Real-Time Process Optimisation Using Hach RTC Modules

Reducing Nitrous Oxide (N_2O) emissions at Kronau WWTP

Problem

Nitrous oxide (N_2O) is a climate killer - 298 times more harmful to the climate than CO_2. N_2O arises in nitrification and denitrification, if those processes are overloaded. The emission of just 1 kg of N_2O corresponds to the effect of around 1,000 kWh of electricity consumption. For wastewater treatment, this means that there is a big need to consider N_2O emissions when implementing real time control.

Solution

Hach RTC modules offer a promising strategy to achieve this goal. To prove this, a project was initiated to identify process conditions that lead to elevated N_2O levels and develop strategies to mitigate these emissions. The insights gained from these studies were used to expand the Real-Time Control (RTC) algorithms to further optimise performance while minimising N_2O emissions.

Benefits

By extending existing RTC modules supporting full nitrification, denitrification and balancing process water addition the N_2O emission could be reduced by over 85 %, from 2.9 kg to just 0.4 kg N_2O-N per day. That's equivalent to avoiding 1,900 kWh of CO_2 emissions every single day.

Initial Situation

The Kronau wastewater treatment plant (Figure 1) was originally designed for 33,000 pe, but now processes around 45,000 pe. A plant extension to 60,000pe is ongoing. Despite the high load, the plant fulfils the discharge requirements: $N_{tot} \leq 9.6$ mg/L, NH_4-N ≤ 5 mg/L, $P_{tot} \leq 1$ mg/L.

Case Studies on N_2O emission

Between Febuary 1st and April 30th, 2025, three targeted tests and one comprehensive investigation were conducted to evaluate the influence of nitrification and denitrification performance, plant loading and dissolved oxygen (DO) levels on N_2O emissions. Sensors measuring N_2O in the liquid phase were added in Z4 and Z5 (Figure 2).

Based on those measured N_2O concentration and air flow data for each zone (derived from measured blower speed) the N_2O process emissions to atmosphere were calculated according to the information provided by the N_2O sensor manufacturer. Emission factors were related to the NH_4-N inflow load to Z2 and not to the N_{tot} load plant influent.



