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A New Plant Wide Modelling Approach for the Reduction of Greenhouse Gas Emission from Wastewater Treatment Plants

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Abstract

Recent studies about greenhouse gas (GHG) emissions show that sewer collection systems and wastewater treatment plants (WWTPs) are anthropogenic GHG potential sources. Therefore, they contribute to the climate change and air pollution. This increasing interest towards climate change has led to the development of new tools for WWTP design and management. This paper presents the first results of a research project aiming at setting-up an innovative mathematical model platform for the design and management of WWTPs. More specifically, the study presents the project's strategy aimed at setting-up a plant-wide mathematical model which can be used as a tool for reducing/controlling GHG from WWTP. Such tool is derived from real data and mechanicistic detailed models (namely, Activated Sludge Model's family). These latter, although are a must in WWTP modelling, hamper a comprehensive and easy application due to complexity, computational time burdens and data demanding for a robust calibration/application. This study presents a summary of the results derived from detailed mechanistic models which have been applied to both water and sludge line of a WWTP: primary treatment, biological reactor, secondary settler, membrane bioreactor, sludge digester etc. The project is organized in overall four research units (RUs) which focus each on precise WWTP units.

Energy consumption; GHG emissions; mathematical modelling, hydrolysis kinetics; wastewater treatment plants

1. Introduction

Wastewater treatment plants (WWTPs) are responsible for the emission of greenhouse gases (GHGs), such as nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2). Efforts for monitoring and accounting for GHG emissions from WWTPs are of increasing interest (Monteith et al., 2005; Kampschreur et al., 2009; Daelman et al., 2013; Caniani et al., 2015; Caivano et al., 2016; Mannina et al., 2016c).

The mathematical modelling of activated sludge (AS) treatment is the most important tool for developing control strategies and designing WWTPs. In 1982, the International Association on Water Pollution Research and Control (IAWPRC) established a Task Group on Mathematical Modelling for Design and Operation of Activated Sludge Processes. From 1982 at now, mathematical modelling has widely developed, evolved and combined with the control systems (Olsson, 2012).

Knowledge acquired over the years has contributed to evolve from simple growth-based kinetics, such as Activated Sludge Models no 1 (ASM1), to more complex models, such as

ASM2d (Henze et al. 2000). The extensions of this first model are the ASM2 (Henze et al. 2000), the ASM2d, and the ASM3 (Henze et al. 2000), in which the biomass internal organic products and biomass structure are better investigated. However, in 2008 Hiatt and Grady introduced the ASM for nitrogen (ASMN), in which nitrification and denitrification processes are adequately investigated (Hiatt & Grady 2008), introducing two steps for nitrification and four steps for denitrification.

The extension of Hiatt & Grady's complex model is the ASM for GHG no.1 (ASMG1) proposed by Mampaey et al. (2013), and slightly modified by Guo & Vanrolleghem (2014), which specifically, proposed a model where the nitrifier denitrification pathway is considered during N_2O formation. The authors presented a model to simulate NO and N_2O emissions by means of nitrifier denitrification (via AOB activity) and NH_2OH pathways considering two different formation mechanisms: Scenario A, in which ammonia is the electron donor, and Scenario B, in which biomass is the electron donor.

Ni et al. (2011) proposed a model able to simulate the N_2O production during both nitrification and denitrification processes. The model includes the two steps nitrification and the four steps denitrification processes. Moreover, the model describes the N_2O formation due to the incomplete ammonia nitrification. Further, the model describes the nitrifier denitrification process occurring at low DO concentration conditions and in presence of NO_2^-. Indeed, when these latter conditions occur, NO_2^- can be used as terminal electron acceptor instead of O_2, causing N_2O formation. Ni et al. (2014) proposed the first model that incorporates both the nitrifier denitrification and the NH_2OH pathways for N_2O production.

Pocquet et al. (2016) developed a new model for nitration, called 2-Pathway (2-P) model. The autotrophic denitrification of nitrite (ND) and the incomplete NH_2OH oxidation by the hydroxylamine oxide reductase enzyme (HAO) are considered to be the major contributors to N_2O production during nitrification. The ND is the reduction of NO_2 to N_2O via NO, by means of the nitrite reduction to NO (NirK) and NO reduction to N_2O (Nor) enzymes, respectively, and is considered the predominant pathway during nitration. The NN pathway leads to the accumulation of NO which is reduced to N_2O by Nor enzyme. Five processes and a new state variable (S_{NH2OH}) were added to the ASMN ones, modelling 18 components and 19 processes.

