$$Emissions_{L1,total} = Emissions_{L2,total}$$

4.2 CASE STUDIES

4.2.1 Case studies for plants with more than one sludge system

4.2.1.1 Bolivar wastewater treatment plant – SA Water Corporation

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(1) Site Description and Operation

The studied wastewater treatment plant (WWTP) is located in Adelaide, Australia, and receives wastewater from a variety of sources, including domestic sewage, industrial effluent, occasional surface water runoff, and infiltrated groundwater. The plant employs two primary biological treatment systems: a sequencing batch reactor (SBR) system and a step-feed plug-flow reactor system. These systems are designed to efficiently remove organic matter and nutrients, ensuring compliance with environmental discharge and reuse standards.

The SBR system consists of six identical tanks, with five in operation at any given time while one remains offline for maintenance during the monitoring period. Each tank receives approximately 20% of the total influent, with an average daily flow of around 25 ML/day. The system follows a cyclic batch operation, with

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15-h hydraulic retention time (HRT) and 12–18 days SRT. Each cycle consists of filling, reaction, settling, and decanting phases, with intermittent aeration controlling nitrification and denitrification. Aeration is regulated by maintaining DO levels between 0.5 and 2.8 mg O_2/L during filling and reaction phases.

The step-feed plug-flow system consists of four identical reactors. Each reactor consists of four treatment paths, receiving a total flow of 50 ML/day. The influent is split into two feeds, with 56% entering the first step (including paths 1 and 2) and 44% entering the second step (including paths 3 and 4). Each step contains an anoxic zone for denitrification, followed by two aerated zones for nitrification. Return activated sludge (RAS) is recycled to the beginning of the anoxic zone. Aeration control is based on DO setpoints, maintained at 1.0 mg O_2/L.

(2) Selection of Monitoring Locations

The selection of N_2O monitoring locations at Bolivar WWTP follows a structured, multi-level design approach to account for system configuration, process dynamics, and spatial variations in emissions. The overall monitoring strategy is illustrated in Figure 4.4, showing the spatial distribution of monitoring locations across different treatment zones.

Level 1: Identify the number of sludge systems (L1 = 2)

Bolivar WWTP consists of two separate biological treatment systems: the SBR system and the step-feed plug -flow system. Since these two treatment systems operate independently with different process configurations and aeration strategies, N_2O emissions from each system must be monitored separately.

Level 2: Determine the Number of Parallel Bioreactors (L2 = 1 per system)

The SBR system consists of five identical tanks operating under the same conditions. However, for the purpose of N_2O monitoring, the system is treated as a single representative unit, meaning L2 is considered as 1.

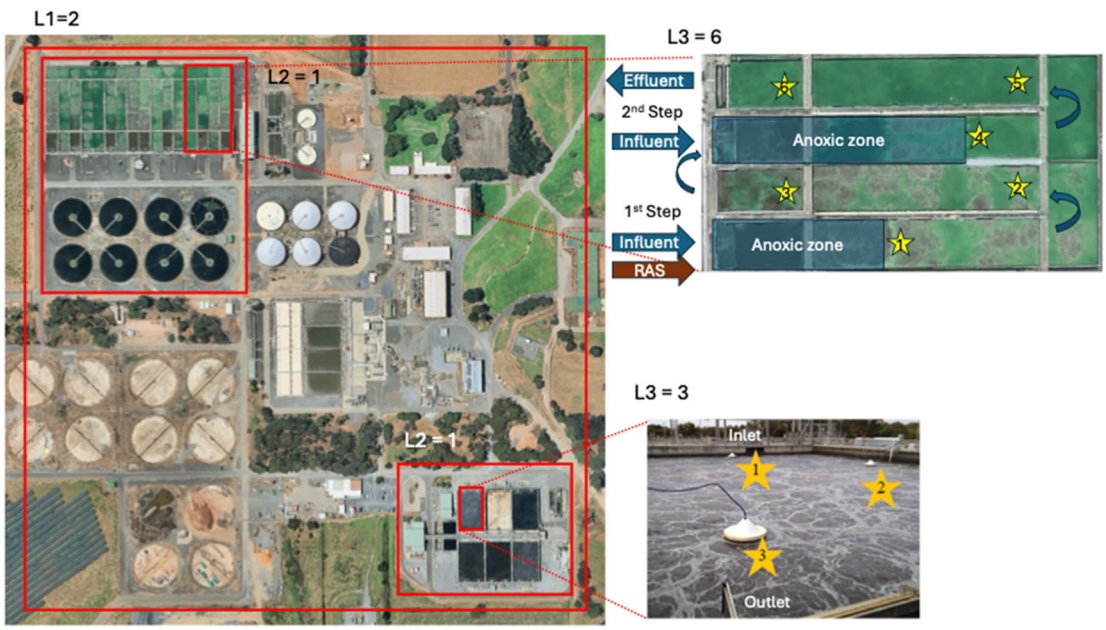


Figure 4.4 Overview of N_2O monitoring locations at Bolivar WWTP. The plant consists of two independent biological treatment systems (L1 = 2): the SBR system (L2 = 1) and the step-feed activated sludge reactor system (L2 = 1). Monitoring locations within each system are designated as L3, with three locations in the SBR (L3 = 3) and six locations in the step-feed (L3 = 6). The image on the right illustrates the specific monitoring locations within each system, highlighting the use of floating hoods for gas-phase N_2O collection.

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Similarly, the step-feed system consists of four continuous-flow reactors that were operated in parallel. Since they operate identically and receive the same influent, L2 is also defined as 1 for this system.

Level 3: Determine the Number of Monitoring Locations Within One Bioreactor (L3 = 3 for SBR, L3 = 6 for Step-feed)

Within the SBR system, three monitoring locations are selected to capture key process phases. One monitoring location is positioned near the influent inlet, where high ammonia concentrations may contribute to relatively higher N_2O production. A second monitoring location is placed in the middle of the aeration zone, where mixing is expected to be relatively sufficient. The third monitoring location is situated near the effluent decanting area to assess potential spatial emissions. The monitoring setup is illustrated in Figure 4.4. It should be noted that the use of three monitoring locations in this study was designed for scientific investigation. For a completely mixed SBR, one representative monitoring location is generally sufficient for routine N_2O quantification.

Within the step-feed system, six monitoring locations are distributed along the start, middle, and end of aerobic zone path to capture spatial variations in emissions. The first step-feed zone is monitored at three locations: at the beginning of the aeration zone, 50 m from the aeration start, and 155 m from the aeration start (locations 1–3). The second step-feed zone is monitored at three locations: at the beginning of the aeration zone, 25 m from the aeration start, and 80 m from the aeration start (locations 4–6). These monitoring locations are chosen based on potential significant differences in N_2O emissions in plug-flow systems, as well as considering the impact of step-feed design. The gas hoods were not placed in the anoxic zones as previous studies have shown that N_2O fluxes from un-aerated zones are negligible.

(3) Key Learnings

N_2O emissions in the SBR system were generally higher near the influent inlet, likely due to localized ammonia oxidation activity following influent addition. However, because the SBR is designed to be well mixed during aeration, the observed spatial variation is not expected to require multiple monitoring locations for routine emission quantification. The use of three monitoring locations in this study was primarily intended to support scientific investigation of spatial emission patterns. For routine monitoring and quantification in a completely mixed SBR, one representative monitoring location is generally sufficient (Duan *et al.*, 2020).

In contrast, the step-feed system showed much stronger spatial variability. N_2O emissions were significantly higher in the second step-feed zone, where biomass-specific nitrogen loading was elevated. The six monitoring locations along the reactor path revealed substantial spatial gradients, demonstrating that a single monitoring point would not adequately capture plant-wide emissions in this configuration (Pan *et al.*, 2016). These findings highlight that the need for distributed sampling should be determined by reactor configuration and expected spatial heterogeneity. For completely mixed systems, one representative location may be sufficient, whereas multi-stage, step-feed, or plug-flow-like systems generally require multiple monitoring locations along the reactor length to capture process-driven variations and improve the accuracy of full-scale N_2O emission assessments.

4.2.1.2 Christies Beach wastewater treatment plant – SA Water Corporation

Authors & Affiliation: Ilda Clos, Petra Reeve and Sarah Aucote from SA Water Corporation

(1) Site Description and Operation

Christies Beach WWTP services southern metropolitan Adelaide, Australia. The WWTP receives municipal and industrial wastewater from the sewer network, as well as infiltrated groundwater, but does not receive non-sewered trade waste.

There are two distinct mainstream activated sludge systems at Christies Beach WWTP: modified Ludzack Ettinger (MLE) and Bardenpho/membrane bioreactor (MBR) plants. The MLE A and B

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plants receive primary effluent from primary sedimentation tanks, while the Bardenpho/MBR C plant receives screened sewage. Accordingly, the mixed liquor suspended solids (MLSS) concentration of A and B plants is maintained at a lower concentration than C plant, equal to ~2500 mg/L in A/B plant and ~4500 mg/L in C plant.

The average daily flow to A and B plants is 7.7 and 7.4 ML/day, respectively, and 18.7 ML/day to C plant. The A and B plants have HRTs of ~9 and 10.4 h and maintain a sludge age of ~13.5 and 15 days, respectively. The average DO concentration of A and B plants is ~2.4 and 3.2 mg/L, respectively.

The MLE plants were designed as integrated fixed-film activated sludge (IFAS) plants but are operated without IFAS media, resulting in oversized blowers for the system. This leads to unintended over-aeration during non-peak periods (i.e., overnight) and is responsible for the relatively high average DO concentration. In contrast, C plant maintains a lower average DO concentration (~1.0–1.3 mg/L) and a sludge age of 9.3 days.

Both activated sludge systems feature swing zones that are aerated during peak periods – 9:00 and 14:00 on weekdays and 9:00 and 21:00 on weekends. Effluent is either discharged to the ocean, used for aquifer recharge, or supplied for commercial irrigation during the warmer months. As such, ethanol-based carbon dosing is required in the cooler months to support denitrification for compliant effluent discharge to the environment.

(2) Selection of Monitoring Locations

N_2O monitoring was conducted using both gas-phase and liquid-phase approaches. Off-gas was collected via closed flux chambers or hoods and analyzed using non-dispersive infrared gas (NDIR) analysis. Each gas-phase greenhouse gas (GHG) monitoring unit continuously measures air flow, pressure, and temperature from three off-gas sources (each source may be connected to one or multiple hoods), and sequentially analyses the N_2O concentration of samples from each – such that each off-gas source is monitored approximately once per hour.

The liquid-phase approach employs Unisense liquid N_2O sensor systems to measure N_2O concentrations in the bioreactors and infer the emissions based on gas–liquid mass transfer. The liquid sensors were deployed to (1) compare the quantification methods between the gas and liquid methods; (2) to calibrate the liquid-gas transfer coefficient; (3) to provide additional data for modelling.

The monitoring locations at the WWTP were selected based on the three-level method that accounts for: the number of sludge systems (Level 1, or L1), number of parallel bioreactors (Level 2, or L2) and number of monitoring locations within one bioreactor (Level 3, or L3) (Figure 4.5).

Level 1: Identify the Number of Sludge Systems (L1 = 2)

Christies Beach WWTP consists of two separate biological treatment systems; the MLE A/B plants and Bardenpho/MBR C plant. These systems are operated entirely independently and receive distinct influent streams; therefore, they must be monitored separately (L1 = 2).

Level 2: Determine the Number of Parallel Bioreactors

A/B plant ($L2_{\_A/B} = 1$)

The MLE A and B plants consist of pairs of identical bioreactors and are only distinct because A plant was commissioned in 1961, followed by B plant in 1980. All four bioreactors within the MLE A/B plants, designated A1, A2, B1, and B2 – are fed simultaneously, and theoretically receive 25% of the total A/B plant influent flow. RAS is pooled between all bioreactors before the stream is reintroduced, while mixed liquor return (MLR) is independent within each bioreactor. Therefore, from an operational perspective, the system functions as four identical bioreactors, therefore ($L2_{\_A/B} = 1$). Each parallel bioreactor operates under comparable SRT and aeration control strategies. Advanced aeration control (AAC), which uses an ammonium-based aeration control strategy, has recently been commissioned in the A/B plants to improve operational performance, but can revert to conventional DO control if necessary.

Although monitor one of the four parallel bioreactors in A/B plants is enough for quantification purpose, we decided to monitor two parallel reactors in A/B plant which allows us to perform the

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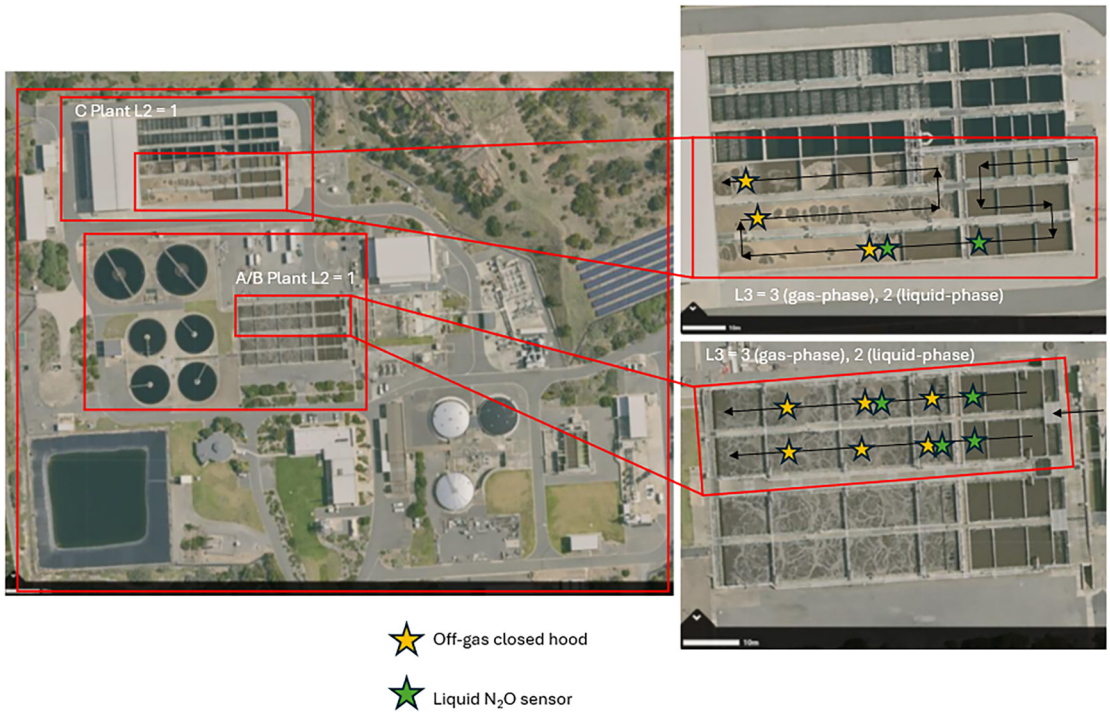


Figure 4.5 Overview of N_2O monitoring locations at Christies beach WWTP. The plant consists of two independent biological treatment systems (L 1 = 2): Bardenpho/membrane bioreactor C plant (L2 = 1) and MLE A/B plants that have capacity to control aeration via either standard DO control or ammonium-based aeration control ($L2_{\_A/B} = 1$). Three gas-phase (off-gas closed hood samples) and two liquid-phase (liquid N_2O sensors) monitoring locations were selected per bioreactor (L3 = 3 gas-phase, 2 liquid-phase).

assessment of AAC impacts on N_2O emissions to use one as control and the other as experimental. Accordingly, N_2O monitoring was conducted in the B1 and B2 plants.

C plant (L2_C = 1)

Only one bioreactor is operational within the Bardenpho/MBR system, designated C1 plant, so this was selected as the sole candidate for monitoring.

Level 3: Determine the number of monitoring locations within one bioreactor (L3 = 3 gas-phase and 2 liquid-phase)

B1 and B2 plants

The MLE plants have several distinct zones, including three anoxic zones, 1 swing zone, 2 aeration zones, and 1 deaeration zone (Figure 4.6).

Despite this, each reactor has one swing zone and one aerobic zone, using a single automatic aeration valve controlled either by conventional DO control via one DO sensor (between aeration zones 1 and 2) or by AAC (ammonium-based aeration control which uses two online ammonium sensors (end of anoxic zone and between aeration zones 1 and 2), along with the existing DO sensor and another in the deaeration zone. While all the aeration zones have the same diffuser density, the swing and aeration zones of each of the bioreactors are equipped with static manual aeration valves set during plant commissioning. Therefore, although, L3 = 2 could be considered sufficient given there is only one DO control setpoint per bioreactor in each aerobic zone, L3 = 3 was applied to enable a more comprehensive assessment of spatial variation, particularly given the presence of fixed manual aeration settings across zones.

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Additionally, two liquid-phase monitoring locations were selected: one sensor in the anoxic zone of each of B1 and B2 to understand the contribution of N_2O stripping to emissions, and one sensor in the aeration zone 1 of B2 and the swing zone of B1, to allow for comparison to gas-phase monitoring.

C1 plant

The Bardenpho/MBR system includes a bioselector zone, followed by six anoxic zones, two aeration zones (aeration zone 1A and 1B), four post-anoxic zones, and one final-aeration zone (aeration zone 2) (Figure 4.7).



Figure 4.6 N_2O monitoring locations in Modified Ludzack Ettinger B1 and B2 plant: three gas-phase (off-gas closed hood samples) and two liquid-phase (liquid N_2O sensors) monitoring locations were selected per bioreactor (L3 = 3).



Figure 4.7 N_2O monitoring locations in the Bardenpho/Membrane Bioreactor C1 Plant: three gas-phase (off-gas closed hood samples) and two liquid-phase (liquid N_2O sensors) monitoring locations were selected per bioreactor (L3 = 3 gas-phase, 2 liquid-phase).

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Aeration control in C plant follows the same principles as conventional DO control used in A/B plant, but C plant has three DO sensors compared to one in A/B plant. These are located at the halfway point of aeration zone 1A, the three-quarter mark of aeration zone 1B, and the midpoint of aeration zone 2. Each sensor controls an automatic aeration valve, resulting in three DO setpoints. Consistent with A/B plant, the aeration zones have the same diffuser density; however, zones 1A, 1B, and 2 contain three, four, and one manual valves, respectively, to control air flow. Again, these static manual valves were set during plant commissioning.

Therefore, L3 = 3 is the minimum required based on the three DO setpoints in C plant. However, ideally, L3 = 8 is preferred as this is equivalent to the number of manual valves that control aeration over the three aeration zones. Due to the capacity of the gas-phase GHG monitoring unit in this study, only L3 = 3 was applied, though spatial variation will be investigated separately and/or off-gas from multiple hoods may be pooled for analysis. As with A/B plant, liquid-phase monitoring was also applied in the anoxic zone and aeration zone 1A. The liquid-phase monitoring designed in this case is more for scientific purpose, rather than for quantification.

(3) Key Learnings

N_2O emission monitoring is being conducted over two years to enable thorough investigation of seasonal variation. This is supported by preliminary data analysis which has revealed prominent seasonal variation. Diurnal variation is also substantial, with N_2O emission peaks corresponding to plant nitrogen loadings and swing zone operation.

Challenges encountered during monitoring are usually technical or logistical issues related to the monitoring equipment. Gas-phase monitoring requires frequent maintenance (2–3 weeks) to manage condensation formed from off-gas sampling. Additionally, there is a requirement to calibrate the NDIR analyzer on a biweekly basis to ensure data accuracy.

Ongoing work and data analysis will investigate the source and cause of N_2O emissions within and between bioreactors, as well as compare monitoring methodologies and understand spatial variation within bioreactor zones. Preliminary results show notable differences N_2O emissions between the MLE and Bardenpho/MBR bioreactors.

4.2.1.3 East Ayrshire wastewater treatment works – Scottish water

Authors & Affiliation: R. McConnell, Scottish Water, E. Russell, M. Stoyanova, K. McGibbon, D. Hume and R. Lucas from Mott MacDonald Limited

(1) Site Description and Operation

Scottish Water are rolling out a N_2O monitoring program across their larger wastewater treatment works (WwTWs). These WwTWs have been identified as high priority for process emissions monitoring as these treat more than 70% of the total population equivalent in Scotland and many of them have the highest N_2O risk factors for high emissions. The sites were assessed using 10 risk factors from existing site data including, among others, final effluent nitrite levels, ammonia failure status, capacity utilization, difference in influent and consent ammonia. Most of these sites are fairly conventional ASPs; however, there are some sites that differ from our conventional treatment, such as Nereda and BAFF. This case study will focus on a site which incorporates three processes which we are monitoring for N_2O emissions:

- **Site *WwTW***

Located in East Ayrshire this WwTW has a population equivalent (PE) of **18,000**. This site has four processes that potentially produce N_2O emissions: Fine bubble diffuser aeration (FBDA) activated sludge plant (ASP), surface aeration ASP, nitrifying SBR and tertiary nitrifying sand filters. For the purposes of our current monitoring program we will be monitoring for N_2O only at the two types of ASP lane and the SBR as no standard methods exist for sand filters.

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(2) Selection of Monitoring Locations

The selection of monitoring locations at this site followed a consultancy-led structured approach based upon current industry best practice and sensor manufacturer guidelines.

There are three separate sludge systems within this site (L1 = 3): two within the wastewater treatment works and one as part of the sludge treatment center (Figure 4.8).

Within the wastewater treatment process, secondary treatment is undertaken firstly through two fine bubble diffuser aerated ASP lanes which operate in parallel followed by two surface aerated ASP lanes which operate in parallel ($L2_{ASP} = 1$). Two liquid phase sensors will be placed in each of these steps of secondary treatment for both the FBDA and for the surface aerated ($L3_{ASP} = 2$).

- For the FBDA ASP, emissions are expected to be highest near the start of the aeration zone since this is where FBDA is most intense and the concentration of ammoniacal nitrogen for nitrification is at its highest. The emission rate is then expected to decrease along the reactor length.
- For the surface aerated ASP, emissions are expected to vary spatially across the lanes and will vary significantly depending on the immersion depth of the aerators, their speed, and the number of aerators in operation. Two liquid sensors are still deployed in lane 1, in both aeration zones, however, the quantification method is different to the fine bubble diffuser system (see chapter 6 for the methodology). Care has to be taken in the placement of the sensors, as they cannot be placed too close to the aerators due to the risk of damage.
- The SBR operates as a batch process involving a series of treatment steps in a single reactor. As such, N_2O emissions are expected to vary over the different sequences of the treatment process. What is expected is that N_2O emissions are highest at the aerated treatment steps and lowest at the settlement and decant steps of the treatment process.

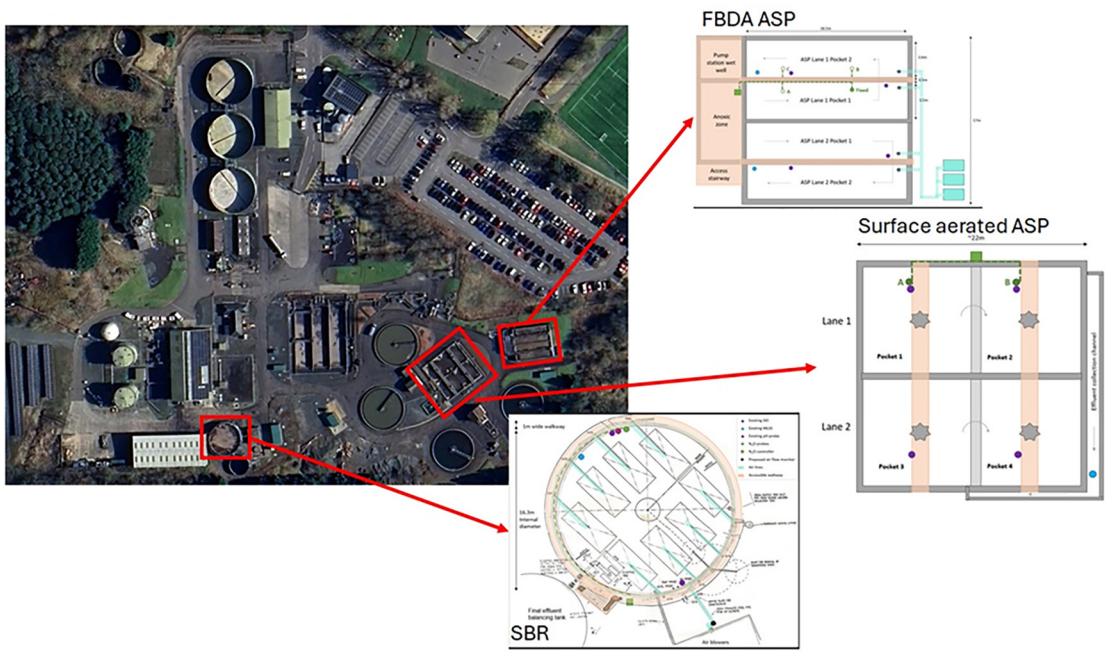


Figure 4.8 Site-wide N_2O liquid sensor locations.