Figure 1: Kronau wastewater treatment plant, Germany

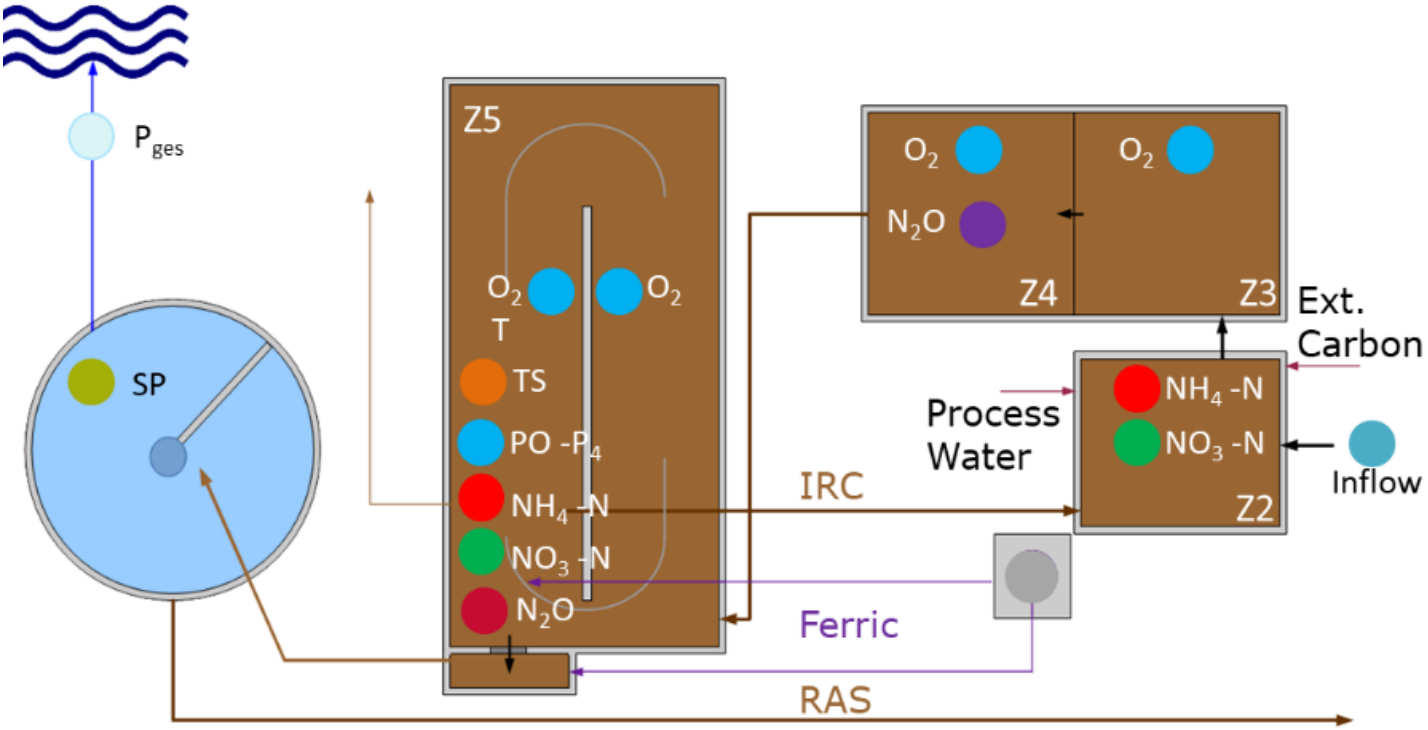


Figure 2: WWTP Kronau and analytical process measurements

Figure 2 shows plant design with its different zones.

- Zone 1: (not shown) anaerobic, mixture of return sludge and effluent primary settling
- Zone 2 (Z2): Anoxic zone (permanent)
- Mixture of effluent Zone 1, internal recirculation, Process Water addition and External carbon addition
- Zone 3, Zone 4 (Z3, Z4): Swing zone (anoxic or aerobic)
- Zone 5 (Z5): aerobic zone, fully mixed reactor and corresponding process instrumentation.

Kronau WWTP is equipped with Hach RTC modules tailored to optimise key biological and chemical treatment steps. These include:

Nitrification (N4Z-RTC):
Adaptive calculation of DO setpoints in nitrification zones, considering NH_4-N load and facultative volumes availabel. This RTC module ensures complete nitrification under variable inflow conditions and reduces the risk of N_2O emissions from ammonia-oxidising bacteria (AOB).

Denitrification (DN-RTC):
Optimised control of internal recirculation and external carbon dosing to enhance denitrification. This module enables complete denitrification and utilises the denitrification zone as an effective sink for N_2O.

Sludge Retention Time (SRT-RTC):
Regulates sludge age to maintain a stable population of nitrifying bacteria, thereby ensuring reliable and robust nitrification performance.

Chemical Phosphorous removal (P-RTC):
Load-dependent and precise control of phosphorus precipitation to avoid overdosing with ferric salts and the associated risk of pH depression.

Return Activated Sludge flow (RS-RTC):
Controls return sludge flow based on turbidity and suspended solids, ensuring consistently high TSS concentrations in the aeration tanks, even under fluctuating hydraulic conditions.

These modules work in combination to maintain process stability and enable dynamic responses to load variations, thereby minimising conditions that foster N_2O generation

