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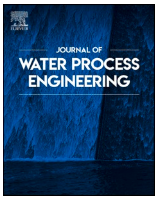

Nitrous oxide reduction in wastewater treatment plants by the regulation of the internal recirculation flow rate with a fuzzy controller

I. Santín [a,b], M. Meneses [a], C. Pedret [a], M. Barbu [a,c], R. Vilanova [a]

[a] Department of Telecommunications and Systems Engineering, School of Engineering, Autonomous University of Barcelona, 08193 Bellaterra, Barcelona, Spain
[b] Salesian University School of Sarrià, Passeig Sant Joan Bosco 74, 08017 Barcelona, Spain
[c] Department of Automatic Control and Electrical Engineering, "Dunarea de Jos" University of Galati, 800008 Galati, Romania

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ABSTRACT

The reduction of greenhouse gas emissions due to anthropogenic causes is one of the world's main challenges to face climate change. Wastewater treatment plants are necessary to improve the quality of wastewater before it is discharged into the receiving environment, but they have the disadvantage of generating nitrous oxide emissions during the biological treatment, which is a potent greenhouse gas. Avoiding partial nitrification by increasing dissolved oxygen is one of the ways to reduce these emissions. However, this article proposes to face a reduction of nitrous oxide emissions by reducing oxygen to minimum levels causing heterotrophic microorganisms to reduce nitrous oxide to dinitrogen. To achieve this objective, the present work proposes a regulation of the internal recirculation flow rate of the biological treatment by means of a fuzzy controller. This regulation is added to a usual control strategy in wastewater treatment plants, which achieves satisfactory results with respect to water quality and operational costs but that generates high nitrous oxide emissions. The Benchmark Simulation Model no. 2 Gas is used as working scenario, which includes the two main nitrous oxide emission pathways: heterotrophic denitrification and ammonia oxidizing bacteria denitrification. The proposed internal recirculation manipulation is shown to achieve nitrous oxide reductions of 26.70 and 30.83 % in different time periods with a slight effluent quality improvement and an operational cost reduction.

1. Introduction

The excess of Greenhouse Gases (GHG) is one of the main global problems, and their reduction is a primary objective in the fight against climate change. Nitrous oxide gas (N_2O) is a powerful GHG that contributes to global warming of the planet [1–4].

On the other hand, wastewater treatment plants (WWTPs) are necessary to reduce wastewater pollution before it is discharged into the receiving environment, improving its quality and thus maintaining the aquatic ecosystem life. Among the WWTP processes, the secondary treatment is essential to reduce the concentrations of suspended solids, organic matter and nutrients. In the secondary treatment, biological processes take place, where microorganisms achieve the aforementioned reductions. However, GHG and especially N_2O are generated

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Abbreviations: ACC, ammonia cascade control; AE, aeration energy (kWh/day); AOB, ammonia oxidizing bacteria; ASM1, Activated Sludge Model no. 1; BOD_5, 5-day Biological Oxygen Demand (mg/l); BSM2, Benchmark Simulation Model no. 2; BSM2G, Benchmark Simulation Model no. 2 Gas; CO_2, carbon dioxide (kg/day); COD_t, total chemical oxygen demand (mg/l); EC, external carbon (kg/day); EQI, Effluent Quality Index (kg of pollutants/day); GHG, greenhouse gases; HRT, hydraulic retention time (s); K_La, oxygen transfer coefficient (d^{-1}); K_La_i, oxygen transfer coefficient in tank i (d^{-1}); N_2O, nitrous oxide gas; N_2O,i, nitrous oxide gas in tank i; N_2, nitrogen gas/dinitrogen; NOB, nitrite oxidizing bacteria; OCI, Operational Cost Index; PE, pumping energy (kWh/day); PI, Proportional-Integral; Q, flow rate (m^3/day); Q_a, internal recirculation flow rate (m^3/day); Q_{in}, influent flow rate (m^3/day); Q_w, wastage flow rate (m^3/day); Q_{po}, flow rate from the primary clarifier (m^3/day); $S_{N_{tot}}$, total nitrogen concentration (mg/l); $S_{N_{tot,e}}$, total nitrogen concentration in the effluent (mg/l); S_{NH}, ammonium and ammonia nitrogen concentration (mg/l); $S_{NH,i}$, ammonium and ammonia nitrogen concentration in tank i (mg/l); $S_{NH,in}$, ammonium and ammonia nitrogen concentration at the input of the primary clarifier (mg/l); $S_{NH,e}$, ammonium and ammonia nitrogen concentration in the effluent (mg/l); S_{NO}, dissolved nitric oxide concentration (mg/l); S_{N_2O}, dissolved nitrous oxide concentration (mg/l); S_{N_2}, dissolved dinitrogen concentration (mg/l); S_{NO_2}, nitrite concentration (mg/l); S_{NO_3}, nitrate concentration (mg/l); S_{NK_j}, Kjeldahl nitrogen (mg/l); S_O, dissolved oxygen concentration (mg/l); $S_{O,i}$, dissolved oxygen concentration in tank i (mg/l); S_{FA}, free ammonia; S_{FNA}, free nitrous acid; S_S, readily biodegradable substrate; T_{as}, temperature (°C); *TSS*, Total Suspended Solids (mg/l); WWTP, wastewater treatment plants; $X_{B,A1}$, ammonia oxidizing bacteria concentration (mg/l); $X_{B,A2}$, nitrite oxidizing bacteria concentration (mg/l); $X_{B,H}$, heterotrophic microorganisms concentration (mg/l).

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during these processes.

The increasing interest in climate change due to GHG emissions has emphasized the need to establish approaches to better control and operate WWTPs at the plant-wide scale. This fact, jointly with the wide acceptance of benchmark simulation models to compare the performance of different control approaches as well as to evaluate them before its practical implementation, motivated the inclusion of accounting for GHG emissions in plant-wide models. One of the most used plant-wide models that takes into account the GHG emissions is the BSM2G Flores-Alsina et al. [5]. Several works in the literature have applied this model to study the effect on GHG emissions when implementing different control/operational strategies Barbu et al. [6]; Flores-Alsina et al. [5,7]; Santín et al. [8,9]; Sweetapple et al. [10] being de facto reference model up to now for testing and comparing control strategies related to mitigation of N_2O emissions. There are however some considerations that need to be highlighted regarding the accuracy of the N_2O predictions read from this model. In fact, this model is based on the ASMN model suggested by Hiatt and Grady [11] as an extension to the well-known ASM models Henze et al. [12]. It accounts for two nitrifying populations; ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB) and also incorporates four step denitrification. It is important to highlight that N_2O production is only considered during heterotrophic denitrification. Other important pathways like N_2O production during nitrification are not considered.

Recent advances published recently in the literature reported different extensions and improvements regarding the different N_2O pathways and their consideration and incorporation into existing models (ASM variants) presenting them as improvements towards N_2O emission considerations. See for example the reviews of Ni and Yuan [13], Mannina et al. [14], Vasilaki et al. [15] and Vasilaki et al. [16]. Even these works confirm the subject is reaching a stage of maturity, there still do exists uncertainty and lack of agreement in a common reference model. As pointed out in Vasilaki et al. [15], the complexity and over-parameterization of such models, makes it difficult and a real challenge their practical application. Even those complexities, some recent results based on the ASM3d extensión can be found in Blomberg et al. [17] where it was also tested on a full-scale plant. Same data was taken in Maktabifard et al. [18] to also test the ASM2d extension previously used in Zaborowska et al. [19]. On another direction, in Solís et al. [20] an extension of the above mentioned BSM2G benchmark scenario (BSM2-PSFe-GHG) including biological COD/N/P removal, GHG emissions, and chemical and physico-chemical models to evaluate resource recovery in Water resource Recovery Facilities is proposed.

Hence, even all the previously mentioned works show solid advances towards a better description of the N_2O pathways, therefore, the quantification of N_2O emissions, there is still the need to reach an agreement on a reference scenario to test and evaluate operation strategies in a comparable way. In this work, the original BSM2G framework is chosen as reference scenario just for an easy and fair comparison with previous works. The main goal is to show the advantages that can be achieved by means of an appropriate operation of the internal recirculation control handle. Therefore, adopting the same scenarios as in previous works. In case new models are taken, the figures of merit and the reference conditions would be too different, and approaches unfairly compared. On that basis, the conclusions stated by this work, must be taken with the uncertainty that may come from the actual arena of existing improved models.

Although there are several works that apply control strategies in WWTPs, the literature regarding the application of automatic control with the objective of reducing GHGs is scarcer. Some works such as Flores-Alsina et al. [5,7] and Barbu et al. [6] evaluate GHG emissions of the usual control strategies applied to improve effluent quality and/or reduce operational costs. Other works such as Santín et al. [8]; Boiocchi et al. [21]; Santín et al. [9] and Solís et al. [20] apply control strategies with the aim of reducing GHGs and specifically N_2O. Santín et al. [8] applies a combination of nitrite concentration (S_{NO_2}) and ammonium and ammonia nitrogen concentration (S_{NH}) in the fifth tank ($S_{NH,5}$) cascade controls that manipulate S_O set-points to take into account both N_2O reduction and effluent quality. Boiocchi et al. [21] designs a fuzzy controller to manipulate the S_O set-points taking into account S_{NH} and nitrate concentration (S_{NO_3}) at the inlet and outlet of the aerobic reactor. Santín et al. [9] designs a fuzzy controller for a plant-wide control adding more manipulated variables, not only with the aim of reducing GHGs, but also to improve effluent quality and costs. However, the N_2O reduction is also carried out in this case by manipulating the S_O set-points. In Solís et al. [20], two of the applied control strategies aim to reduce N_2O by S_{NO_2} and dissolved N_2O (S_{N_2O}) control, both by means ofS_O set-point manipulation.

The referred works regulate S_O in the aerobic tanks of the biological treatment, increasing it during the necessary periods to carry out complete nitrification in order not to generate N_2O emissions through the AOB denitrification pathway. However, in comparison with partial nitrification, by complete nitrification more S_{NO_3} is generated and consequently more total nitrogen ($S_{N_{tot}}$), which is a nutrient that causes eutrophication. This is due to the fact that by partial nitrification, some of the nitrogen dissolved in the water present in S_{NO}, S_{N_2O} and S_{N_2} molecules is converted into gas.

The present work also aims to reduce N_2O through the application of control techniques. However, this reduction is not carried out by an S_O increase. The objective is to ensure that the biological treatment is capable of oxidizing S_{NH} with the minimum possible S_O added during the periods when large N_2O emissions are most likely to occur. This results in partial nitrification, which could lead to N_2O emissions through the AOB denitrification pathway. However, if S_O levels are low enough, heterotrophic microorganisms ($X_{B,H}$) consume the oxygen from N_2O, reducing it to dinitrogen (N_2). In addition, by the reduction of the internal recirculation flow rate (Q_a), the hydraulic retention time (HRT) can be increased. This fact allows the oxidation of the S_{NH} peaks to be carried out for a longer period of time, reducing the N_2O emission peaks. It should be noted that the N_2O reduction to N_2 depends on the amount of organic matter since there is a relationship between oxygen consumption and organic matter degradation by $X_{B,H}$. To apply the proposed control in another plant, an analysis of the amount of organic matter present in the aerobic tanks should be carried out. The possibility of adding carbon in the aerated tanks can be assessed in the case of there is not enough organic matter.

Thus, the main novelty of this work compared to the above referenced papers is the achievement of the N_2O reduction by reducing S_O, instead of increasing it. This is carried out using a control strategy commonly applied in WWTPs as starting point. This control strategy is designed to obtain optimal results with respect effluent quality and operational costs, but does not take into account N_2O emissions. Specifically, the S_{NH} cascade control implemented in Santín et al. [8] is used. This one obtains the best results in terms of water quality and costs, but emits higher N_2O concentrations compared to the other control strategies shown in the referred article. The objective is to maintain the S_O regulation of this control strategy, but adding a regulation of Q_a, which leads part of the water from the last biological treatment tank to the first one.

A fuzzy controller is proposed to perform this Q_a manipulation. This control achieves a nitrification process improvement by reducing the necessary S_O levels to keep the established S_{NH} set point. With the original control strategy, a partial nitrification takes place with high N_2O emissions. The objective of the Q_a manipulation with the fuzzy controller is to achieve a greater S_O reduction and consequently a greater N_2 generation to reduce N_2O emissions, while maintaining optimal nitrogen levels and operational costs. The HRT increase by the Q_a regulation also can help reduce the N_2O peaks.