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Location of liquid probes for N_2O:
N_2O emissions typically vary spatially along ASP lanes which is why an approach has been developed which uses one fixed probe located one third of the way down an aeration lane and then a mobile probe which is moved at fixed intervals from halfway down the lane to close to the end of the lane (Figure 4.9). Two probes used in this way can give an approximation of spatial variation and the overall lane emissions. Only one lane is being monitored in each type of ASP (FBDA and surface aerated) as there is an assumption that each is operating at similar parameters and therefore the N_2O readings from one lane will be representative of all lanes ($L2_{ASP} = 1$).

For the sludge treatment center, the liquors produced by the sludge treatment center are treated in a single SBR ($L2_{SBR} = 1$). One liquid N_2O probe will be placed in the SBR as it is assumed to be well mixed ($L3_{SBR} = 1$). The effluent from the SBR is then recycled into the WwTW upstream of the ASP.

Site-specific sensor locations for this site are listed below (Figure 4.9):

Process Unit	Recommended Monitoring
FBDA ASP	Two liquid phase N_2O sensors situated in ASP lane 1 (one in each aeration zones, with the mobile location indicated as in location A, B and C).
Surface aerated ASP	Two liquid phase N_2O sensors adjacent to existing DO sensors in pockets 1 and 2.
SBR	One liquid phase N_2O sensor in SBR tank adjacent to existing pH and DO sensors.

For all liquid N_2O probes, we aim to locate them near other existing probes, such as DO, MLSS, and pH. This allows for various site data parameters to be brought together, and they are at comparable spatial points in the treatment process which is more meaningful for data analysis.

Scottish Water plan on using gas hood measurement to undertake spot checks over a short period of time to validate the data from the liquid phase N_2O monitors and the air flow rate measurements. The gas hoods will be placed as close as practical to the liquid phase monitors in order to allow good validation of data. The gas hoods are likely not to be utilized on the surface aerated treatment process because of the challenges around how agitated the surface becomes creating difficulties for the hoods to operate.

(3) Key Learnings
Due to delays in the installation of the liquid phase monitors these have only been in place since end of July 2025. Therefore, key learnings on N_2O are difficult to identify at this stage.

Air flow measurements are proving to be a challenge at our sites and the three different types of aeration technologies are expected to provide additional challenges, especially when undertaking a site wide emission factor (EF) calculation.

- For the FBDA ASP lanes having air flow measurements at each lane is key, this has been difficult at other sites as air flow is not measured at each lane. At this site however, there are four existing air flow monitors, measuring air flow to each pocket of the two FBDA ASP lanes. To ensure good quality data, the air flow readings need to be validated and the monitors recalibrated if needed.
- For the surface aerated ASP lanes, air flow measurement is not dependent on air flow monitors as it is based on a calculation on power consumption of the aerators. The difficulty for this method is the standard aeration efficiency measurement, this is not always accurate as the SAE for rotors is a very wide and very poorly evaluated field. The SAE number can be quite wide dependent upon brush rotor type. There is an alternative method, using online k_La estimation using fast DO sampling.
- The SBR on this site operates its aeration blowers at a fixed speed and constant air flow rate until a DO set point is reached. To achieve an even air flow is reliant on operators making manual changes to individual airline valve positions to create an even air flow split across the reactor surface. This is done by visual inspection, and it is assumed that the SBR is well-mixed but there could be over- or under-estimation of emissions.

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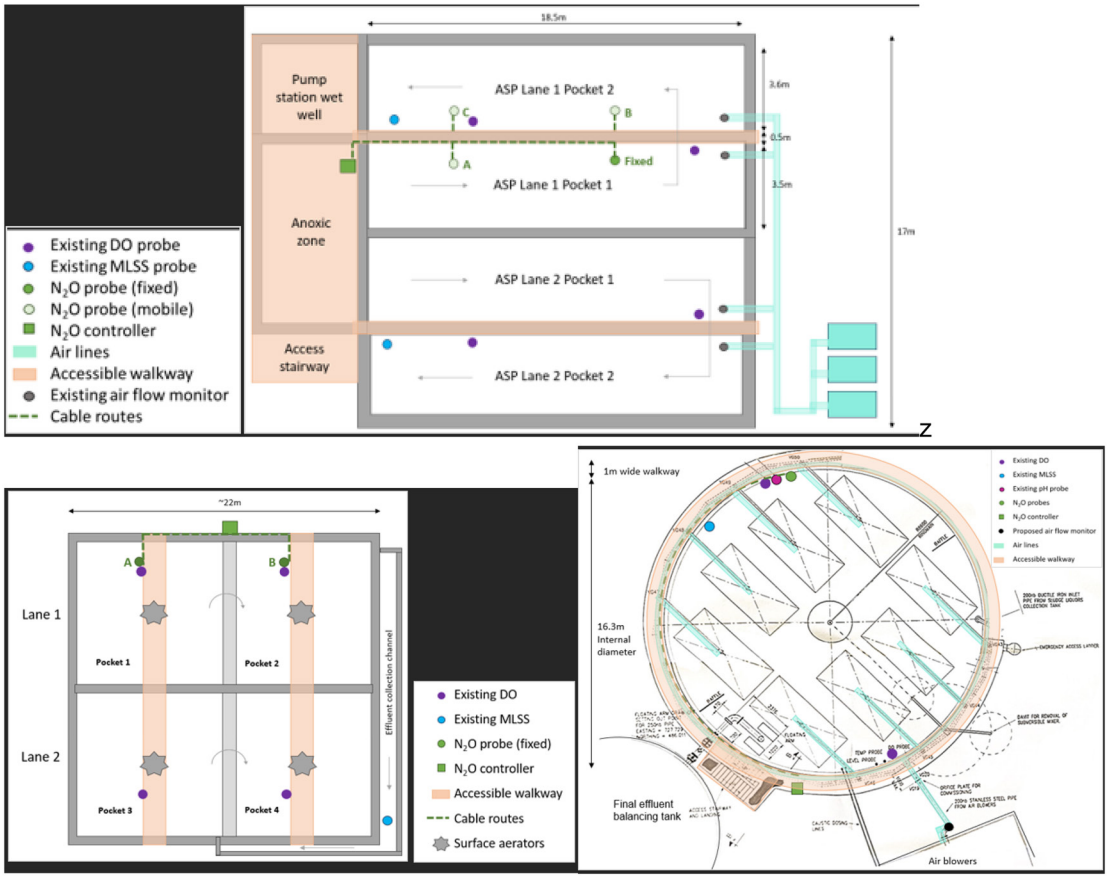


Figure 4.9 ASP lane liquid sensor locations (top). Surface aerated ASP lane liquid sensor locations (bottom left). SBR liquid sensor locations (bottom right).

Air flow is an ongoing challenge in the calculation of emissions factors for N_2O on our sites. We are also investigating the use of soft sensors and modeling to reduce the need to install air flow meters.

4.2.2 Step feed

4.2.2.1 Melbourne waterNnutrient Removal plant (NRP) at western treatment plant – Melbourne water

Author & Affiliation: Peter Wardrop from Melbourne Water

(1) Site Description and Operation

The Western treatment plant is one of the two largest wastewater treatment facilities operated by Melbourne Water. Nutrient Removal Plant (NRP) at Melbourne Water's Western Treatment Plant is a full-scale step-feed activated sludge system with a treatment capacity of approximately 140 ML per day. The plant is designed for biological nitrogen removal, achieved through nitrification (aerobic oxidation of ammonia to nitrate) followed by denitrification (anoxic reduction of nitrate to nitrogen gas). The scope of this case study focuses on the NRP system only.

Key NRP process and configuration features (see Figures 4.10 and 4.11):

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Figure 4.10 NRP site layout and process configuration, showing four circular reactors each operating with a four-pass step-feed arrangement.

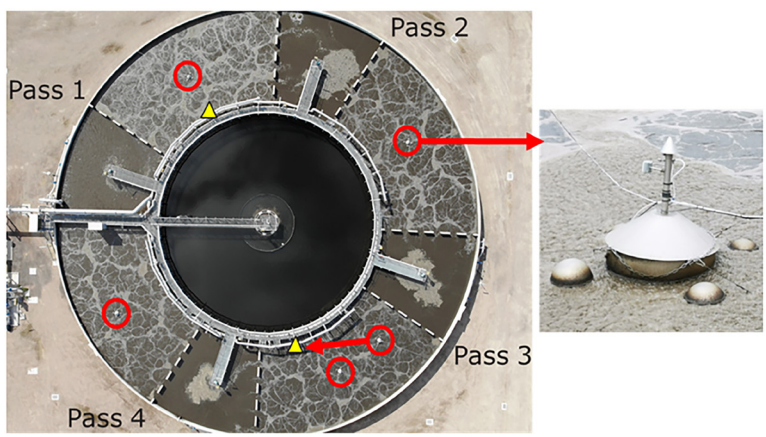


Figure 4.11 NRP Tank 2 configuration and monitoring layout showing the locations of gas collection hoods (red circles) and dissolved N_2O sensors (yellow triangles). Four hoods were installed – one in the center of each aerated pass – and an additional movable hood in pass 3 to assess spatial variation in emissions within that pass.

- Four circular biological reactors operated in parallel, each received around 35 ML/d.
- Each reactor configured in a four-pass plug-flow layout.
- Each pass consists of paired anoxic and aerobic (aerated) zones.

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- Influent to the NRP is sourced from an upstream anaerobic lagoon that treats raw sewage; NRP influent is collected both midway through the lagoon and at the lagoon effluent.
- Influent is distributed within each reactor using a 4:3:2:1 step-feed ratio (from Pass 1 to Pass 4) to optimize carbon availability for nitrogen removal across passes.
- Final NRP effluent flows to secondary clarifiers in the center of each circular reactor for solids–liquid separation, enabling the return and wasting of activated sludge.

(2) Selection of Monitoring Locations

Level 1: Identify the number of sludge systems (L1 = 2)

The overall nutrient removal system receives the same wastewater that all goes through the same biological processes.

Level 2: Determine the number of parallel bioreactors (L2 = 1)

There four bioreactors are operated under the same conditions and they are fed simultaneously and perform comparably and so are assumed to be exhibiting comparable N_2O dynamics. This means that L2 is considered as 4. To quantify N_2O emissions, Melbourne Water installed off-gas collection hoods on Tank 2 of the NRP for direct emissions monitoring.

Level 3: Number of monitoring locations within one bioreactor (L3 = 4)

Hoods were deployed on all four aerated passes of Tank 2 (shown in Figure 4.11).

Hood collection and gas sampling system:

- Floating hoods were mounted in the middle of each aerated pass of Tank 2 to capture off-gas for N_2O concentration measurement. To verify the spatial variation within one aeration zone, a roving hood was designed to move in different locations (Figure 4.11, this hood was located in pass 3 aerobic zone).
- Each hood included a velocity sensor within a central vent stack for air flow rate measurement.
- An external vacuum pump extracted gas from the vent stack and delivered it to the analyzer.
- Gas-phase analysis was performed using Horiba Sample Conditioning Units (VS-3000/5000) and Horiba Gas Analyzers (VA-3000/5000).

(3) Results

Nitrous Oxide Patterns

More than two years of continuous monitoring at the 160S Nutrient Removal Plant (NRP_1) revealed significant spatial and temporal variability in N_2O and methane emissions. The results show that emissions are strongly influenced by treatment configuration, feed characteristics, operational conditions, and seasonal effects.

Figure 4.12 presents the N_2O concentration trends across the aerated passes of NRP_1. Emissions displayed pronounced seasonal variations, with higher concentrations generally observed during warmer months. Strong spatial variability was also evident across the four aerated passes:

- The highest N_2O concentrations consistently occurred in Pass 3 and Pass 4, where carbon availability was lowest and nitrate concentrations were highest.
- Measurements from the two hood positions in Pass 3 (Pass 3 and Pass 3_R) showed minimal spatial variation, indicating relatively uniform emissions across that aerated zone.
- These patterns highlight the sensitivity of N_2O production to operational and environmental conditions.

Emission Factor Analysis

Daily EF calculations showed substantial variability across the monitoring period (Figure 4.13). When averaged across the full period:

- The mean EF on a total nitrogen load basis was 1.2%
- The mean EF on a total nitrogen removed basis was 1.4%

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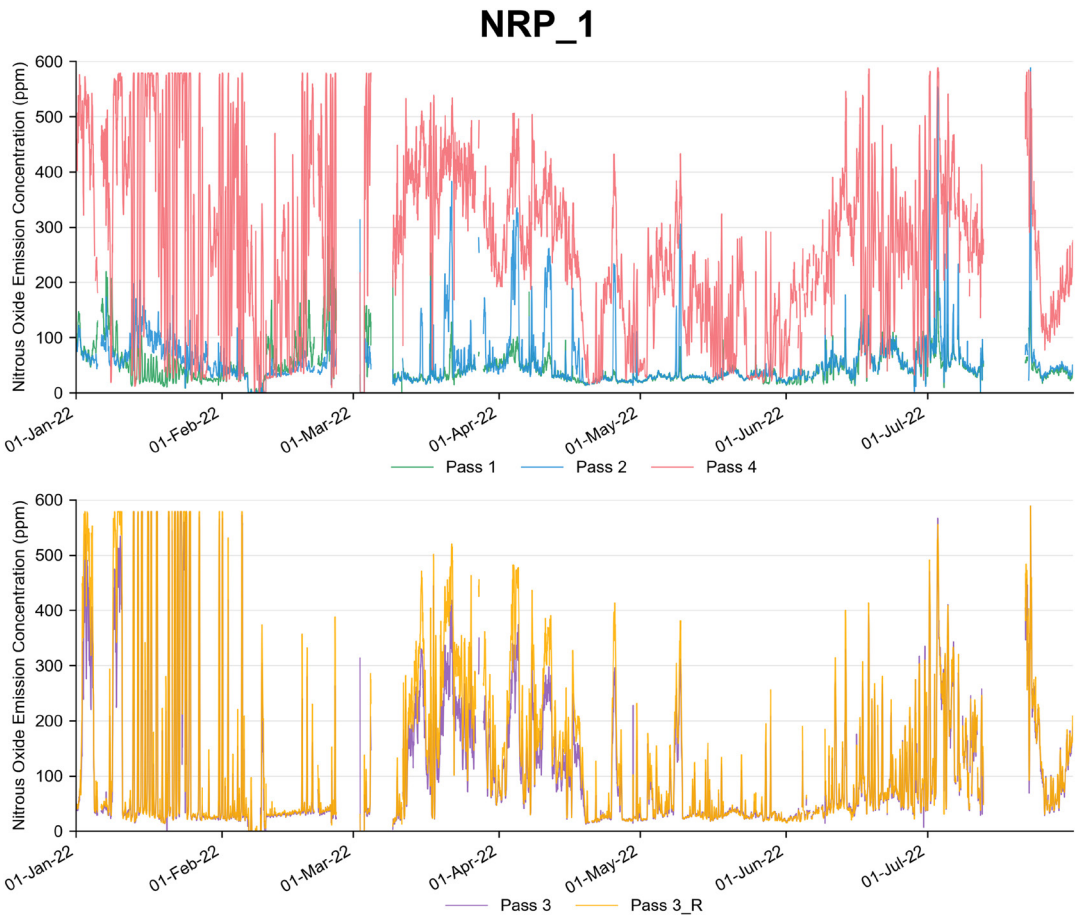


Figure 4.12 N_2O concentration trends across the four aerated passes of the NRP, showing strong seasonal and spatial variation and the consistently higher emissions in downstream passes (pass_3 and pass_4).

These results indicate that:

- Actual emissions at NRP_1 would be slightly lower than those implied by international reporting guidelines (IPCC default = 1.6% of total nitrogen load), and
- Almost three times higher than those reported under Australian national standards (NGERS default = 0.5% of nitrogen removed).

This variation highlights the limitations of both national and international default EFs and underscores the importance of direct measurement and/or improved reporting tools and methodologies to better characterize real emissions under site-specific operating conditions.

(4) Key Learnings

Air flow measurement challenges

The original monitoring system used open vent stacks with velocity sensors to infer air flow through each hood. However, several issues emerged during operation:

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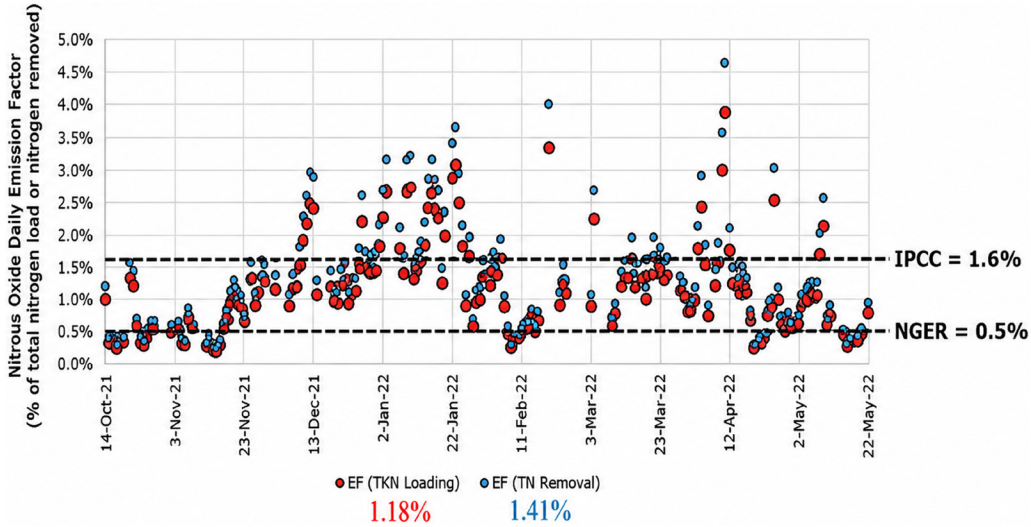


Figure 4.13 Daily N_2O EFs for NRP_1 calculated on both total nitrogen load (international IPCC basis) and total nitrogen removed (national NGERS basis). Default IPCC and NGERS EFs are shown as dashed reference lines.

- Sludge and biofilm accumulated inside the vent stacks, leading to velocity sensor fouling and occasional blockages.
- Fouling reduced the accuracy of air flow measurements and caused instability in calculated emission fluxes.
- The corrosive, humid gas stream resulted in short sensor lifespans and frequent sensor failures, requiring ongoing replacement.

Accurate air flow measurement is essential for reliable emission flux estimation, and both monitoring sites experienced similar challenges. Air flow sensors were found to have corroded, likely due to:

(i) splash and aerosol carryover from the mixed liquor beneath the hoods;
(ii) temporary foam build-up; and/or
(iii) rain ingress into the vent stacks.

To address these issues, hoods were retrofitted with elongated vent stacks and improved rain guards to protect the sensors (Figure 4.14). This modified design has since informed updated monitoring standards now adopted across multiple water utilities in Australia and New Zealand.

In parallel, Melbourne Water is trialling a fully enclosed gas collection hood system at the Eastern Treatment Plant. This new system uses inline volumetric flow meters, rather than open vent stacks and velocity sensors, to significantly improve air flow and emission flux measurement accuracy and enhance the overall robustness of future monitoring installations.

The monitoring program provided several important insights into emissions behavior and the practical requirements for reliable full-scale N_2O quantification. These learnings are summarized in Table 4.1.

Sector Value and Impact

The project has delivered significant value for Melbourne Water and the wider water sector by:

- Producing globally significant full-scale N_2O data that demonstrates the limitations of current reporting methods in capturing plant-specific variability; contributing to the evidence base

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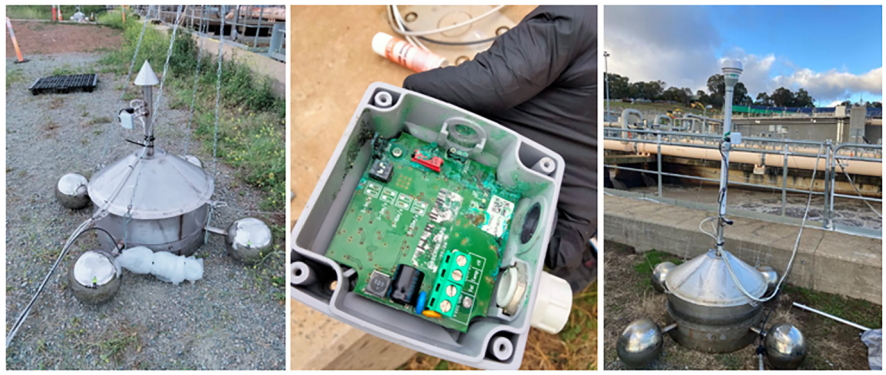


Figure 4.14 Retrofitting of off-gas hoods to improve flow sensor longevity, showing: (i) the original hood design (left), (ii) corroded flow sensor (center), and (iii) the modified hood with elongated vent stack and improved rain protection (right).

Table 4.1. Summary of key operational learnings from the NRP N_2O monitoring program.

Category	Key Learning
Sampling integrity	Closed systems are essential – open vent configurations resulted in fouling, corrosion, and unstable air flow measurements.
Data continuity	Continuous monitoring is required; intermittent or grab sampling does not capture short-term peaks or diurnal fluctuations.
Process behavior	Highest N_2O emissions consistently occurred in the later aerated passes, where carbon availability was lowest and nitrate concentrations were highest.
Seasonal sensitivity	N_2O emissions increased markedly during warmer periods, reflecting increased microbial activity and nitrogen transformation rates.

needed to develop more accurate and representative estimation approaches that better reflect actual emissions and support genuine reductions.

- Identifying key operational and environmental drivers of N_2O generation, informing optimization opportunities and supporting more effective mitigation strategies that are now being trialled at the Western Treatment Plant.
- Contributing essential data to a 15-utility, 20-plant national research program led by The University of Queensland and supported by the Australian Research Council, strengthening sector-wide understanding of emissions across diverse treatment configurations.

Melbourne Water continues to share findings transparently and collaborate across the sector to improve reporting practices and develop more accurate, evidence-based methods that support genuine emissions reduction and progress toward net zero.

4.2.3 Modified Ludzack Ettinger/AAO

4.2.3.1 Icon water

Authors & Affiliation: Clare Idriss from Icon Water & Xueying Zhang from The University of Queensland

(1) Site Description and Operation

Icon Water's main WWTP, Lower Molonglo Water Quality Control Center (LMWQCC), is located in Canberra, Australian Capital Territory, Australia. It typically receives and treats ~100 ML/day.

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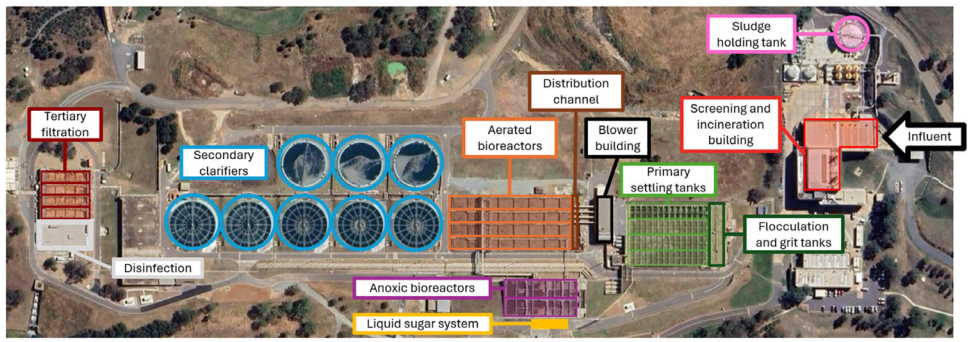


Figure 4.15 LMWQCC plant layout. Influent goes through mechanical screening then chemical dosing before primary treatment. Primary effluent enters the secondary treatment system where N_2O monitoring is carried out on a representative aerated bioreactor. The liquid stream then continues to the secondary clarifiers and then filtration and disinfection. Solids including screenings, grit, primary sludge and waste activated sludge (WAS) are directed to the sludge holding tank and on to heat treatment.

LMWQCC has primary, secondary, and tertiary treatment stages for the liquid stream and uses heat (thermal) treatment for solids management.

Figure 4.15 shows the overall layout of the site.

The primary stage includes chemical dosing of ferric chloride and lime to support chemical phosphorous removal and to aid sedimentation. There is also polymer dosing to aid sedimentation. Following dosing, flocculation, and grit removal, the liquid stream enters the primary settling tanks. Solids from these processes are sent to the sludge holding tank. Primary effluent proceeds to secondary treatment.