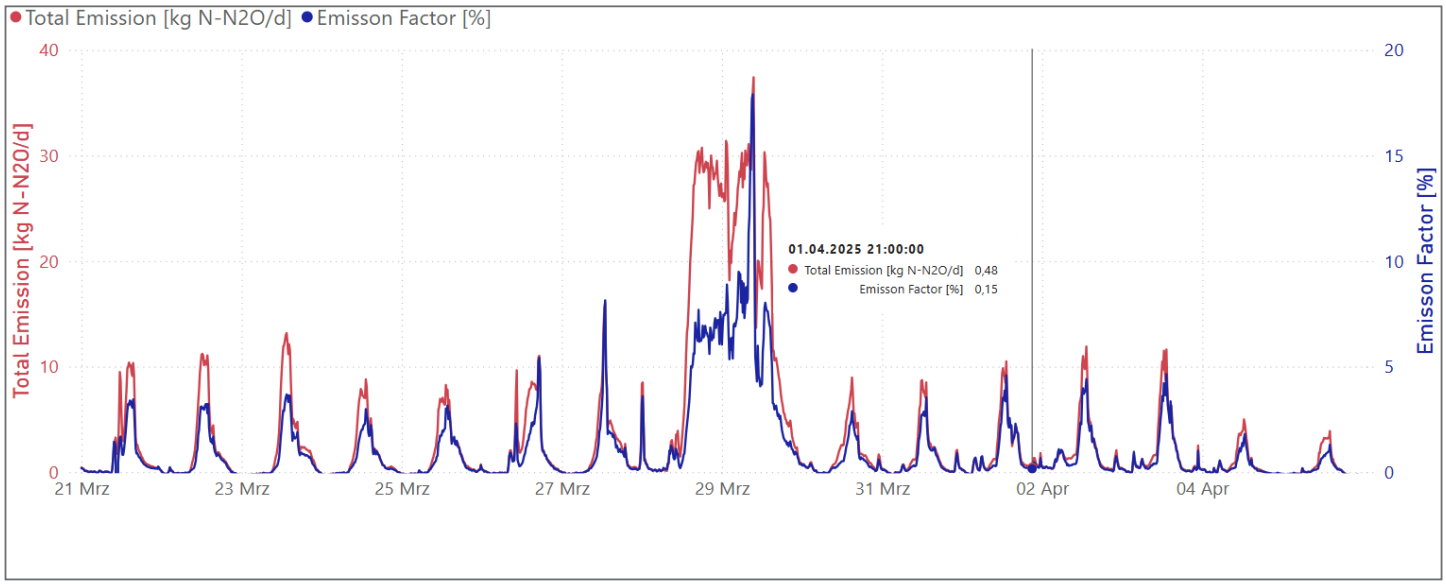


Figure 3: Typical N_2O emissions and emission factors over a two-week monitoring period

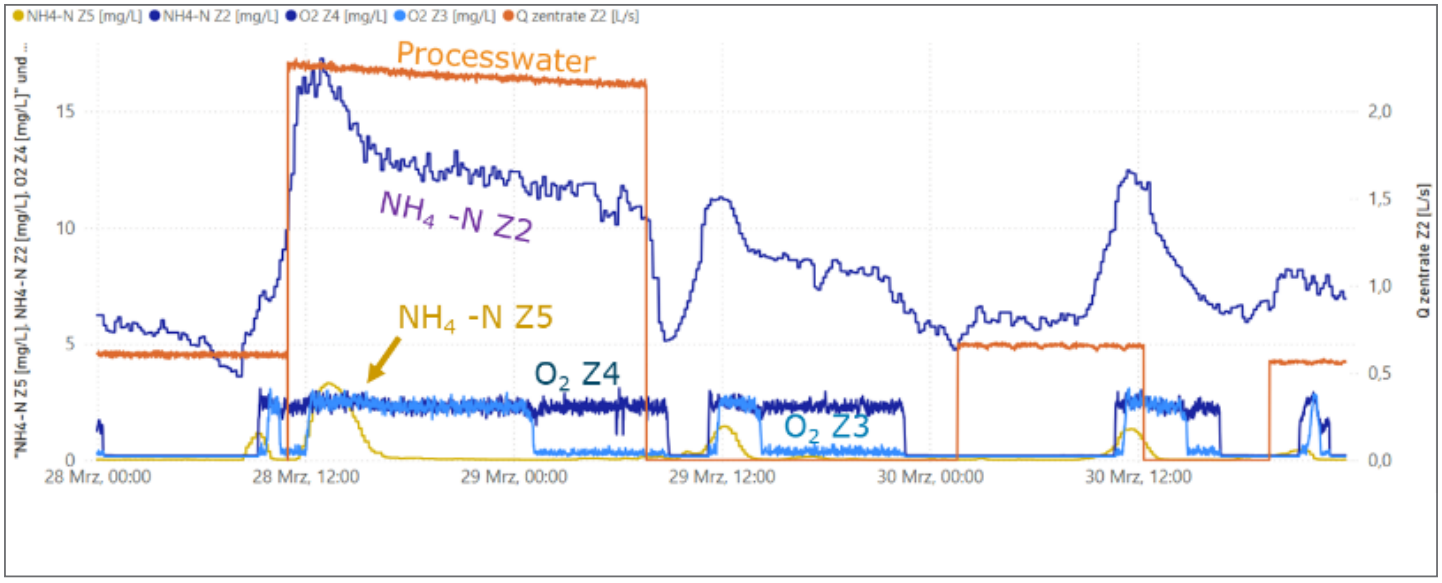


Figure 4: Process Water addition and NH_4-N concentrations

Effect of high NH_4-N load on N_2O emission

Figure 3 illustrates typical N_2O emissions [kg/d] and emission factors [% of NH_4-N inflow aeration] over a two-week monitoring period. A recurring pattern is observed, with minor emission peaks occurring each morning. A notable deviation occurred on March 28, when an unusually high volume of process water was added (orange in Figure 4). This led to elevated NH_4-N concentrations in biological basin Z2 (purple), which in turn triggered aeration in both Z4 and Z3 — as indicated by increased O_2 levels in these zones in Figure 4 (blue lines). Despite utilising Z3 and Z4 for nitrification the NH_4-N effluent in Z5 increased up to 3mg/L (yellow line).