Regarding the sludge line, IWA Task Group for Mathematical Modelling of Anaerobic Digestion Processes developed the Anaerobic Digestion Model No.1 (ADM1) (Batstone et al., 2002) to reach a common basis for further model development. ADM1 represents the state of the art regarding CH_4 production due to AD. Studies have been performed in modelling CH_4 emissions from pressure sewers systems (Guisasola et al. 2008; Foley et al. 2009). However, there is still work to be done to link this knowledge acquired and integrate it at system-wide framework level.

Moreover, N_2O emission from wastewater treatment plants (WWTP) represents a frontier of Research that still requires to be crossed. N_2O emissions primarily occur in aerated zones owing to the fact that the main contributors are active stripping and ammonia-oxidizing bacteria, rather than heterotrophic denitrifiers. Indeed, despite during the last years efforts have been done to better understand the key elements on the N_2O production/modelling, several questions remain scarcely understood (Caniani et al., 2015; Mannina et al., 2016c).

In this work, we present the key methodological features and some of the results of a research project aiming at developing an innovative simulation platform for the design and management of WWTPs. Such a platform is aimed at reducing the energy consumption and pollutant/residue emissions (namely, residual pollutants in the effluent, sludge and GHGs) from WWTPs. More specifically, in this paper we present the results of the ASM family mechanistic models developed by each research unit of the project concerning the water line and the sludge line of conventional and advanced wastewater treatment systems.

The activities and the results presented here belong to the project “Energy consumption of GreenHouse Gas (GHG) emissions in wastewater treatment plants: a decision support system for planning and management”, which is supported by grant of the Italian Ministry of Education, University and Research (MIUR), and, started in 2014 and ended in March 2017. Overall, the project is constituted by four research units (RUs): University of Palermo (RU1), University of Basilicata (RU2), University of Cassino and Southern Lazio (RU3) and University of Florence (RU4).

2. Materials and methods

2.1 Research Unit 1

The objective of Research Unit 1 (RU1) is the study of the chemical/physical/biological phenomena of the water line of advanced wastewater treatment systems, through designing, building and operating an MBR plant at pilot scale aimed at removing nutrients. The pilot plant is monitored in order to set-up an extensive database useful for phenomena interpretation and raising knowledge about some aspects that are still in need of further investigation (Mannina et al., 2016b).

Three mechanistic integrated membrane bioreactor (MBR) mathematical models (namely, Model I, Model II and Model III) all of the Activated Sludge Model (ASM) family (Henze et al., 2000) have been implemented by RU1. All models simulate MBRs taking into account both biological and physical processes (Mannina et al., 2011). Specifically, the model structure of the MBR model consists of two related sub-models: physical and biological sub-model.

Regarding the physical sub-model, the key processes occurring during membrane physical separation, including the membrane fouling are taken into account. Such sub-model is identical for the three Models. Details on such model can be drawn from literature (Mannina et al., 2011).

Regarding the biological processes, these models are able to simulate greenhouse gases as state variables in terms of nitrous oxide (N_2O) and carbon dioxide (CO_2) (as dissolved and off-gas concentration). Moreover, the models include the soluble microbial products (SMP) formation/degradation processes according to Jiang et al. (2008). However, despite the similarities, substantial differences distinguish the biological sub-model of the three models as it follows.

Model I is based on the ASM1 model and includes nitrous oxide (N_2O) modelling approach according to literature (Hiatt and Grady, 2008). The carbon and nitrogen removal processes are described. According to the employed literature approach (Hiatt and Grady, 2008) Model I considers N_2O formation only during the heterotrophic denitrification neglecting N_2O production by ammonia oxidizing bacteria (AOB).

Model II is based on the ASM2d and includes, similarly to Model II, N_2O modelling according to a modified version derived from literature (Hiatt and Grady, 2008). Model II describes the carbon and nutrients (nitrogen and phosphorus) removal processes. Details on Model II can be drawn from previous literature (Mannina and Cosenza, 2015).

Finally, Model III is based on the ASM2d approach and differently to the previous to models considers N_2O formation both due to heterotrophic and autotrophic biomass. In particular, regarding the autotrophic role Model III describes the N_2O formation during nitrification combining the two major AOB formation pathways according (Pocquet et al., 2016; Chandran et al., 2011; Law et al., 2012): i. autotrophic denitrification; ii. incomplete hydroxylamine oxidation by AOB. N_2O formation during the heterotrophic denitrification is described according to Hiatt and Grady (2008).

Model I has been applied to a pilot plant having a pre-denitrification scheme (anoxic and aerobic reactors in series) and equipped with an hollow fiber membrane for the solid – liquid separation (20 L h^{-1} of saline industrial wastewater were considered as influent) (Mannina et al., 2016a).