Secondary treatment uses a MLE process for biological nitrogen removal (BNR). The process configuration includes a pair of parallel anoxic bioreactors (ABRs) and four parallel aerobic bioreactors (BRs) followed by clarifiers for sludge settling. The secondary treatment system is described in more detail below including context for N_2O monitoring. Clarified effluent from the secondary clarifiers proceeds to tertiary treatment.

Tertiary treatment includes flocculant dosing followed by filtration, dosing with hypochlorite and then dechlorination by sulfur dioxide, prior to discharge to the Molonglo River.

Figure 4.16 shows the overall layout of the secondary process.

In Figure 4.16, the gray arrow at the bottom right shows where the primary effluent enters the ABRs together with RAS from the secondary clarifiers. Flow is equally split between the parallel ABR tanks. The blue arrows show the path of the mixed liquor being returned to the ABRs from a short anoxic zone in the BRs. Supplementary carbon (liquid sugar) is dosed to the ABRs to aid denitrification. The ABRs each have seven cells with the last two cells (swing cells) able to operate as swing as aerated zones to allow extended nitrification time when required.

The ABR effluent enters a distribution channel (not aerated) feeding the parallel BRs. There are eight cells in each of the four BRs and all cells are aerated apart from the second half of cell six – the short anoxic zone. The mixed liquor is returned (pumped) from this location to the ABRs.

(2) Selection of Monitoring Locations

There are four monitoring locations, and these were selected using the top-down three-level criteria-based method. The overall determination of the values for each of the three levels in this method are demonstrated in Figure 4.17.

Level 1: Identify the number of sludge systems (L1 = 1)

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The overall system receives the same wastewater that all goes through the same biological processes and one sludge system. This includes flows returned to the head of plant and mixed with the influent such as waste backwash water from the tertiary filtration system and scrubber water from the incineration exhaust system.

Level 2: Determine the number of parallel bioreactors (L2 = 1)

The anoxic and aerobic parts of the overall system both have parallel bioreactors (see Figure 4.17). Each set of parallel tanks (one set of anoxic and one set of aerobic) are fed simultaneously and perform comparably and so are assumed to be exhibiting comparable N_2O dynamics. This means that L2 is considered as 1.

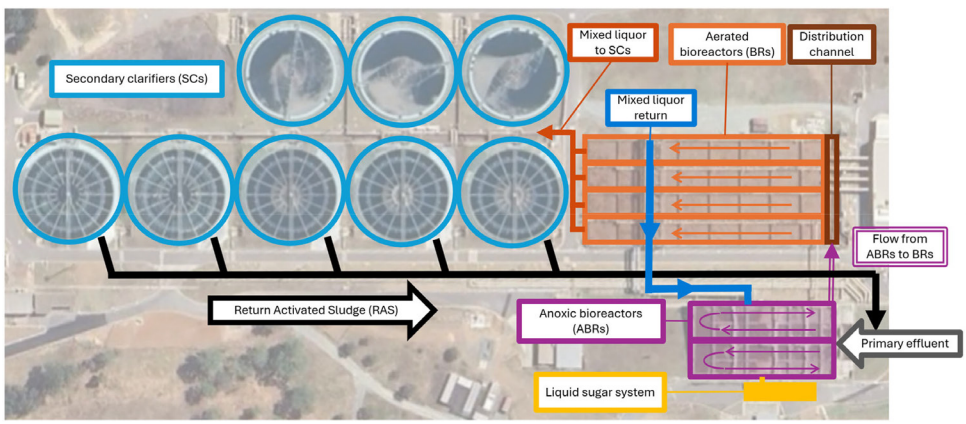


Figure 4.16 Layout of LMWQCC secondary treatment processes. The secondary treatment uses a MLE process with recycles of mixed liquor and RAS to the ABRs. The two tanks of the ABRs are parallel as are the four tanks of the BRs.

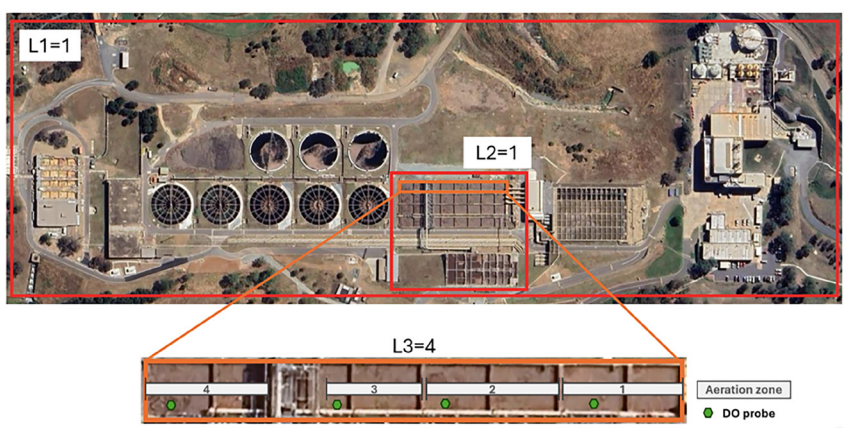


Figure 4.17 Overview of monitoring locations required at LMWQCC. The plant consists of one biological treatment system (L1 = 1). The MLE process in place uses parallel tanks (L2 = 1). Monitoring locations within the system are determined by the aeration control with each parallel aerated tank having four aeration zones (L3 = 4).

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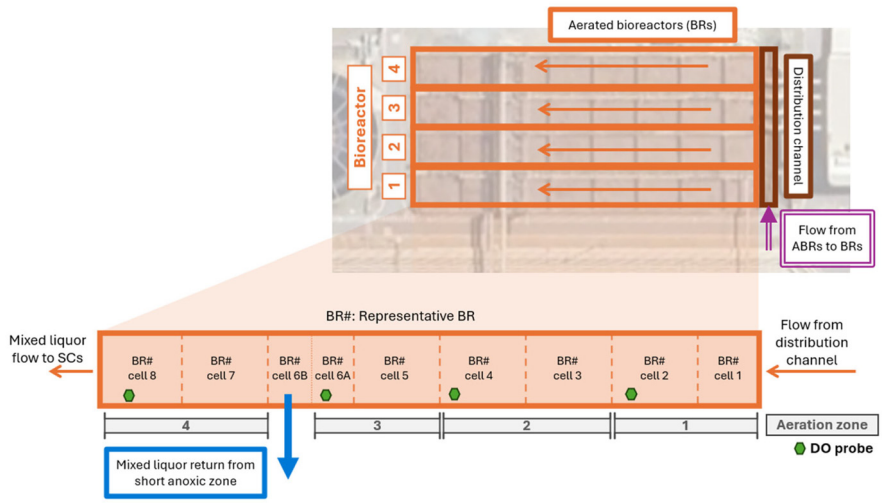


Figure 4.18 Aeration zone arrangement for a representative aerated bioreactor (BR). The upper part of the figure shows the section above and the lower part of the figure shows detail of the aeration zone arrangement that applies to each BR. The effluent from the anoxic bioreactors (ABRs) flows to the distribution channel and then into the BRs. Cell 6 is divided into cells 6A and 6B. Cell 6B is a short anoxic zone from which mixed liquor is returned to the ABRs. Each pair of cells is an aeration zone (apart from cell 6B) controlled together with one DO probe per pair. Aeration zone 3 covers only cell 5 and cell 6A.

Level 3: Number of monitoring locations within one bioreactor (L3 = 4)

Figure 4.18 shows the BRs and distribution channel with additional detail presented for a representative BR. This additional detail shows how each BR is divided into eight cells with cell 6 further divided into two sections, 6A and 6B. DO is monitored in every second cell and aeration is controlled for pairs of cells based on the DO for that pair. The figure shows the configuration of these pairs as aeration zones. There are four aeration zones in each BR with each zone having one DO probe. Examination of emissions when the swing cells are in operation in the ABRs has not yet been undertaken at this stage.

Monitoring locations and set up: Total number of sampling points = 4

With all wastewater received at LMWQCC going through the same set of processes and only one sludge system (L1 = 1), and given each parallel BR can be assumed to be equivalent (L2 = 1) with four aeration zones (L3 = 4), the number of locations required overall is four.

Figure 4.19 shows the location of the hoods *in situ*.

Gas sampling lines run from the hoods to a dedicated cabinet with gas conditioning, Horiba analyzer, and data logger. Gas is drawn from one hood for 10 min and then from the next, and so on. The data from the first 2 min after each hood change is discarded. Data from the gas analyzer is collated along with operational data for analysis. The operational data includes, but is not limited to, flow rates, ammonia concentration, DO, temperature, pH, and air flow rate and pressure. Many of these are provided for multiple locations through the plant.

(3) Key Learnings

There have been some unexpected findings around the pattern of emissions over time and space. The first two of these findings were regarding the trend from the beginning to the end of the BR. For both N_2O and methane monitoring it was expected that emissions would be highest in cell 1 and decreasing from there. However, for methane frequent peaks were occurring in cell 7 and N_2O concentrations

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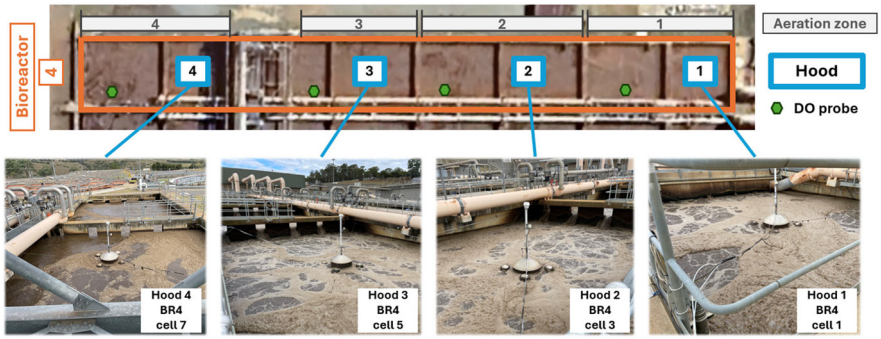


Figure 4.19 Bioreactor 4 (BR4) with aeration zones noted and images of hood locations. The hood locations are shown in aerial view in the upper section of the figure and images of the hoods in situ along with labeling are in the lower section.

were consistently highest from cell 7 after a low in cell 5. The methane peaks have been determined to be from a build-up of sludge in the short anoxic zone in cell 6B. This has been mitigated through adjusting the MLR pump operation to disrupt this build up. The pattern of N_2O emissions is still under investigation and appears to have multiple factors including cell lysis.

The other unexpected finding was that in the first year of monitoring emissions were higher over the warmer months and since then the emissions have been more in line with expectations for seasonality with higher levels during the cooler months. This highlights the importance of longer-term monitoring.

A less surprising finding has been that emissions have been lower following cleaning of BR4. This is likely due to improved aeration efficiency and reduced sludge build up. This leads to the question of how varied the emissions may be between the BRs. Addressing this is touched on in next steps below regarding the new design.

There have been a range of challenges with the monitoring project including:

- Weight of the hoods makes them challenging to retrieve and redeploy;
- Flow meters being damaged by corrosion;
- Limited options for where the hoods can be placed in the cell as the tethering cables need to work around pipework; and
- Condensation freezing in sample lines leading to data errors.

Originally, it was intended that monitoring would only be for 12 months. Longer term monitoring has been required to gain further understanding and will need to be permanent to enable testing of strategies, enable ongoing monitoring and, in the future, allow emissions to form part of the operating algorithm of the secondary treatment process. The initial design is not fit for the purpose as a permanent fixture, and an adapted design is required. It has been proposed that the new design will use volumetric flow, have condensation control, and be connected to the plant SCADA system. It is also proposed that it will include eight hoods which will allow flexibility including monitoring of two tanks simultaneously or monitoring two locations in one aeration zone. This will help with data validation and checking for differences between tanks.

Apart from the new design, other next steps also include development and testing of a range of mitigation strategies, examining the emissions when the swing cells are in operation and determining what emission there may be between the ABRs and the BRs as this transition includes a vertical drop with significant turbulence.

The monitoring plan initially included deploying the hoods in the swing cells. This has proved to not be practicable. Installing online dissolved N_2O monitoring will allow assessment of emissions from the

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swing cells as well as determining the emissions from the vertical drop between the ABRs and BRs. It may also support validation of the data from the hoods in BR4. It is intended that the sensors will be installed in different configurations including before and after swing cells at times when they will operate, before and after the vertical drop between the ABRs and BRs and at the beginning and end of BR4.

Further important activities include validation of the flow rate algorithm being used to ensure data to date is accurate. Addressing the flow rate issue longer term will be achieved by changing to volumetric flow measurement.

4.2.4 Bardenpho

4.2.4.1 Mangaree – Watercare

Authors & Affiliation: Sela Maka from Watercare Services Limited

(1) Site Description and Operation

The Mangere WWTP, operated by council-controlled organization Watercare in Auckland, New Zealand, receives an average of 400,000 cubic meters of wastewater volume per day from a network of 1.7 million people. This wastewater comprises of domestic wastewater which also includes some stormwater connections, industrial effluent, infiltration, and illegal downpipe connections. The plant utilizes primary, secondary, and treatment processes to treat wastewater with an average dry weather flow of 400 MLD and up to 900 MLD during wet weather.

The activated sludge process for secondary treatment takes place in reactor/clarifiers (RCs) 1–9, reactors 10 and 11 and their associated clarifiers. The process removes carbonaceous and nitrogenous biochemical oxygen demand, solids and nutrients. Some phosphorus is removed in the waste biomass but not in an enhanced luxury uptake mode as with excess biological phosphorus removal plants. Downstream of the reactors, the secondary clarifiers separate settleable solids (activated sludge), floatable solids (scum), and liquid (clarified effluent). RCs 1–9 have a four-step feed design while reactors 10 and 11 are a Bardenpho configured system.

N_2O monitoring is currently focused on two of the RCs operating at different DO setpoints and one of the reactors in the Bardenpho system, reactor 11.

(2) Selection of Monitoring Locations

The selection of monitoring locations at the Mangere WWTP followed a structured multi-level approach similar to the N_2O Monitoring protocol.

Level 1: Identify the Number of Sludge Systems (L1 = 2)

The Mangere WWTP adopts two separate activated sludge system designs, that is, the four-step feed and the Bardenpho configuration. Since these are independently operated with different process design strategies, the N_2O must be monitored on at least one of these reactors.

Level 2: Determine the Number of Parallel Bioreactors (L2 = 1 per system)

There are about nine RCs in total with four-step feed design. However, there are two different aeration control strategies being implemented. The RCs run on either control so the N_2O must then be monitored on at least one of these reactors with a different control strategy. RC 5 was specifically chosen as it was the only RC with installed air flow meters to help calculate emissions. RC 4 was chosen due to its location proximity, and instrument access relative to RC 5 and the fact that it also shares the same influent load from its designated splitter box. Reactor 4 was installed with gas hoods in addition to the liquid phase sensors to measure air flow and off-gas concentration measurements. This was also done to compare the Kla calculations between gas-phase and liquid phase emission calculation methods.

Reactors 10 and 11 both operate under the same conditions so only one of these reactors were monitored for N_2O.

In summary, the selected reactors were chosen based on instrumentation access and availability and hence data, location proximity, practical feasibility, and process similarity.

Figures 4.20 and 4.21 show the monitoring flow diagram in both activated sludge systems.

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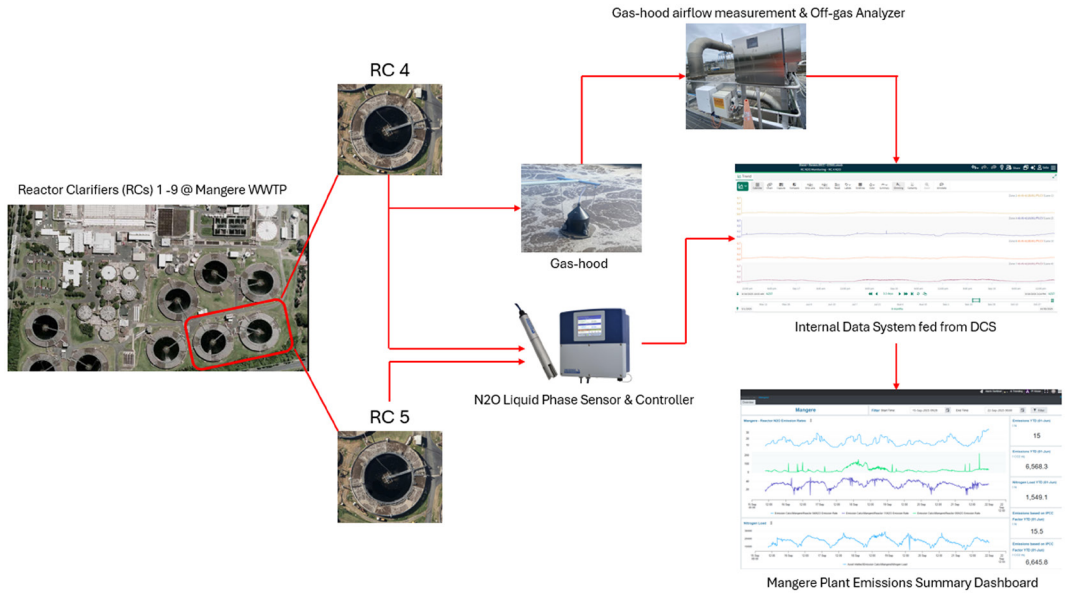


Figure 4.20 Reactor clarifier N_2O monitoring process.

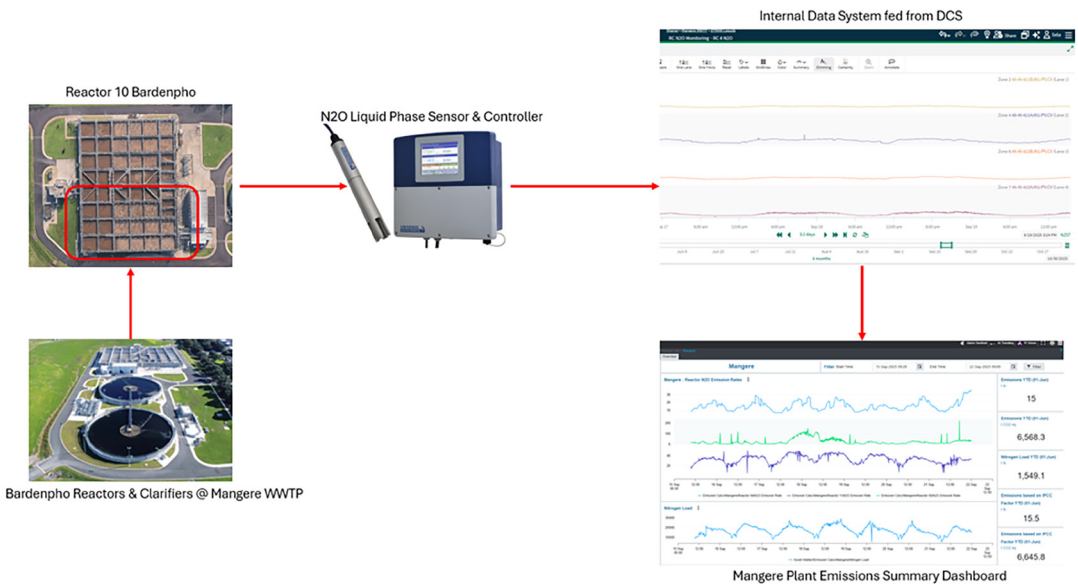


Figure 4.21 Bardenpho reactor 11 N_2O monitoring process.

Level 3: Determine the Number of Monitoring Locations Within One Bioreactor (L3 = 4 for Step-feed RCs and L3 = 4 for Bardenpho reactors)

Due to the complexity of the step-feed design, this case study will only focus on level 3 of the Bardenpho system in reactor 11. This system has three aeration zones under different control strategies and so at least one monitoring location is chosen for each aeration zone. Aerobic zone 1 and 2 have

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long lanes without subdivision into cascades so three monitoring locations were chosen while Aerobic 3 with a relatively shorter lane has a single measuring location. Aerobic zone 1 has two measuring points, one at the start and one at the end to cover the spatial variation of emission along the flow direction. The second monitoring location in Aerobic zone 1 is in proximity to the start of Aerobic zone 2 so there is only a single measurement location at the end of the Aerobic zone 2 – Aerobic zone 3 then has a single measurement location in the middle of the lane. This is shown in Figure 4.22.

The table below summarizes the monitoring tools and systems involved in calculating the emissions from the reactors in the activated sludge system at the Mangere WWTP:

Reactor	Process Control	Monitoring Instruments	Other Monitoring Information
4	ABAC Control	4×liquid phase sensors, 8 gas-hoods (two per aerated zone), 8×air flow meters from gas-hood flow, ammonia, and DO in aerated zones, nitrate and nitrite (one zone only)	Composite sampling data from influent splitter box (ammonia & flowrate measurements)
5	Nitrite Shunt	4×liquid phase sensors, 4×thermal mass air flow meters, ammonia and DO in aerated zones, nitrate (one zone only)	
11	Normal	4×liquid phase sensors, 3×air flow meter, ammonia and DO in aerated zones	

(3) Key Learnings

Since commissioning the monitoring campaign, one of the key challenges has been maintaining high-quality, accurate data that not only supports emissions reporting but also deepens our understanding of the underlying drivers. To address this, a comprehensive management plan is required, supported by clear documentation and records that are regularly updated to ensure consistency and reliability.

This includes:

- instrumentation faults or failures, calibrations, upgrade, or replacements
- process control changes – aeration control setpoints

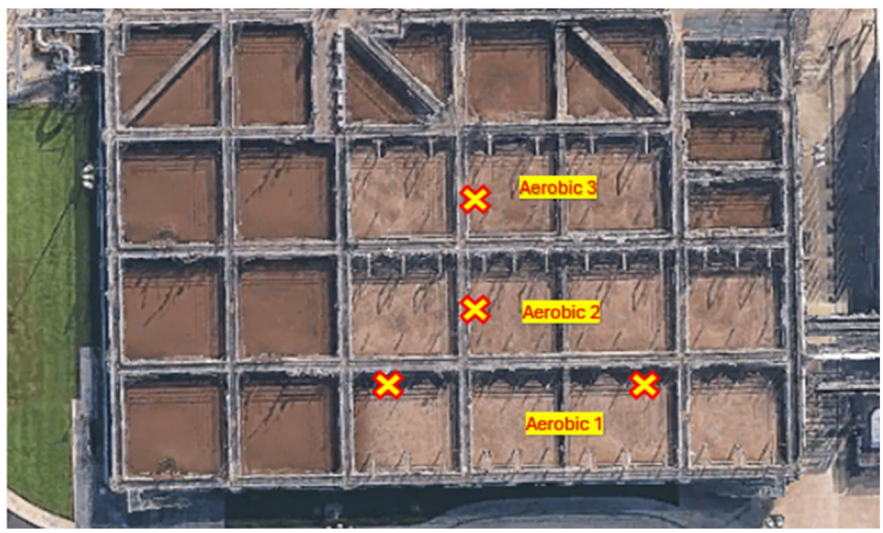


Figure 4.22 Reactor 11 Bardenpho N_2O monitoring locations.

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- wastewater flow and characteristic changes – shock loads, cleaning schedules, seasonal variations (wet vs dry weather)
- WWTP maintenance or repair schedules – RC and associated process units, for example, blower upgrades, zone mixer replacements, diffuser upgrades
- data validation through internal audit calculations

4.2.4.2 Murrumba Downs – Unitywater

Authors & Affiliation: Niloshree Mukherjee & Liam Owen from Unitywater

(1) Site Description and Operation

Unitywater's Murrumba Downs WWTP located in Murrumba Downs, Queensland, Australia employs a five-stage Bardenpho configuration for its activated sludge system.

The five-stage Bardenpho begins with four anaerobic zones, followed by four anoxic cells, a swing zone (operated mainly as anoxic), four aerobic zones, a de-aeration zone, three post-anoxic zones, and a final re-aeration zone. The anaerobic, anoxic, swing, and post-anoxic zones are covered, while the other zones remain uncovered. The MLR is returned from the de-aeration zone to the first anoxic cell, while the RAS is directed to the first anaerobic zone. Centrate and all other plant recycles are returned to the general purpose pump station (GPPS), which then flows into the second aerobic zone. Finally, the backwash from the cloth media filtration process is returned to the third aerobic zone.