The use of a fuzzy control approach is chosen because the fuzzy logic provides capabilities to introduce both an intuitive and formal representation of the process as well as to include operator experience and

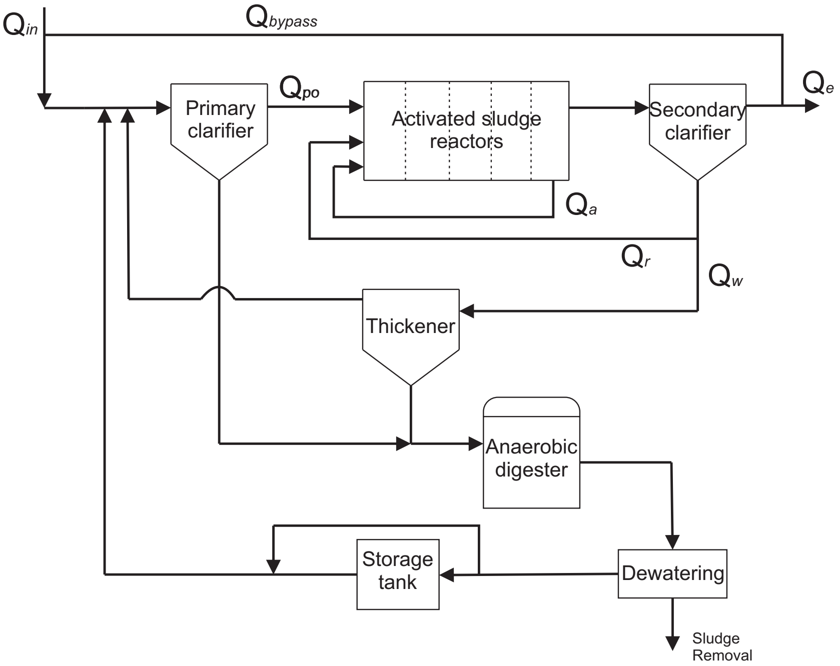

Fig. 1. BSM2 plant with notation used for flow rates.

process knowledge in the controller. This latest point is crucial in gaining process operator confidence and for an easy way of posterior improvement of the controller by means of fine-tuning of actual fuzzy rules or even adding new ones to better reflect actual dynamics. Within the wastewater treatment community, there have been several works that show its application to different control problems.

Different works can be found on the literature based on fuzzy logic. From the initial works of Tong et al. [22] in the 80s, to different works that during the last decade have been approaching the dissolved oxygen control and nutrient removal problems Meyer and Pöpel [23]; Traore et al. [24]; Yong et al. [25]; Baroni et al. [26]; Bertanza et al. [27], until some latest results where the authors also show the potential of fuzzy logic on plant wide approaches to deal with Greenhouse gas emissions Santín et al. [8,9]. This spectrum suggests fuzzy logic as a good candidate to introduce what in the paragraphs above authors have been referencing as a complementary control action to improve greenhouse gas emissions of an existing operation strategy.

Summarizing, the present paper proposes a N_2O emission reduction in WWTPs through applying the following novelties:

- Carrying out a partial nitrification by reducing S_O in the tanks, instead of a total nitrification by increasing S_O.
- Manipulating Q_a with a fuzzy controller, showing its effects on N_2O emissions.

Starting from a commonly used control strategy, without modifying the S_O control.

Driven by the use of dynamic simulation models as a common practice to assess and compare control strategies in WWTPs or to evaluate them before full-scale implementation, as mentioned above, this work uses Benchmark Simulation Model no. 2 Gas (BSM2G), which includes the evaluation of GHG emissions in WWTPs. This version was introduced by Flores-Alsina et al. [5] and later improved by the same authors, including two pathways for N_2O emissions: heterotrophic denitrification and AOB denitrification. Even this model does not include all available knowledge at present date, it is the one that provides the most suitable framework for comparing control strategies under the same conditions. Therefore, previously highlighted uncertainties (missing pathways in BSM2G) regarding the specific predicted N_2O values should be considered.

The paper is organized as follows. First, BSM2G working scenario is explained. Next, the proposed control strategies and the fuzzy control designed are presented. After, results are shown, as well as the discussion about them. Finally, the most important conclusions are drawn.

2. Materials and methods

The proposed control strategy is tested in BSM2G, which is an extended version of Benchmark Simulation Model no. 2 (BSM2) [28].

BSM2G adds to BSM2 the assessment of the following GHGs: methane (CH_4), carbon dioxide (CO_2) and N_2O. BSM2G was presented in Flores-Alsina et al. [5] with the heterotrophic denitrification pathway for N_2O emissions. The same authors updated and provided a new version of BSM2G including the AOB denitrification pathway based on Guo and Vanrolleghem [29].

2.1. Layout

The plant layout of the BSM2G (Fig. 1) is the same as that of the BSM2, which includes a primary clarifier, a wastewater biological treatment, a secondary clarifier and a sludge treatment.

The biological treatment is carried out in five tanks connected in series, of which the first two are anoxic and the last three aerobic, with an internal recirculation from the latter to the first tank. Denitrification reactions take place in the anoxic tanks and nitrification reactions in the aerobic tanks.

Biological reactions inside the reactors are modeled by the Activated Sludge Model no. 1 (ASM1) [12], which is extended on the basis of Hiatt and Grady [11] and Mampaey et al. [30] to include, in addition to S_{NO_3}, the concentration of the S_{NO_2}, nitric oxide (S_{NO}), S_{N_2O} and dissolved N_2 (S_{N_2}). The equations of these concentrations and S_{NH} are shown below:

$$S_{NH} = -0.086\cdot proc_1 - 0.086\cdot proc_{2.1} - 0.086\cdot proc_{2.2} - 0.086\cdot proc_{2.3} - 0.086\cdot \cdot proc_{2.4} - 5.6416\cdot proc_{3.1} - 0.086\cdot proc_{3.2} + proc_6 - 6.7794\cdot proc_9 - 6.7794\cdot proc_{10} \tag{1}$$

$$S_{NO_3} = -0.5756\cdot proc_{2.1} + 16.6667\cdot proc_{3.2} \tag{2}$$

$$S_{NO_2} = 0.5756 \cdot proc_{2.1} - 1.1522 \cdot proc_{2.2} + 5.5556 \cdot proc_{3.1} - 16.6667 \cdot proc_{3.2} - \\ -6.6964 \cdot proc_9 + 6.6964 \cdot proc_{10} \tag{3}$$

$$S_{NO} = 1.1522 \cdot proc_{2.2} - 1.1522 \cdot proc_{2.3} + 13.3869 \cdot proc_9 - 13.3869 \cdot proc_{10} \tag{4}$$

$$S_{N_2O} = 1.1522 \cdot proc_{2.3} - 1.1522 \cdot proc_{2.4} + 13.3869 \cdot proc_{10} \tag{5}$$

$$S_{N_2} = 1.1522 \cdot proc_{2.4} \tag{6}$$

where $proc_1$, $proc_{2.1}$, $proc_{2.2}$, $proc_{2.3}$, $proc_{2.4}$, $proc_{3.1}$, $proc_{3.2}$, $proc_6$, $proc_9$ and $proc_{10}$ are biological processes, which are defined as follows:

$$proc_1 = \mu_{HT} \cdot \left(\frac{S_S}{15 + S_S}\right) \cdot \left(\frac{S_O}{0.2 + S_O}\right) \cdot X_{B,H} \tag{7}$$

where S_S is the readily biodegradable substrate and μ_{HT} is:

$$\mu_{HT} = \left(0.0625 \cdot (T_{as} + 20) \cdot \left(1 - e^{0.3 \cdot (T_{as} - 50)}\right)\right)^2 \tag{8}$$

$$proc_{2.1} = \mu_{HT} \cdot 0.3 \cdot \left(\frac{S_S}{20 + S_S}\right) \cdot \left(\frac{S_{NO_3}}{1.5 + S_{NO_3}}\right) \cdot \left(\frac{0.2}{0.2 + S_O}\right) \cdot X_{B,H} \tag{9}$$

$$proc_{2.2} = \mu_{HT} \cdot 0.3 \cdot \left(\frac{S_S}{20 + S_S}\right) \cdot \left(\frac{S_{NO_2}}{0.3 + S_{NO_2}}\right) \cdot \left(\frac{0.2}{0.2 + S_O}\right) \cdot \left(\frac{0.5}{0.5 + S_{NO}}\right) \cdot X_{B,H} \tag{10}$$

$$proc_{2.3} = \mu_{HT} \cdot 0.6 \cdot \left(\frac{S_S}{20 + S_S}\right) \cdot \left(\frac{S_{NO}}{0.04 + S_{NO} + \left(S_{NO}^2/0.3\right)}\right) \cdot \left(\frac{0.2}{0.2 + S_O}\right) \cdot X_{B,H} \tag{11}$$

$$proc_{2.4} = \mu_{HT} \cdot 0.8 \cdot \left(\frac{S_S}{30 + S_S}\right) \cdot \left(\frac{S_{N_2O}}{0.02 + S_{N_2O}}\right) \cdot \left(\frac{0.2}{0.2 + S_O}\right) \cdot \left(\frac{0.2}{0.2 + S_{NO}}\right) \cdot X_{B,H} \tag{12}$$

$$proc_{3.1} = \mu_{A1T} \cdot \left(\frac{S_{FA}}{0.004 + S_{FA} + \left(S_{FA}^2/0.1\right)}\right) \cdot \left(\frac{S_O}{0.6 + S_O}\right) \cdot \left(\frac{0.1}{0.1 + S_{FNA}}\right) \cdot X_{B,A1} \tag{13}$$

where $X_{B,A1}$ is the concentration of AOB in mg/l and μ_{A1T} is:

$$\mu_{A1T} = \left(0.0255 \cdot (T_{as} + 15) \cdot \left(1 - e^{0.15 \cdot (T_{as} - 50)}\right)\right)^2 \tag{14}$$

while T_{as} is the temperature, S_{FA} is free ammonia and S_{FNA} is free nitrous acid defined as:

$$S_{FA} = \frac{S_{NH} \cdot 10^{pH}}{e^{6344/(273.15 + T_{as})} + 10^{pH}} \tag{15}$$

$$S_{FNA} = \frac{S_{NO_2}}{1 + e^{2300/(273.15 + T_{as})} \cdot 10^{pH}} \tag{16}$$

$$proc_{3.2} = \mu_{A2T} \cdot \left(\frac{S_{FNA}}{5 \cdot 10^{-6} + S_{FNA} + \left(S_{FA}^2/0.1\right)}\right) \cdot \left(\frac{S_O}{1.2 + S_O}\right) \cdot \left(\frac{0.5}{0.5 + S_{FA}}\right) \cdot X_{B,A2} \tag{17}$$

where $X_{B,A2}$ is the concentration of Nitrite Oxidizing Bacteria (NOB) in mg/l and μ_{A2T} is:

$$\mu_{A2T} = \left(0.0235 \cdot (T_{as} + 25) \cdot \left(1 - e^{0.05 \cdot (T_{as} - 57)}\right)\right)^2 \tag{18}$$

$$proc_6 = K_{aT} \cdot S_{ND} \cdot X_{B,H} \tag{19}$$

Table 1
Limits for the effluent pollutants.

Variable	Value
$S_{N_{tot}}$	<18 mg/l
COD_t	<100 mg/l
S_{NH}	<4 mg/l
TSS	<30 mg/l
BOD_5	<10 mg/l

$$proc_9 = \mu_{A1T} \cdot \left(\frac{S_{FNA}}{0.0006 + S_{FNA}}\right) \cdot \left(\frac{S_{FA}}{0.0027 + S_{FA}}\right) \cdot \\ \cdot \left(\frac{S_O}{11.4 - 35.0952 \cdot S_O + \left(S_O^2/0.0035\right)}\right) \cdot X_{B,A1} \tag{20}$$

$$proc_{10} = \mu_{A1T} \cdot \left(\frac{S_{NO}}{1 + S_{NO}}\right) \cdot \left(\frac{S_{FA}}{0.0027 + S_{FA}}\right) \cdot \\ \cdot \left(\frac{S_O}{11.4 - 35.0952 \cdot S_O + \left(S_O^2/0.0035\right)}\right) \cdot X_{B,A1} \tag{21}$$

And the transfer to N_2O is as follows:

$$N_2O = 0.9137 \cdot pH \cdot 1.024^{T_{as} - 15} \cdot S_{NO} \cdot vol \tag{22}$$

where vol is the volume of the tank.

The sludge is deposited by gravity from the lower level of the secondary clarifier. Some of this biomass is directed to the sludge treatment (wastage) and the other part is recirculated to the biological treatment inlet. The secondary clarifier is modeled as a 10 layers non-reactive unit.

The sludge treatment consists of a thickener, an anaerobic digester and a dewatering unit and includes the recirculation of water from the dewatering outlet and part of the thickener outlet to the first clarifier inlet.

The plant is designed for an average influent flow rate (Q_{in}) of 20,648.36 m^3/day with an average biodegradable Chemical Oxygen Demand (*COD*) of 592.53 mg/l. BSM2 defines a 609-day influent, although only results from days 245 to 609 are evaluated. The capacity of the different elements of the biological treatment is as follows: 900 m^3 the first clarifier, 1500 m^3 each anoxic tank, 3000 m^3 each aerobic tank and 600 m^3 the secondary clarifier. The resulting hydraulic retention time is 22 h. The influent wastewater composition follows the principles outlined in Gernaey et al. [31]. It includes diurnal flow rate and concentration variations, corresponding to diurnal pollutant flux profiles for the wastewater derived from households. Also, slowest effects are introduced such as a holiday effect (reducing the pollutant fluxes and the wastewater flow rate) and also a seasonal correction taking account of both yearly temperature variations (between 10 and 20 °C). As the influent is the same as in BSM2, more information about it can be found in Jeppsson et al. [32], Jeppsson et al. [33], Vrecko et al. [34,37], Nopens et al. [35]. The influent characteristics also do consider the sewer model provided in Gernaey et al. [36].