Model II and III have been applied to a pilot plant with a University Cape Town (UCT) (anaerobic, anoxic and reactors in series) MBR scheme (20 L h^{-1} of real wastewater were considered as influent) (Mannina et al., 2016b).

Each model has been calibrated by means of an innovative calibration protocol adopting an extensive dataset acquired during the long-term monitoring of the pilot plants (Mannina et al., 2011). By comparing measured and simulated data the efficiency of each model output (E_i) and the total model efficiency (E_{MOD}) have been evaluated as proposed by Mannina et al. (2011).

2.2 Research Unit 2

The aim of RU2 was the deepening of the chemical/physical/biological phenomena of thickening and aerobic digestion more effectively. To this end, RU2 has designed, built and operated a pilot scale plant for such treatment units. The pilot plant is used to investigate the GHG emissions from the different pilot plant units, which are measured in different operating conditions. A monitoring campaign of the qualitative and quantitative characteristics of the sludge and operating parameters of a full-scale treatment plant have been also carried out. Data gathered from experimental activities are collected in a database in order to increase knowledge concerning the influence of management parameters on GHG emissions from aerobic treatment of sludge and to develop and calibrate an ASM type model. Indeed, a new Aerobic Digestion Model 1, AeDM1, has been developed (Caivano et al., 2015). The proposed AeDM1 model simulates the aerobic digestion processes including also GHG emissions and it has been validated on experimental measurements at pilot scale.

The AeDM1 simulates AeD with an aerobic activated sludge unit (ASU) working in discontinuous feeding of sludge, in which the mass balances on each state variables are performed as suggested by Alex et al. (2008). The biological phenomena taking place in AeD are described by a modified ASMN model (Hiatt and Grady, 2008), as proposed by Pocquet et al. (2016), suggesting an integrated approach to better simulate the Biological Nitrogen Removal (BNR) processes, as well as their influence on N_2O production. Furthermore, the fate of N_2O in the liquid and gaseous phase is described by means of the mass balances proposed by Ye et al. (2014), whereas the CO_2 fate is evaluated according to the bicarbonate system (Caivano et al., 2016). Therefore, 21 state variables and 22 dynamic processes were modelled, respectively.

The AeDM1 model has been calibrated using the data collected during the lab-experimental tests performed on June-August 2015 (Caniani et al., 2015). A pilot-scale aerobic digester was realized to simulate sludge stabilization, quantifying CO_2 and N_2O emissions during sludge treatment (Caniani et al., 2015). A 10 L reinforced polyethylene tank was equipped with an aeration system, supplying an air flow rate of 0.05 m^3h^{-1}. The pilot digester was firstly fed with 6L of sludge from the settling underflow of a full-scale WWTP and, subsequently, 0.06 L of fresh sludge were introduced every testing day to compensate the same discharged amount, ensuring the discontinuous feeding. After the achievement of the equilibrium conditions for a conventional aerobic digestion, a 13 days monitoring campaign was performed, assuming 20 days as sludge retention time. The off-gas pparatus, consisting of a reinforced polyethylene hood coupled with an off-gas analyzer was used to capture the gas fluxes by means of Tadlar sampling bags.

The influent and effluent sludge characteristics (e.g. COD, TSS, NH_4^+, NO_2^- and NO_3^-), estimated according to Standard Methods (APHA-AWWA-WEF, 2005), and the kinetic parameters, evaluated by means of the respirometric tests (in collaboration with RU3), were used as input data. The sensitivity analysis (Caivano, 2017), carried out by applying the Morris screening method (Morris, 1991), on the main kinetic parameters allowed us to individuate the parameters that have a higher influence (on a scale from I as small/negligible influence to IV as very high influence) on the model output, allowing the model calibration.

In order to obtain a ranking of the input parameters, a normalized sensitivity index (I) is evaluated as in the following Equation, indicating the sensitivity of each variable:

$$I = \bar{d}_{i,norm}(x_i) = \sum_{j=1}^{10} \frac{|d_{norm}(x_{i,j})|}{10}$$

where the standardized values of the elementary effects (d_{norm}) are calculated in the following Equation:

$$d_{norm}(x_{i,j}) = d_i \ \frac{x_{i,avg}}{y_{i,avg}}$$

Table 2.1 shows the five sensitivity classes (I, II, III, IV, V) introduced to classify the parameters as a function of the normalized sensitivity index, I, defined earlier:

Table 2.1 Sensitivity Classes.