The disturbance resulted in a sharp increase in N_2O emissions, reaching up to 30 kg N–N_2O per day, with emission factors exceeding 10% (Figure 3), underscoring the sensitivity of N_2O dynamics to ammonia load shocks and the subsequent process responses.

Impact on plant operation

To prevent such events in the future, plant operation will increasingly rely on the Hach load management controller (CENTRTC). This system enables strategic timing of process water addition favoring periods of low influent loading. By doing so, it minimises the risk of overloading the biological system and prevents conditions conducive to excessive N_2O formation.

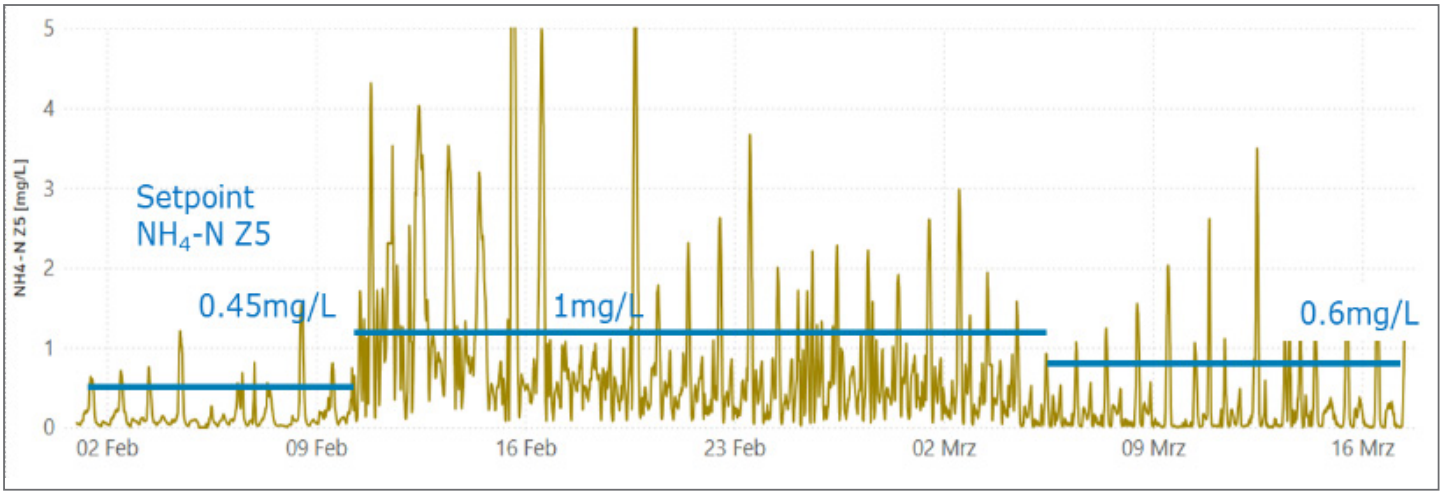


Figure 5: Impact on NH_4-N in Z5 on N_2O process emissions

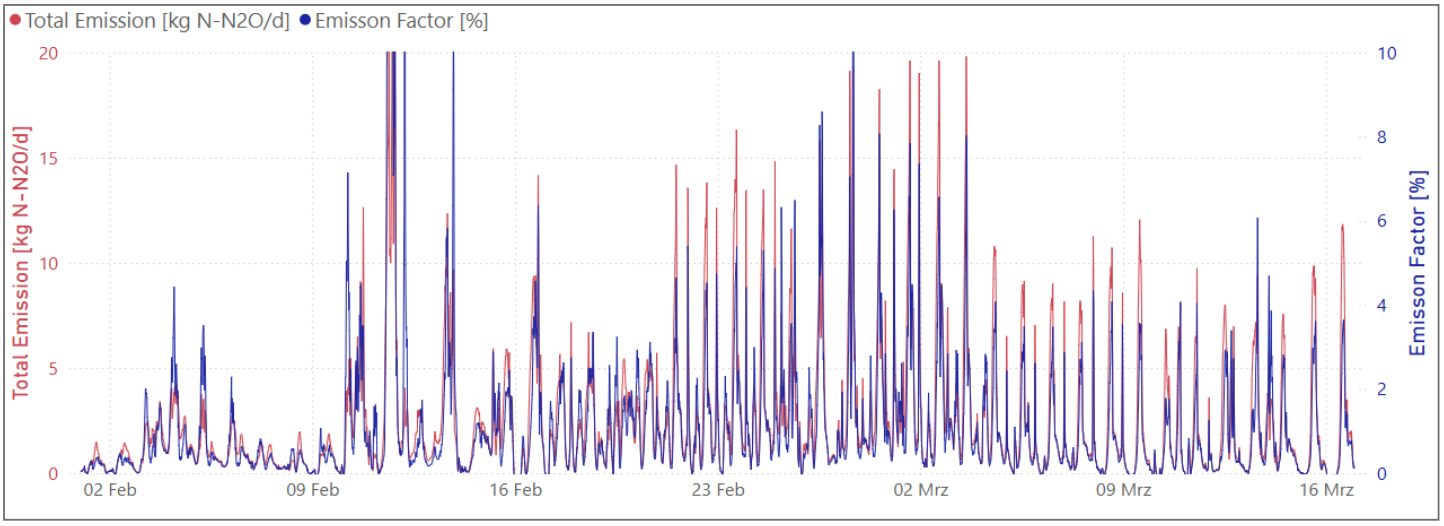


Figure 6: Impact on NH_4-N Z5 on N_2O process emissions

Table 1: Impact on NH_4-N in Z5 on N_2O

Date	... 9.2.	10.2. – 4.3	5.3 – 16.3
Setpoint NH_4-N Z5 [mg/L]	0,45	1,0	0,6
NH_4-N Z5 [mg/L]	0,13	0,80	0,23
Total Emission [kg/d]	0,97	3,33	2,05
Emission factor [%]	0,48	1,56	0,74

Effect of NH_4-N set point on N_2O emission

Figure 5 presents the NH_4-N concentrations in Z5 between February 2nd and March 16th. During this period, the NH_4-N setpoint in Z5 was adjusted twice:

- initially increased from 0.45 mg/L to 1.0 mg/L on February 10th, and
- subsequently reduced to 0.6 mg/L on March 4th

Figure 6 illustrates the corresponding changes in N_2O emissions and the emission factor. An increase in N_2O emissions was observed following the initial rise in the NH_4-N setpoint, while a subsequent decrease occurred after the setpoint was lowered to 0.6 mg/L. The results are summarised in Table 1.

Impact on plant operation

The Hach N-RTC system supports full nitrification by dynamically adjusting the dissolved oxygen (DO) setpoints and the aerated volume. This control strategy contributes to reduced N_2O emissions by maintaining stable process conditions and avoiding periods of incomplete nitrification.