2.2. Evaluation criteria

The performance of control strategies is assessed by effluent quality, operational costs and GHG emissions.

Effluent quality is determined by the percentage of time that pollutant concentrations exceed the legally established limits and by the Effluent Quality Index (EQI).

The legal effluent concentration limits of total nitrogen ($S_{N_{tot}}$), total COD (CODt), S_{NH}, Total Suspended Solids (TSS) and 5-day Biological Oxygen Demand (BOD_5) are shown in Table 1.

$S_{N_{tot}}$ is the sum of S_{NO_3}, S_{NO_2}, S_{NO}, S_{N_2O} and Kjeldahl nitrogen (S_{NKj}), which includes organic nitrogen and S_{NH}.

This article only evaluates the violations of $S_{N_{tot}}$ in the effluent ($S_{N_{tot,e}}$)

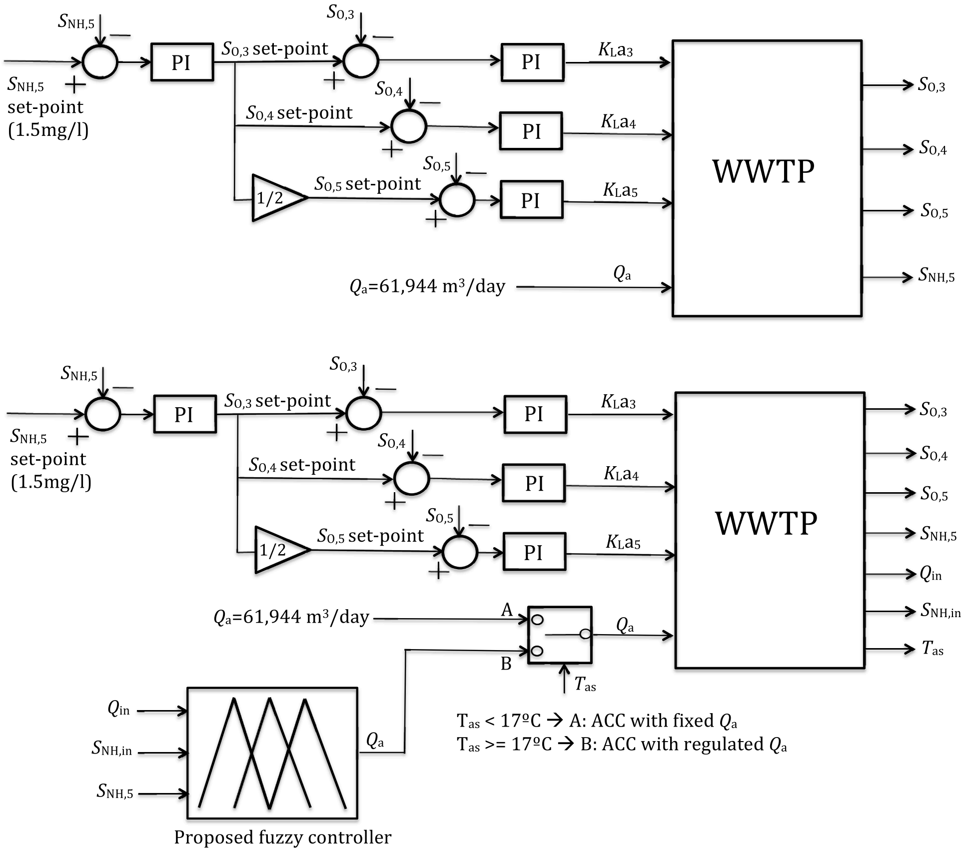

Fig. 2. Schemes of the original ACC with fixed Q_a based on Santín et al. [8] (a) and ACC combining fixed and regulated Q_a with the proposed fuzzy controller, depending on T_{as} (b)).

and S_{NH} in the effluent ($S_{NH,e}$), as the other pollutants are easily kept below the limits and there are only violations of them when there is a bypass due to a rain event that increases the flow rate above that allowed by the plant.

EQI is measured in kg of pollutants per day and is calculated by weighting the effluent concentrations of the different pollutants according to the following equation:

$$\mathrm{EQI}=\frac{1}{1000\cdot \mathrm{T}}\int_{t=245days}^{t=609days}\Big(2\cdot TSS(t)+COD(t)+30\cdot S_{NKj}(t)+ +10\cdot\left(S_{NO_3}+S_{NO_2}+S_{NO}+S_{N_2O}\right)(t)+2\cdot BOD_5(t)\Big)\cdot Q(t)\cdot dt \tag{23}$$

where T is the evaluation period and Q is the flow rate.

Costs are assessed by the Operational Cost Index (OCI), which is calculated by weighting the different costs according to the following equation:

$$\mathrm{OCI}=\mathrm{AE}+\mathrm{PE}+3\cdot\mathrm{SP}+3\cdot\mathrm{EC}+\mathrm{ME}-6\cdot\mathrm{MET}_{prod}+\mathrm{HE}_{net} \tag{24}$$

where AE is the aeration energy (kWh/day), PE is the pumping energy (kWh/day), SP is the sludge production (kg/day), EC refers to the carbon that could be added to improve denitrification (kg/day), ME is the mixing energy (kWh/day), MET_{prod} is the produced methane (kWh/day) and HE is the heating energy (kWh/day).

The GHG emissions are calculated according to the principles proposed by Hiatt and Grady [11] and Mampaey et al. [30]. The following sources of GHG emissions are taken into account in BSM2G: the biological treatment, the sludge treatment, the difference between electric consumption and electric generation, the EC production and the sludge to be disposed.

In the present work, only the N_2O emissions in the biological treatment and CO_2 due to electrical consumption have been evaluated, due to the specific objectives of the applied control strategy. As mentioned before, the heterotrophic denitrification and the AOB denitrification pathways are taken into account for N_2O emissions, which are assessed on the basis of Hiatt and Grady [11] and Guo and Vanrolleghem [29], respectively.

3. Control approach

During the nitrification process, S_{NH} is oxidized by AOB, allowing the S_{NH} reduction. The required S_O in this process depends on the S_{NH} values, so varying S_O based on S_{NH} is more efficient than keeping it fixed.

This is the reason why the S_O regulation in aerated tanks to control S_{NH} is a common practice in WWTPs, both in real plants and in research works such as Vrecko et al. [34,37]; Stare et al. [38]; Nopens et al. [35]; Vrecko et al. [39]; Santín et al. [40]; Santín et al. [8]. These works apply and evaluate different control techniques. Nevertheless, GHG emissions are not commonly evaluated in this control strategy.

The present work uses the Ammonia Cascade Control (ACC) applied in Santín et al. [8] as a starting point (Fig. 2a). The referenced research shows how the ACC obtains satisfactory results of EQI, OCI and $S_{N_{tot,e}}$ limit violations, but GHG and specifically N_2O emissions result to be very high.

In this ACC applied in Santín et al. [8] Q_a is kept fixed. In the present work a fuzzy controller is proposed to manipulate Q_a with the aim of reducing N_2O emissions. The proposed Q_a regulation is only applied with daily average T_{as} above 17 °C because at low T_{as} the nitrification process is worse performed. Therefore, it is not possible to reduce S_O to low concentrations by regulating Q_a while keeping S_{NH} below the established limits. This T_{as} has been chosen for this benchmark, through an approximate observation of the behavior of the plant. In the case of carrying out the present proposal in a real plant or another model, the effect of T_{as} in the nitrification process should be taken into account and observe up to what T_{as} can be applied. When the average T_{as} is lower than 17 °C, Q_a is kept fixed as in the original ACC. The control strategy composed of ACC and the fuzzy controller for Q_a manipulation is shown in Fig. 2b.

Therefore, the possible scenarios for the application of Q_a control are all those plants that use this usual ACC, with the objective of reducing N_2O emissions without modifying the S_O control, while maintaining satisfactory levels of EQI, limit violations of pollutants and OCI. It should be noted that the proposed Q_a manipulation can be applied in any other control strategy that regulates S_O set-points based on $S_{NH,5}$, regardless of the manipulation of other variables. In the case of operating with another $S_{NH,5}$ set-point or with an alternative control technique to manipulate the S_O set-points or with a different WWTP, the proposed Q_a manipulation would also be advantageous, although the fuzzy controller would have to be adapted by adjusting the ranges of some membership functions.

3.1. *Proposed fuzzy controller for internal recirculation flow rate manipulation*

Fuzzy logic can be defined as a control approach based on human expertise. Fuzzy controller adapts the input and output variables into suitable linguistic values by membership functions. Rules between input and output variables are established by words. Non-expert readers can found further information about fuzzy control in standard references such as Klir and Yuan [41]. The FIS[1] Editor from Matlab is used in this work for the implementation of the proposed fuzzy controller.

The proposed Q_a regulation requires a study of the plant and an exhaustive knowledge of the biological treatment operation. Consequently, a fuzzy controller based on the process knowledge is proposed in this work.

The objective of the Q_a manipulation is to reduce the S_O required by ACC, by increasing the oxygen consumption of S_{N_2O} by $X_{B,H}$ that reduces S_{N_2O} to N_2.

Mamdani [42] is the method of inference used in this paper. The design of the proposed fuzzy controller is explained below, and its code is shown in Annex I.

3.1.1. *Inputs and output*

The fuzzy controller has three inputs and one output. The inputs are Q_{in}, S_{NH} at the WWTP inlet ($S_{NH,in}$), and $S_{NH,5}$. The output is Q_a, which is the variable to be regulated. The inputs and output of the proposed fuzzy controller are shown in Fig. 2.

Q_{in} affects the HRT of the biological treatment. $S_{NH,in}$ provides information on the S_{NH} that will need to be oxidized in the biological treatment and thus on the S_O required. While Q_{in} has immediate effects on $S_{NH,5}$, $S_{NH,in}$ has effects on $S_{NH,5}$ with a time delay that depends on HRT, which in turn depends on Q_{in} and Q_a. During dry weather there is a relationship between the $S_{NH,in}$ and Q_{in} values since both variables vary simultaneously during the day, and the $Q_{in}/S_{NH,in}$ ratio allows to know if there is a period of dry weather. The membership functions and the decision rules explained in Sections 3.1.1 and 3.1.2 explain specifically what ranges of values of Q_{in} and $S_{NH,5}$ are considered for dry weather. In rain events, there is a Q_{in} increase and simultaneously a S_{NH} dilution, which results in an increase of the $Q_{in}/S_{NH,in}$ ratio. However, there is also a HRT reduction. $S_{NH,5}$ determines the S_O required for the nitrification process. Q_a is regulated with the aim of reducing the S_O required to keep $S_{NH,5}$ at the set-point of 1.5 mg/l by the PI controllers of ACC.

Table 2
Ranges, types and parameters of the membership functions of the proposed fuzzy controller for Q_a manipulation.

Variables		Range	Membership functions	Type	Parameters
Inputs	$S_{NH,in}$	[12 40]	Low	Z-shaped	[12 24.2]
			Medium	Triangular	[16 25 34]
			High	S-shaped	[26 40]
	$S_{NH,5}$	[1.35 1.49]	Low	Z-shaped	[1.35 1.397]
			Medium-Low	Triangular	[1.35 1.397 1.443]
			Medium	Triangular	[1.397 1.443 1.49]
			High	S-shaped	[1.443 1.49]
	Q_{in}	[1e + 04 5e + 04]	Low	Z-shaped	[1e + 04 2.25e + 04]
			Medium	Triangular	[1.7e + 04 2.75e + 04 4e + 04]
			High	S-shaped	[3.75e + 04 4.25e + 04]
Output	Q_a	[0 2e + 05]	Very-low	Triangular	[−1000 0 1000]
			Low	Triangular	[0 1e + 04 2e + 04]
			Medium-Low	Triangular	[1e + 04 3e + 04 5e + 04]
			Medium	Triangular	[3e + 04 6e + 04 9e + 04]
			High	Triangular	[6e + 04 9e + 04 1.2e + 05]
			Very-high	Triangular	[9e + 04 2e + 05 3.1e + 05]

3.1.2. *Membership functions*

The fuzzy control is defined by words instead of numbers and sentences instead of equations. However, process variables are measured in numbers instead of words. For this reason, the fuzzifier adapts the input variables into suitable linguistic values by membership functions.

Table 2 provides the information related to the membership functions: range, fuzzy sets, type and parameters.

The ranges of $S_{NH,in}$ and Q_{in} variations correspond to usual values of the plant's influent, and have been established on the basis of practical knowledge ($S_{NH,in}$: 12–40 mg/l and Q_{in}: $1{\cdot}10^4$ - $5{\cdot}10^5$ m^3/day). Both inputs have three membership functions: "Low", "Medium", "High". The significant increase in the Q_{in} with respect to $S_{NH,in}$ that occurs with rainfall events can be used to detect them. This fact can be observed with the membership function ranges shown in Table 2 and the decision rules explained in Section 3.1.3. Also, if the Q_{in} value is "High" (higher than $3.75{\cdot}10^4$ m^3/day), a rain event is considered regardless of the $S_{NH,in}$ value, since the Q_{in} values are above the usual ones during dry weather.