Sensitivity Classes	Index Range	Sensitivity
I	0 ≤ I <0.05	Negligible
II	0.05 ≤ I < 0.20	Small
III	0.20 ≤ I < 1.00	Medium
IV	I ≥ 1.00	High
V	I >> 1.00	Very High

2.3 Research Unit 3

RU3 has linked the operative conditions of the anaerobic digestion (sludge age, sludge concentration, retention time) and the quality of the reactors feed, to the biogas production, energy recovery and GHGs emission. The RU3 gives essential information for operating the wastewater treatment line which greatly affects the quality of the anaerobic digestion feed and, in turn, affects the biogas and methane production and thus the GHGs emission of WWTPs. Activities of the RU3 are carried through both experimental and modeling approaches. Data gathered from experimental activities are collected for setting up a database in order to increase knowledge and develop detailed models able to properly predict the observed phenomena.

The proposed mathematical model is a modified version of the ADM1 model (Batstone et al., 2002) and it is based on differential mass balance equations for substrates, products and biomasses involved in the anaerobic digestion process. The main novelty of the proposed model consists in applying a surface based kinetics approach for the hydrolysis process, which is useful when hydrolysis is the rate limiting step of the anaerobic digestion. The model simulates the dynamics of 32 state variables and includes more than 70 parameters.

The surface based kinetic equation is formulated as follows (Esposito et al. 2011a):

$$\frac{dC}{dt} = -\mathrm{K}_{\mathrm{sbk}} \cdot a^{*} \cdot \mathrm{C}$$

where:

C is the concentration of complex organic substrate content in the sewage sludge $[ML^{-3}]$;

K_{sbk} denotes the disintegration kinetic constant $[M\ L^{-}2\ T^{-1}]$;

a* is the mass-specific disintegration surface area $[L^{2}]$.

2.4 Research Unit 4

The applicability of available kinetic models to the case of a full-scale WWTP in Italy was investigated. One of the most advanced kinetic models was selected as the test model seen its recent application to another full scale scenario (Guo and Vanrolleghem, 2014). The model of the plant was already implemented by the plant manager in WEST (DHI) currently in use for normal plant optimization operation. Other available kinetic models were not considered for the full-scale application as they were only validated at lab-scale (Pocquet, 2015) or were showing very uncertain (e.g. >100% uncertainty) and not realistic parameter sets resulting from over-calibration (Spérandio, 2016).

The selected model describes the production of N_2O through a single pathway approach (i.e. AOB denitrification) based on Mampaey et al. (2013) with the addition of terms for oxygen limitation and inhibition, and terms for free ammonia (FA) and free nitrous acid (FNA) inhibition.

The use of Principal Component Analysis (PCA) was chosen as an alternative method for approaching N_2O emission modelling to investigate for an alternative to the current kinetic models. Indeed, the large quantity of available data makes possible to look for hidden relations between operational variables and N_2O emission.

PCA is one of the most flexible and widely accepted multivariate statistical methods for data mining and it is often used for process understanding, monitoring (fault detection), and control of industrial processes such as wastewater treatment (Gernaey, 2004). The principle of PCA is to reduce the amount of information available to a smaller number of variables (PCs) capable of explaining most of the variance of the dataset. In this way, it is possible to unravel hidden dependencies among known key variables. Therefore, a dataset from a field measurement campaign and SCADA data available from a WWTP were used to build a

PCA-based statistical model. In particular, a typical working day was selected based on the 95th percentile of 5 days of validated data.

3. Results and discussion

3.1 Research Unit 1

A general improvement of the model output efficiency between Model II and Model III has been observed. This result is mainly evident for the aerated reactors thus demonstrating that detailing the N_2O formation process during nitrification has led to the improvement of the model results.

For sake of conciseness in Figure 3.1 the measured versus simulated data for both dissolved (Figure 3.1a) and off-gas N_2O (Figure 3.1b) in the aerobic reactors are shown. Data of Figure 3.1 show a good agreement between measured and modelled values. However, an overestimation of simulated data occurred for the three models, excepting two cases, both for dissolved and off-gas N_2O. This result is likely debited to the discrete sampling. Continuous sampling would improve the results.