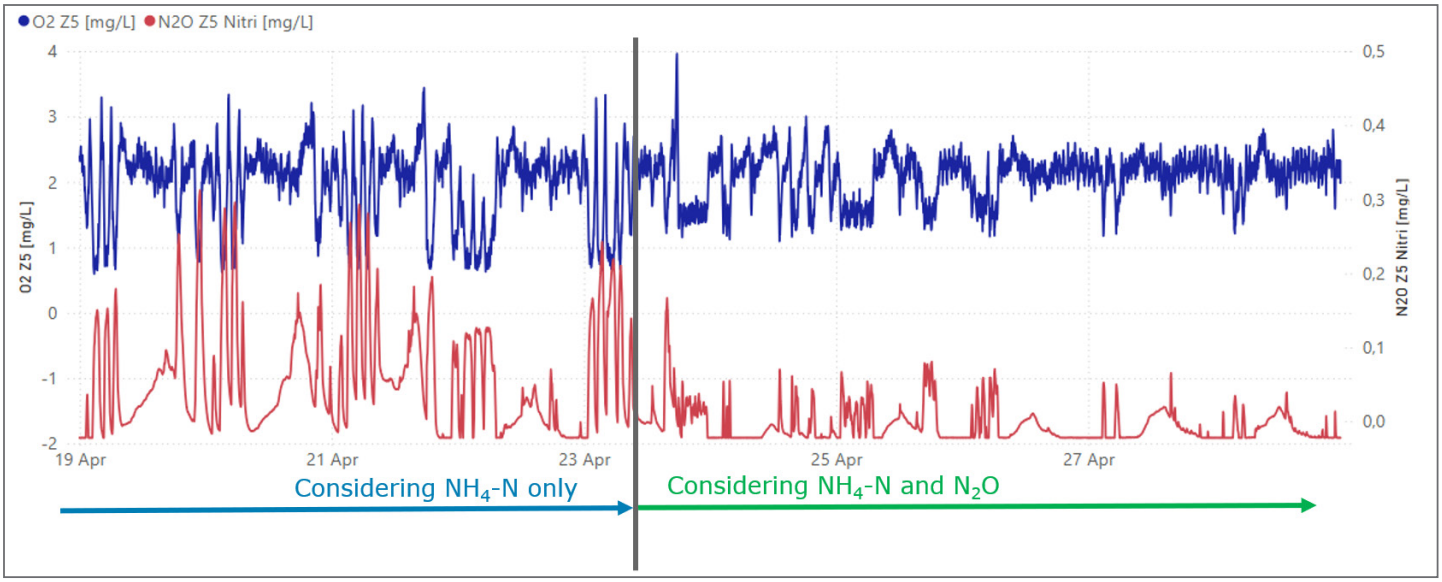


Figure 7: Fluctuations DO in Z5 and impact on N_2O

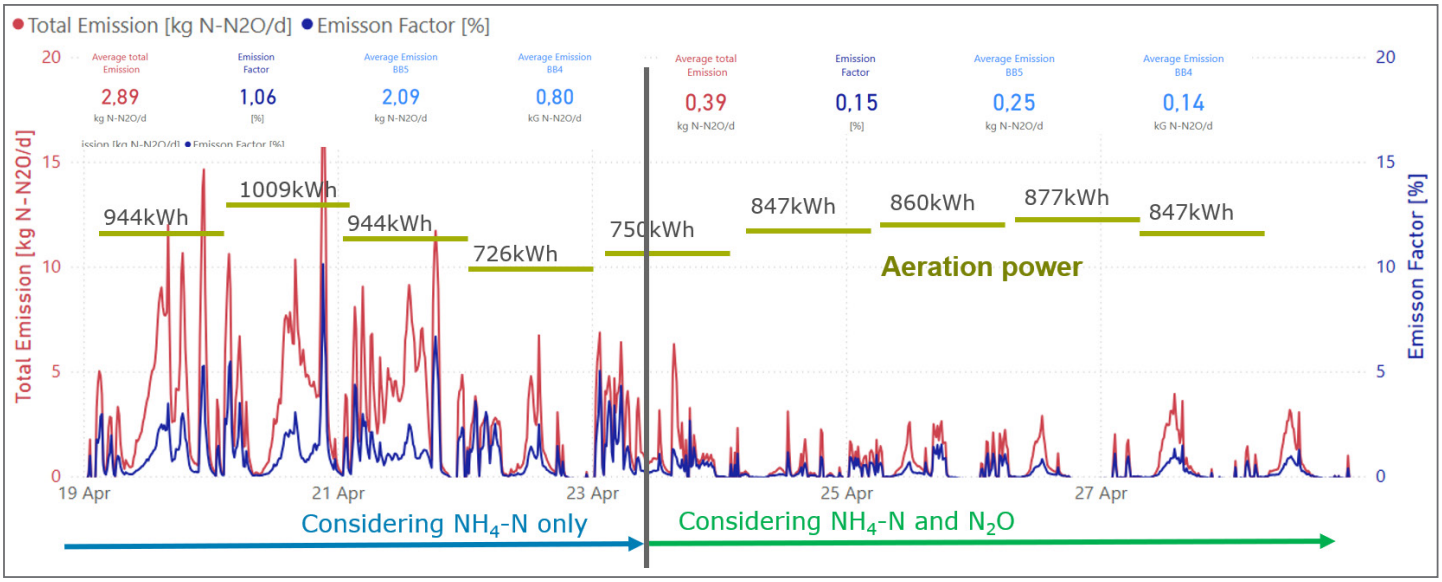


Figure 8: Impact on N_2O emission by improved N-RTC

Effect of DO concentration on N_2O Emissions

Between April 19th and April 23rd, an increased frequency of activation and deactivation of the swing zones Z3 and Z4 led to strong fluctuations in the dissolved oxygen (DO) concentration in Z5 (Figure 7, blue).These fluctuations significantly impacted the N_2O concentration measured in this zone (Figure 7, red). Specifically, lower DO concentrations were associated with elevated N_2O levels due to two main effects:

- A decrease in DO below 1 mg/L enhances biological N_2O formation (main effect).
- Reduced airflow at low DO levels limits the stripping of N_2O from the liquid phase, resulting in higher measured soluble N_2O concentrations.