The plant has an average dry weather flow (ADWF) of 25.5 ML/d. The SRT is 12 days with a typical HRT of 24.5 h. Aeration in the aerobic zones is controlled using a DO setpoint strategy, with typical DO concentrations ranging from 0.5 to 1.0 mg/L depending on influent loads and operational needs. The online sensors available in the bioreactor include DO sensors at each aerobic zone; nitrate (NO_3) sensor at the de-aeration zone; and DO, solids, ammonia (NH_3), nitrate (NO_3), and phosphate (PO_4) sensors in the re-aeration zone, which is the final zone of the bioreactor.

The treated effluent is discharged into the North Pine River hence the plant operates under strict license conditions which requires the plant to have effective nitrogen, phosphorus, BOD, suspended solids, and fecal coliform removal. To mitigate diurnal and other variations in flow and contaminant loads, the screened and degritted wastewater is attenuated in the flow limiting and attenuation tanks (FLATs) before entering the bioreactor.

(2) Selection of Monitoring Locations

Four Unisense N_2O liquid probes are used for continuous monitoring of the liquid phase N_2O concentrations at Murrumba Downs. One probe is installed near the end of each aerobic zone, the measured dissolved N_2O concentrations are then used to calculate the N_2O emissions using the gas–liquid mass transfer method.

Figure 4.23 illustrates the monitoring locations at Murrumba Downs that were selected based on the three-level method that outlines the number of sludge systems (L1), number of parallel bioreactors (L2) and number of monitoring locations within the one bioreactor (L3).

Level 1: Identify the Number of Sludge Systems (L1 = 1)

Murrumba Downs WWTP has one sludge system in operation during the monitoring campaign, hence L1 = 1.

Level 2: Determine the Number of Parallel Bioreactors (L2 = 1)

The activated sludge system is a single five-stage Bardenpho with no parallel bioreactors (L2 = 1).

Level 3: Determine the Number of Monitoring Locations within One Bioreactor (L3 = 4)

The five-stage Bardenpho begins with four anaerobic zones, followed by four anoxic zones, one swing zone, four aerobic zones, one de-aeration zone, three post-anoxic zones, and a reaeration zone. See Figures 4.24 and 4.25 for the location of the probes, and how it is situated at the plant.

The DO setpoint in each zone varies depending on the plant's operational requirements on the day but typically ranges from 0.5 to 1.0 mg/L, and the DO is achieved by the control systems adjusting the aeration flowrate based on set points and readings. Each zone is equipped with a single DO sensor, and the aeration is controlled by adjusting the opening of the aeration valves, where the diffuser density is consistent across

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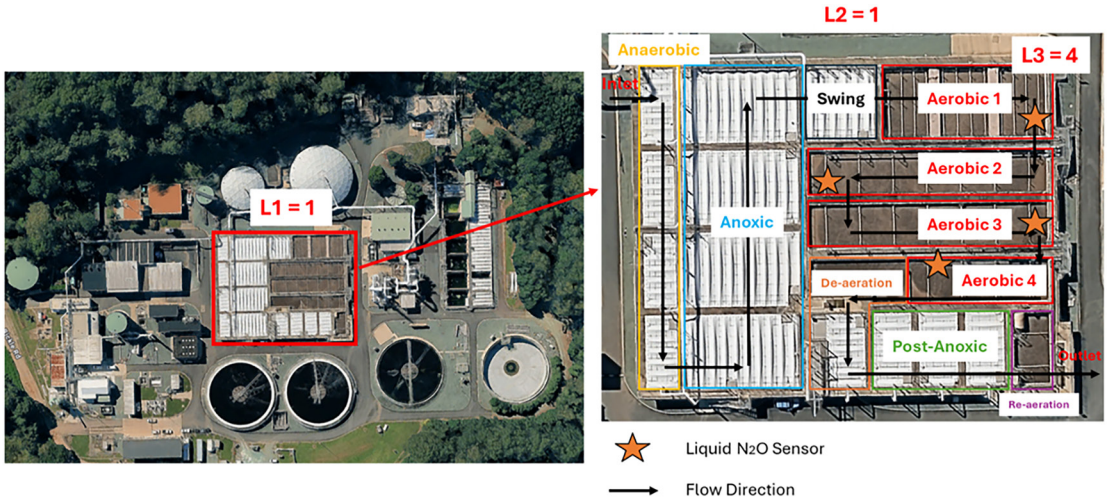


Figure 4.23 Monitoring locations at Murrumba downs WWTP. During the monitoring period the plant operated a single activated-sludge system (L1 = 1) configured as a five-stage Bardenpho (L2 = 1). Four liquid N_2O sensors were used to monitor each aerobic zone of the bioreactor (L3 = 4).

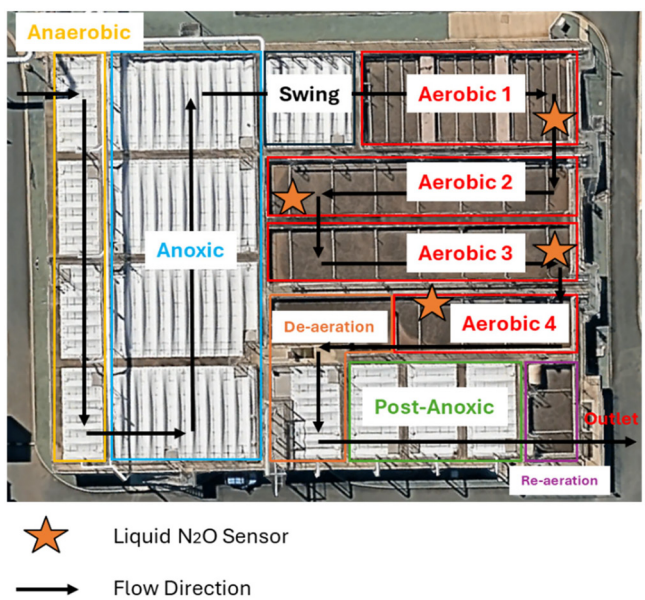


Figure 4.24 Liquid N_2O sensors location at Murrumba Downs WWTP.

all four zones. Accordingly, one N_2O liquid probe is installed in each aerobic zone to measure the dissolved N_2O concentration, and then the N_2O flux from each zone is calculated using the mass transfer method.

(3) Key Learnings

Challenges encountered during monitoring at Murrumba Downs included a probe malfunction, where the probe in aerobic zone 2 was not working for eight months, resulting in emissions from this zone not being accurately captured.

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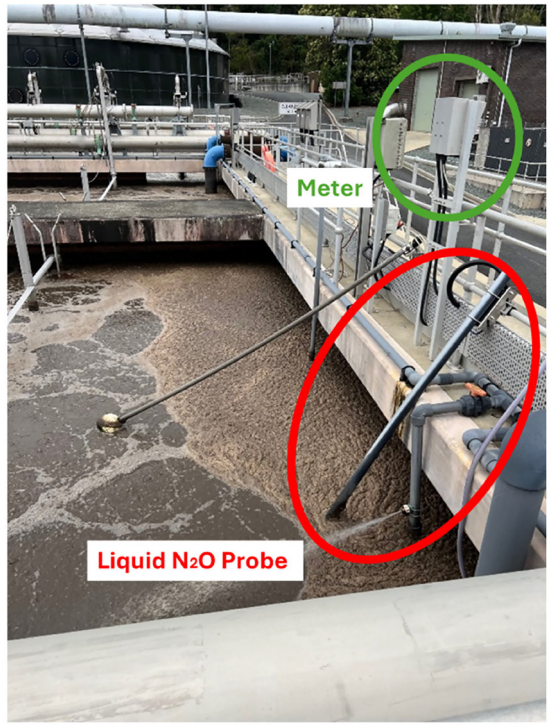


Figure 4.25 Liquid N_2O sensor location installed at Murrumba Downs.

Another issue was verifying the accuracy of the probe readings, as some periods of the monitoring campaign showed abnormally high readings and evidence of sensor drift occurring.

4.2.5 Oxidation ditch

4.2.5.1 Aalborg east

Authors & Affiliation: Wenzel Gruber from Upwater

(1) Site Description and Operation

Aalborg Vest WWTP located in Denmark (57°02′53.2″N 9°51′53.2″E) consists of a mechanical pretreatment with screens, grit chamber, and primary clarifiers, followed by a biological treatment and secondary clarifiers. An aerial view of the plant can be seen in Figure 4.26.

Aalborg Vest WWTP employs a Biodentiro S-Select process for carbon, nitrogen, and phosphorous removal. It has six parallel oxidation ditches. It treats wastewater with a load of roughly 200,000 population equivalents.

(2) Selection of Monitoring Locations

Eight flux chambers and liquid electrodes are used for continuous monitoring for the gas phase N_2O emissions at Aalborg Vest WWTP. Two different configurations have been tested to find the best monitoring setup.

Figures 4.27 and 4.28 illustrate the monitoring locations at Aalborg WWTP that were selected based on the three-level method that outlines the number of sludge systems (L1), number of parallel bioreactors (L2) and number of monitoring locations within the one bioreactor (L3).

Level 1: Identify the Number of Sludge Systems (L1 = 1)

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Figure 4.26 Aerial view of Aalborg Vest WWTP.



Figure 4.27 All-Tank setup: monitoring locations at Aalborg WWTP.

There are six oxidation ditches with the same volume and operation. Hence, there is only one sludge system at the plant (L1 = 1).

Level 2: Determine the Number of Parallel Bioreactors (L2 = 6)

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Figure 4.28 1-Tank setup: monitoring locations at Aalborg WWTP.

The lanes receive wastewater alternatingly. Aeration patterns are time dependent and differ for the tanks. Hence, each tank was sampled individually.

Level 3: Determine the Number of Monitoring Locations within One Bioreactor (L3 = 1)

The oxidation ditch consists of aerated and unaerated sections. The high flow through the reactor enables a very good mixing and N_2O concentration is consistent in the whole reactor. This could be confirmed by the 1-tank setup (see Result section).

Total number of sampling points

Total number of sampling points = L2*L3

With L2 = 6, L3 = 1

The total number of sampling points results in 6.

However, the total number was increased to eight to investigate the variation within one tank (1-tank setup) (Figures 4.29–4.31).

4.2.5.2 Apeldoorn – STOWA

Authors & Affiliation: Ellen van Voorthuizen (Haskoning), Frank van de Grootevheen (Vallei en Veluwe), Floris de Heer (IMD)

(1) Site Description and Operation

The treatment plant at Apeldoorn has a design capacity of 350.000 p.e. based on 150 g of total oxygen demand. At this site an additional amount of sludge from other treatment plants within the area of Vallei and Veluwe is handled. This amount of sludge is the equivalent of almost 500.000 p.e. This implies an additional load to the mainstream treatment. This load is reduced by the presence of side

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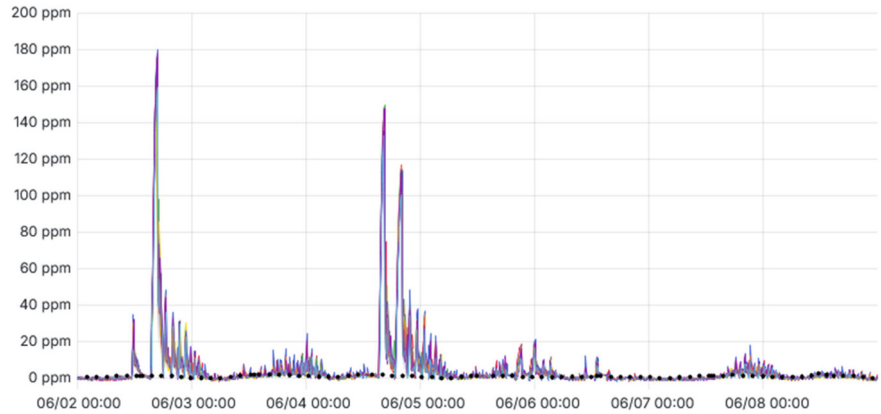


Figure 4.29 1-Tank setup: Gas concentrations of all hoods during a selected period. Almost the same N_2O concentrations were observed in all sampling locations of one reactor over the whole campaign. Hence, L3 = 1 is justified.

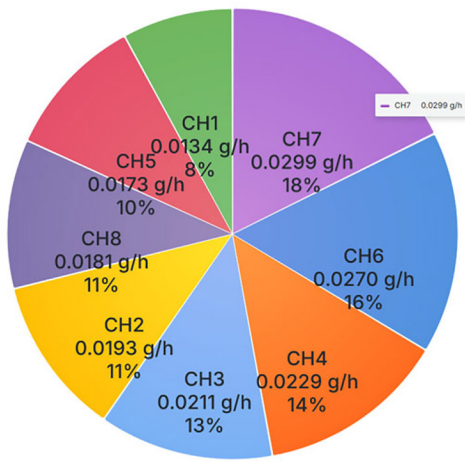


Figure 4.30 All-Tank setup: share of total emissions assessed with the hood-based approach. Substantial differences between tanks in emissions (up to factor 2.25).

stream treatment of the reject water via a struvite reactor, and a DEMON reactor. The effluent of the side stream process is transferred back to the mainstream treatment.

The mainstream treatment is configured as MUCT reactor. This type of reactor is one of the most widely used reactor types in the Netherlands and consists of a selector/anaerobic tank in the middle (number 3 in Figure 4.32), followed by an anoxic (number 4) and aerobic zone (number 5). The outer aerobic ring is equipped with two separately controlled aeration fields. There are two return flows within the reactor. One from the anoxic zone to the selector/anaerobic tank where also the return sludge is coming back, and one return flow from the aerobic zone to the anoxic zone. The return flows within this configuration results in a completely mixed system. The primary and secondary sludge are digested in two digesters. The secondary sludge of Apeldoorn and the external secondary sludge is first pre-treated via thermal hydrolysis. The digested sludge is dewatered, and the reject water is treated in a struvite and DEMON reactor.

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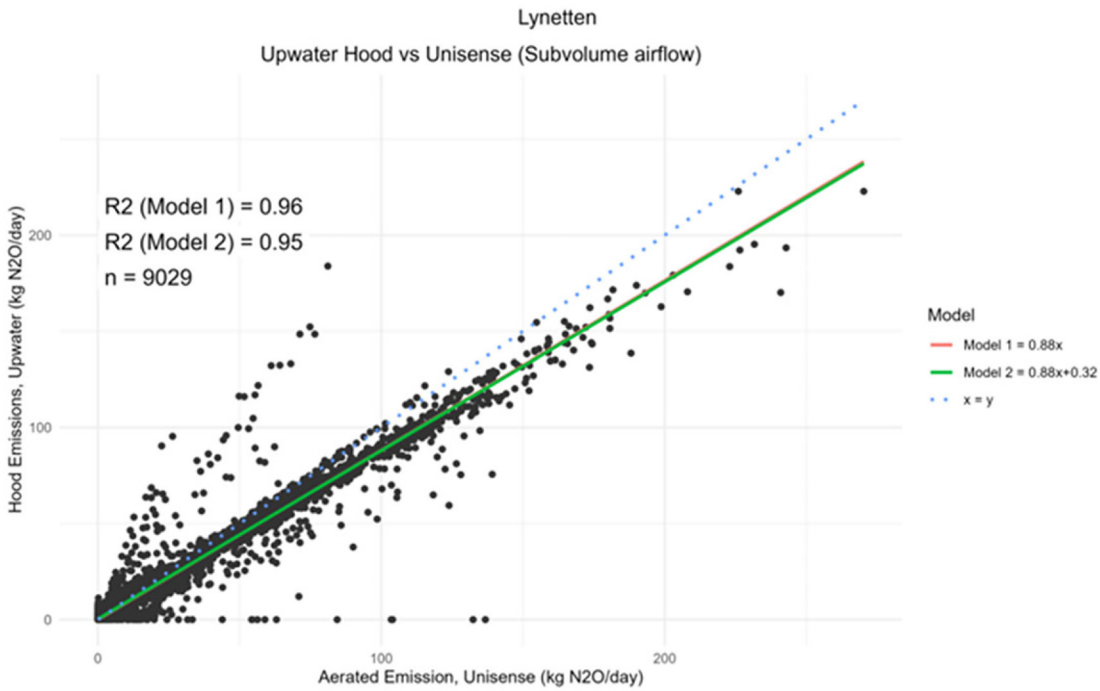


Figure 4.31 Correlation plot of hood emissions and liquid probe emissions. Very good correlation between liquid and gas-based emission monitoring for both monitoring setups.

(2) Selection of Monitoring Locations

The mainstream biological treatment consists of two identical bioreactors with a MUCT configuration, with both their own (return) sludge system (see Figure 4.32). During the measuring campaign it was found that the N_2O concentration in the bioreactors differed significantly. The reason can be found in the uncertainty on how the return flows from the sludge system and the effluent from the DEMON are diverted over the two bioreactors. This implies that the two bioreactors could have two different microbial communities, and as there is also a separate side stream treatment L1 = 3. Because the two MUCT reactors and the side-stream treatment do not have parallel lanes L2 = 1. Each bioreactor exists of three separate tanks of which N_2O formation can be expected in two tanks (the anoxic, and aerobic tank), but mainly emit from one tank, the aerobic tank. Although a little emission from the anoxic tank cannot be neglected completely, the placement of one sensor in only the aerobic tank would be sufficient to determine a representative EF for each bioreactor, so L3 = 1. In the case of Apeldoorn it was still decided to place a second sensor in each bioreactor in the anoxic tank to gain also insight in the formation processes of N_2O.

To determine the most representative locations in the anoxic and aerobic tank the N_2O concentration was measured at different locations in different periods as presented in Figure 4.33.

The purpose of having four measurement locations in the anoxic tank was to see if N_2O production or consumption took place. The rationale behind the five locations in the aerobic zone is to see if there would be any difference between the two aeration zones (33% and 67%), and what would be the concentration in between the aeration zones (15%, 50%, and 100%).

(3) Key Learnings

The N_2O concentrations that were measured between November 2023 and March 2024 for both the anoxic and aerobic zone are for all locations shown in Figure 4.34.

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Figure 4.32 Overview of monitoring locations required at WWTP Apeldoorn. The plant consists of three sludge systems (L1 = 3), because the two MUCT can differ in microbial composition. Each MUCT and the side stream reactor does not have a parallel lane so L2 = 1. The MUCT configuration consist of three separate reactors, where only from the aerobic reactor N_2O emission can occur, so L3 = 1.

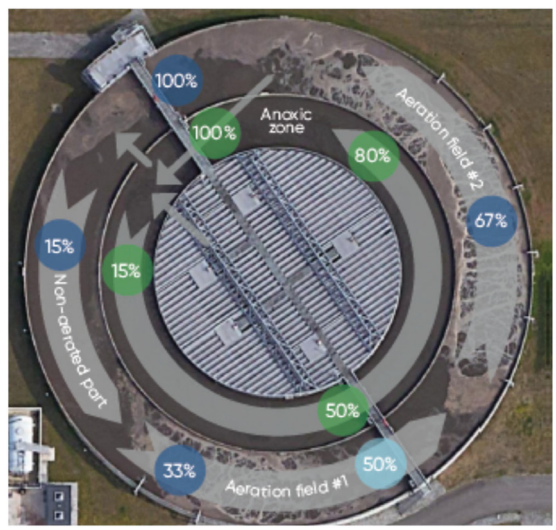


Figure 4.33 Measurement locations within the MUCT reactor at WWTP Apeldoorn. The percentages in the left picture refers to the percentage of the distances of the total tank.

The measurement campaign showed that one sensor in each aerobic tank of the two bioreactors is sufficient to determine an accurate and representative EF for each bioreactor. The sensor in the aerobic tank can be placed anywhere, as long as the location is practical and safe while calibrating or replacing the sensor (head). In the case more information about the formation of N_2O would be desired a second sensor could be placed anywhere in the anoxic tank as the results show comparable concentrations throughout the tank.

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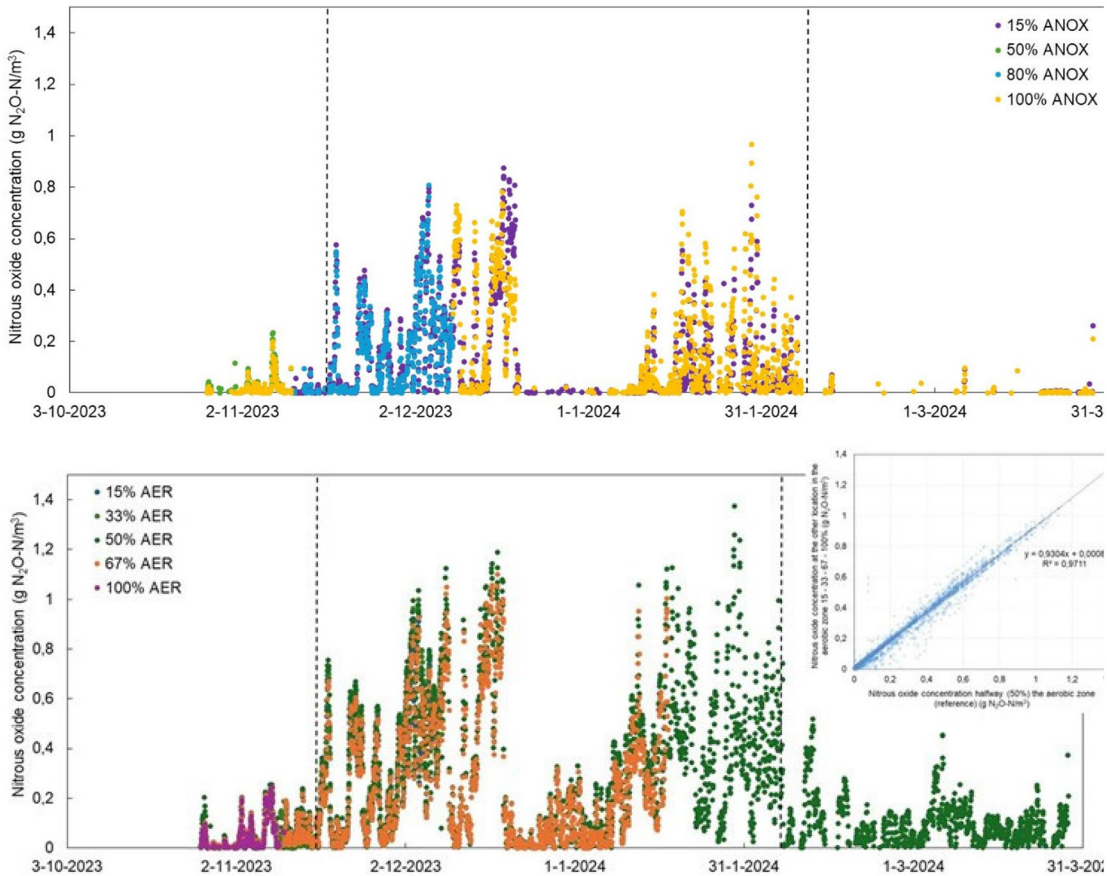


Figure 4.34 Concentration profile of N_2O in both the anoxic zone (upper graph) and aerobic zone (lower graph) at the WWTP of Apeldoorn. (Inserted in the lower graph is the hourly average N_2O concentrations measured in the aerobic zones of the reactors. Comparison between the reference sensor (50%) position with all other locations is shown. Each position was monitored for 15–111 days. Linear correlation is shown as dotted line and formula). The two dotted lines represents a period where the aeration control was not optimal.

The period between mid-November 2023 and mid-February 2024 shows a significant higher N_2O concentration than in the periods before and after that (section between the two dotted lines). The difference between the periods is the way the aeration is controlled. It is thought that with the original aeration control more oxygen is returned to the anoxic zone, which inhibits the denitrification, leading to higher N_2O concentrations. With the original aeration control more air is applied than required, leading to formation of N_2O because of over aeration (hydroxyl-amine route). The same removal rate of ammonium can be achieved with advanced process control (APC) that supplies sufficient oxygen for full nitrification, but level of aeration will follow the ammonium concentrations. This leads to a more stable process conditions (oxygen levels) that results in lower N_2O emissions when APC is applied. The lesson learned (mitigation strategy) from here is to avoid over-aeration so that full denitrification can take place resulting in lower N_2O emissions. At the time of the measurement campaign no EFs were calculated yet. In a later stage the utility can execute those calculations as aeration flows are known.

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Challenges and Next Steps

A practical challenge was to install the sensor at locations where no railing was present. This was solved with a kind of clamps that was placed over the wall (see Figure 4.35). The use of a Peli Case with all the equipment made it possible to monitor the N_2O concentration at different locations for a short period of time (see Figure 4.35).

