Application of Event-Based Real-Time Analysis for Long-Term N_2O Monitoring in Full-Scale WWTPs

V. Vasilaki[1], M. Danishvar[2], Z. Huang[2], A. Mousavi[2], and E. Katsou[1](✉)

[1] Department of Mechanical, Aerospace and Civil Engineering; Institute of Environment, Health and Societies, Brunel University London, Uxbridge Campus, Middlesex, Uxbridge UB8 3PH, UK
Vasileia.Vasilaki.1@my.brunel.ac.uk, Evina.Katsou@brunel.ac.uk

[2] Systems Engineering Research Group, Department of Electronic and Computer Engineering, Brunel University London, Middlesex, Uxbridge UB8 3PH, UK
{Morad.Danishvar, Zhengwen.Huang, Ali.Mousavi}@brunel.ac.uk

Abstract. Nitrous oxide (N_2O) emissions from wastewater treatment plants (WWTPs) are gaining increased attention globally. Several operating parameters, the configuration, environmental conditions and microbiological diversity of the biological processes affect significantly nitrous oxide (N_2O) formation in WWTPs. However there are still uncertainties regarding the exact triggering mechanisms and the dependancies between the N_2O emissions and main performance parameters of the plant. The aim of this work is to apply an event-based sensitivity analysis (EventTracker) to investigate dependencies and potential patterns between the operating parameters monitored online in wastewater treatment processes and N_2O emissions. The complete dataset from long-term N_2O monitoring in a full-scale plug-flow and two Carrousel reactors published by Daelman et al. (2015) was used for the analysis. The event-based sensitivity analysis indicated significant dependencies between the system parameters (i.e. nitrite, nitrate, ammonia) and N_2O emissions. Spearman's rank correlation coefficient was applied using monthly datasets indicating significant correlations between nitrite and nitrate sensor signals with the N_2O emissions. The latter was mainly observed in cases characterised by high N_2O emission fluxes supporting the event-based sensitivity analysis. The examined method enabled the grouping of the system parameters based on the identified dependencies. The results indicated that N_2O emissions can provide information for the state of the examined biological processes.

Keywords: N_2O emissions · Full-scale WWTPs · Sensitivity analysis · Real-time control

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1 Introduction

The wastewater treatment sector is responsible for 6% of the anthropogenic nitrous oxide (N_2O) emissions, according to the intergovernmental panel on climate change (IPCC) estimates (Palut and Canziani 2007). N_2O is generated during nitrification and it is an intermediate during denitrification; however the exact triggering mechanisms, operational and environmental conditions for its formation are still under investigation. Several N_2O monitoring studies in the past years have led to (i) a better understanding of N_2O generation pathways, (ii) the development of strategies for site-specific N_2O emissions mitigation and (iii) the development of mechanistic process-based models that aim to integrate GHG emissions generation in the design, operation and optimization of biological processes. However, the monitoring and control of the N_2O emissions in full-scale wastewater treatment processes remains a challenge. This is mainly attributed to the complexity of interacting biological processes that consume or produce N_2O (Todt and Dörsch 2016). Statistical analysis has been widely used in the literature to identify correlations in N_2O dynamics with target operating parameters (i.e. dissolved oxygen, ammonia, nitrite) in full-scale plants. However, regression analyses seem to provide inconclusive evidence of dependencies of N_2O generation with specific triggering process parameters (Ahn et al. 2010; Abookabar et al. 2013). The aim of this study is to apply an event-based sensitivity analysis based on cause-effect relationships to evaluate potential relationships between the parameters monitored online and the N_2O emissions in the plug-flow and two Carrousel reactors applied in the work of Daelman et al. (2015). The introduction of un-biased event-based real-time data pattern recognition will evaluate whether an alternative to classical statistical method can be used to: (i) track and register the real-time data generated by the monitoring and control system, (ii) find the interrelationship between system parameters and identify patterns, (iii) evaluate the efficacy of event-based data analysis to potentially control and optimize the performance of the WTTPs regarding N_2O emissions.

2 Materials and Methods

2.1 Process Description and Data Origin

The description of the studied configurations of the plug-flow reactor and of the two Carrousel reactors, influent concentrations, efficiency of the system, as well as the complete dataset used for the analysis is included in the study of Daelman et al. (2015). The plant treats 80.000 m^3d^{-1} domestic wastewater. Secondary treatment consists of an anoxic-oxic plug-flow reactor with subsurface aerators followed by a primary settler and anaerobic selector connected with two parallel Carrousel reactors. The applied scheme includes alternation of anoxic/oxic zones in the Carrousel reactors that are equipped with surface aerators and controlled by the ammonia level. The overall efficiency of the system in terms of total nitrogen (TN) removal during the monitoring campaign was 81%.