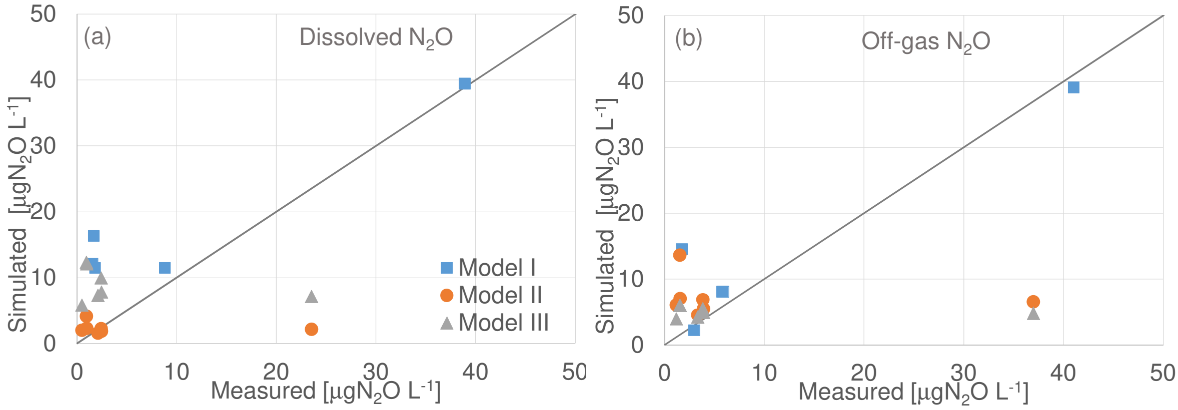

Figure 3.1 Measured versus simulated data for each model of the dissolved N_2O (a) and off-gas N_2O (b) concentration

3.2 Research Unit 2

The output variables analysed in this work are represented by NH_4^+, NO_2^-, NO_3^-, NH_2OH, and N_2O gaseous emission. Table 3.1 shows the sensitivity classes obtained. The maximum specific growth rate of heterotrophs ($_H$) is the more sensitive parameter for all the model outputs. The results show that N_2O emission from aerobic digestion mainly depends on the maximum specific growth rates of heterotrophs, $_H$, ammonia-oxidizing bacteria $_{AOB}$, nitrite-oxidizing bacteria, $_{NOB}$, and growth yield of heterotrophs, Y_H, (Caivano, 2017).

Table 3.1. Results of the sensitivity analysis: sensitivity classes for AeD

	NH_4^+	NO_3^-	NO_2^-	N_2O	NH_2OH
$_H$	IV	III	IV	IV	IV

$_{AOB}$	III	I	III	III	III
$_{NOB}$	III	II	III	III	III
b_H	II	I	II	II	I
b_{AOB}	II	I	II	II	I
b_{NOB}	II	I	I	II	I
Y_H	II	I	III	III	II
Y_{AOB}	I	I	I	II	I
Y_{NOB}	II	I	II	II	I
$i_{N/XD}$	I	I	I	I	I
η_{AOB_ND}	II	I	II	II	I
η_{AOB_NN}	I	I	I	I	I

The comparison between the model output and the lab-measurements (Figure 3.2) showed the reliability of the constructed model, including the estimation of the N_2O emissions. The regression analysis proves that the model values of COD, TSS, and VSS are closed than those recorded during experimental tests, admitting R^2 values in the range 35 - 50 %. More experimental tests on both pilot scale and full-scale aerobic digesters are needed to improve the model in simulating nitrogen compounds.

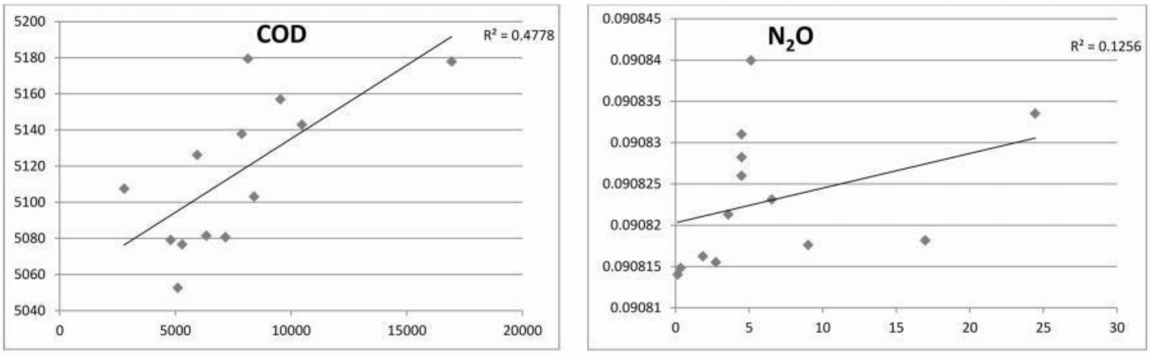

Figure 3.2. Results of the model validation

3.3 Research Unit 3

A sensitivity analysis for 75 model parameters has been performed by using a derivative method in order to investigate their effects on simulation outputs. The results for the surface based kinetic constant, K_{sbk} are reported in Figure 3.3