The $S_{NH,5}$ range (1.35–1.49 mg/l) has been established taking into account that ACC tries to control $S_{NH,5}$ at the set-point of 1.5 mg/l by regulating S_O. Therefore $S_{NH,5}$ values below 1.35 mg/l are not usual. Four membership functions have been established for $S_{NH,5}$: "Low", "Medium-Low", "Medium" and "High". Although the range of values is small, four membership functions are applied to reduce abrupt Q_a variations. This is because the Q_a regulation instantly affects the $S_{NH,5}$ value, and the fuzzy controller regulates Q_a based on $S_{NH,5}$.

Regarding the output variable (Q_a), the regulation range is established between 0 and $2{\cdot}10^5$ by six membership functions: "Very-Low", "Low", "Medium-Low", "Medium", "High", "Very-High". However, the "Very-High" membership function is applied only in some cases such as rain events and unusual influent conditions. Therefore, the usual range of operation is lower. The fixed Q_a value applied in ACC equal to 61,944 m3/day is taken as a reference point.

3.1.3. *Decision rules*

The proposed fuzzy controller includes 26 decision rules, which are shown in Table 3. By these rules, a value is assigned to Q_a for any

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[1] FIS: Fuzzy Inference System

Table 3
Decision rules of the proposed fuzzy controller for Q_a manipulation.

Rule number	$S_{NH,in}$	$S_{NH,5}$	Q_{in}	Q_a
1	If is low	And is low	And is low	Then is medium
2	If is low	And is low	And is medium	Then is high
3	If is low	And is low	And is high	Then is very-high
4	If is low	And is medium-low	And is low	Then is medium-low
5	If is low	And is medium-low	And is medium	Then is medium
6	If is low	And is medium-low	And is high	Then is high
7	If is low	And is medium	And is low	Then is low
8	If is low	And is medium	And is medium	Then is medium-low
9	If is low	And is medium	And is high	Then is medium
10	If is medium	And is low	And is low	Then is high
11	If is medium	And is low	And is medium	Then is high
12	If is medium	And is low	And is high	Then is very-high
13	If is medium	And is medium-low	And is low	Then is medium
14	If is medium	And is medium-low	And is medium	Then is medium
15	If is medium	And is medium-low	And is high	Then is high
16	If is medium	And is medium	And is low	Then is medium-low
17	If is medium	And is medium	And is medium	Then is medium-low
18	If is medium	And is medium	And is high	Then is medium
19	If is high	And is low	–	Then is very-high
20	If is high	And is medium-low	And is low	Then is high
21	If is high	And is medium-low	And is medium	Then is high
22	If is high	And is medium-low	And is high	Then is very-high
23	If is high	And is medium	And is low	Then is medium
24	If is high	And is medium	And is medium	Then is medium
25	If is high	And is medium	And is high	Then is high
26	–	If is high	–	Then is very-low

combination of input values.

As mentioned above, the manipulation of Q_a tries to reduce the S_O necessary to maintain $S_{NH,5}$ at the set-point of 1.5 mg/l, by increasing the oxygen consumption of S_{N_2O} by $X_{B,H}$ that reduces S_{N_2O} to S_{N_2} (Eqs. (1), (3) and (12)).

The decision rules are established taking into account the following premises to keep $S_{NH,5}$ at 1.5 mg/l with lower S_O by regulating Q_a:

- Effect of Q_a on the inlet of the biological treatment: S_{NH} is reduced by oxidation during the biological treatment. Therefore, the $S_{NH,5}$ value is lower than the value of S_{NH} at the input of the biological treatment. Hence, S_{NH} at the secondary treatment inlet can be diluted by increasing Q_a. Conversely, the dilution is lower if Q_a is decreased.
- Q_a effect on the nitrification process: Increasing Q_a results in an HRT decrease. This fact worsens the nitrification process and less S_{NH} is oxidized. HRT increases if Q_a decreases, enhancing the nitrification process and further reducing S_{NH}.
- Effect of a Q_{in} increase due to a rain event: A rain event has a similar effect as a Q_a increase, but without the possibility of control. Rain dilutes the pollutant concentration and specifically that of S_{NH}, and at the same time reduces HRT. Therefore, rain can be beneficial or

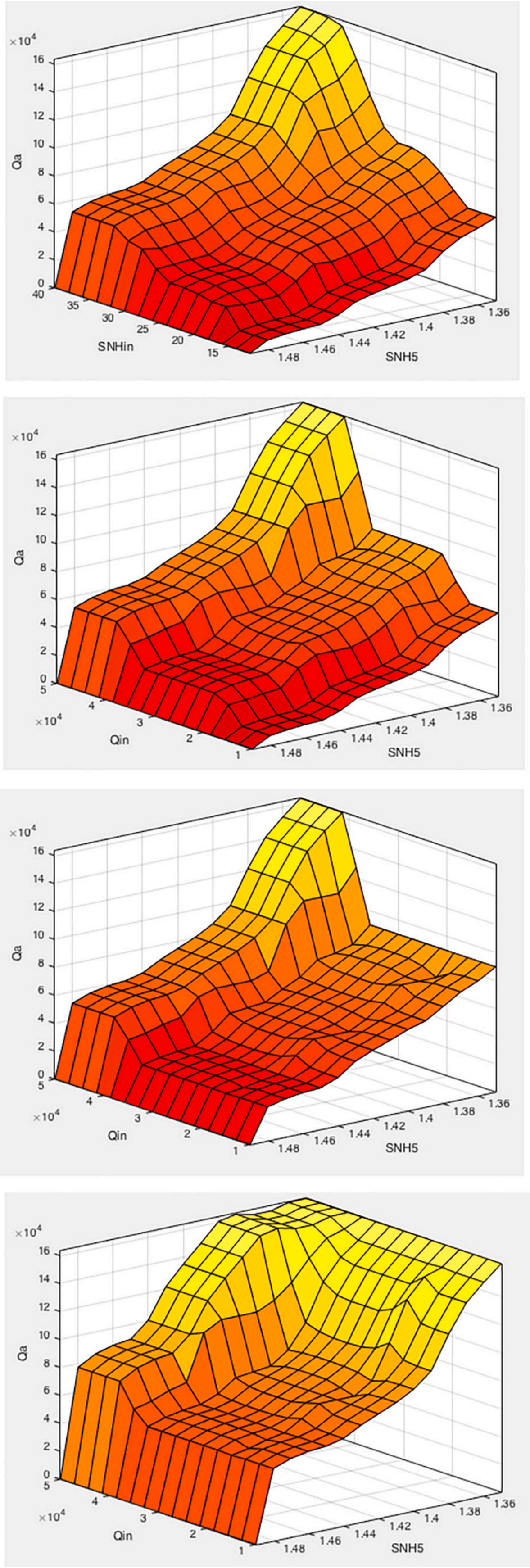

Fig. 3. Graphic surfaces of the fuzzy control output related to the inputs.

Table 4

Simulation results of GHG emissions, effluent quality and operational costs of ACC with fixed Q_a and regulating Q_a with the proposed fuzzy controller for the two time periods evaluated.

	Evaluation Criteria	From day 245 to day 338			From day 569 to day 609		
		ACC with fixed Q_a	ACC with regulated Q_a	% of improvement	ACC with fixed Q_a	ACC with regulated Q_a	% of improvement
GHG emissions	N_2O emissions (kg CO_2eq/day)	12,669.41	8762.78	30.83	16,135.26	11,826.79	26.70
	CO_2 due to electric consumption (kg CO_2/day)	1955.98	1857.62	5.03	2071.06	1975.49	4.61
	Total GHG (kg CO_2/day)	26,914.998	22,919.75	14.84	31,506.51	27,108.92	13.96
Operational costs	OCI	8163.0014	7962.21	2.46	8326.22	8134.13	2.26
	Pumping energy (kWh/day)	262	61.97	76,35	261.60	73.52	71.89
	Areation energy (kWh/day)	3451.08	3189.094	7,59	3453.22	3434.42	0.54
Effluent Quality	EQI	3408.52	3379.35	0.86	4230.54	4188.24	1.01
	$S_{N_{tot,e}}$ limits violations (% of time)	–	–	–	–	–	–
	$S_{NH,e}$ limits violations (% of time)	–	–	–	0.18	0.18	–
	COD limits violations (% of time)	–	–	–	0.34	0.34	–
	TSS limits violations (% of time)	0.045	0.045	–	1.17	1.17	–
	BOD_5 limits violations (% of time)	0.045	0.045	–	1.07	1.07	–

detrimental depending on whether or not it coincides with an S_{NH5} peak, on its duration and on its intensity.

Fig. 3 shows the surface plots that relate the inputs and the output based on decision rules. These surface plots are explained below:

Fig. 3a shows the relationship of the output Q_a with the inputs $S_{NH,in}$ and $S_{NH,5}$ setting the Q_{in} value to $1{\cdot}10^4$ m^3/day. With this Q_{in}, it is considered that there is no rainfall event, regardless of the value of $S_{NH,in}$. This Fig. 3a shows how Q_a increases when $S_{NH,in}$ increases to dilute S_{NH} at the inlet of the biological treatment. However, Q_a is always conditioned by $S_{NH,5}$, since if S_{NH} increases in the tanks where nitrification takes place, Q_a must be reduced to improve this process and thus require less S_O. Since ACC controls $S_{NH,5}$ at the set-point of 1.5 mg/l, Q_a is reduced to 0 when $S_{NH,5}$ is equal to 1.49 mg/l or greater, trying to maintain the set-point without requiring a S_O increase.

Fig. 3b, c and d show the relationship between Q_{in} and $S_{NH,5}$ for the three membership functions of $S_{NH,in}$: “Low”, “Medium” and “High”, respectively.

Increasing Q_a to dilute S_{NH} is not usually necessary with $S_{NH,in}$ values belonging to the range of the membership function “Low” (Fig. 3b). However, Q_a increases progressively if Q_{in} reaches “Medium” and “High” membership functions ranges, because a possible rain event is considered. Although rain dilutes S_{NH}, higher Q_a values help to dilute it further. Nevertheless, Q_a is reduced to increase HRT in the case that $S_{NH,5}$ approaches the set-point of 1.5 mg/l, taking into account that higher Q_{in} values hinder the nitrification process by the HRT reduction.

If the $S_{NH,in}$ values are in the range of the membership function “Medium” (Fig. 3c) there is a Q_a increase compared to Fig. 3b when Q_{in} is “Low”. This is because the S_{NH} dilution must be greater if $S_{NH,in}$ increases. In this case ($S_{NH,in}$ is “Medium”), the rain event is only considered when Q_{in} is “High”. If Q_{in} is “Medium”, Q_a keeps the same values as in Fig. 3b because $S_{NH,in}$ increases in the case of Fig. 3c, but a rain event is considered in Fig. 3b. In Fig. 3c, Q_a is also reduced if $S_{NH,5}$ increases.

If $S_{NH,in}$ increases to values within the membership function “High” (Fig. 3d), Q_a is increased to dilute S_{NH}. As in the previous cases, the Q_a values are lower if $S_{NH,5}$ increases, and are reduced to 0 if $S_{NH,5}$ reaches the set-point of ACC. If $S_{NH,5}$ is “Low”, the Q_a value is “Very-High” regardless of the Q_{in} value. If $S_{NH,5}$ is “Medium-Low” or “Medium”, the Q_a value is higher if Q_{in} is “High”, since it corresponds to a rain event.

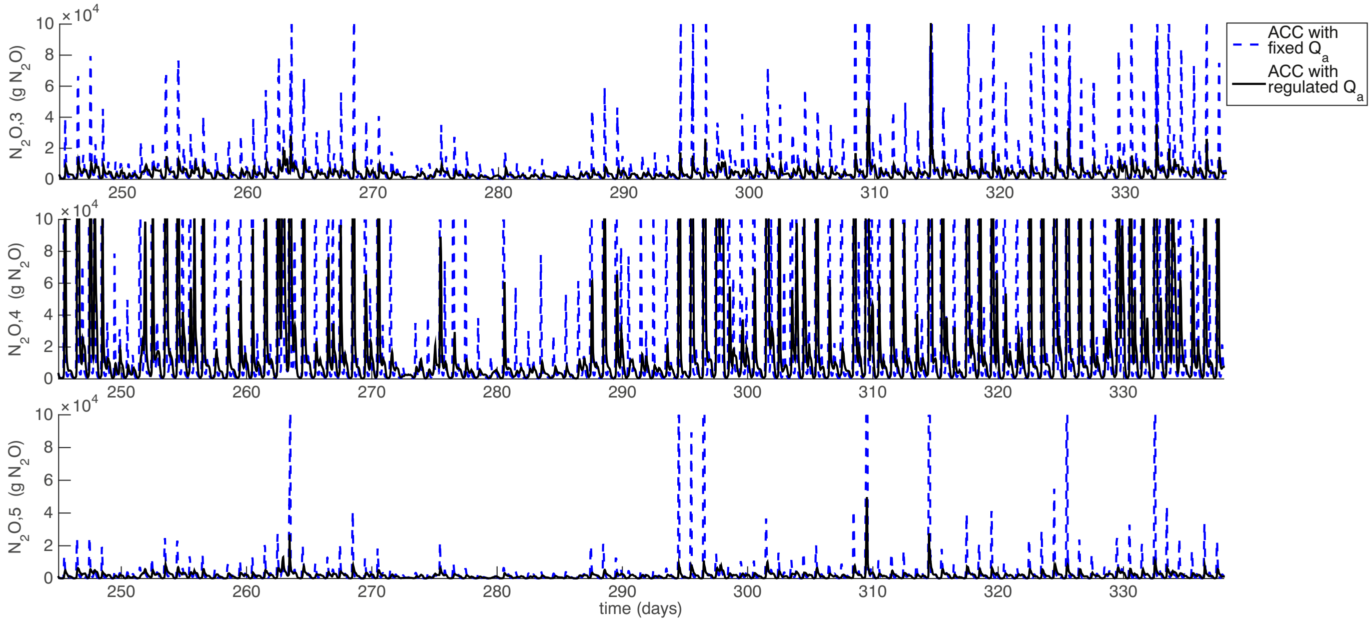

Fig. 4. Time evolution of $N_2O,3$, $N_2O,4$ and $N_2O,5$ for ACC with fixed Q_a and regulating Q_a with the proposed fuzzy controller from day 245 to day 338.