The analysis has been focused on one of the Carrousel reactors (Carrousel 2) equipped with ammonia (NH_4), nitrate (NO_3), total suspended solids (TSS), temperature and three dissolved oxygen (DO) probes as shown in Fig. 1 (Daelman et al. 2015).

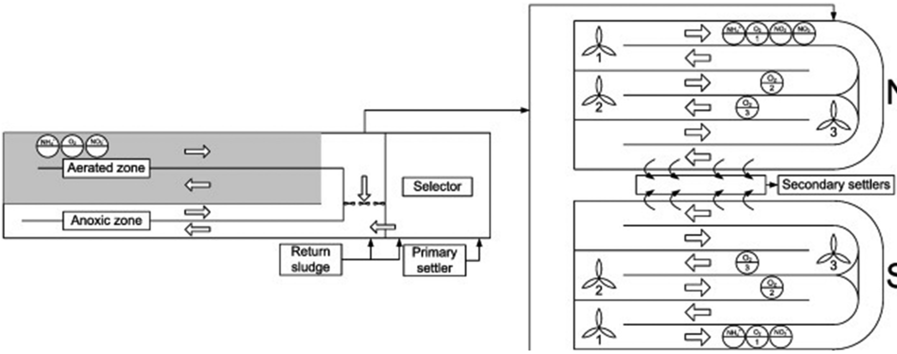

Fig. 1. Plug-flow and Carrousel reactors (Carrousel bottom: Carrousel 1, Carrousel top: Carrousel 2) (Daelman et al. 2015)

2.2 Event-Based Real-Time Analysis for N2O Monitoring

A novel event-based learning mechanism is deployed to better understand the relationship between N_2O emissions and other parameters monitored online in the WWTP. The steps are: (i) implementation of the unbiased EventTracker (Tavakoli et al. 2013) technique to identify relationships between observed and latent variables of the system (ii) validation of patterns (strength of relations) found by EventTracker with spearman's rank correlation coefficient, (iii) implementation of the EventiC (Danishvar et al. 2017) method to group the system input-output and control parameters, resulting in a simple scenario builder as a look up table, (iv) identification of cases (in the time series) that the system has low or high N_2O emissions.

In this context, events are the tangible and reasonable changes to a specific signal (from sensors, machines, actuators, and other sources of data) that coincide with one another. Event tracking identifies such relationships in real-time. In order to track events in a sensor signal the standard deviation of the signal fluctuation for all the time period is calculated. Threshold for registering an event is taken if the difference between two consecutive values is $\geq 10\%$ of this standard deviation. By implementing the algorithm using the data from the database of Daelman et al. (2015) the un-biased event tracker detects and defines the most relevant input parameters of the system with the outputs. Thus, the sensitivity of the system output (i.e. N_2O and NOx) for all the potential influential parameters of the system emerges. The application of EventiC showed which group of system parameters are highly coupled and potentially influence each other during the process. A false negative test was conducted as described by Danishvar et al. (2017) to validate the results of eventTracker and EventiC.

3 Results and Discussion

3.1 Monitored Parameters

Table 1 shows the average values and standard deviations of the parameters monitored online in the Carrousel reactor 2. There is significant variation of N_2O emissions and NO_3 concentration (see Daelman et al. 2015).

Table 1. Parameters monitored in the Carrousel reactor 2

	N_2O (kg/h)	NH_4 (mg/l)	NO_3 (mg/l)	NO_2 (mg/l)	DO1 (mg/l)	DO2 (mg/l)	DO3 (mg/l)	Temperature (°C)
Average	1.40	1.63	5.8	1.2	0.6	0.8	1.9	16
Standard deviation	2.1	2.2	4	1.1	0.9	0.9	0.6	3.5

3.2 EventTracker and EventiC

Table 2 compares the results of EventTracker with Spearman's rank correlation coefficient ($p < 0.01$) for 295 days of hourly aggregated data. EventTracker identified significant dependencies between the N_2O emissions and ammonia, nitrate and DO1 (dissolved oxygen probe 1) in the Carrousel reactor 2. Similar trends were also observed

Table 2. Eventracker algorithm and linear regression analysis of N_2O emissions in Carrousel reactor 1

Output parameter (location)	Input parameters (location)	Level of sensitivity (this study)	Pearson's correlation and coefficient of determination
N_2O emissions Carrousel 2 (kg N_2O/h)	N_2O plug-flow	High	Low
	N_2O Carrousel 1	High	Low
	NH_4-N Carrousel 2	High	Low
	NO_3-N Carrousel 2	High	Low
	DO1 Carrousel 2	High	Low
	DO2 Carrousel 2	Low	Low
	DO3 Carrousel 2	Medium	Low
	TSS Carrousel 2	Low	Low
	Temperature Carrousel 2	Low	Low

in the two Carrousel reactors treating the effluent of the plug-flow reactor and operating at the same set-points DO. Therefore, similar emission dynamics are expected.