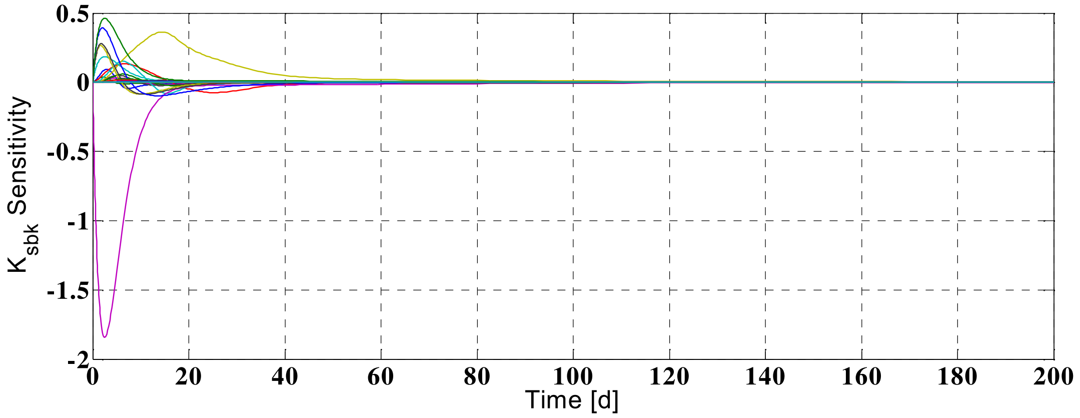

Figure 3.3 model sensitivity for $K_{sbk.}$

Model calibration was used to estimate the parameter K_{sbk}. Calibration was performed by adopting the protocol introduced by Esposito et al. (2011b) and comparing model results with experimental measurements of methane production from sewage sludges of different wastewater treatment plant technologies (e.g. MBR and CAS). Comparison between experimental data and modelling results after calibration is reported in Figure 3.4.

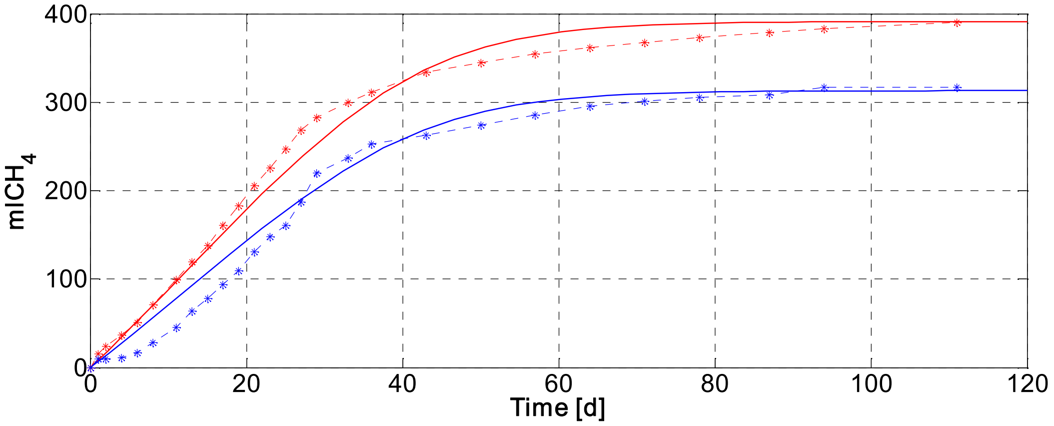

Figure 3.4 Comparison between experimental data and modelling results after calibration: red-continuous line is modelled CAS biogas production, red-starred line is experimental CAS biogas production.; blue-continuous line is modelled MBR biogas production, blue-starred line is experimental MBR biogas production.

3.4 Research Unit 4

Results of the measurement campaign were used for developing a stochastic model based on PCA that could be implemented to estimate and mitigate N_2O emissions. Long datasets of different parameters recorded during the measurement campaigns and other plant data acquired, in parallel, by the WWTP SCADA system, were used to mine hidden information about N_2O production. This information was unravelled using a combination of data processing methods and mathematical tools available in literature. These methods and the relative results were reported in detail in this project so to allow replicability and facilitate applicability. Results show that even only DO, NH_4 and NO_3 (known to be the most meaningful variables for N_2O emissions among the ones normally monitored in a SCADA system) could manage to cluster high N_2O emissions data.