To mitigate these elevated N_2O levels, the N-RTC algorithm was adjusted to prevent DO concentrations from falling when an increase in N_2O concentration is detected in Z5. Following the implementation of this control strategy after April 23rd, a substantial reduction in N_2O emissions and in the N_2O emission factor was observed (Figure 8).

Importantly, the increase in DO concentration did not lead to higher energy consumption by the blower, as shown in Figure 8. Daily consumption for aeration remained at app. 1000kWh/day.

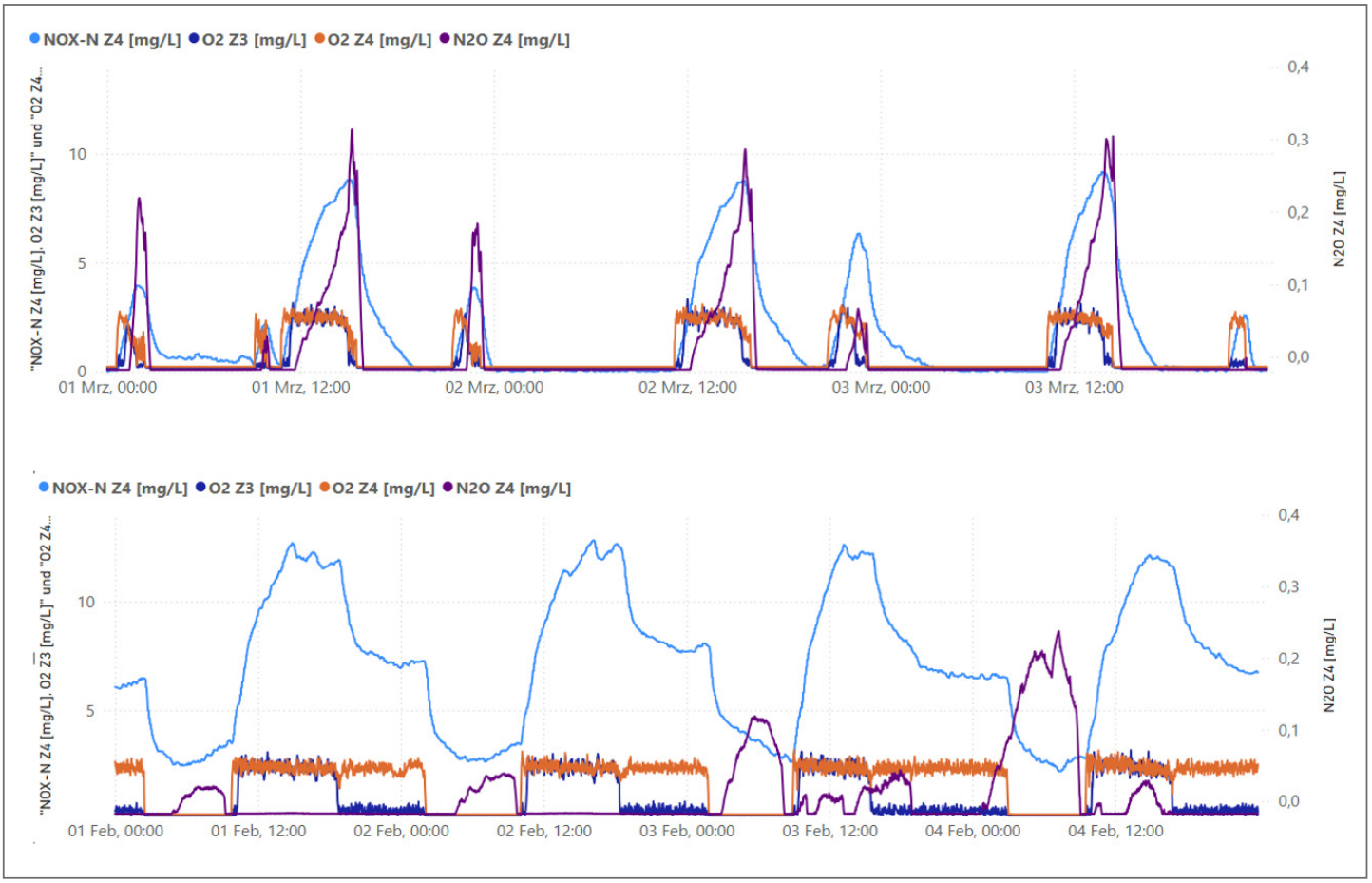


Figure 9: Impact of Denitrification performance on N_2O concentration measured in Z4

Effects of Denitrification on N_2O Emissions

Figure 9 shows the concentrations of N_2O and NO_x-N in Z4 (swing zone), along with the corresponding DO concentrations indicating whether Z3 and Z4 were operating under nitrifying or denitrifying conditions. Figure 9 top graph demonstrates that when denitrification is fully completed—evidenced by NO_x-N dropping close to 0 mg/L—N_2O is also effectively removed.