Moreover, changes in the NH_4, DO and NO_3 concentrations in the Carrousel reactor 2 seem to coincide with changes in N_2O emissions load. Spearman's correlation coefficient for the whole dataset indicated that there is no significant relationship between these variables and N_2O emissions. The application of Spearman's correlation coefficient to the hourly sensor signals taken at different months indicated that there is a variation in the relationship between N_2O emissions and operating parameters in Carrousel 2. More specifically, in cases of increased and variable N_2O emissions, significant dependencies between nitrate and nitrite concentrations and N_2O emissions were observed. On the other hand, at low N_2O emission levels with not significant variability, we didn't identify dependencies. However, as shown in Fig. 2 Spearman's rank correlation results in less sensitivity of N_2O emissions to the DO probes in the reactor the respective one indicated by the EventTracker. Rodriguez-Caballero et al. (2014) demonstrated that N2O dynamics were not significantly affected by changes in DO (1.5–2 mg/l) or aeration flow rate; the latter is attributed to the constant nitrification efficiency.

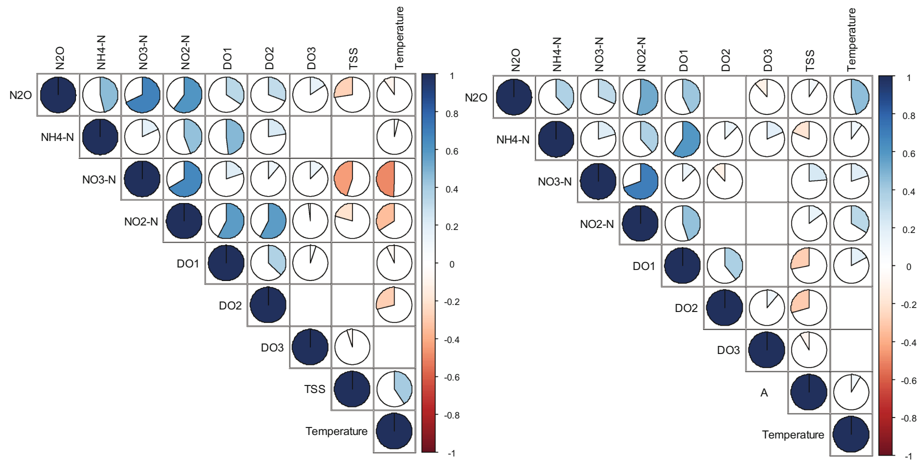

Fig. 2. Spearman's rank correlation coefficient (left): month 6/2011 (right): month: 9/2011 for sensor signals in Carrousel reactor 2 (only results with p-value < 0.01 are shown)

Observed data from operation (Fig. 3) show that the profile of N_2O emissions in Carrousel reactor 2 follows the same pattern with NO_3-N concentration profile, confirming the results of EventTracker. Significant correlation between N_2O fluxes and NO_3-N concentration have been also identified in soils (Cowan et al. 2015). However, NO_3-N is not directly involved in the known pathways for N_2O formation; thus there are limited studies that examine potential relationship interconnections and further analysis is required.

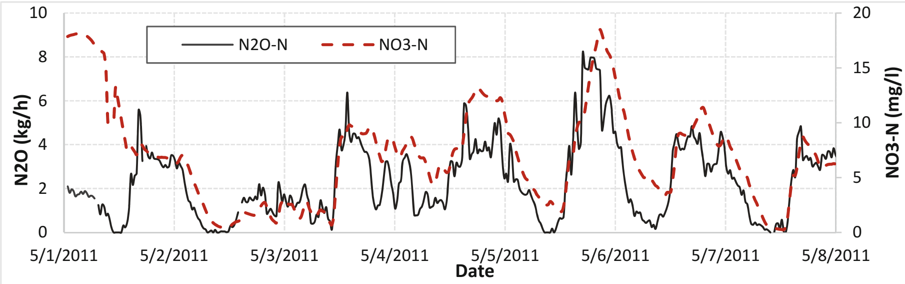

Fig. 3. N_2O emissions and NO_3 concentration data for Carrousel reactor 1

EventiC was applied to the hourly aggregated data in order to identify the group of system parameters that influences each other during the process (Fig. 4). Two different groups were identified; one is consisting of the TSS and temperature variables in the two Carrousel reactors, while the other with all the other monitored parameters. It can