4.2.5.3 Hoogvliet – STOWA

Authors & Affiliation: Ellen van Voorthuizen (Haskoning), Pui Tan Li (waterschap Hollandse Delta)

(1) Site Description and Operation

Hoogvliet has a design capacity of 90.000 p.e. based on 150 g of total oxygen demand. An overview of the plant is shown in Figure 4.36. The WWTP of Hoogvliet consists of only one (mainstream) sludge system in two identical treatment lanes. The configuration that is applied at this treatment plant is named after the place it is located: 'Hoogvliet.' A typical feature of the 'Hoogvliet' configuration is a separate pre-nitrification plug flow tank (7), with a recirculation to the pre-denitrification tank (6)



Figure 4.35 Left picture: The 'clamp' that was placed over the wall to install the sensor in the aeration zone. Right picture: Peli case as a mobile solution to monitor a concentration profile over a tank.

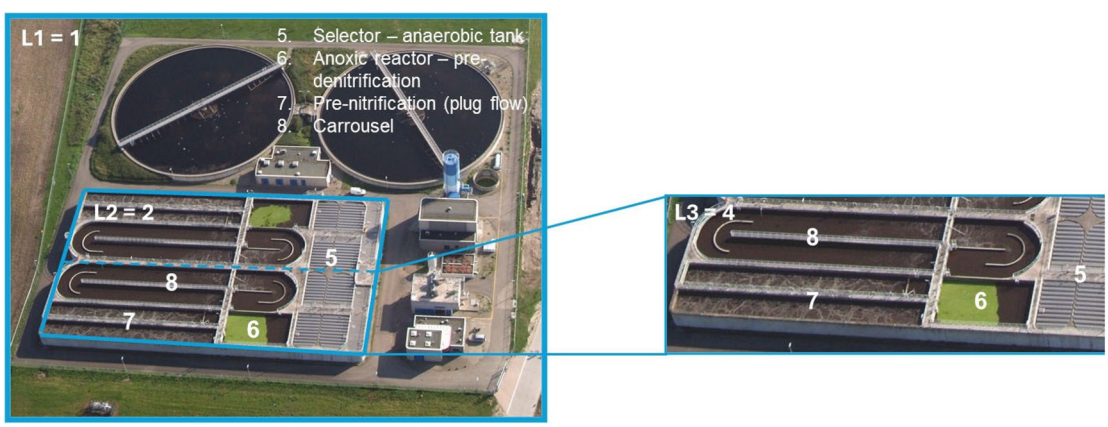


Figure 4.36 Overview of monitoring locations required at WWTP Hoogvliet. The plant consists of one biological treatment system (L1 = 1). The Hoogvliet process in place uses two parallel bioreactors (L2 = 1). The Hoogvliet concept consists of four separate tanks from which 2 tanks N_2O emission can be expected, so L3 = 2. Monitoring locations are the plug-flow pre-nitrification tank (indicated as location 7 in the figure) and the carrousel (indicated as location 8 in the figure).

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and an overflow to a carrousel (8). In the carrousel the mixed liquor first flows through an anoxic part after which it enters the aerated zone. There is no recirculation between the carrousel (completely mixed) and the pre-nitrification tank. The mixed liquor leaves the carrousel straight into one of the secondary clarifiers. The return sludge is brought back in the selector/anaerobic tank where it is mixed with fresh wastewater. Phosphorus is completely removed through a biological process. The waste sludge is mechanically thickened and transported to a central dewatering and/or digestion location within the area of the water utility of Hollandse Delta.

(2) Selection of Monitoring Locations

The overall treatment plant receives the same wastewater that all goes through the same biological processes and one sludge system. On level 1, the number of sludge systems is one (see Figure 4.36).

The Hoogvliet concept is applied in two parallel reactors, therefore only one of the two needs to be quantified (L2 = 1). Each reactor consisting of an anaerobic/selector, an anoxic/pre-denitrification tank, a plug-flow pre-nitrification tank, and a carrousel. Although a little emission from the anoxic tank (indicated as location 6 in Figure 4.36) cannot be neglected completely, the placement of two sensors in the plug-flow pre-nitrification tank and carrousel would be sufficient to determine a representative EF for each bioreactor, so L3 = 2. In the case of Hoogvliet it was still decided to place a third sensor in the anoxic tank to gain also insight in the formation processes of N_2O.

To determine the most representative location in the plug-flow pre-nitrification tank and carrousel a monitoring campaign was executed in both tanks (see Figure 4.37). After the most representative locations were determined, each lane was equipped with three sensors, one in the anoxic tank, one in the plug-flow pre-nitrification tank, and one the carrousel. With the placement of another set of sensors in the second bioreactor so the utility can use one lane as a reference bioreactor to determine a year-round EF, while in the other bioreactor mitigation strategies to reduce N_2O can be tested. Important though is that both lanes are fed and perform equally. This can be checked by using some temporary equipment that measures the N_2O concentrations in both tanks at the same location. The preferred period for this comparison between two bioreactors would be a minimal of two–three months.



Figure 4.37 Locations of the sensors in the period a representative location was determined in the plug-flow pre-nitrification tank and carrousel.

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(3) Key Learnings

Location determinations

The trial for the location determination in the plug-flow pre-nitrification tank took place between August 13– and August 31, 2024. The N_2O concentrations and emissions in this period are shown in the upper graph of Figure 4.38. The trial for the location determination in the carrousel took place between July 28 and August 5, 2024. The N_2O concentrations and emissions in this period are shown in the lower graph of Figure 4.38.

In the plug-flow pre-nitrification tank a clear N_2O concentration profile was observed. Throughout the tank the concentration of N_2O increased, mainly between location V2 and V3. This indicates that formation of N_2O s took place within this reactor. On most occasions the average emission of the four sensors was closest to V2 and V3 (upper graph in Figure 4.39). To determine the most representative location, the measured value at location of V2 or V3 was plotted against the average concentration of the other three locations. In the left graph of Figure 4.39, the emission measured at V2 is compared with the average emission at V1, V3, and V4. The dotted line shows the real relation between V2 and

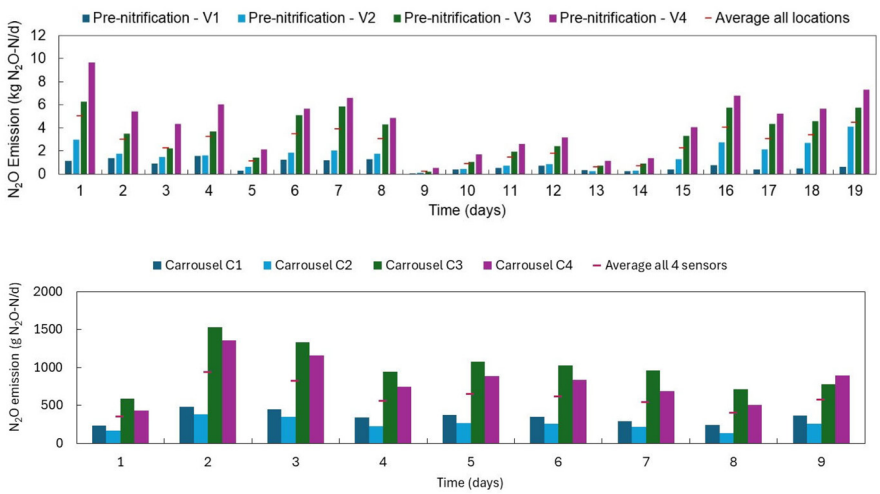


Figure 4.38 Upper graph: N_2O concentration profile in plug-flow pre-nitrification (locations V1 – v4); lower graph: daily average N_2O emission per location in the plug-flow pre-nitrification tank. The small black line indicates the daily average N_2O emission for all four locations.

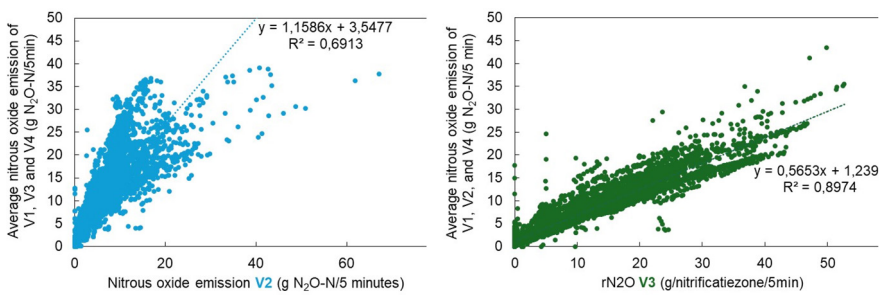


Figure 4.39 Left: measured emission at V2 compared with the average emission of sensors V1, V3, and V4. Right: measured emission at V3 compared with the average emission of sensors V1, V2, and V4.

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the other three sensors. In the right graph of Figure 4.39 the same is done, but then for location V3. The comparison with three sensors instead of four is done, to observe a more distinct difference between the ideal situation and the real relation. When comparing the linear relationship between the measured emissions at location V2 or V3 and the average of the other three sensors, it becomes apparent that location V3 is the most representative location to place the sensor in the plug-flow reactor as the R2 is closer to one than V2, and the intercept is closer to zero. However, the measurement campaign did not last long enough to measure the seasonal variations in the tank. This will have affected the most representative location as this location can differ over the seasons.

From the concentration profile in the carrousel, it can be seen that the tank is completely mixed, there is almost no distinct difference in the measured N_2O concentrations. In terms of emission there is a distinct difference between the emission in the anoxic zone (C1, C2) and the aerobic zone (C3, C4). This is logical as N_2O is not stripped within the anoxic zone. From this perspective it is logical to place the sensor just before the aeration zone, where the N_2O from both the anoxic as aerobic zone is stripped and gives the most representative EF for the carrousel. The lower graph in Figure 4.39 supports this, as there is not a real distinct difference between location C3 and C4 (also compared to the average emission of all sensors).

The EF could be determined for each tank. In the plug-flow pre-nitrification tank the EF varied between 0.02% and 0.7% (as kg N_2O-N/kg $N_{influent}$; three data points). In the carrousel only two data points were available, but both showed a comparable EF of 0.2% (as kg N_2O-N/kg $N_{influent}$).

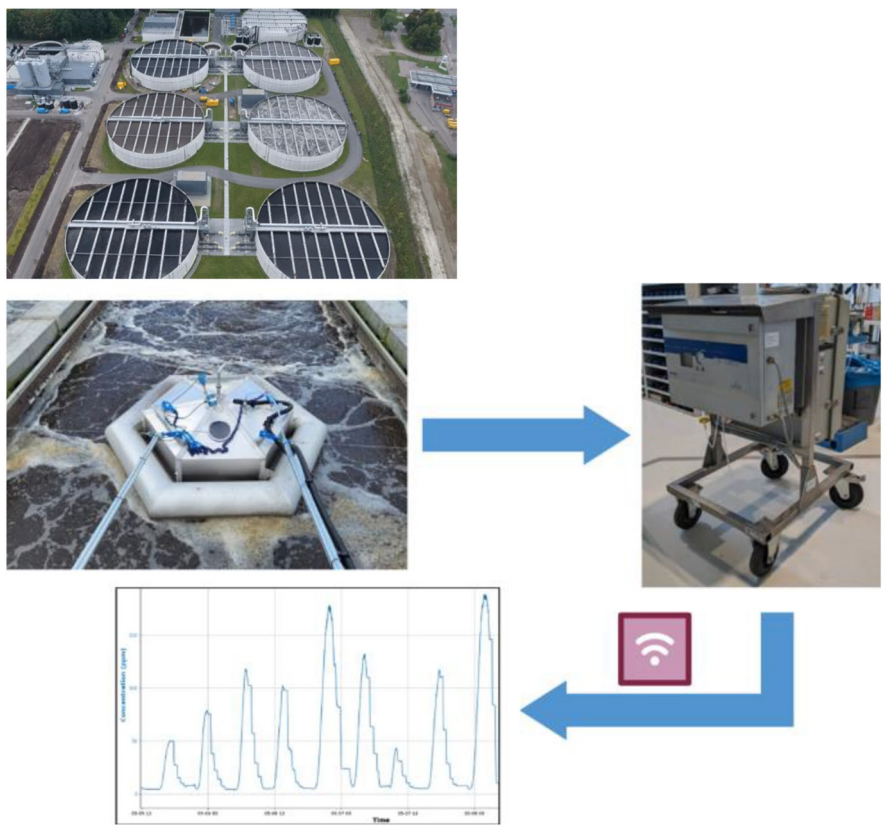


Figure 4.40 Lay-out of the six AGS reactors in Utrecht and the hood and gas analyzer installation for the N_2O monitoring in two of the reactors.

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(4) Key Learnings
The lessons learned at Hoogvliet were:

- In a plug flow reactor, a determination of the most representative location should be performed at any time. A full year would be needed to take the seasonal effect into account for selecting the most representative location.
- In a completely mixed system one sensor is sufficient to determine a reliable EF. This was seen here in the carrousel in Hoogvliet but was also seen at Apeldoorn (see ***Case Study – 4.2.5.2 Apeldoorn – STOWA***), and at other treatment plants in the Netherlands as well.
- In case of two (or more) identical lanes are present it is worthwhile to check if they are identical in practice as well, and not only on paper! In Hoogvliet it was found that after the installation of three sensors in each lane, significant differences were found in the N_2O concentrations.
- It is important to check on a regular basis preferably every day or week, the output of the sensor to determine abnormalities in the measured concentrations. This improves your data availability and quality.
- The sensor from Unisense needs to be calibrated every two months or when there is a temperature difference of +/− 3°C. When at a regular calibration a temperature drop of more than +/− 3°C is expected before the following calibration it is advised to calibrate the sensor not at the actual temperature but two degrees higher or lower than the actual temperature, depending on an expected increase or decrease in temperature.

4.2.6 Sequencing batch reactor (SBR)

4.2.6.1 Utrecht WWTP – KWR

Authors & Affiliation: Johann Poinapen (KWR Water Research Institute) and Siddharth Seshan (KWR Water Research Institute)

(1) Site Description and Operation
The Utrecht WWTP, operated by Hoogheemraadschap de Stichtse Rijnlanden (HDSR), is a full-scale aerobic granular sludge (AGS) system treating domestic and industrial wastewater for over 430,000 PE. The plant uses the AGS process in six parallel SBR-type reactors, designed for simultaneous carbon, nitrogen, and phosphorus removal in a compact footprint without secondary clarifiers. The plant utilizes AGS that settles faster and allows for higher biomass concentrations (~8 g/L), and the plant capacity can support an average dry-weather flow of ~76,300 m³/day.

The plant operates in mainstream treatment configuration with no separate side-stream sludge systems. All six reactors function under the same operational philosophy but are individually controlled and monitored. N_2O monitoring is currently focused on two representative bioreactors (AGS tanks 2 and 5, respectively) to initiate emission quantification and understand seasonal variations.

(2) Selection of Monitoring Locations
The monitoring design at Utrecht follows a criteria-based, top-down approach, aligned with the N_2O Monitoring Protocol:

- Parallel Bioreactors (Figure 4.40): Six reactors exist; two reactors were selected for detailed monitoring, representing system-wide operation due to similar hydraulic and loading conditions.
- Monitoring Within the Reactor: N_2O monitoring was done at one point within each of the two reactors selected using: A permanently installed two liquid-phase N_2O sensors.
- A cutting-edge floating flux chamber system equipped with Internet of Things sensors (pressure and temperature) and connected to a gas analyzer for real-time N_2O emission measurements. The off-gas sample line is always heated between 50 and 60°C to prevent condensation and moisture build-up.

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- Online sensors for DO, NH_4^+, NO_3^-, PO_4^{3-}, pH, temperature, feed flow meters, and reactor-level dynamics.
- Grab and composite samples from influent, effluent, and reject water.
- Information on how many of the AGS reactors were in operation were accounted for in the loading calculations for the specific reactors monitored for N_2O.
- The selected reactors (namely AGS reactors 2 and 5), as illustrated in Figure 4.40, were chosen due to practical feasibility, instrumentation access, and the ability to retrofit with permanent sensors.

The selected reactors (namely AGS reactors 2 and 5), as illustrated in Figure 4.40, were chosen due to practical feasibility, instrumentation access, and the ability to retrofit with permanent sensors.

The N_2O monitoring campaign in the gas phase lasted over a year, and it was possible to capture rich and dynamic N_2O emission data, revealing clear patterns when compared with other process parameters related to the wastewater treatment.

(3) Key Learnings

From the preliminary data analysis, significant N_2O emissions from the bioreactor were observed. These could be attributed to the following factors and challenges encountered during the monitoring campaign.

(i) *Key Findings – N_2O emission dynamics*

- The N_2O EFs in AGS reactor 2 are shown below in the following graphs (Figures 4.41–4.44). An average EF for an 8-month period in AGS reactor 2 was calculated to be 1.54%.
- Within a typical batch/cycle of the AGS process, interesting N_2O production and emission dynamics were observed. An example time window of the N_2O measurements along with key process parameters is illustrated in Figure 4.43.
- The loading rate to the monitored AGS tank (which is governed by how many of the total AGS tanks are operational) directly influenced the amount of N_2O emitted.
- Similar trends were observed for both the N_2O liquid measurements from the liquid sensors and the N_2O gaseous measurements from the floating hood and gas analyzers.
- In a majority of batches, increasing N_2O production and emissions were observed during the aeration cycle and thereby the aerobic phase. This could suggest the activation of the ammonia oxidizing bacteria (AOB)-related N_2O production pathways.
- In some cases, at the onset of the aeration cycle, and when the valves are opened to allow for air flow to diffuse into the bioreactor, a sudden spike in N_2O is seen. This might suggest that

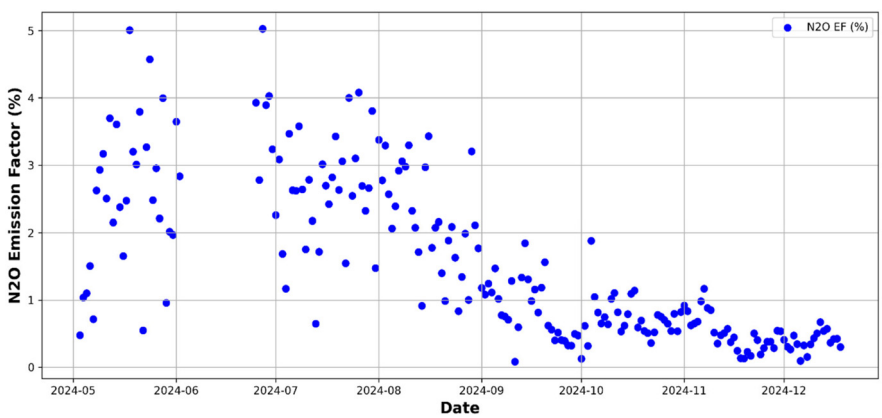


Figure 4.41 Daily N_2O EF calculated over an 8-month period for AGS reactor 2.

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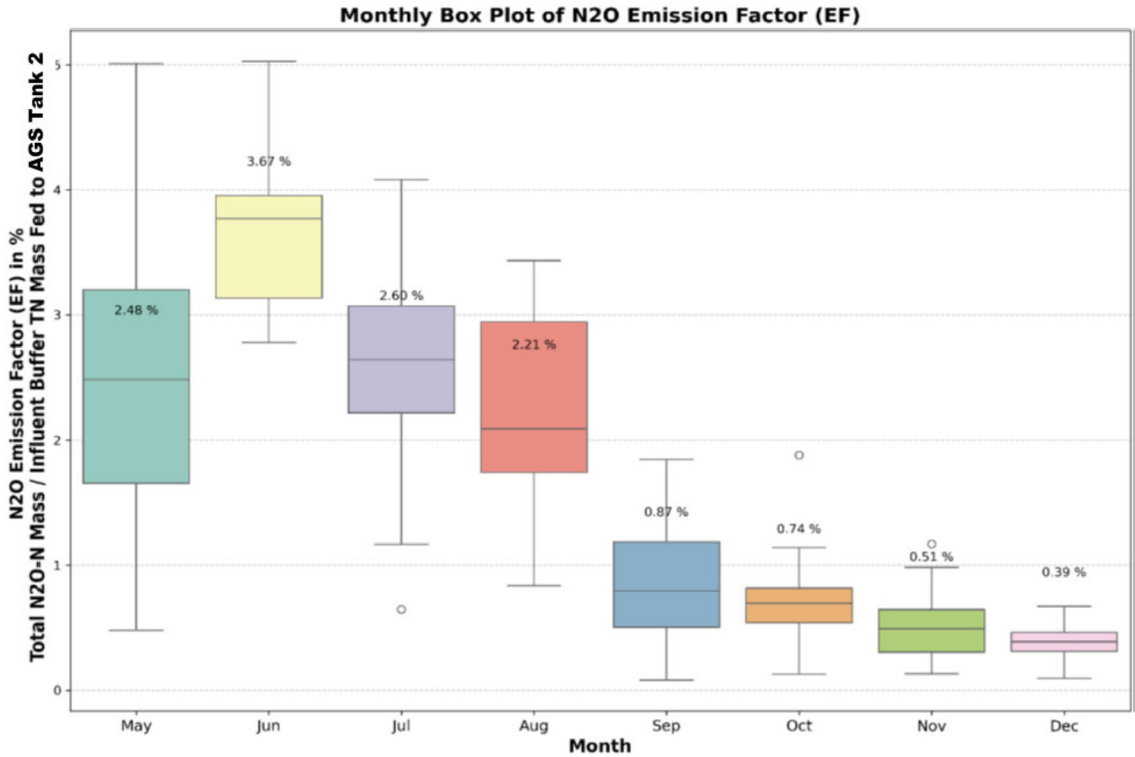


Figure 4.42 Monthly averages and variations in N_2O EF calculated over an 8-month period for Nereda 2.

NO_2^- accumulation due to incomplete denitrification from the previous batch's anoxic phase during the settling phase of the batch, might be in turn converted to N_2O.

- During the entire monitoring campaign, the duration and operation of the batches for a AGS tank led to differing dynamics in N_2O production and emissions.

Figure 4.43 illustrates the trends of key parameters related to N_2O production and emission in AGS reactor 2.

(ii) Challenges

Related to measurement campaign and influence of WWTP operations/maintenance/failures

- The aeration system and the diffusers in AGS reactor 2 were failing over time, which potentially led to the downward trend of N_2O emitted. Unfortunately, there is insufficient N_2O liquid data in AGS reactor 2 to fully assess the differences in N_2O production before and after the deficiencies in the aeration system were recorded.
- As a result, the monitoring location was moved to AGS reactor 5, which was recently upgraded with a new aeration system. Measurements were conducted for 7 months in this tank. The data collected is currently being analyzed.
- Other AGS reactors present were one by one subsequently under maintenance and put out of operation. Therefore, the additional loading expected per reactor which was monitored was accounted for.

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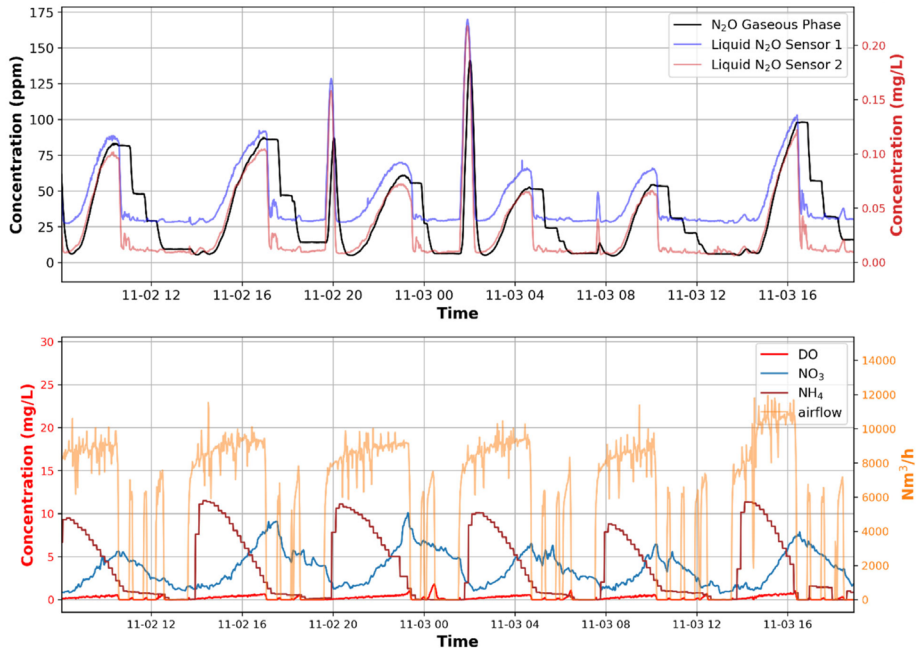


Figure 4.43 Analysis of key parameters related to N_2O production and emission in AGS reactor 2.

(4) Supporting Information

The N_2O sensor and hood setup is part of a Dutch Top Sector Knowledge and Innovation program.