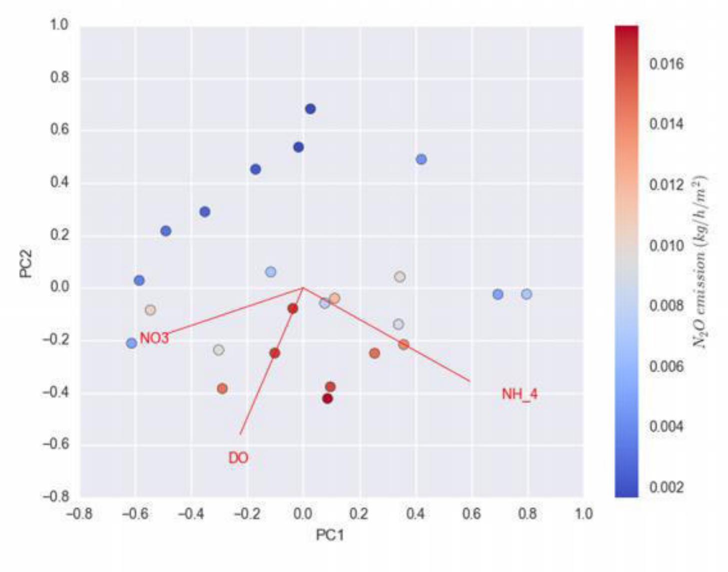

Figure 3.5 – Example of the application of the statistical PCA model to a full scale dataset

4. Conclusion

Traditionally, WWTPs have had the aim of meeting the quality standards of effluent, ensuring a high quality of water bodies and sustainable management costs. However, in recent years, the wastewater treatment objectives have been expanded and include the reduction of greenhouse gas emissions, as a result of the growing concern about climate change and environmental protection. Therefore, it is necessary to develop innovative approaches for an integrated WWTP management system. One of the objectives of this project is to perform modelling activities to minimize the production of greenhouse gases and energy consumption, while maintaining a high quality of the effluent. The collected database of measurements allowed us to develop and apply models of biological processes occurring in the water line and the sludge line of conventional and advanced treatment systems.

The main preliminary conclusions are summarized in the following:

- Concerning the modelling of the MBR treatment, detailing the N_2O formation process during nitrification has led to the improvement of the model results.
- Concerning aerobic digestion modelling, N2O emission from aerobic digestion mainly depends on the maximum specific growth rates of heterotrophs, ammonia-oxidizing bacteria and nitrite-oxidizing bacteria and on the growth yield of heterotrophs.
- The mathematical model for anaerobic digestion, which is a modified version of the ADM1 model, is useful when hydrolysis is the rate limiting step of the anaerobic digestion.
- The obtained findings derived for full-scale modelling application, highlight the capabilities of online data when combined to full-scale measurements.

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References

Bani Shahabadi, M.; Yerushalmi, L.; Haghighat, F. Impact of process design on greenhouse gas (GHG) generation by wastewater treatment plants. Water Res. 2009, 43, 2679–2687.

D.J. Batstone, J. Keller, I. Angelidaki, S.V. Kalyuzhnyi, S.V. Pavlostathis, A. Rozzi, et al. (2002) Anaerobic digestion model no.1, Rep. No. 13 IWA Publishing, London p. 74.

Caivano M., Novel criteria to evaluate energy consumption and GreenHouse Gas emissions in wastewater treatment plants: towards a decision support tool for minimizing environmental impacts of water cycle. PhD Thesis, University of Basilicata, Potenza.

Caivano M., Bellandi G., Mancini I.M., Masi S., Brienza R., Panariello S., Gori R., Caniani D., Monitoring the aeration efficiency and carbon footprint of a medium-sized WWTP: experimental results on oxidation tank and aerobic digester, Environ. Technol. DOI: 10.1080/09593330.2016.1205150 (2016).

Caniani D., Esposito G., Gori R., Mannina G. (2015), Towards A New Decision Support System for Design, Management and Operation of Wastewater Treatment Plants for the Reduction of Greenhouse Gases Emission. Water 2015, 7, 5599-5616; doi:10.3390/w7105599.

Chandran, K., Stein, L.Y., Klotz, M.G., van Loosdrecht, M.C.M., 2011. Nitrous oxide production by lithotrophic ammonia-oxidizing bacteria and implications for engineered nitrogen-removal systems. Biochem. Soc. Trans. 39, 1832-1837.

Chandran, K., 2011. Protocol for the Measurement of Nitrous Oxide Fluxes from Biological Wastewater Treatment Plants, in: Methods in Enzymology. Elsevier Inc., pp. 369–385.

Daelman, M.R.J., van Voorthuizen, E.M., van Dongen, L.G.J.M., Volcke, E.I.P., van Loosdrecht, M.C.M., 2013. Methane and nitrous oxide emissions from municipal wastewater treatment – results from a long-term study. Water Sci. Technol. 67, 2350.

Esposito, G., Frunzo, L., Panico, A., & Pirozzi, F. (2011a). Modelling the effect of the OLR and OFMSW particle size on the performances of an anaerobic co-digestion reactor. Process Biochemistry, 46(2), 557-565.

Esposito, G., Frunzo, L., Panico, A., & Pirozzi, F. (2011b). Model calibration and validation for OFMSW and sewage sludge co-digestion reactors. Waste Management, 31(12), 2527-2535.