In contrast, Figure 9 bottom graph shows that if denitrification is incomplete and NO_x-N concentrations remain around 2 mg/L, soluble N_2O is not only retained but even increases during the denitrification phase up to 0,3mg/L.

These findings highlight the critical role of complete denitrification as a sink for N_2O and emphasise its importance in minimising N_2O emissions. The Hach Denitrification RTC supports this by optimising denitrification through controlled internal recirculation and, if necessary, controlled addition of external carbon sources.

Operational Strategy to Minimise N_2O Emissions

To effectively reduce N_2O emissions in biological wastewater treatment, a combination of proactive planning and reactive control measures is required. The following approach outlines a the operational strategy based on real-time monitoring and automated process control implemented in Hach RTC modules.

Addition of Process Water (Predicted Measures)

The controlled addition of process water is a proactive measure to manage daily nitrogen loading:

Initiation Timing:

The process water dosing should begin at the time of the daily minimum NH_4-N load, as calculated by the Hach Nitrification RTC module (N4Z). This ensures that the system is operating under low-load conditions when additional nitrogen input is least disruptive.

Dosing Duration and Completion:

The total volume and dosing rate must be adjusted so that the addition ends by 6:00 a.m. the following day, just before the onset of the typical morning load peak. This approach is implemented in the Hach Load Management RTC and helps prevent an overload of NH_4-N during the most sensitive time of day and maintains stable nitrification conditions.

Reactive Control Measures

Real-time monitoring of process parameters enables adaptive responses to early signs of process instability, particularly those that may lead to elevated N_2O emissions.

Condition 1: Incomplete Nitrification and Elevated N_2O

- Trigger:
  If NH_4-N concentrations exceed 0.5 mg/L and N_2O levels begin to rise, this is a strong indication of incomplete nitrification. This condition is typically associated with stress on ammonia-oxidising bacteria (AOB), which can result in elevated N_2O production due to disrupted metabolic pathways.
- Control Actions:
  – Increase DO Concentration in Z5 > 1.5 mg/L:
  Raising the dissolved oxygen concentration helps ensure complete nitrification and suppresses the alternative pathways in AOB that lead to N_2O formation. Stable and sufficient DO also improves the resilience of the nitrification process during load fluctuations.
  – Increase Internal Recirculation (IRC):
  Enhancing internal recirculation rates transports NO_3, NO_2, and N_2O from the aerobic zones to the upstream denitrification zones. There, these compounds can be biologically reduced to N_2, effectively removing them from the system and minimising emissions.

Condition 2: Incomplete Denitrification

- Trigger:
  If NO_3-N concentrations in the effluent remain high during denitrification, this typically signals a carbon deficiency. Without sufficient carbon, denitrification stalls and N_2O is not completely reduced to N_2, increasing the risk of N_2O emissions.
- Control Actions:
  – Addition of External Carbon Source
  To restore denitrification performance, an external carbon source can be added. The dosing is regulated based on real-time monitoring of NO_3-N and/or N_2O levels to ensure it is supplied only when needed. This promotes complete denitrification and supports the reduction of N_2O to benign nitrogen gas (N_2).

This integrated control approach, leveraging both real-time monitoring and dynamic operational adjustments, forms the basis of an effective strategy for minimising N_2O emissions while maintaining stable nitrogen removal performance.



Kronau wastewater treatment plant, Germany

Conclusion

The targeted combination of proactive and reactive control strategies has proven effective in minimising N_2O emissions from the biological treatment process. By optimising the timing and quantity of process water addition, maintaining stable DO concentrations, and dynamically adjusting internal recirculation rates, critical conditions that lead to elevated N_2O emissions can be avoided. In particular, the ability to detect early signs of incomplete nitrification and denitrification allows for timely interventions—such as increasing DO or supplying external carbon—to restore biological stability and reduce emission risks.

The integration of real-time data and adaptive control logic within the N-RTC and DN-RTC frameworks not only enhances process performance but also supports climate-relevant goals by significantly lowering N_2O emissions. This approach demonstrates how intelligent Hach RTC systems can transform traditional wastewater treatment into a more sustainable and environmentally responsible operation.

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