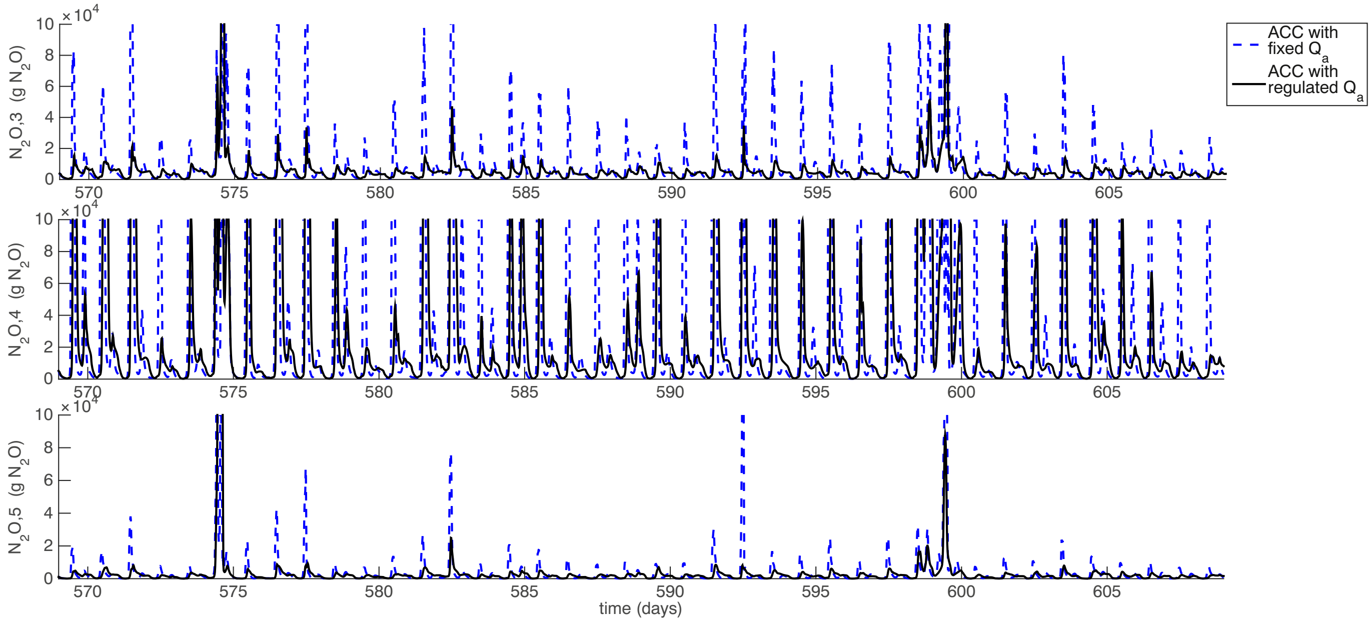

Fig. 5. Time evolution of $N_2O,3$, $N_2O,4$ and $N_2O,5$ for ACC with fixed Q_a and regulating Q_a with the proposed fuzzy controller from day 569 to day 609.

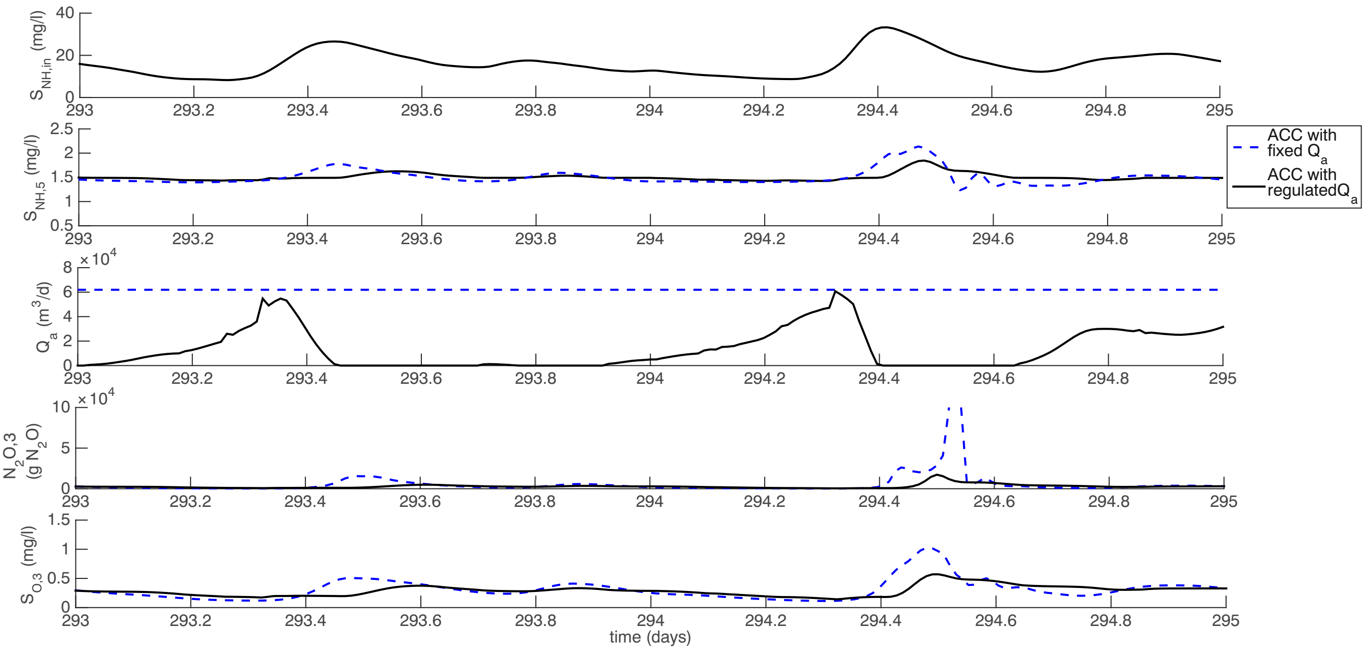

Fig. 6. Time evolution of $S_{NH,in}$, $S_{NH,5}$, Q_a, $S_{O,3}$ and $N_2O,3$ for ACC with fixed Q_a and regulating Q_a with the proposed fuzzy controller during days 293 and 294.

4. Simulation results and discussion

Results of effluent quality, costs and GHG emissions have been obtained by simulating BSM2G with Matlab. According to the simulation protocol, 609 days are simulated, of which from day 245 to day 609 can be evaluated.

As mentioned in Section 3, the Q_a regulation is only applied with average daily T_{as} equal to or greater than 17 °C since at high T_{as} the nitrification process is better performed, and it is possible to reduce S_O to lower concentrations by regulating Q_a.

In this way, at average daily T_{as} lower than 17 °C the original ACC with fixed Q_a is applied; while at average daily T_{as} equal to or greater than 17 °C, Q_a is regulated with the proposed fuzzy controller.

Table 4 shows the numerical results obtained with the original ACC (fixed Q_a) and with ACC including Q_a regulation with the proposed fuzzy controller during time periods when daily average T_{as} is equal to or greater than 17 °C. These time periods are from day 245 to day 338 (93 days) and from day 569 to day 609 (40 days). Out of these periods, the plant is operated just with ACC, therefore no comparison makes sense.

On the other hand, Figs. 4, 5, 6, 7, 8, 9, 11 and 12 present the evolution over time of the main variables showing the differences between Q_a regulated and fixed Q_a.

Next, these numerical results are discussed by analysing the figures, arguing the reasons for the improvements obtained by regulating Q_a.

4.1. N_2O *emissions*

The addition of Q_a regulation to the already applied ACC aims to

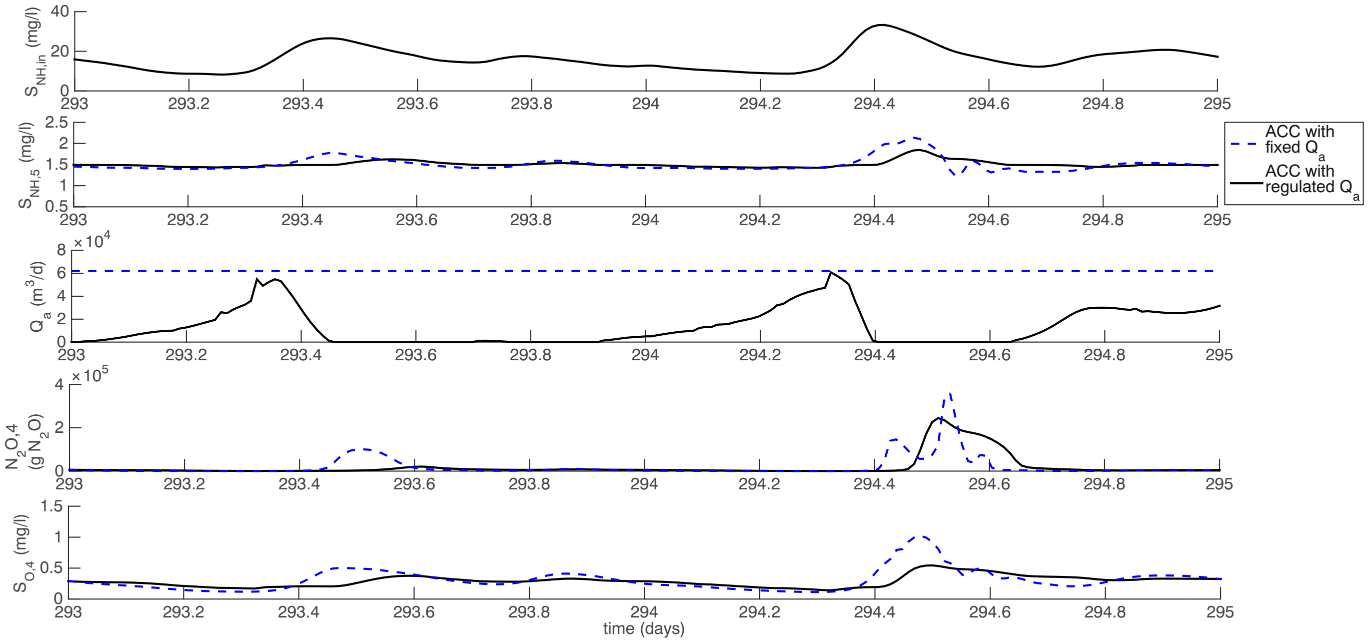

Fig. 7. Time evolution of $S_{NH,in}$, $S_{NH,5}$, Q_a, $S_{O,4}$ and $N_2O,4$ for ACC with fixed Q_a and regulating Q_a with the proposed fuzzy controller during days 293 and 294.