4.2.6.2 Birs

Authors & Affiliation: Wenzel Gruber from Upwater

(1) Site Description and Operation

Birs WWTP located in Switzerland (47°32′36.8″N, 7°37′26.1″E) consists of a mechanical pretreatment with screens, grit chambers, and primary clarifiers, followed by an activated sludge system in SBR configuration as biological treatment. The plant treats wastewater with roughly 110,000 PE. An aerial view of the plant can be seen below.

(2) Selection of Monitoring Locations

The figures below illustrate the monitoring locations at Birs WWTP that were selected based on the three-level method that outlines the number of sludge systems (L1), number of parallel bioreactors (L2) and number of monitoring locations within the one bioreactor (L3).

Level 1: Identify the Number of Sludge Systems (L1 = 1)

Birs WWTP has five SBRs on-site with the same volume and operational mode (L1 = 1)

Level 2: Determine the Number of Parallel Bioreactors ($L2_1 = 5$)

All five SBRs have different inflows due to discontinuous and independent feeding and are therefore considered not parallel (L2 = 5).

Level 3: Determine the Number of Monitoring Locations within One Bioreactor (L3 = 1)

SBRs are considered fully mixed and the same gas concentration is expected in a tank at a time point.

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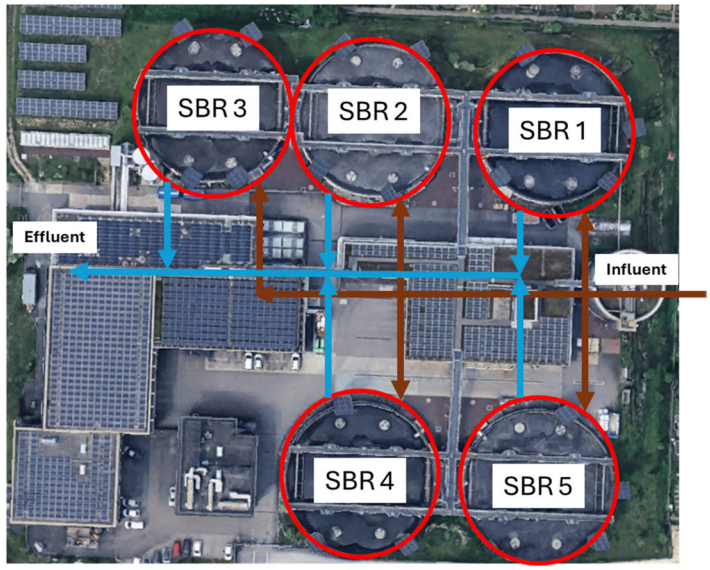


Figure 4.44 Aerial view of Birs WWTP.

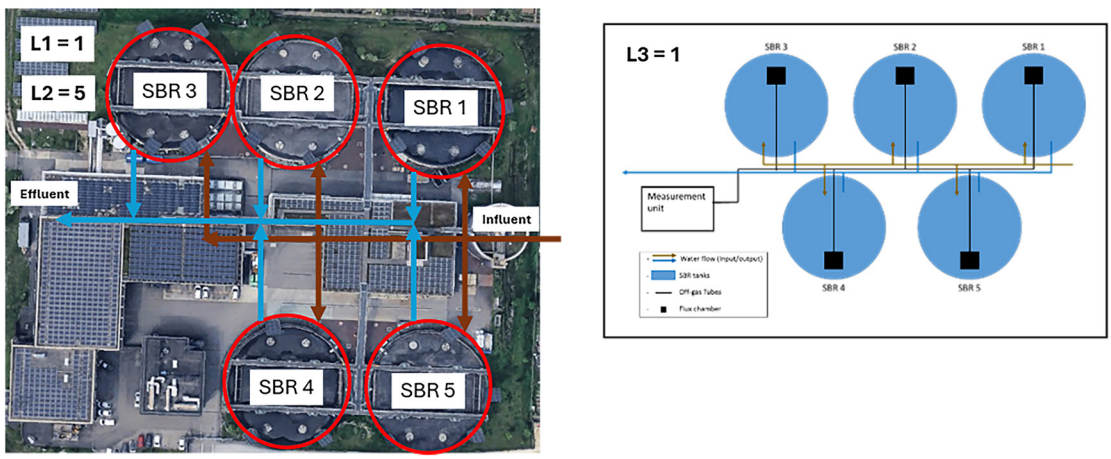


Figure 4.45 Monitoring locations at Birs WWTP. There are five SBRs present on-site, but this is considered one activated sludge system as they share the same influent, L1 = 1. The five SBRs are identical in configuration and operation, are parallel to each other, L2 = 5. For monitoring, one flux chamber is placed in each SBR to ensure they are identical in N_2O emissions, L3 = 1.

Total number of sampling points

Total number of sampling points = $L2_1$*$L3_1$

With $L2_1 = 5$, $L3_1 = 1$

The total number of sampling points results in 5.

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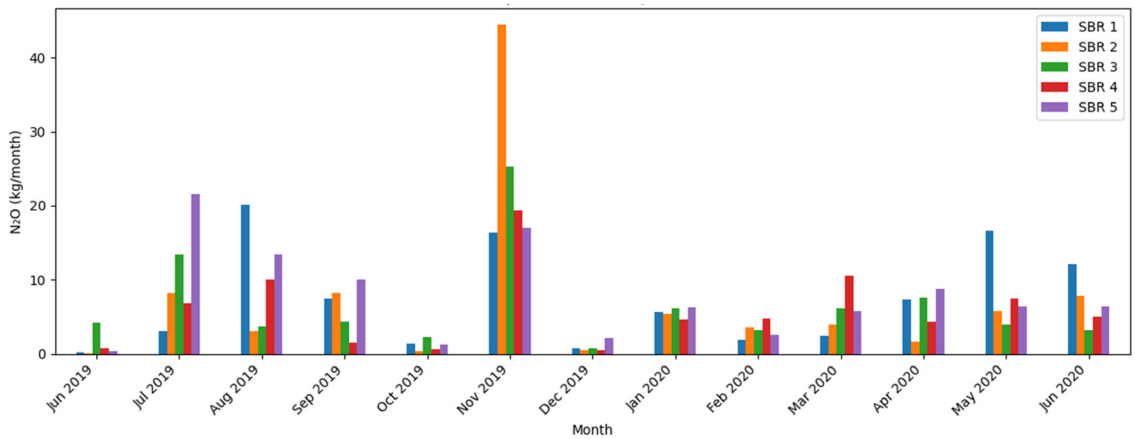


Figure 4.46 Monthly N_2O emissions of the SBRs investigated.

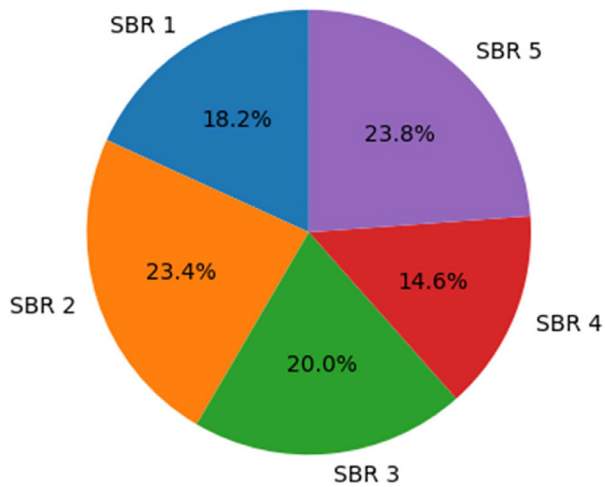


Figure 4.47 Share of total emissions for each SBR over the whole monitoring period.

Five flux chambers were used for monitoring at Birs WWTP, with one flux chamber at each SBR to capture any variation in N_2O emission between the SBRs.

(3) Key Learnings

A monitoring campaign with the above-described setup has been conducted between June 2019 and June 2020. The following conclusions have been drawn:

- Seasonal variation with peak month in November 2019 in average (see Figure 4.46).
- Emission factor: 0.2%
- Strong variation between reactors (up to factor 1.6). The reactors behave differently on a seasonal scale (see Figures 4.46 and 4.47).

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4.2.7 Membrane bioreactor (MBR/MABR)

4.2.7.1 Te Kauwhata – Watercare

Authors & Affiliation: Sela Maka from Watercare Services Limited

(1) Site Description and Operation

The Te Kauwhata WWTP, located in the Waikato region south of Auckland, was recently upgraded from a two-pond oxidation system with a constructed wetland to a compact, close-coupled hybrid membrane aerated biofilm reactor (MABR)–membrane bioreactor (MBR) process, supported by newly constructed headworks. Prior to the upgrade, the facility experienced repeated non-compliance with several resource consent parameters. The new treatment technologies were selected to achieve enhanced total nitrogen removal and high-quality solids separation through membrane filtration, while providing a small physical footprint, increased hydraulic capacity, and improved opportunities for future expansion and operational flexibility.

The plant receives an average daily flow of approximately 1500 m³/d. Influent is pumped through fine screens, passes over a weir box, and then flows by gravity to the MABR–MBR treatment system. Screened raw sewage is mixed with recycled mixed liquor and conveyed to the first stage MABR tanks. The biological process is arranged as two parallel trains, each comprising two MABR units in plug-flow configuration followed by a downstream aerobic tank for ammonia polishing (Figure 4.48). Each MABR tank contains five membrane cassettes supplied with low-pressure air, facilitating simultaneous nitrification and denitrification within the biofilm. RAS from the MBR is introduced upstream of the MABRs to maintain the activated sludge inventory. The former oxidation ponds are now repurposed as emergency storage to manage stormwater surcharges during peak wet-weather events exceeding 2000 m³/d, providing additional system resilience.

The full-scale MABR units generate a process exhaust stream that can be used to characterize gaseous emissions. Instrumentation for N_2O, oxygen, and carbon dioxide measurement was installed to monitor off gas from all four MABR tanks, enabling quantification of total N_2O emissions from the facility. In addition, dissolved N_2O sensors were installed within the biological process to assess in-system N_2O production dynamics.

(2) Selection of Monitoring Locations

The selection of monitoring locations at the Te Kauwhata WWTP followed a structured multi-level approach similar to N_2O Monitoring protocol.

Level 1: Identify the Number of Sludge Systems (L1 = 1)

The Te Kauwhata WWTP employs a single-sludge biological treatment process comprising of the MABR and aerobic tank operating in plug-flow design. Given this configuration, the system can be classified under the monitoring approach as L1 = 1.

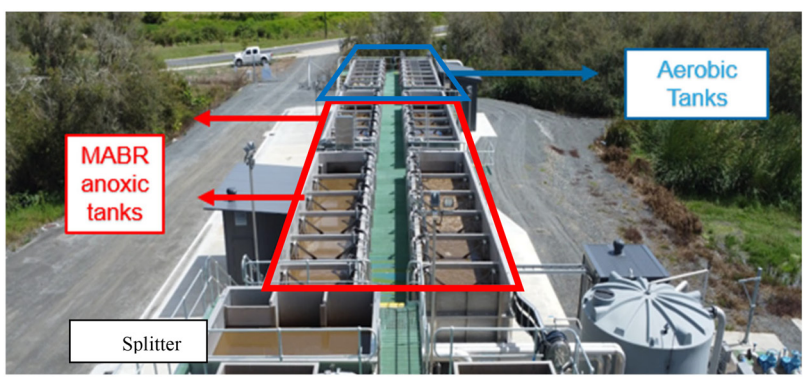


Figure 4.48 Te Kauwhata WWTP MABR and aerobic tank layout.

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Level 2: Determine the Number of Parallel Bioreactors in MABR Process (L2 = 1)

The biological treatment process consists of two parallel trains, each comprising MABR tanks followed by an aerobic tank. Screened influent, combined with RAS, is divided evenly in a splitter box and conveyed to both trains. The upstream MABR units in each train receive identical wastewater characteristics and operate with comparable mixing, scouring, and cassette-level process aeration rates. Similarly, the downstream aerobic tanks are equipped with equivalent diffuser configurations and operate under the same DO control strategy.

Owing to these parallel and hydraulically equivalent configurations, N_2O emissions measured from a single treatment train are representative of emissions from the entire plant.

Level 3: Determine the Number of Monitoring Locations Within One Bioreactor (L3 = 3)

One train with three monitoring locations (one in each MABR tank and aerobic reactor) is sufficient for quantifying N_2O emissions in this layout since they are operated in parallel and under similar process conditions. Given the MBR is mainly used for filtration with very low NH_3 concentration, therefore it is not considered as a main spot of N_2O generation. Thus, Level 3 in this context can be defined as three locations.

Given the relatively compact footprint of the facility (78 m^3 per MABR and aerobic tank), off-gas monitoring was able to be conducted on all four MABR units using an installed gas analyzer to quantify the total N_2O flux from the full-scale system. Similarly, both aerobic tanks – although operating under comparable design and process control conditions – were instrumented with dissolved N_2O sensors (Unisense) at the end of the tank. This arrangement was also possible by the Unisense controller's capability to accommodate two sensor probes, enabling simultaneous monitoring in both tanks. The aerobic tanks are relatively modular in configuration, with a shallow operating depth of 3.2 m and a length of 2.45 m. Owing to their compact geometry, a single dissolved N_2O sensor was sufficient to provide representative monitoring for each aerobic tank. In summary, the monitoring system at the Te Kauwhata WWTP comprises six N_2O measurement locations: four off-gas monitoring points on the MABR tanks and two dissolved-phase monitoring points within the aerobic tanks (Figure 4.49). For the minimal requirement, only one train with three monitoring locations is sufficient to be used to quantify emissions.

(3) Key Learnings

Two off-gas analyzer units (Aquagas SmartCEMS GHG) were installed on site to continuously monitor the concentrations of exhaust gases from the treatment process. One analyzer is configured to measure N_2O and carbon dioxide (CO_2), while the second unit measures oxygen (O_2). Both analyzers draw from the same air sample stream, or alternatively collect samples simultaneously from the same tank. Each tank is sampled for a duration of 6 min, with an adequate purge period between successive sampling events. Although the supplier offers a single analyzer capable of measuring all three gases simultaneously, the analyzers were retained as separate units to allow for its deployment at other facilities.

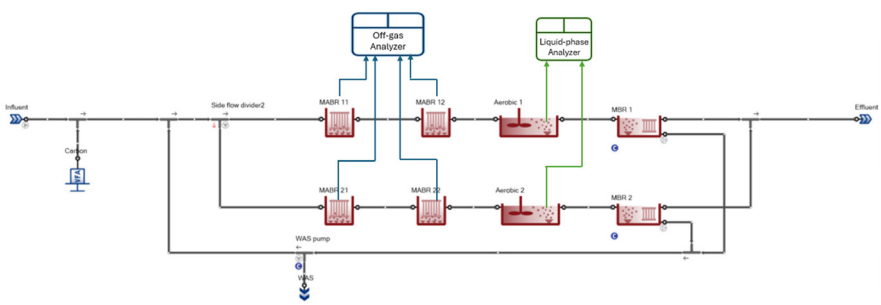


Figure 4.49 Te Kauwhata WWTP 6 N_2O Monitoring Locations.

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The analyzers can be configured to report concentrations in either parts per million (ppm) or milligrams per cubic meter (mg-N/m^3). These are computed and converted internally in the analyzer with temperature and pressure. For this study, measurements were recorded in mg/m^3 to enable direct calculation of total N_2O mass flux (Figures 4.50 and 4.51).

A key operational requirement is the routine maintenance of hydro filters in-house the gas unit analyzers to prevent saturation with particulate matter or accumulated moisture, both of which can compromise the accuracy of gas concentration measurements. The use of certified calibration gases is also recommended to verify analyzer performance. In the absence of on-site calibration, routine servicing by the equipment supplier is strongly advised to ensure optimal analytical performance.



Figure 4.50 Snapshot of Aquagas process exhaust gas analyzer (left) and example of a saturated zero air filter (right).

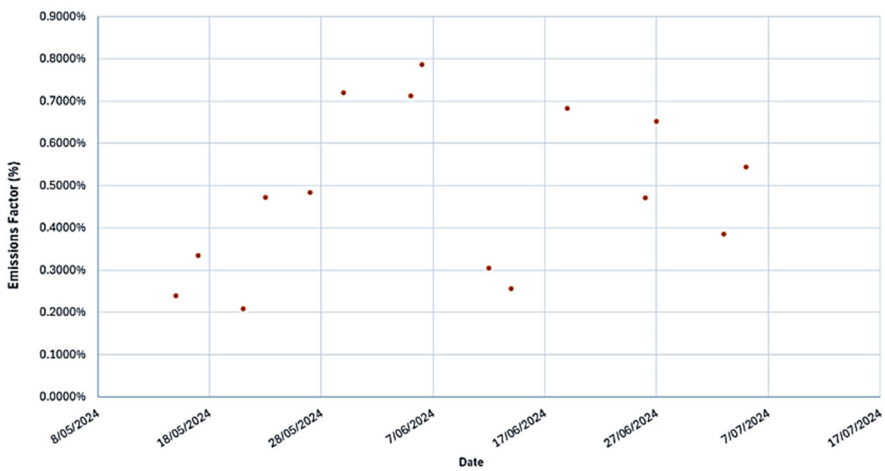


Figure 4.51 Measured N_2O-N emissions factor (%) from Te Kauwhata WWTP full-scale MABR tanks.

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Recommended maintenance and operational actions include:

- Regular flushing of sample lines to remove excessive moisture in external tubing, with further investigation into automated drain and purge systems
- Maintaining an inventory of recommended spare parts and consumables on site
- Procuring calibration gases for upcoming servicing activities

Emission Measurements

The MABR technology offers the benefit of coupling the nitrification and denitrification process so that the N_2O intermediates generated from the inner and/or outer layer of the biofilm can be removed in the outer layer or bulk anoxic tank before being stripped into the atmosphere.

In 2024, N_2O emissions were closely monitored for a period of 2 months (May–July). N_2O off-gas emissions were measured from the exhaust gas across the four MABR tanks using Aqua gas analyzers. The analyzer measures the N_2O emissions in milligrams per cubic meter which is then converted into a daily mass flux (g/d) per tank using the process air flow rates and the number of cassettes per tank (five per tank). The total N_2O-N emissions factor from the MABR was calculated using the Intergovernmental Panel on Climate Change (IPCC) method:

$$Total\ N_2O - N\ Emissions\ Factor = \frac{Total\ MABR\ N_2O\ Emissions\ (g/d)}{Influent\ TN\ Load} \times 28/44$$

The measurements from the two liquid N_2O probes from Unisense were also monitored in the aerobic reactors. During this period, the N_2O readings were mostly zero. Given that most of the ammonia is removed from the upfront MABR tanks, this is expected as minimal residual ammonia travels downstream to be polished. Therefore, the emissions presented in Figure 4.51 are only representative of the off-gas measurements.

The IPCC New Zealand level 2 factor provisionally recommends a fixed EF of 1% or 0.01 kg N_2O-N/kg N influent. Figure 4.51 shows the overall N_2O emissions expressed as a fraction of the ammonia load, averaging 0.35%, significantly lower than New Zealand's IPCC level 2 factor.

4.2.8 Other biofilm systems

4.2.8.1 Langmatt (AB IFAS)

Authors & Affiliation: Wenzel Gruber from Upwater

(1) Site Description and Operation

Bazenheid WWTP is located in Switzerland (47°24′53.8″N, 9°04′33.1″E). The mechanical pretreatment of the plant consists of screens, grit chambers, and primary clarifiers, followed by the biological treatment and secondary clarifiers.

The biological treatment step is a hybrid biofilm carrier with activated sludge (IFAS) system with three lanes. An aerial view of Bazenheid WWTP can be seen in Figure 4.52.

The anoxic volume is 926 m^3 for denitrification and an aerobic volume of 3186 m^3 for nitrification and COD removal. The plant receives an average daily inflow of 4894 m^3/d, which varies by 1866 m^3/d. The inflow has an average organic load of 2200 kg_{CSB}/d with 687 kg_{CSB}/d variability and a nitrogen load of 216 kg_N/d that varies 68 kg_N/d, which is a population equivalent of 20,000 (COD basis) or 18,000 (N basis). The total sludge and aerobic sludge age is 5.25 days, which is a relatively short SRT to limit nitrification activity but support denitrification activity.

(2) Selection of Monitoring Locations

Six flux chambers were used for continuous monitoring for the gas phase N_2O emissions at Bazenheid WWTP, with three located in the aerobic zones of Lane 1, and the last three in the aerobic zones of Lane 3.

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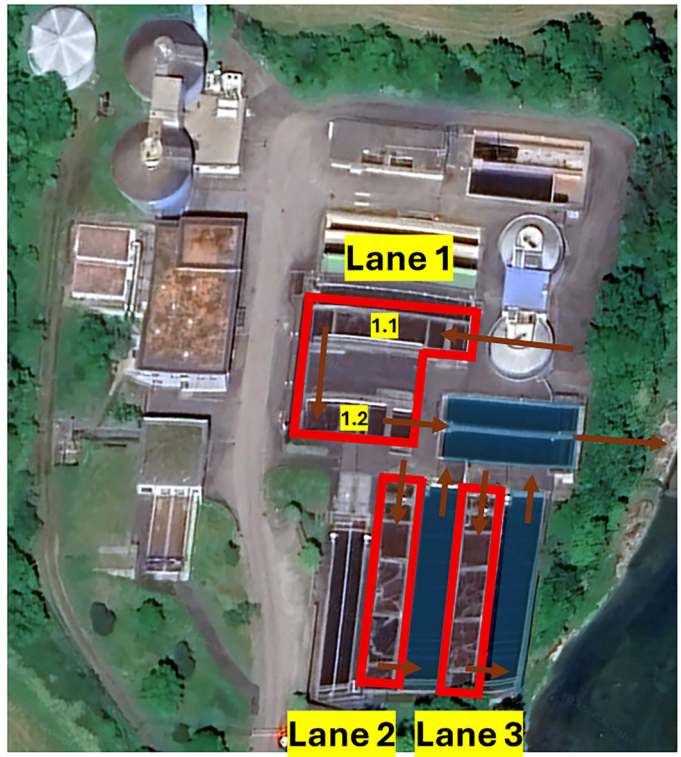


Figure 4.52 Aerial view of Bazenheid WWTP. Lane 1 is divided into two reactors (1.1 and 1.2). Reactor 1.1 consists of an anoxic zone followed by three aerobic zones. Reactor 1.2 comprises of one aerobic zone and a subsequent anoxic zone. Lane 1 has two trains of secondary clarifiers. The clarified effluent is discharged into the river. Lanes 2 and 3 are identical in configuration. Each lane begins with an anoxic zone, followed by four aerobic zones, then entering a secondary clarifier (highlighted in blue), before being discharged into the river.

Figure 4.53 illustrates the monitoring locations at Bazenheid WWTP that were selected based on the three-level method that outlines the number of sludge systems (L1), number of parallel bioreactors (L2), and number of monitoring locations within the one bioreactor (L3).

Level 1: Identify the Number of Sludge Systems (L1 = 2)

The plant has two sludge systems (lanes 1 and 2/3).

Level 2: Determine the Number of Parallel Bioreactors (L2 = 2)

For sludge system 1 (lane 1) has one bioreactor ($L2_1 = 1$). For sludge system 2, two bioreactors (lanes 2 and 3) with equal design and operation are used ($L2_2 = 1$).

Level 3: Determine the Number of Monitoring Locations within One Bioreactor (L3 = 3)

Lane 1 (sludge system) is broken into two parts: reactor 1.1 and reactor 1.2. The flow first enters lane 1.1 which starts off with an anoxic zone, followed by three aerobic zones, before entering lane 1.2 which consists of an aerobic zone then an anoxic zone, before entering the secondary clarifiers. In summary, sludge system 1 has four aerated zones ($L3_1 = 4$). Lanes 2 and 3 begin with an anoxic zone, followed by four aerobic zones ($L3_2 = 4$).