	N2O PF	N2O CARR 1	N2O CARR 2	NO3 CARR 1	NO3 CARR 2	DO1 CARR 2	NH4 CARR 1	DO1 CARR 1	NH4 CARR 2	DO3 CARR 2	DO2 CARR 1	DO2 CARR 2	DO3 CARR 1	Temperature CARR 1	TSS CARR 1	TSS CARR 2	Temperature CARR 2
N2O PF	1	0.864	0.844	0.827	0.803	0.765	0.748	0.718	0.694	0.52	0.449	0.463	0.299				
N2O CARR 1	0.864	1	0.905	0.854	0.823	0.813	0.762	0.779	0.748	0.554	0.49	0.483	0.32				
N2O CARR 2	0.844	0.905	1	0.854	0.83	0.786	0.782	0.752	0.755	0.582	0.503	0.503	0.286				
NO3 CARR 1	0.827	0.854	0.854	1	0.895	0.789	0.765	0.755	0.718	0.585	0.507	0.486	0.316				
NO3 CARR 2	0.803	0.823	0.83	0.895	1	0.779	0.721	0.731	0.728	0.568	0.483	0.503	0.293				
DO1 CARR 2	0.765	0.813	0.786	0.789	0.779	1	0.711	0.81	0.677	0.578	0.514	0.507	0.33				
NH4 CARR 1	0.748	0.762	0.782	0.765	0.721	0.711	1	0.724	0.83	0.582	0.558	0.524	0.388				
DO1 CARR 1	0.718	0.779	0.752	0.755	0.731	0.81	0.724	1	0.711	0.585	0.534	0.514	0.35				
NH4 CARR 2	0.694	0.748	0.755	0.718	0.728	0.677	0.83	0.711	1	0.582	0.558	0.558	0.401				
DO3 CARR 2	0.52	0.554	0.582	0.585	0.568	0.578	0.582	0.585	0.582	1	0.575	0.588	0.507				
DO2 CARR 1	0.449	0.49	0.503	0.507	0.483	0.514	0.558	0.534	0.558	0.575	1	0.694	0.551				
DO2 CARR 2	0.463	0.483	0.503	0.486	0.503	0.507	0.524	0.514	0.558	0.588	0.694	1	0.565				
DO3 CARR 1	0.299	0.32	0.286	0.316	0.293	0.33	0.388	0.35	0.401	0.507	0.551	0.565	1				
Temperature CARR 1														1	0.915	0.939	0.956
TSS CARR 1														0.915	1	0.956	0.952
TSS CARR 2														0.939	0.956	1	0.976
Temperature CARR 2														0.956	0.952	0.976	1

Fig. 4. Eventic algorithm grouping the system parameters with interelations (dark green: high impact, light green:moderate impact) (Color figure online)

be concluded that the system is less sensitive to changes in the DO2 and DO3 probes in both Carrousel reactors.

The data fed to the EventiC algorithm indicated that N_2O emissions can potentially be used as an additional parameter for process monitoring. Figure 5, shows the box-plots of NO_2-N concentration in the Carrousel reactor 2 for all the periods with (i) low N_2O emissions (ranging from 0 to 0.05 kg/h)), (ii) high N_2O emissions (emissions higher than 4.5 kg/h representing 10% of the highest values), (iii) complete dataset. High N_2O emissions present similar trends with higher than average NO_2-N concentration in the reactor.

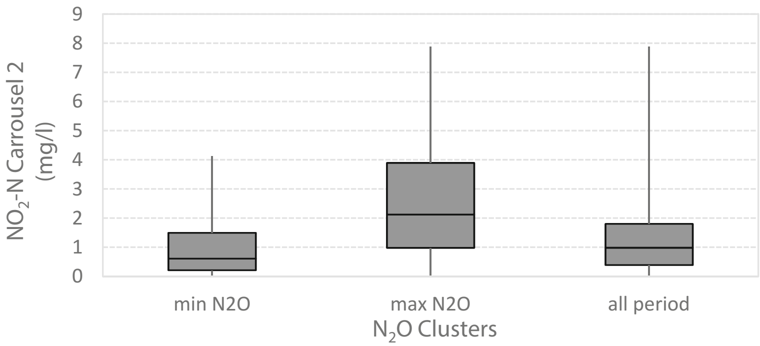

Fig. 5. Boxplots of the NO_2-N concentration (mg/l) in the Carrousel reactor 2 for different clusters of N_2O emissions

4 Conclusions

The unbiased real-time event based sensitivity analysis has provided useful information on the dependencies of N_2O emissions with specific operating variables monitored online (nitrite, nitrate, ammonium) in a full-scale Carrousel reactor. Spearman's rank correlation analysis for the whole dataset was unable to identify correlations between system parameters and N_2O emissions, mainly due to the fact that the relationship of the examined parameters was highly variable during the system operation (considering monthly data). EventiC groupping of relevant system parameters in order of importance and relevance can potentially filter abundant sensor signals and lead to an improved mathematical formulization of complex biological processes.

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