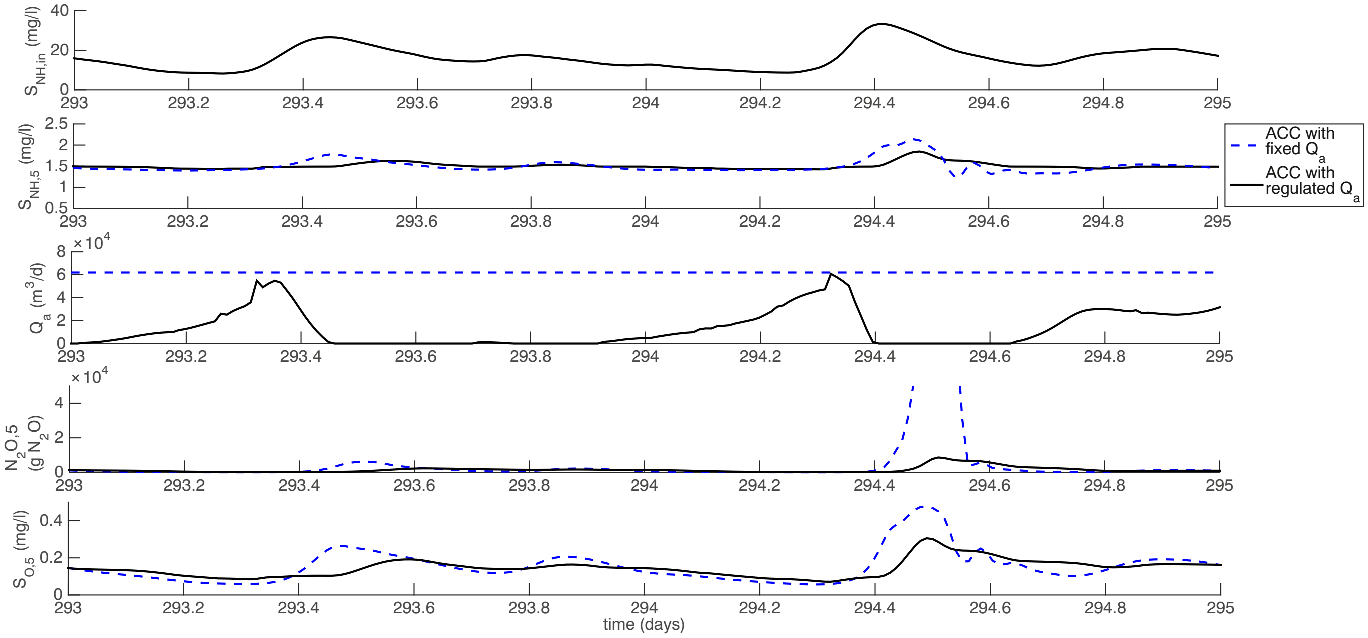

Fig. 8. Time evolution of $S_{NH,in}$, $S_{NH,5}$, Q_a, $S_{O,5}$ and $N_2O,5$ for ACC with fixed Q_a and regulating Q_a with the proposed fuzzy controller during days 293 and 294.

reduce N_2O emissions without worsening effluent quality and operational costs compared to ACC with fixed Q_a.

Table 4 shows an N_2O reduction of 30.83 and 26.70 % achieved in the two evaluated periods by regulating Q_a compared to fixed Q_a. These N_2O reductions can also be observed in Figs. 4 and 5, where the time variation of N_2O in tank 3 (N_2O,3), in tank 4 (N_2O,4) and in tank 5 (N_2O, 5) is shown for the two time evaluated periods. A reduction of the daily N_2O peaks by the proposed Q_a regulation can be clearly observed, especially in tanks 3 and 5.

This reduction is argued below by means of Figs. 6, 7 and 8, which show the variations of $S_{NH,in}$, $S_{NH,5}$, Q_a, S_O and N_2O for two days in the three aerobic tanks. Only two days have been chosen for a better visualization. As shown in Figs. 4 and 5, there are days when the N_2O peaks are higher and other days when they are lower. For this reason, a day with a lower N_2O peak (day 293) and a day with higher N_2O peak (day 294) have been chosen in Figs. 6, 7 and 8 to discuss the time variation of the most important variables. $S_{NH,in}$, $S_{NH,5}$ and Q_a are the same in all three figures. Only the values of N_2O and S_O are specific to each tank.

The three figures show how Q_a is progressively increased to dilute S_{NH} at the biological treatment inlet when $S_{NH,5}$ is decreasing during the beginning of the day. The variation of $S_{NH,5}$ is slight, but it should be noted that the value ranges of the $S_{NH,5}$ membership functions are short, as mentioned in Section 3.1.2. The further $S_{NH,5}$ is from the ACC setpoint, the lower S_O is, reducing the risk of a N_2O increase. Consequently, Q_a is increased to dilute S_{NH} at the biological treatment inlet.

The Q_a increase is greater when $S_{NH,in}$ increases since a greater

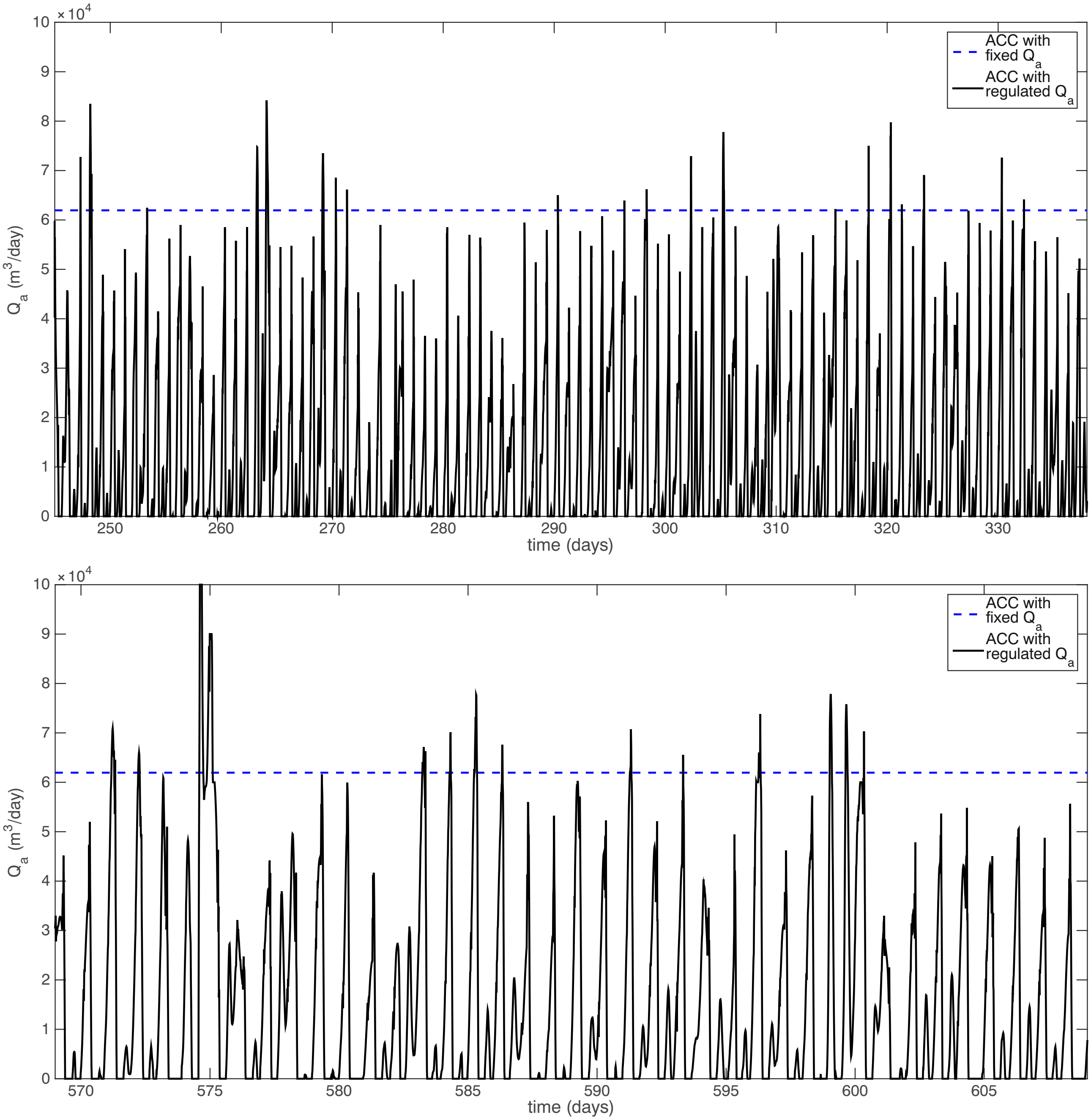

Fig. 9. Time evolution of Q_a for ACC with fixed Q_a and regulating Q_a with the proposed fuzzy controller from day 243 to day 338 (a) and from day 569 to day 609 (b).

dilution is necessary, as long as $S_{NH,5}$ does not reach 1.49 mg/l. Although Q_a increases, most of the time it is below the fixed value of 61,944 m3/day (Fig. 9). While a higher Q_a increase would result in greater dilution, it would take longer to subsequently decrease it when $S_{NH,5}$ increases.

The results of the Q_a regulation are reflected in Figs. 6, 7 and 8, which show the differences in S_O and N_2O in the three aerobic tanks between regulating Q_a and with fixed Q_a. As explained in Section 3, the S_O value regulated by the PI controller of ACC is the same for tanks 3 and 4 and half for tank 5.

As shown in Fig. 6, ACC with fixed Q_a needs an $S_{O,3}$ level of approximately 0.5 mg/l on day 293 and 1 mg/l on day 294 to reduce $S_{NH,5}$ to the set-point of 1.5 mg/l. On the other hand, by regulating Q_a with the proposed fuzzy controller, the maximum $S_{O,3}$ needed is approximately 0.37 mg/l on day 293 and 0.57 mg/l on day 294. Consequently, by the proposed Q_a regulation, there is a reduction in the $N_2O,3$ peak of approximately 15.4 kg on day 293 and almost 200 kg on day 294. The main difference between both days is the $S_{NH,in}$ peak with an approximate variation of 5 mg/l that subsequently results in a $S_{NH,5}$ increase and therefore higher needs of $S_{O,3}$. On both days the $N_2O,3$ emissions begin to increase when $S_{O,3}$ reaches values of between 0.4 and 0.5 mg/l approximately and increase much more to extremely high values as $S_{O,3}$ increases further. This is because there is not enough S_O for AOB to perform full nitrification and oxidize S_{NO_2} to S_{NO_3} (Eqs. (3), (2) and (17)). If there is not enough S_O, AOB also oxidize S_{NH} with the oxygen of S_{NO_2}, reducing it to S_{NO} and subsequently to S_{N_2O} (Eqs. (1), (3), (4), (5), (20) and (21)). When S_O is less than 0.4 or 0.5 mg/l approximately, S_O is so reduced that $X_{B,H}$ consume more oxygen from S_{N_2O}, reducing it to S_{N_2} (Eqs. (5), (6) and (12)). Furthermore, due to the fact

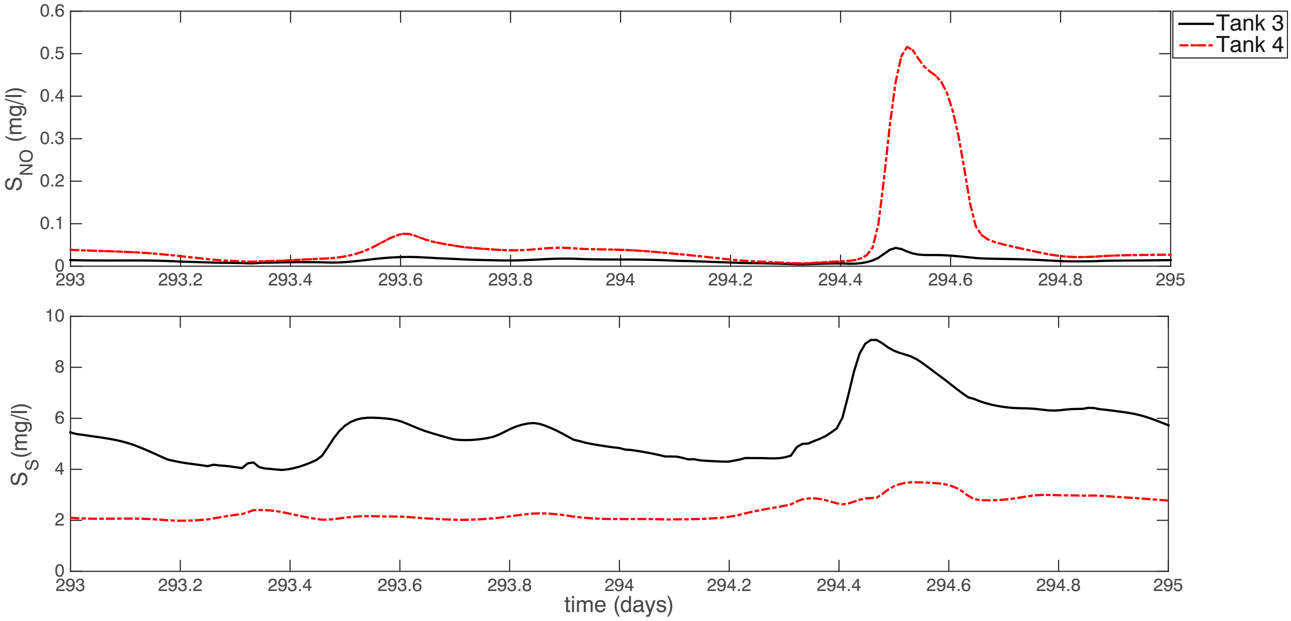

Fig. 10. Time evolution of S_{NO} and S_S for ACC with regulated Q_a in tanks 3 and 4 during days 293 and 294.

that the Q_a reduction results in a HRT increase together with the S_O reduction, the AOB denitrification takes place more slowly, reducing the N_2O peaks.

On day 294 there is a slight reduction in $N_2O,3$ in a short period of time during the $S_{O,3}$ increase, probably due to a slight S_{NH} reduction. The N_2O generation by the AOB denitrification pathway is related to the S_{NH} since the higher the S_{NH}, the greater its oxidation by AOB through the oxygen of S_{NO_2} and S_{NO} (Eqs. (1), (3), (4), (20) and (21)).