Total number of sampling points

Total number of sampling points = $L2_1$*$L3_1$ + $L2_2$*$L3_2$

With $L2_1 = 1$, $L3_1 = 4$, $L2_2 = 1$, $L3_2 = 4$,

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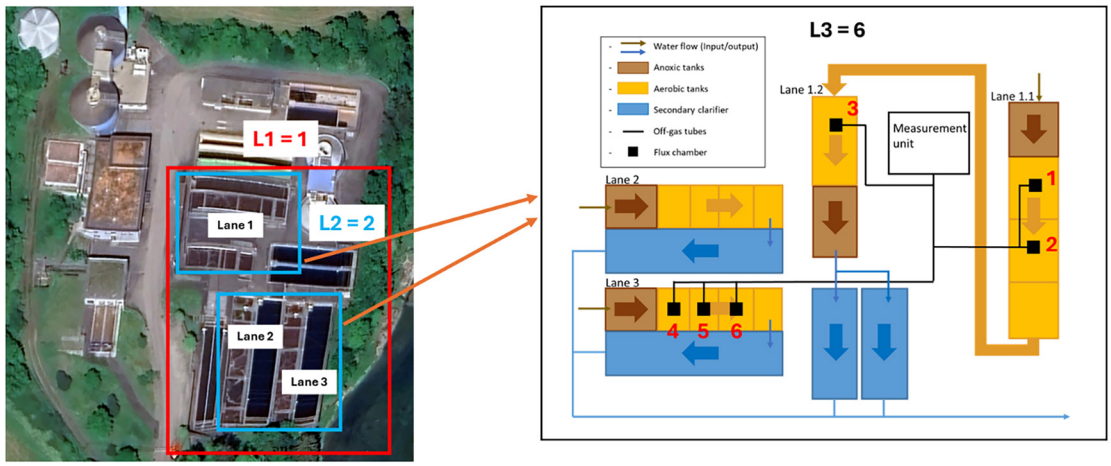


Figure 4.53 Monitoring locations at Bazenheid WWTP. Visually, there is more than one activated sludge system, but these systems share the same influent, therefore L1 = 1. There are three parallel bioreactors (lane 1, 2, and 3), but lanes 2 and 3 are the same configuration, while lane 1 differs, therefore only one of each configuration is required to be monitored (L2 = 2). Three flux chambers are in the aerobic zone of lane 1, while the other three flux chambers are in lane 3 (L3 = 6).

The total number of sampling points results in 8.

However, the total number was reduced by one per lane due to constraints in equipment. Three flux chambers are in lane 3, with it being in the first three aerobic zones. Three flux chambers were applied in lane 1, with one being at the first and second aerobic zone of lane 1.1, and the last located at the first aerobic zone in lane 1.2.

(3) Key Learnings

A monitoring campaign with the above described setup has been conducted between January 2018 and June 2019. The following conclusions have been drawn:

- Strong seasonality of the emissions with a peak phase during summer 2018. The high emission period coincides with the summer holidays. The plant still received high nitrogen load from a large meat processing plant. Meanwhile, COD load dropped due to the holidays, leading to an unfavorable C/N ratio (see Figure 4.54).
- Emission patterns from the two sludge systems were very similar (see Figure 4.54). In this case monitoring one lane would be sufficient.
- Emission factor: 1.4%.

4.2.8.2 Luggage point (ANITA Mox (Annamox) system) – urban utilities

Authors & Affiliation: Kenny Liew, Jason Dwyer & Wakib Khan from Urban Utilities

(1) Site Description and Operation

Urban Utilities' Luggage Point Resource Recovery Center (RRC) located in Pinkenba, Queensland (QLD), Australia, employs a five-stage Bardenpho configuration for its mainstream bioreactors, together with an ANITA™Mox (anammox) sidestream treatment process. This study focused on N_2O monitoring design for the sidestream Anammox process.

The Anammox system is now successfully treating up to 900 kgN-NH_4/day, which is significantly in excess of the 800 kgNH_4-N/day design capacity from the sidestream return, with removal efficiency

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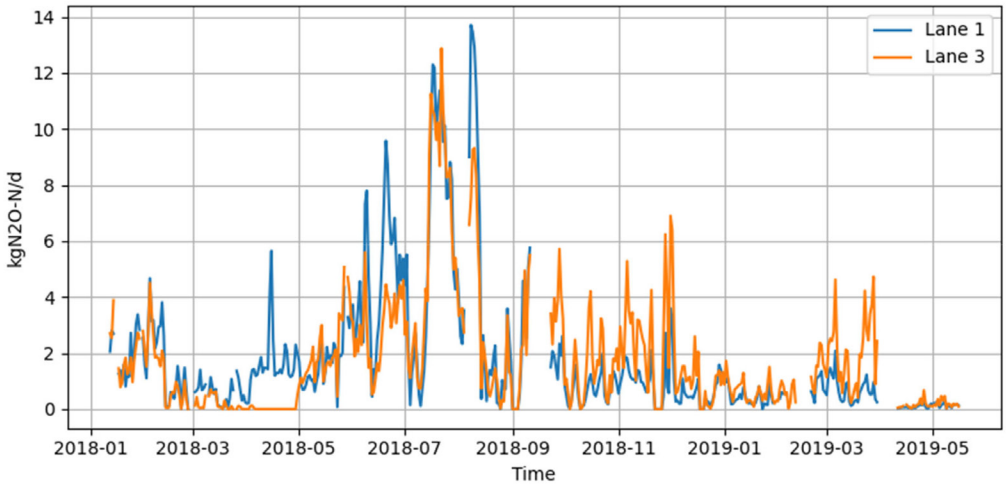


Figure 4.54 Daily N_2O emissions of both lanes investigated.

exceeding 90%. The centrate from sludge dewatering is collected in a wet well, then passed through filtration units before being pumped into the Anammox process. The flow is distributed to two parallel Anammox bioreactor trains (Trains 1 and 2), each train consisting of two aeration tanks (1A and 1B in Train 1 and 2A and 2B in Train 2). The tanks facilitate partial nitration and anaerobic ammonium oxidation using pH-DO-Flow Cascade control or DO-Flow Cascade control, where ammonia and nitrite are converted to nitrogen gas under intermittent aeration with low-oxygen conditions. Online sensors are installed for continuous monitoring of ammonium, nitrite, nitrate, pH, temperature, and flow, enabling optimal performance. The treated effluent is discharged via the effluent wells and returns to the mainstream bioreactor.

(2) Selection of Monitoring Locations

Two Unisense N_2O liquid probes are installed in Train 1 and are used for continuous monitoring of the liquid phase N_2O concentrations in the sidestream Anammox system at Luggage Point. One probe is installed at the end of the first aeration zone (Tank 1A), near the plant's DO sensor, and the other liquid probe is installed at the second aeration zone (Tank 1B) which is also near a DO and NH_3 sensor. Using the dissolved N_2O concentration, the N_2O emissions can be calculated using the gas–liquid mass transfer method.

Figure 4.55 illustrates the monitoring locations at Luggage Point that were selected based on the three-level method as outlined in the N_2O monitoring protocol.

Level 1: Identify the Number of Sludge Systems (L1 = 2)

There are both a Bardenpho system for mainstream wastewater treatment and a sidestream Anammox, therefore Level 1 equals 2. In this case study, only the sidestream treatment of Luggage Point was considered and presented, the mainstream system is excluded from this case study.

Level 2: Determine the Number of Parallel Bioreactors (L2_Anammox = 1)

Luggage Point has two trains of sidestream Anammox reactors, both trains receive the same influent and operate in parallel under similar conditions, therefore, one train was selected as representative for monitoring (L2 = 1).

Level 3: Determine the Number of Monitoring Locations within One Bioreactor (L3 = 2)

The two liquid N_2O sensors are located in the second half of the first and second aeration tank, next to the DO and NH_4 sensors. Figure 4.55 shows the liquid N_2O sensor locations in the sidestream Annamox treatment system.

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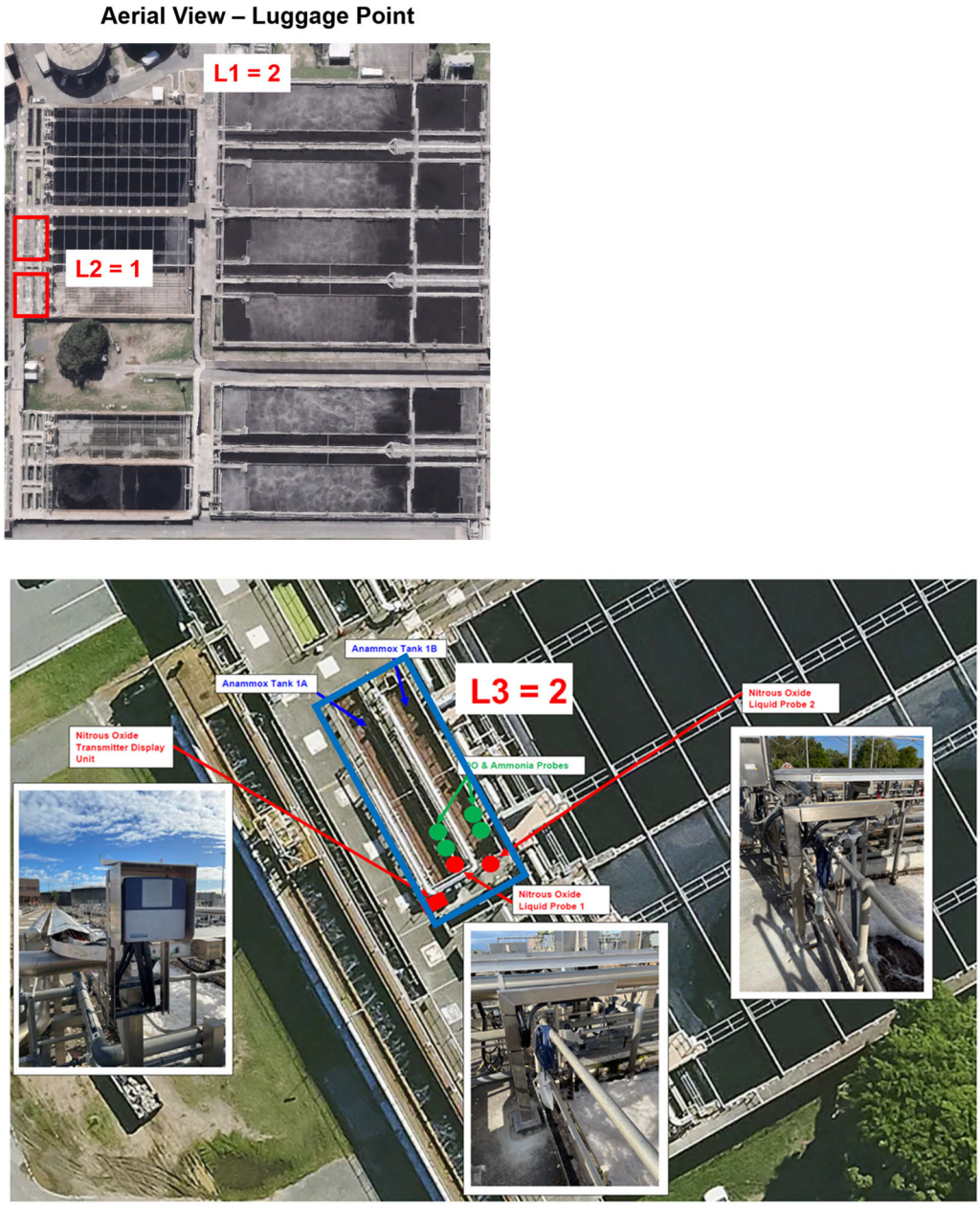


Figure 4.55 Monitoring locations at luggage point WWTP. Two parallel trains of anammox sidestream treatment with the same configuration and inlet (L2 = 1) (train 1 is indicated by the blue box). Two liquid N_2O sensors are used to monitor the 2nd aeration tank of each train (L3 = 2).

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(3) Key Learnings

The N_2O monitoring at Luggage Point Anammox process commenced in August 2025 and is planned to continue for 1–2 years to capture any seasonal variations. The concentrations of dissolved N_2O in 1B were consistently higher than those in 1A since the monitoring commenced. These findings need further validation through long-term monitoring and more data analysis. Short-term gas-phase measurement will also be conducted during the intensive sampling plan to cross-check the emissions.

Initial challenges during the installation included accessibility around the Anammox Tanks due to the narrow walkway between Tanks 1A and 1B and the number of nutrient analyzers located in the tanks (including ammonia, nitrate, DO, pH, etc.). It was important to ensure that the instrument technicians would have sufficient access to remove the N_2O sensors (for calibration and cleaning every two months) and return them to service.

4.2.9 Other configurations

4.2.9.1 Giubiasco ASP

Authors & Affiliation: Wenzel Gruber from Upwater

(1) Site Description and Operation

Giubiasco WWTP located in Switzerland (46°10′25.6″N 8°59′27.7″E) consists of a mechanical treatment with screens, grit chamber, and a primary clarifier, followed by a conventional activated sludge system and secondary clarifiers. An aerial view of the plant can be seen in Figure 4.56.

Giubiasco WWTP employs a conventional activated sludge (fully aerobic) system (CAS) for carbon removal. It has two lanes, each with a volume of 6200 m^3. The plant receives an average daily inflow of 17,866 m^3/d. It treats wastewater with a load of roughly 75,000 population equivalent.

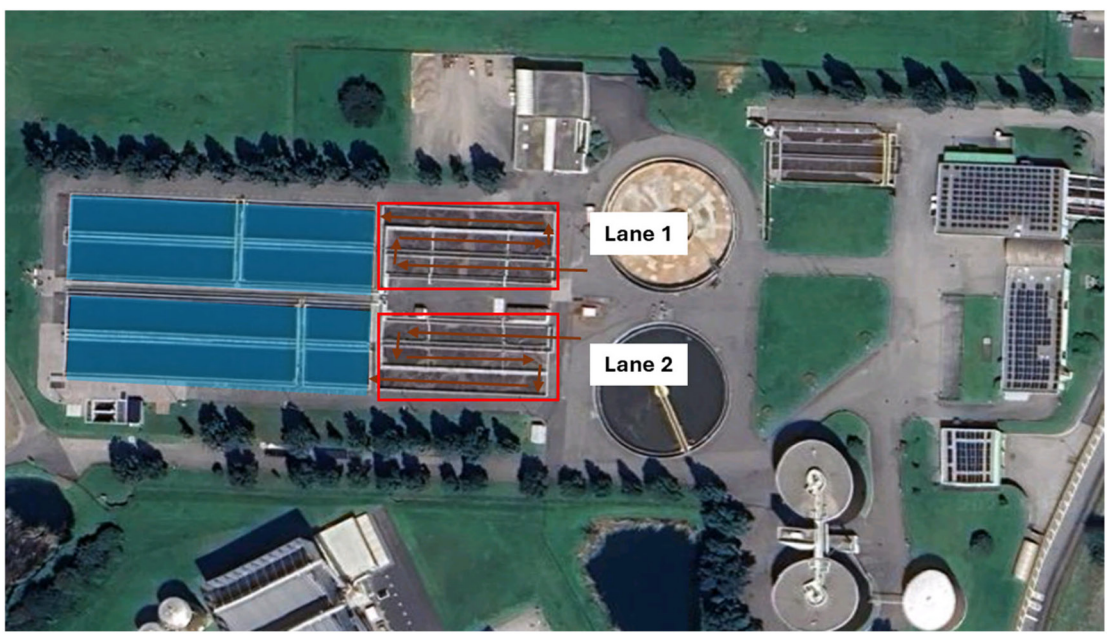


Figure 4.56 Aerial view of Giubiasco WWTP.

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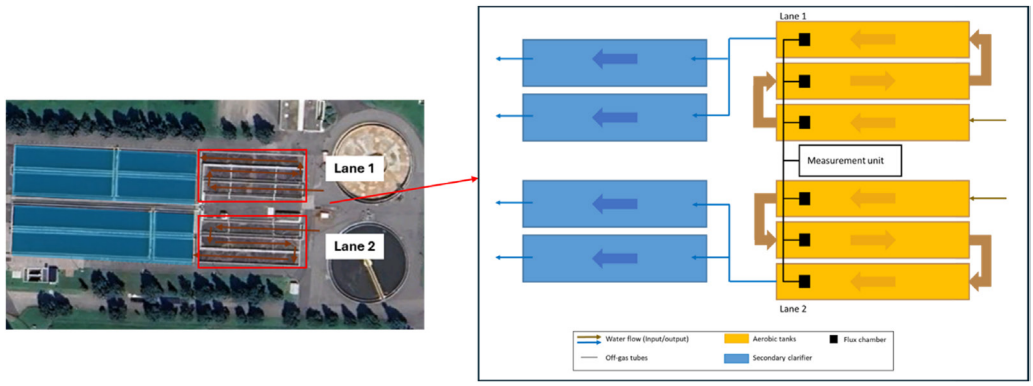


Figure 4.57 Monitoring locations at Giubiasco WWTP. There are two CAS lanes at Giubiasco WWTP (lanes 1 and 2) and each have different source of influent, therefore they are two separate sludge systems, L1 = 2. The two lanes of CAS are different in design and operation, therefore are not parallel to each other, L2 = 1. For monitoring, one flux chamber is placed in each aerobic tank of the two CAS lanes, L3 = 6.

(2) Selection of Monitoring Locations

Five flux chambers are used for continuous monitoring for the gas phase N_2O emissions at Giubiasco WWTP, with one chamber located in each aerobic tank across the two lanes.

Figures 4.57 illustrates the monitoring locations at Giubiasco WWTP that were selected based on the three-level method that outlines the number of sludge systems (L1), number of parallel bioreactors (L2), and number of monitoring locations within the bioreactors (L3).

Level 1: Identify the Number of Sludge Systems (L1 = 1)

There are two lanes of CAS with the same volume and operation. Hence, there is only one sludge system at the plant (L1 = 1).

Level 2: Determine the Number of Parallel Bioreactors (L2 = 1)

Each lane receives the same influent. Therefore, the two lanes are parallel to each other (L2 = 1).

Level 3: Determine the Number of Monitoring Locations within One Bioreactor (L3 = 3)

Lanes 1 and 2 both have three aerobic zones (L3 = 3).

Total number of sampling points

Total number of sampling points = L2*L3

With L2 = 1, L3 = 3

The total number of sampling points results in 3.

However, the total number was increased to 6 to cover both lanes.

(3) Key Learnings

A monitoring campaign with the above described setup was conducted between January 2018 and June 2019. The following conclusions were drawn:

Very high EF of 8%.

Emission peak phases during Winter (January–March 2019) coinciding with nitrification wash-off and during Summer (June–July 2019) with regrowth of nitrification (see Figure 4.58).

Expected parallel behavior of parallel lanes.

4.2.9.2 Biostyr

Authors & Affiliation: Ahlem Filali (INRAE-PROSE), Rania Krimou (SIAAP) and Sabrina Guérin-Rechdaoui (SIAAP).

(1) Site Description and Operation

The Seine Aval WWTP, located in the Paris region (France), is the largest WWTPs in Europe, with a nominal capacity of 1.7 million m³/d (≈ 20 m³/s), serving around 5 million population equivalents (PE).

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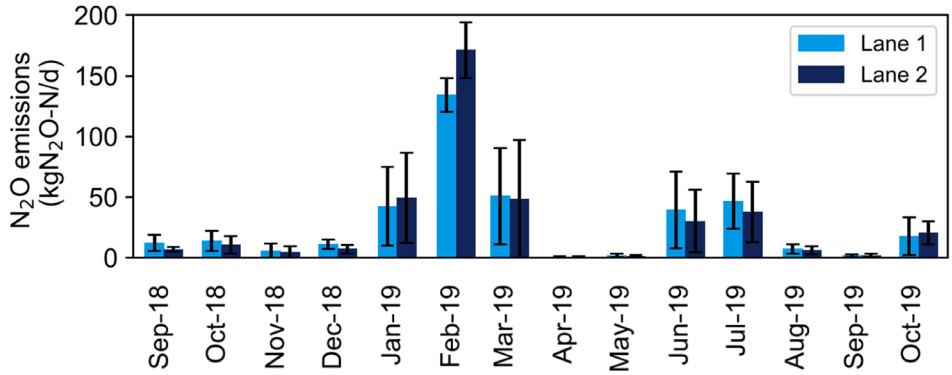


Figure 4.58 Monthly N_2O emissions of both lanes investigated. This figure has been previously published in Gruber *et al.* (2021).

The configuration described in this case study reflects the plant layout during the N_2O monitoring campaigns and does not correspond to the current configuration, as the facility has since undergone modernization.

The influent first underwent preliminary treatment including mechanical screening and grit removal, followed by primary treatment in settling tanks to remove suspended solids and settleable organic matter. The secondary treatment comprised a high-loaded conventional activated sludge (CAS) process designed primarily for organic carbon removal. The effluent from the CAS stage was then directed to a ballasted flocculation process for phosphorus and suspended solids removal. Finally, the nitrogen removal stage relied on biological aerated filters (BAFs) also referred to as biofiltration. It consisted of two distinct biological systems operated in series. The first comprised 84 nitrifying Biostyr® filters functioning under aerobic conditions for ammonium oxidation to nitrate. The second comprised post-denitrifying BAFs, made up of 18 Biostyr® filters and 12 Biofor® filters, operated under anoxic conditions with methanol dosing as an external carbon source for nitrate reduction.

Each Biostyr® unit operated in upflow mode, with influent entering from the bottom and passing upward through a 3.5 m-deep bed of 3–4 mm polystyrene Biostyrene® media. In the nitrifying BAFs, aeration was provided by diffusers located at the reactor base and automatically regulated according to the effluent ammonium concentration and loading rate. The post-denitrifying Biostyr® filters were also operated in upflow but under anoxic conditions. Methanol dosing was adjusted to maintain an influent BOD: NO_x-N ratio of about 3.5:1. The Biofor® units also performed post-denitrification but used a different granular material and operated in downflow mode. These biofilters treated a smaller fraction of the nitrate load and were not included in the N_2O monitoring campaign.

(2) Selection of Monitoring Locations

Given the very large scale and multiplicity of BAF units at the Seine Aval WRRF, the first goal of the two N_2O monitoring campaigns was not to provide a complete quantification of total plant emissions, which would have been prohibitively ambitious. Instead, the campaigns aimed to collect high-resolution data on N_2O dynamics within the nitrogen-removal stage, in order to support the development of process-based models capable of predicting plant-scale emissions under varying operating conditions and to inform mitigation strategies. The monitoring configuration described below therefore represents a research-oriented design, implemented during the campaigns to capture representative process-level insights (Figure 4.59).

Level 1 – Number of Sludge Systems (L1 = 2)

The nitrogen-removal stage comprised two independent biological systems within the BAF process:

(1) Nitrifying Biostyr® filters (aerobic), and
(2) Post-denitrifying BAFs (anoxic), including both Biostyr® and Biofor® technologies.

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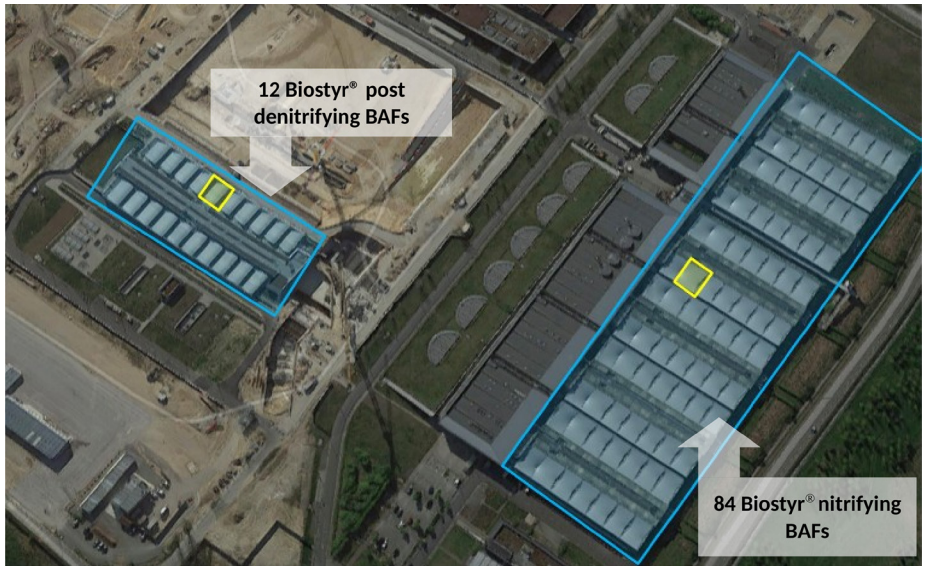


Figure 4.59 Overview of the N_2O monitoring strategy at the biological nitrogen removal (BNR) stage of the Seine Aval WRRF. This stage comprised two independent biological systems (L1 = 2): the nitrifying BAFs (L2 = 1) and the post-denitrifying BAFs (L2 = 2). Within each system, a single representative monitoring location was selected (L3 = 1). The colors indicate the two measurement campaigns (yellow for summer and blue for winter) and the corresponding monitoring configurations. In both campaigns, gaseous and dissolved N_2O were measured on one representative nitrifying BAF. In addition, during the winter campaign, dissolved N_2O concentrations were monitored at the outlet of all nitrifying BAFs. For the post-denitrifying BAFs, the first campaign included both gaseous and dissolved N_2O monitoring on one Biostyr® filter, whereas the second campaign focused solely on dissolved N_2O measurements at the inlet and outlet of all 18 Biostyr® post-denitrifying units.