K. V. Gernaey, M. C. M. Van Loosdrecht, M. Henze, M. Lind, and S. B. Jørgensen, "Activated sludge wastewater treatment plant modelling and simulation: State of the art," Environ. Model. Softw., vol. 19, no. 9, pp. 763–783, 2004.

Guo, L.S., Vanrolleghem, P. a., 2014. Calibration and validation of an activated sludge model for greenhouse gases no. 1 (ASMG1): Prediction of temperature-dependent N2O emission dynamics. Bioprocess Biosyst. Eng. 37, 151–163.

Henze, M., Gujer, W., Mino, T., Van Loosdrecht, M.C.M. 2000 Activated sludge models ASM1, ASM2, ASM2d and ASM3. In: IWA Task Group on Mathematical Modelling for Design and Operation of Biological Wastewater Treatment. IWA Publishing, London, UK.

Hiatt, W.C., Grady Jr, C.P.L., 2008. An updated process model for carbon oxidation, nitrification, and denitrification, Water Environ. Res. 80, 2145–2156.

Jiang, T., Myngheer, S., De Pauw, D.J.W., Spanjers, H., Nopens, I., Kennedy, M.D., Kennedy, M.D., Amy, G., Vanrolleghem, P.A., 2008. Modelling the production and degradation of soluble microbial products (SMP) in membrane bioreactors (MBR). Water Res 42(20), 4955–4964.

Kampschreur, M.J., Temmink, H. Kleerebezem, R., Jetten, M.S.M., van Loosdrecht, M.C.M., 2009. Nitrous oxide emission during wastewater treatment, Water Res. 43, 4093–4103.

Law, Y., Ni, B.-J., Lant, P., Yuan, Z., 2012. N2O production rate of an enriched ammonia-oxidising bacteria culture exponentially correlates to its ammonia oxidation rate. Water Res. 46, 3409-3419.

Mampaey K.E., Beuckels B., Kampschreur M.J., Kleerebezem R., van Loosdrecht M.C.M., Volcke E.I.P. (2013), Modelling nitrous and nitric oxide emissions by autotrophic ammonia-oxidizing bacteria. Environmental Technology, 2013 Vol. 34, No. 12, 1555–1566.

Mannina, G., Ekama, G., Caniani, D., Cosenza, A., Esposito, G., Gori, R., Garrido-Baserba, M., Rosso, D., Olsson, G., 2016c. Greenhouse gases from wastewater treatment — A review of modelling tools. Science of the Total Environment 551–552, 254–270.

Mannina G., Capodici M., Cosenza A., Di Trapani D., 2016b. Carbon and nutrient biological removal in a University of Cape Town membrane bioreactor: Analysis of a pilot plant operated under two different C/N ratios. Chemical Engineering Journal 296, 289–299.

Mannina G., Capodici M., Cosenza A., Di Trapani D., Viviani G. 2016a. Sequential Batch Membrane BioReactor for wastewater treatment: effect of salinity increase. Bioresour. Technol. 209, 205-212.

Mannina, G., Cosenza, A., 2015. Quantifying sensitivity and uncertainty analysis of a new mathematical model for the evaluation of greenhouse gas emissions from membrane bioreactors. Journal of Membrane Science 475, 80–90.

Mannina, G., Cosenza, A., Vanrolleghem, P.A., Viviani, G., 2011. A practical protocol for calibration of nutrient removal wastewater treatment models. Journal of Hydroinformatics 13.4, 575-595.

Monteith, H.D., Sahely, H.R., MacLean, H.L., Bagley, D.M., 2005. A rational procedure for estimation of greenhouse-gas emissions from municipal wastewater treatment plants. Water Environ. Res. 77, 390–403.

Ni, B.J., Yuan, Z., 2015. Recent advances in mathematical modeling of nitrous oxides emissions from wastewater treatment processes. Water Res.

Olsson, G., 2012. ICA and me - A subjective review. Water Research 46, 1585-1624.

Pocquet, M, Wu, Z., Queinnec, I., Spérandio, M., 2016. A two pathway model for N2O emissions by ammonium oxidizing bacteria supported by the NO/N2O variation. Water Res. 88, 948-959.

Pocquet, M., Wu, Z., Queinnec, I., Spérandio, M., 2015. A two pathway model for N2O emissions by ammonium oxidizing bacteria supported by the NO/N2O variation. Water Res. 88, 948–959

Spérandio, M., Pocquet, M., Guo, L.S., Ni, B.J., Vanrolleghem, P.A., Yuan, Z., 2016. Evaluation of different nitrous oxide production models with four continuous long-term wastewater treatment process data series. Bioprocess Biosyst. Eng.