Fig. 7 shows the variations of the variables in tank 4. As mentioned above, the S_O set-point in tank 4 is the same as in tank 3, and therefore the S_O values are similar. However, the N_2O emissions are higher in tank 4 than in tank 3, especially on day 294, where the N_2O reduction compared to ACC with fixed Q_a is smaller. As it is can be observed in Fig. 10, S_{NO} increases and S_S decreases as the wastewater advances through the tanks of the aerobic reactor. In addition, there is a greater S_{NO} increase when S_{NH} increases. Thus, the greater S_{NO}, the greater generation of S_{N_2O} and consequently of N_2O (Eqs. (5) and (21)), while the reduction of S_S hinders the reduction of S_{N_2O} to S_{N_2} by $X_{B,H}$ (Eqs. (6) and (12)). This results in $N_2O,4$ peaks of approximate 100 kg with fixed Q_a and 20.6 kg with variable Q_a on day 293 and 360 kg with fixed Q_a and 244 with variable Q_a on day 294.

Fig. 8 shows the evolution over time of the same variables in tank 5 during the same days (293 and 294). ACC regulates the $S_{O,5}$ set-point to half the value of $S_{O,3}$ and $S_{O,4}$ set-point, with the objective of recirculating less S_O is recirculated to the anoxic tanks, which can worsen the denitrification process. The $S_{O,5}$ reduction compared to $S_{O,3}$ and $S_{O,4}$ also results in a $N_2O,5$ reduction. Specifically, $S_{O,5}$ peaks are approximately 0.19 mg/l on day 293 and 0.3 mg/l on day 294 by regulating Q_a, resulting in $N_2O,5$ peaks of approximately 2.28 kg on day 293 and 8.645 kg on day 294. The $N_2O,5$ reduction compared to ACC with fixed Q_a is much greater when $S_{NH,in}$ is higher (day 294) since ACC with fixed Q_a increases $S_{O,5}$ up to approximately 0.47 mg/l, which results in a maximum peak of around 113 kg. This represents a reduction of over 104 kg on day 294 by regulating Q_a in comparison with fixed Q_a.

4.2. CO_2 due to electric consumption

Table 4 shows that a CO_2 reduction due to electric consumption of 5.03 % is achieved in the time period between day 245 and day 338 and of 4.61 % between day 569 and day 609 by means of ACC with the proposed Q_a regulation compared to ACC with fixed Q_a.

As mentioned above, the Q_a regulation by the proposed fuzzy controller aims to reduce S_O to very low values to achieve a greater S_{N_2O} reduction to S_{N_2} by $X_{B,H}$. This S_O reduction also results in a reduction in CO_2 due to electric consumption.

In addition, this S_O reduction is achieved with a Q_a regulation, whose values are most of the time below the fixed value of 61,944 m^3/day (Fig. 9) established in ACC, and which corresponds to the default value of BSM2 and BSM2G. This Q_a reduction also results in a reduction in CO_2 due to electric consumption. When $S_{NH,5}$ reaches values above 1.49 mg/l, Q_a is reduced to zero, which leads to a large reduction in electrical energy during these time periods.

4.3. Operational costs

As mentioned in Section 2.2, operational costs are evaluated using OCI. Table 4 shows an OCI reduction of 2.46 % from day 245 to day 338 and of 2.26 % from day 569 to 609 by the proposed Q_a regulation compared to fixed Q_a.

OCI includes the expenses of AE and PE (24). AE is mainly based on the value of K_La, which is directly related to S_O. PE is based on the flow rates of the pumps used in WWTP and therefore partly on Q_a. In this way, the OCI reduction is related to the S_O and Q_a reduction achieved by the proposed Q_a regulation explained above, as the CO_2 reduction due to electricity consumption. Specifically, ACC with regulated Q_a achieves a reduction in average pumping electrical energy of 200 kWh/day in the first period of time evaluated and 188 kWh/day in the second period of time. The average electrical energy for aeration is reduced by 262 kWh/day and 19 kWh/day in the two time periods evaluated, respectively.

4.4. Effluent quality

As mentioned in Section 2.2, the effluent quality is evaluated by the EQI (1) and by pollutant limit violations.

Table 4 shows an EQI reduction of 0.86 % from day 245 to day 338 and of 1.01 % from day 569 to 609 by regulating Q_a compared to fixed Q_a in ACC.

It is worth mentioning that ACC with fixed Q_a is the control strategy with the best EQI and lowest $S_{N_{tot,e}}$ violations tested in Santín et al. [8] (called CS2 in the referenced paper) being the improvement of the EQI

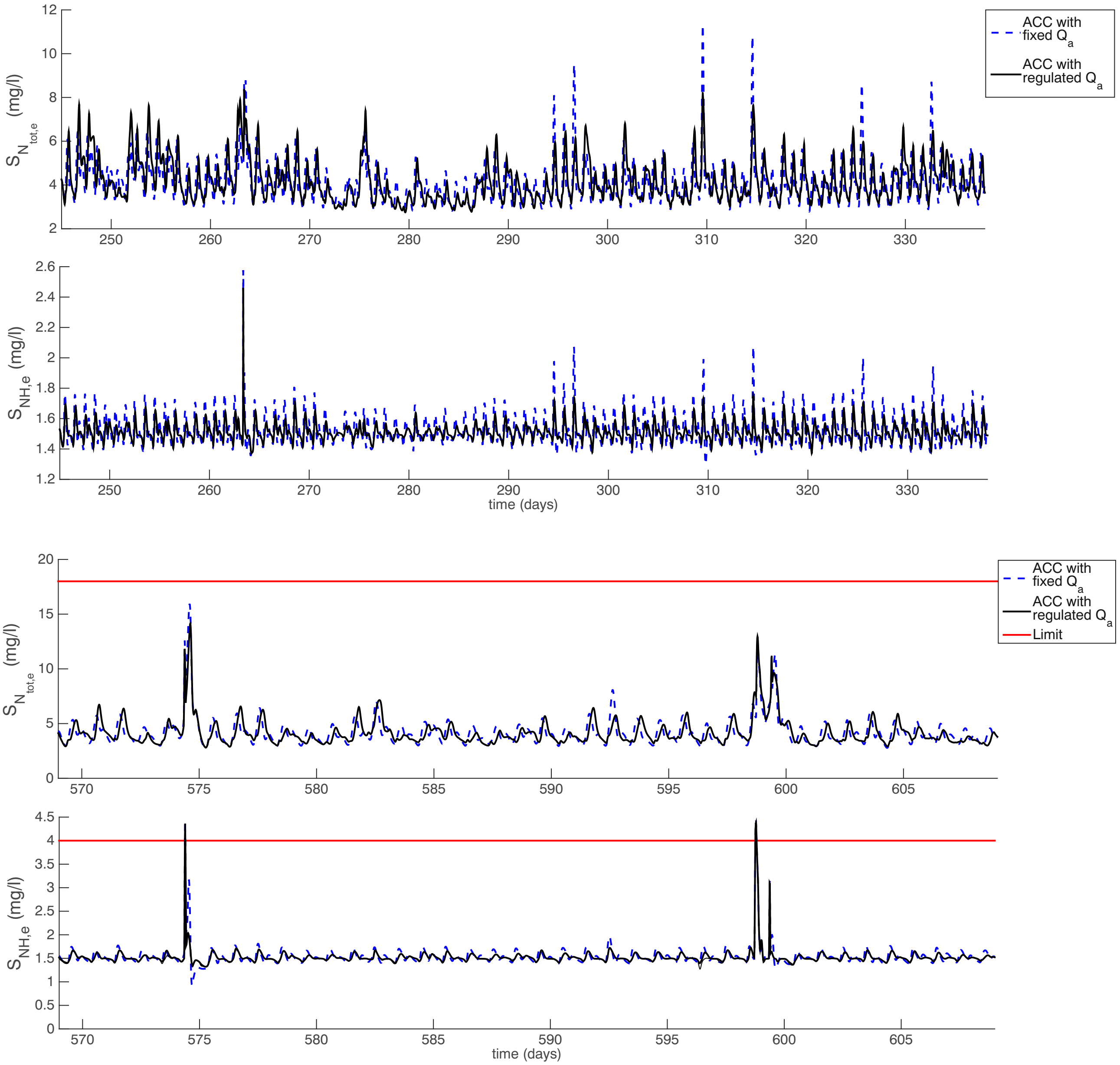

Fig. 11. Time evolution of $S_{N_{tot,e}}$ and $S_{NH,e}$ for ACC with fixed Q_a and regulating Q_a with the proposed fuzzy controller from day 243 to day 338 (a) and from day 569 to day 609 (b).

due to a $S_{N_{tot,e}}$ reduction. ACC with regulated Q_a keeps low $S_{N_{tot,e}}$ values by partial nitrification (Fig. 11). Some of the nitrogen dissolved in the water present in S_{NO}, S_{N_2O} and S_{N_2} molecules is converted into gas, but it does not happen with total nitrification, which generates S_{NO_3}. Therefore, with full nitrification higher $S_{N_{tot,e}}$ is generated.

On the other hand, the Q_a regulation combines the S_{NH} dilution and the nitrification process improvement, as explained above. Consequently, $S_{NH,e}$ peaks are reduced compared to fixed Q_a (Fig. 11). This $S_{NH,e}$ reduction result in a slight EQI reduction.

Regarding the established limit violations of nutrients, organic matter and TSS, Table 4 shows that there is no variations between ACC with fixed Q_a and with variable Q_a.

With respect to $S_{N_{tot,e}}$, there are no limit violations during the evaluated periods. Due to the $S_{N_{tot,e}}$ reduction by partial nitrification, it is kept below the established limit (18 mg/l) even though it increases in rain events (Fig. 11).

$S_{NH,e}$ violations occur on days 574 and 598 coinciding with rain events (Figs. 11 and 12). As shown in the figures, the $S_{NH,5}$ levels remain most of the time below the established limit (4 mg/l), specially by the Q_a regulation where $S_{NH,5}$ does not stray too far from the set-point established in ACC (1.5 mg/l). However, $S_{NH,e}$ overcomes the limit of 4 mg/l because the flow rate in the biological treatment cannot exceed 60,000 m^3/day and thus the wastewater is directed bypassed without being treated. The proposed Q_a regulation takes into account rain events, increasing Q_a. It is considered that there is a rain event when there is an increase of Q_{in} with respect to $S_{NH,in}$, as long as $S_{NH,5}$ does not exceed 1.49 mg/l. However, this regulation depends on $S_{NH,5}$ and not on $S_{NH,e}$. Therefore, it does not take into account the bypass when the biological treatment cannot assume more flow.

Organic matter (COD and BOD_5) and TSS keep the same limit violations by regulating Q_a as with fixed Q_a.

It should be noted that the proposed Q_a regulation aims to reduce N_2O emissions of ACC with fixed Q_a, without worsening the operational cost and effluent quality indicators. Finally, not only they are not worsened, but a slight improvement is achieved.

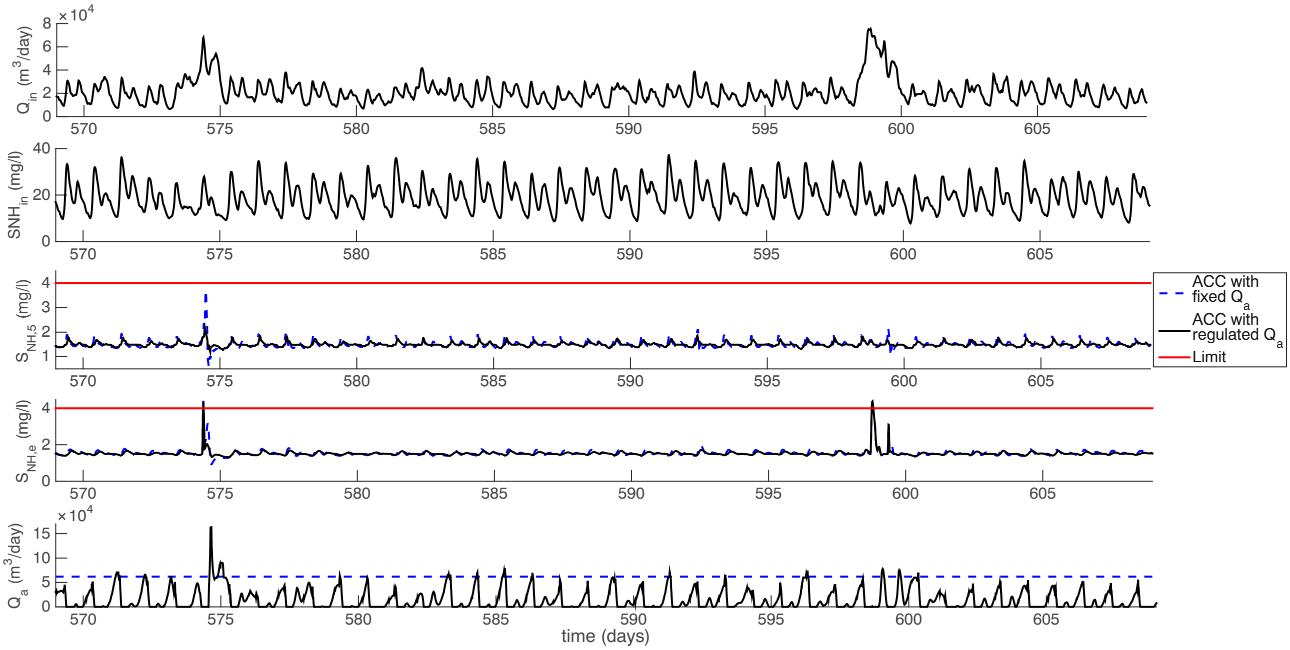

Fig. 12. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,5}$, Q_a and $S_{NH,e}$ for ACC with fixed Q_a and regulating Q_a with the proposed fuzzy controller from day 569 to day 609.