Because these systems operated under clearly distinct redox conditions, microbial populations, and operational strategies, they were considered two separate sludge systems in the monitoring-design framework.

Level 2 – Number of Parallel Bioreactors (L2 = 1 for nitrification and L2 = 2 for post-denitrification)

The 84 nitrifying Biostyr® filters operated in parallel, each receiving the same influent and being controlled under comparable aeration conditions. Consequently, the nitrification stage was considered a set of parallel reactors, and one representative nitrifying Biostyr® unit was selected for detailed monitoring.

In the post-denitrifying stage, the 18 Biostyr® filters operated in parallel; however, their performance was not fully uniform due to gradients in methanol concentration along the treatment chain. While the nitrate load was evenly distributed, variations in methanol dosing along the flow path led to differences in the influent BOD-to-N ratio among the filters.

After close consultation with the plant operators, monitoring during the first campaign focused on one post-denitrifying Biostyr® filter that received an average BOD-to-N ratio representative of the entire post-denitrification stage, and for which methanol inflow was well characterized from total injection records. The results of this first campaign indicated that N_2O largely remained in the liquid phase, with extremely low off-gas emissions compared to the dissolved N_2O flux.

Based on these findings, the second campaign was expanded to include dissolved N_2O measurements at the inlet and outlet of all 18 post-denitrifying Biostyr® filters, which together treated more than 85% of the total nitrate load. This broader monitoring approach provided a more comprehensive assessment of N_2O dynamics across the post-denitrification stage.

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Level 3 – Number of Monitoring Locations within One Bioreactor (L3 = 1 per filter)

Biostyr® filters are well known to operate as upflow plug-flow reactors, with concentration gradients forming along the bed height. However, the upper overflow zone, located above the packed-bed and accessible for hood and sensor installation, is well mixed. This was confirmed at the Seine Aval WRRF through surface-water mapping conducted before the N_2O monitoring campaign.

Accordingly, a single monitoring location was installed in the top mixed (overflow) zone of each filter. At this point, air flow and off-gas N_2O concentration were measured simultaneously, and dissolved N_2O concentrations were recorded at both the inlet and outlet of the monitored filter.

(3) Key Learnings

The nitrifying BAFs were identified as a major N_2O source, with EF twice as high in winter compared to summer. Between 50% and 80% of the total N_2O produced in nitrifying biofilters was released to the gas phase, with the partitioning strongly influenced by aeration rate and temperature. The elevated winter emissions were likely linked to increased nitrite accumulation and reduced DO availability within the biofilm.

In contrast, the post-denitrifying BAFs mainly acted as N_2O sinks, consuming up to 90% of the dissolved N_2O entering from upstream units. Almost all N_2O remained in the liquid phase (> 99%), with negligible off-gas emissions. Occasional methanol dosing failure was the primary factor driving N_2O production events. Maintaining a BOD-to-N ratio above the stoichiometric threshold (~3.2) favored complete denitrification and maximized N_2O consumption.

Overall, the studies demonstrated that **nitrifying BAFs were the main sources of N_2O,** whereas **post-denitrifying BAFs played a mitigating role**, consuming a substantial fraction of dissolved N_2O. From a methodological standpoint, **dissolved N_2O was shown to contribute significantly to total N_2O production** in both nitrification and, more prominently, in denitrification, **highlighting the importance of assessing both gas-phase and liquid-phase N_2O to establish a reliable mass balance.** More detailed information is provided in Bollon *et al.* (2016a; 2016b). Finally, the monitoring data offered a **robust foundation for process-based modeling and emission mitigation strategies** in the **biological nitrogen removal stage** of the **Seine Aval WRRF** (Gonzalez Vasquez *et al.*, 2021).

4.2.9.3 Riverstone – Sydney Water

Authors & Affiliation: Elliot Cichero & Marybeth Dela Cruz from Sydney Water

(1) Site Description and Operation

Sydney Water's Riverstone WRRF located in Sydney, Australia, employs a multi-stage biological nutrient removal process commonly referred to as a four-stage Bardenpho configuration for its secondary treatment process. This configuration involves a sequence of anoxic and aerobic zones to remove pollutants from wastewater.

Riverstone's secondary treatment process operates four biological reactors in parallel. Each reactor consists of a selector, anoxic 1, aerobic 1, de-aeration, anoxic 2, followed by aerobic 2. The MLR is recycled to the anoxic 1, while the recycled activated sludge is returned to the feed distribution chamber. The centrate from thickening and dewatering is recycled to the inlet works. An aerial view of the Riverstone secondary treatment process is seen in Figure 4.60.

The anoxic zone is divided into two sections (Ax 1A and Ax 1B), while aerobic 1 is divided into four sections (Ab 1A, Ab 1B, Ab 1C, and Ab 1D). Similarly, anoxic 2 is divided into A and B, and aerobic 2 is also divided into A and B.

The aeration system is designed with coupled control zones. Specifically, aerobic zones 1A and 1B share a common air supply, with a single control valve controlling the total air flow rate delivered to the blowers of both compartments simultaneously. This paired configuration is repeated for zones 1C/1D and zones 2A/2B.

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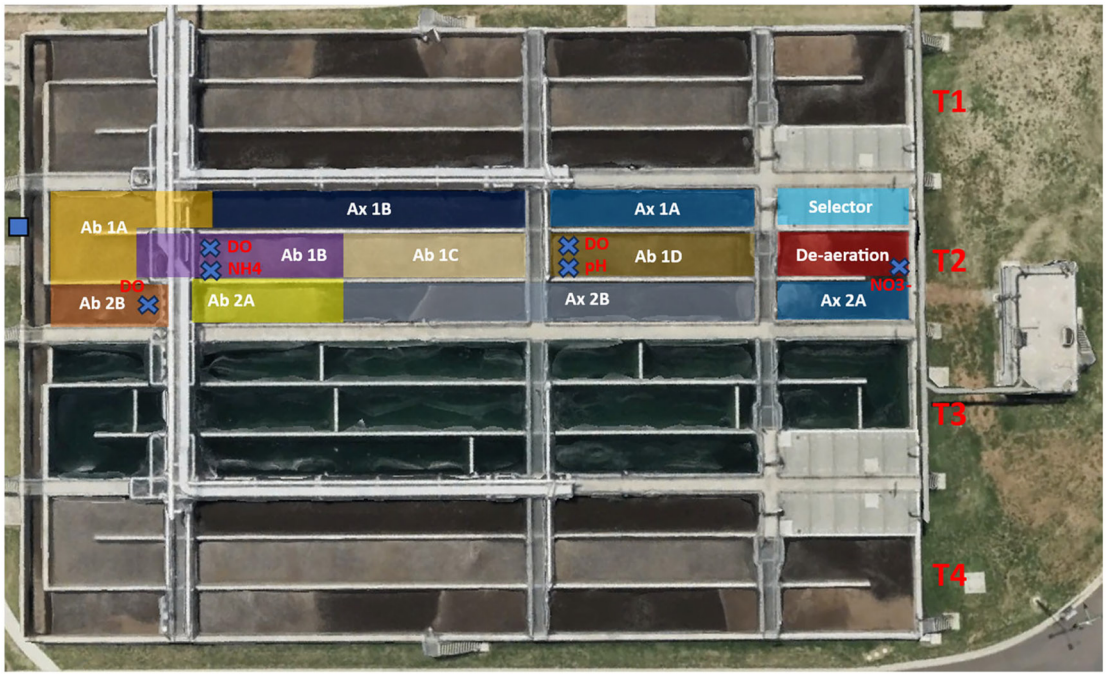


Figure 4.60 Aerial view of the Riverstone secondary treatment process.

The plant has an average dry weather flow of 230 L/s with a treatment capacity of 19 ML/day. The SRT ranges from 20 to 25 days, with a typical HRT of 24 h.

Aeration in the aerobic zones is controlled using a DO setpoint strategy, with aerobic 1 having a setpoint of 1.5 mg/L and aerobic 2 DO is controlled based on ammonia (NH_3) concentration. The online sensors available in the bioreactor include:

(1) Three DO sensors, two situated in the first and second half of aerobic zone 1, and the third in aerobic 2.
(2) One ammonia sensor in aerobic 1.
(3) One nitrate sensor in the de-aeration zone.
(4) One solids analyzer in the mixed liquor channel.
(5) Plant influent ammonia and TSS.

(2) Selection of Monitoring Locations

One liquid probe is situated in anoxic 1, while the other is situated in anoxic 2. This is to capture the differences between DO air supply in each different zone.

Figure 4.61 illustrates the monitoring locations at Riverstone WRRF, which were selected based on a three-level condition determination that considers the number of sludge systems (level 1), the number of parallel bioreactors (level 2), and the number of monitoring locations within a single bioreactor (level 3).

Riverstone operates a single activated-sludge system (L1 = 1) configured as a four train four-stage Bardenpho

(L2 = 4). Each train has three aerobic zones controlled by individual air flow (L3 = 3).

Level 1: Identify the Number of Sludge Systems (L1 = 1)

Riverstone WRRF has a single sludge system in operation during the monitoring campaign, hence L1 = 1.

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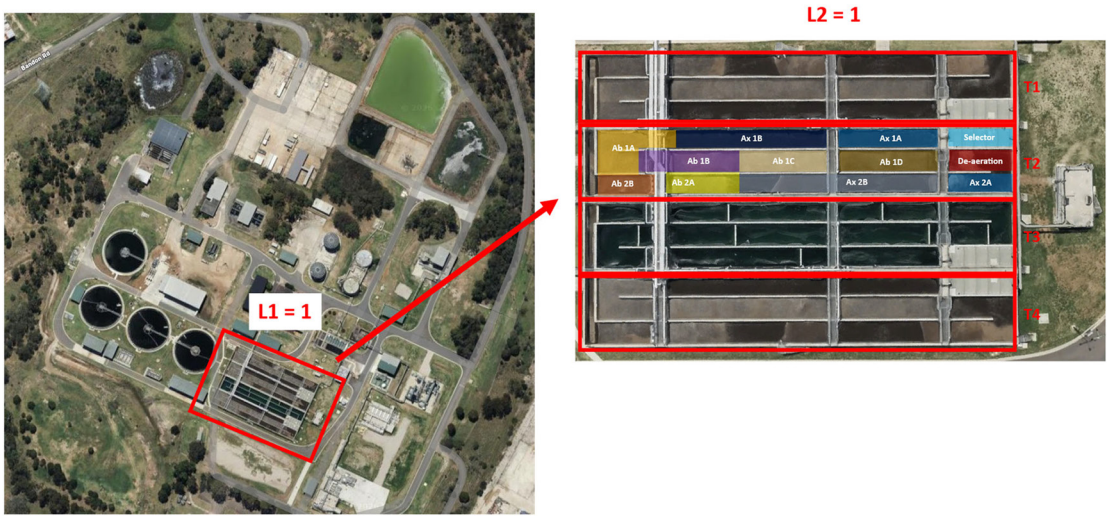


Figure 4.61 Monitoring locations at Riverstone WRRF.

Level 2: Determine the Number of Parallel Bioreactors (L2 = 1)

The activated sludge system is a four train four-stage Bardenpho with four parallel reactors (L2 = 1).

Level 3: Determine the Number of Monitoring Locations within One Bioreactor (L3 = 3)

The four-stage Bardenpho consists of a selector, anoxic 1, aerobic 1, de-aeration, anoxic 2, then aerobic 2. A minimum of three monitoring locations is required. Ab 1A/1B have different air supply to Ab 1C/1D, requiring one hood in each of these two areas. The last hood is in Ab 2A which shares the same air supply as Ab 2B, and so only one hood is required in this zone. Therefore, for quantification purposes, gas hoods are used for continuous monitoring.

Additionally, in order to understand the N_2O generation contribution from the two anoxic zones, Riverstone's setup includes two liquid probes located at the end-of the two anoxic zones. In the meantime, these two probes will also be relocated to cross-check the gas emissions from the hoods during the expected 1–2 years monitoring campaign to compare quantification results between the gas hoods and liquid probe method. See Figure 4.62 for the location of the N_2O hoods and probes.

Due to the length of the aerobic zones, short-term relocation of the hoods within the same aeration zones is also planned to capture the spatial variation along the aerobic zone. Hood 1 is planned to be relocated to the first half of Ab 1B, and Hood 2 relocated to start of Ab 1D while Hood 3 will not be relocated. Additionally, the N_2O Probe 1 will be relocated next to Hood 1 in first half of Ab 1B, and Probe 2 will be relocated next to Hood 3 in Ab 2A to cross check the results from the hoods. A summary of the short-term monitoring locations is summarized in Figure 4.63.

The locations of the gas hoods and liquid sensors were selected to allow ease of access for maintenance and calibration. At the time of writing, the liquid probes are still being installed, while the gas hood setup can be seen in Figures 4.64–4.66.

(3) Key Learnings

Preliminary N_2O gas monitoring results indicate that hoods 1 and 2, located at the start and end of aerobic zone 1, recorded the highest N_2O emissions. In contrast, relatively low N_2O emissions were observed at hood 3 in aerobic 2.

These results need further verification through extended monitoring. Riverstone experiences scum formation on the surface of the aerobic zones, as shown in Figure, which can lead to hood blockages.

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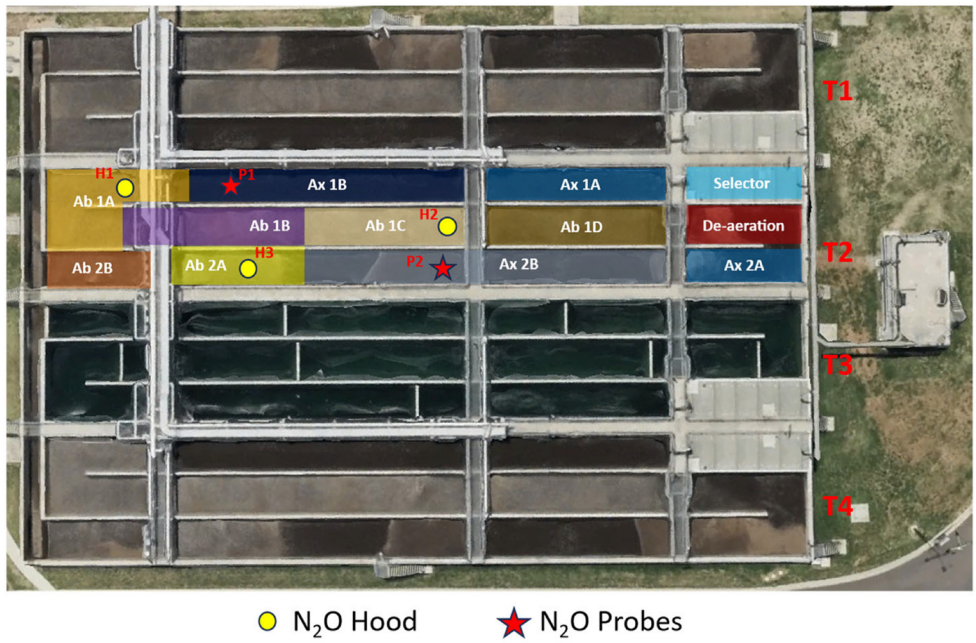


Figure 4.62 Gas N_2O hoods and liquid N_2O sensors locations at Riverstone WRRF.

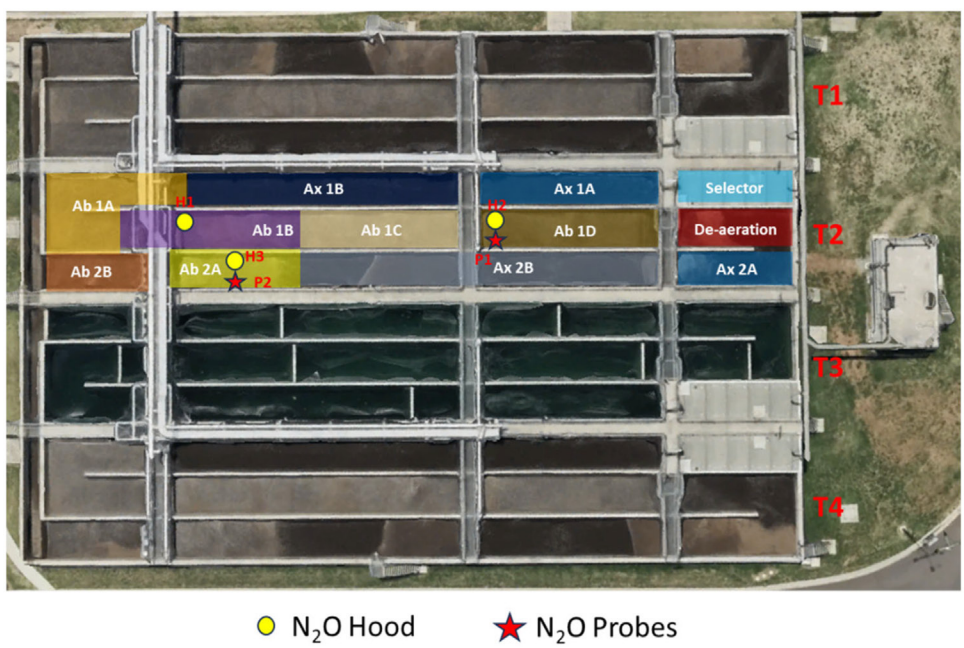


Figure 4.63 Short-term gas N_2O hoods and liquid N_2O sensors locations at Riverstone WRRF.

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Figure 4.64 Hoods 1 (top right) and 3 (bottom).



Figure 4.65 Hood 2.



Figure 4.66 Gas cabinet kiosks below bioreactors.

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Regular observation, maintenance and cleaning of the hoods are therefore essential to ensure reliable N_2O data.

Close collaboration with the operating team at Riverstone WRRF has been crucial to the installation and ongoing maintenance of the hoods. This has helped reduce risk, support safe working practices, and minimize impacts to the WRRF while equipment was installed.

4.2.9.4 Burlington Skyway WWTP, Burlington, Ontario, Canada

Authors & Affiliation: John Duong, Sanjeev Oberoi and Lizanne Pharand from Halton Region
Jeremy Kraemer from GHD

(1) Site Description and Operation

Halton Region (Ontario, Canada) owns and operates six WWTPs, providing wastewater treatment services for approximately 600,000 people. The Skyway WWTP is the largest (Figure 4.67), located in Burlington, Ontario, with a rated capacity of 140 ML/d which received an annual average daily flow of 88 ML/d in 2025. The facility provides liquid treatment comprised of influent screening, pumping, aerated grit removal, primary clarification, nitrifying activated sludge, deep-bed tertiary sand filtration, and UV disinfection. Dual point ferric addition is employed for phosphorus removal, with about 70% dosed ahead of the aerated grit tanks and as a consequence also achieving high levels (~70%) of BOD5 removal in the primary clarifiers. Sludge treatment is comprised of waste activated sludge thickening in rotary drum thickeners, mesophilic anaerobic digestion, and centrifuge dewatering.

(2) Selection of Monitoring Locations

Two Unisense N_2O sensors are used for continuous monitoring of the liquid phase N_2O concentrations. The description below explains how the monitoring locations at Skyway WWTP align with the three-level method as outlined in this N_2O monitoring protocol.

Level 1: Identify the Number of Sludge Systems (L1 = 1)

The Skyway WWTP has only one sludge system, which is the mainstream secondary wastewater treatment. All return sludge from the clarifiers is blended in a common RAS line before being split between the bioreactors (Figure 4.68). Although the plant has a sidestream SBR installed which was intended for treating centrate, the system does not function as intended and the facility staff use it for centrate flow equalization without any biological treatment. Therefore, level 1 is 1.

Level 2: Determine the Number of Parallel Bioreactors (L2 = 1)



Figure 4.67 Aerial view of the skyway WWTP located in Burlington, Ontario, Canada. (Source: Halton region).

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Figure 4.68 Skyway WWTP has one nitrifying activated sludge system in 10 bioreactors. Also shown are the secondary clarifiers and centrate SBR which is operated as an equalization tank. (Source: Halton region).

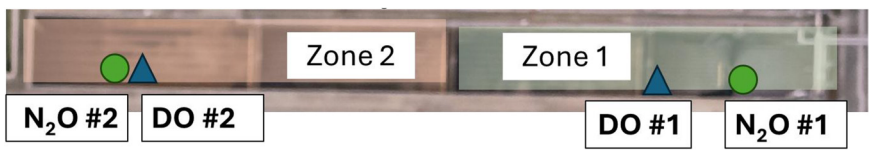


Figure 4.69 Skyway WWTP bioreactors have two aeration control zones with independent air flow measurement.

The bioreactors are configured as long single-pass tanks (Figure 4.68) and operated fully aerobic. Tanks #9 and #10 have anoxic swing zones in the design, however, staff do not operate them anoxically due to lack of readily degradable carbon in the primary effluent. All bioreactors receive the same primary effluent and operate under the same conditions, therefore all 10 bioreactors are operated in parallel. Thus, monitoring one of the 10 bioreactors is deemed representative of all and level 2 is 1.

Level 3: Determine the Number of Monitoring Locations within One Bioreactor (L3 = 2)

The Skyway bioreactors are plug-flow with spatial gradient along their length. There are two aeration control zones, roughly dividing the tank in half. Each aeration control zone has a DO sensor, air flow meter, and air flow control valve. The region installed one N_2O sensor in each zone, in proximity to the DO sensors. The sensors and zones are illustrated in Figure 4.69. Therefore, level 3 is 2.

Monitoring Locations and Setup:

Total number of sampling points = 2.

According to Equation (4).(1) of the protocol, with only one sludge system, L2×L3 = 1×2 = 2.

Figure 4.70 shows the Unisense sensor installed at the front of the bioreactor.

(3) Key Learnings

Halton Region installed N_2O sensors in December 2023 at Skyway WWTP and as of writing this case study has performed more than two years of monitoring. The Region has several learnings which may be of value to other utilities embarking on N_2O monitoring:

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Figure 4.70 Unisense N_2O sensor installed in zone 1 at the skyway WWTP. (Source: Aquafy Water Technologies).

- Do not let the protocol limit action. The Region has a second site (Mid-Halton WWTP) that also has two Unisense sensors, but does not meet the explicit requirements of this protocol. The Region has completed more than two years of monitoring at this second facility as well as tested mitigation activities.
- Implement the mass emission calculation right away. Initially, the Region only included the measured N_2O concentration on its SCADA screens and recorded in the data historian. However, operations staff have requested the mass emission to be calculated within SCADA so it can be displayed and recorded, instead of doing it after the fact outside of SCADA.
- Provide sensor location flexibility. The Region has found it useful to have sensors with cable lengths of 30 m and removable mountings, to allow relocating them and/or using them for profiling along the tank lengths.
- Be prepared to deal with sensor issues. Halton has worked through several sensor issues at Skyway WWTP including oxygen sensitivity and range. The sensors at Skyway WWTP became oxygen sensitive owing to high residual DO levels in the bioreactors, which was remedied by obtaining sensors with more oxygen scavenger in the sensor head. The Region also had to re-scale the N_2O output from 0–2 mg-N/L to 0–5 mg-N/L.
- Have a plan to check the data regularly. Halton Region employs the N_2O sensors for monitoring only, they are not used for process control. This means the data was initially not being checked

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regularly. After the sensor issues, the Region implemented an automated weekly report showing last week's time series trend for operations and technical staff to review.

- Halton Region found it helpful to have expert N_2O partners to help them on their new N_2O monitoring endeavor, including GHD (consultant), Aquafy Water Technologies (sensor maintenance), Cobalt Water Global (data analytics), and Prof. Liu Ye (advisor).

4.3 CONCLUSIONS AND RECOMMENDATIONS

The three-level location-selection principle offers a transparent, scalable path from plant complexity to a defensible, minimal set of N_2O monitoring points. By separating sludge systems (L1), distinguishing truly parallel from non-parallel bioreactors (L2), and resolving spatial heterogeneity within reactors (L3), the method aligns monitoring intensity with expected variability. The aggregation equations (Equations 4.2–4.6) provide a consistent basis to roll up fluxes from zones to lanes to site totals. Eighteen international case studies spanning step-feed, MLE/AAO, Bardenpho, oxidation ditches, SBR/AGS, MBR/MABR, MUCT, IFAS, and biofilters show recurring themes: (i) plug-flow systems with multiple aeration zones often need multi-point coverage; (ii) completely mixed zones can be assumed to be representative by single points monitoring; (iii) liquid-phase sensors in anoxic zones reveal production/consumption dynamics critical for mass balance; and (iv) robust air flow measurement and maintenance (condensation, fouling, corrosion) are decisive for off-gas accuracy. Long-term monitoring captures seasonality, diurnal load shifts, and control changes (e.g., advanced aeration control) that strongly modulate emissions.

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