5. Conclusions

This work has presented the design of a fuzzy controller for the Q_a manipulation in the biological treatment of WWTPs with the aim of reducing N_2O emissions. This is conceived as a complementary control action, to be applied jointly with another existing control strategy with the aim of reducing GHG emissions. The Q_a regulation has been added to the ACC control strategy, which with fixed Q_a achieves satisfactory results in terms of effluent quality and operational costs but with the drawback of large N_2O emissions. The main conclusions of the Q_a regulation in ACC by means of the proposed fuzzy controller are:

- The Q_a regulation in the periods of time in which T_{as} is greater than 17 °C reduces N_2O emissions by 26.70 and 30.83 % compared to keeping Q_a fixed.
- The Q_a manipulation with the proposed fuzzy controller is mainly based on combining the S_{NH} dilution at the entrance of the biological treatment with improving the nitrification process. This combination is carried out according to the priorities of each time frame, which are determined by the input variables of the controller ($S_{NH,in}$, Q_{in}, $S_{NH,5}$).
- The Q_a manipulation allows to oxidize S_{NH} for a longer period of time. This fact results in a reduction of S_{N_2O} peaks. In addition, S_O is so reduced that $X_{B,H}$ consume more oxygen from S_{N_2O}, reducing it to S_{N_2}.
- The reduction of N_2O emissions is greater in tanks 3 and 5 than in tank 4, although in tank 4 the oxygen set-point is the same as in tank 3. The higher N_2O emissions are mainly due to higher S_{NO} but also to lower S_S, especially when Q_{in} is higher.
- The S_O reduction by the proposed Q_a regulation results in slight reductions in GHG emissions due to the electric consumption and in operational costs compared to fixed Q_a.
- The Q_a regulation keeps partial nitrification and improves the nitrification process. These facts result in a maintenance of $S_{N_{tot,e}}$ values and a slightly reduction of $S_{NH,e}$ peaks, which results in a slight improvement in effluent quality compared to fixed Q_a.
- The proposed fuzzy controller is designed to be applied jointly with any other control strategy that manipulates the S_O set points based on $S_{NH,5}$, regardless of the control of other variables. A future work will be aimed at combining the proposed Q_a manipulation with other control strategies applied in WWTP. The fact of using a fuzzy logic controller to determine the complementary Q_a actuation, makes this extension to other baseline control strategies (other than the ACC) more suitable. As the control logic is based on process dynamics reasoning, the controller input signals will be the same and there may be the need to adapt the fuzzy logic controller membership functions.

Declaration of competing interest

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Data availability

The controller code is added as an appendix.

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Appendix A. [System]

Name = 'Proposed fuzzy controller'
Type = 'mamdani'
Version = 2.0
NumInputs = 3
NumOutputs = 1
NumRules = 26
AndMethod = 'min'
OrMethod = 'max'
ImpMethod = 'min'

```
AggMethod = ‘max’
DefuzzMethod = ‘centroi d’
[Input1]
Name = ‘SNHin’
Range = [12 40]
NumMFs = 3
MF1 = ‘Low’: ‘zmf’, [1 2 2 4. 2]
MF2 = ‘Medium’: ‘trimf”, [1 6 25 34]
MF3 = ‘High’: ‘smf’, [2 6 40]
[Input2]
Name = ‘SNH5’
Range = [1. 3 5 1. 4 9]
NumMFs = 4
MF1 = ‘Low’: ‘zmf’, [1. 3 5 1. 3 9 7]
MF2 = ‘Medium−Low’: ‘trimf’, [1. 3 5 1. 397 1. 4 4 3]
MF3 = ‘Medium’: ‘trimf’, [1. 3 9 7 1. 443 1. 4 9]
MF4 = ‘High’: ‘smf’, [1. 4 4 2 1. 4 9]
[Input3]
Name = ‘Qin’
Range = [10000 50000]
NumMFs = 3
MF1 = ‘Low’: ‘zmf’, [1 0 0 0 022500]
MF2 = ‘Medium’: ‘trimf’, [1 7 0 0 0 27500 40000]
MF3 = ‘High’: ‘smf’, [3 7 5 0 0 42500]
[Output1]
Name = ‘Qa’
Range = [0200000]
NumMFs = 6
MF1 = ‘Low’: ‘trimf’, [0 10000 20000815]
MF2 = ‘Medium–low’: ‘trimf’, [1 0 0 0 0 30000 50000]
MF3 = ‘Medium’: ‘trimf’, [3 0 0 0 0 60000 90000]
MF4 = ‘Very–High’: ‘trimf’, [9 0 0 0 0 200000 310000]
MF5 = ‘Very–low’: ‘trimf’, [−1000 0 1000]
MF6 = ‘High’: ‘trimf’, [6 0 0 0 0 90000 120000]
[Rules].
1 1 1, 3 (1): 1
1 1 2, 6 (1): 1
1 1 3, 4 (1): 1
1 2 1, 2 (1): 1
1 2 2, 3 (1): 1
1 2 3, 6 (1): 1
1 3 1, 1 (1): 1
1 3 2, 2 (1): 1
1 3 3, 3 (1): 1
2 1 1, 6 (1): 1
2 1 2, 6 (1): 1
2 1 3, 4 (1): 1
2 2 1, 3 (1): 1
2 2 2, 3 (1): 1
2 2 3, 6 (1): 1
2 3 1, 2 (1): 1
2 3 2, 2 (1): 1
2 3 3, 3 (1): 1
3 1 0, 4 (1): 1
3 2 1, 6 (1): 1
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3 2 3, 4 (1): 1
3 3 1, 3 (1): 1
3 3 2, 3 (1): 1
3 3 3, 6 (1): 1
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References

[1] J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, C. Johnson, Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge university press, 2001.

[2] B. Netz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer, et al., Climate change 2007: mitigation. contribution of working group iii to the fourth assessment report of the intergovernmental panel on climate change. summary for policymakers, in: Climate change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers, 2007.

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

[4] D. Richardson, H. Felgate, N. Watmough, A. Thomson, E. Baggs, Mitigating release of the potent greenhouse gas n2o from the nitrogen cycle–could enzymic regulation hold the key? Trends Biotechnol. 27 (2009) 388–397.

[5] X. Flores-Alsina, L. Corominas, L. Snip, P.A. Vanrolleghem, Including greenhouse gas emissions during benchmarking of wastewater treatment plant control strategies, Water Res. 45 (16) (2011) 4700–4710.

[6] M. Barbu, R. Vilanova, M. Meneses, I. Santin, On the evaluation of the global impact of control strategies applied to wastewater treatment plants, J. Clean. Prod. 149 (2017) 396–405.

[7] X. Flores-Alsina, M. Arnell, Y. Amerlinck, L. Corominas, K.V. Gernaey, L. Guo, E. Lindblom, I. Nopens, J. Porro, A. Shaw, L. Snip, P.A. Vanrolleghem, U. Jeppsson, Balancing effluent quality, economic cost and greenhouse gas emissions during the evaluation of (plant-wide) control/operational strategies in WWTPs, Sci. Total Environ. 466-467 (2014) 616–624.

[8] I. Santín, M. Barbu, C. Pedret, R. Vilanova, Control strategies for nitrous oxide emissions reduction on wastewater treatment plants operation, Water Res. 125 (2017) 466–477.

[9] I. Santín, M. Barbu, C. Pedret, R. Vilanova, Fuzzy logic for plant-wide control of biological wastewater treatment process including greenhouse gas emissions, ISA Trans. 77 (2018) 146–166.

[10] C. Sweetapple, G. Fu, D. Butler, Does carbon reduction increase sustainability? A study in wastewater treatment, Water Res. 87 (2015) 522–530.

[11] W. Hiatt, J.C. Grady, An updated process model for carbon oxidation, nitrification, and denitrification, Water Environ. Res. 80 (11) (2008) 2145–2156.

[12] M. Henze, C. Grady, W. Gujer, G. Marais, T. Matsuo, Activated Sludge Model 1, Scientific and Technical Report No.1, IAWQ, London, UK, 1987.

[13] B.-J. Ni, Z. Yuan, Recent advances in mathematical modeling of nitrous oxides emissions from wastewater treatment processes, Water Res. 87 (2015) 336–346.

[14] G. Mannina, G. Ekama, D. Caniani, A. Cosenza, G. Esposito, R. Gori, M. Garrido-Baserba, D. Rosso, G. Olsson, Greenhouse gases from wastewater treatment - a review of modelling tools, Sci. Total Environ. 551 (2016) 254–270.

[15] V. Vasilaki, T. Massara, P. Stanchev, F. Fatone, E. Katsou, A decade of nitrous oxide (n2o) monitoring in full-scale wastewater treatment processes: a critical review, Water Res. 161 (2019) 392–412.

[16] V. Vasilaki, V. Conca, N. Frison, A. Eusebi, F. Fatone, E. Katsou, A knowledge discovery framework to predict the n2o emissions in the wastewater sector, Water Res. 178 (2020), 115799.

[17] K. Blomberg, P. Kosse, A. Mikola, A. Kuokkanen, T. Fred, M. Heinonen, M. Mulas, M. Lübken, M. Wichern, R. Vahala, Development of an extended asm3 model for predicting the nitrous oxide emissions in a full-scale wastewater treatment plant, Environ. Sci. Technol. 52 (2018) 5803–5811.

[18] M. Maktabifard, K. Blomberg, E. Zaborowska, A. Mikola, J. MÄ...kinia, Model-based identification of the dominant n2o emission pathway in a full-scale activated sludge system, J. Clean. Prod. 336 (2022), 130347.

[19] E. Zaborowska, X. Lu, J. Makinia, Strategies for mitigating nitrous oxide production and decreasing the carbon footprint of a full-scale combined nitrogen and phosphorus removal activated sludge system, Water Res. 162 (2019) 53–63.

[20] B. Solís, A. Guisasola, X. Flores-Alsina, U. Jeppsson, J.A. Baeza, A plant-wide model describing ghg emissions and nutrient recovery options for water resource recovery facilities, Water Res. 215 (2022), 118223.

[21] R. Boiocchi, K.V. Gernaey, G. Sin, A novel fuzzy-logic control strategy minimizing N_2O emissions, Water Res. 123 (2017) 479–494.

[22] R. Tong, M. Beck, A. Latten, Fuzzy control of the activated sludge wastewater treatment process, Automatica 16 (1980) 695–701.

[23] U. Meyer, H. Pöpel, Fuzzy-control for improved nitrogen removal and energy saving in wwt-plants with pre-denitrification, Water Sci. Technol. 47 (2003) 69–76.

[24] A. Traore, S. Grieu, S. Puig, L. Corominas, F. Thiéry, M. Polit, J. Colprim, Fuzzy control of dissolved oxygen in a sequencing batch reactor pilot plant, Chem. Eng. J. 111 (2005) 13–19.

[25] M. Yong, P. Yong-Zhen, W. Xiao-Lian, W. Shu-Ying, Intelligent control aeration and external carbon addition for improving nitrogen removal, Environ. Model. Softw. 21 (2006) 821–828.

[26] P. Baroni, G. Bertanza, C. Collivignarelli, V. Zambarda, Process improvement and energy saving in a full scale wastewater treatment plant: air supply regulation by a fuzzy logic system, Environ. Technol. 27 (2006) 733–746.

[27] G. Bertanza, L. Menoni, P. Baroni, Energy saving for air supply in a real wwtp: application of a fuzzy logic controller, Water Sci. Technol. 81 (2020) 1552–1557.

[28] K. Gernaey, U. Jeppsson, P. Vanrolleghem, J. Copp, Benchmarking of Control Strategies for Wastewater Treatment Plants, Scientific and Technical Report No.23, IWA Publishing, London, UK, 2014.

[29] L. Guo, P.A. Vanrolleghem, Calibration and validation of an activated sludge model for greenhouse gases no. 1 (ASMG1): prediction of temperature-dependent N_2O emission dynamics, Bioprocess Biosyst. Eng. 37 (2014) 151.

[30] K.E. Mampaey, B. Beuckels, R.K.M.J. Kampschreur, M.C. van Loosdrecht, E. I. Volcke, Modelling nitrous and nitric oxide emissions by autotrophic ammonia-oxidizing bacteria, Environ. Technol. 34 (12) (2013) 1555–1566.

[31] K. Gernaey, C. Rosén, U. Jeppsson, Wwtp dynamic disturbance modelling–an essential module for long-term benchmarking development, Water Sci. Technol. 53 (2006) 225–234.

[32] U. Jeppsson, C. Rosen, J. Alex, J. Copp, K. Gernaey, M.-N. Pons, P. Vanrolleghem, Towards a benchmark simulation model for plant-wide control strategy performance evaluation of WWTPs, Water Sci. Technol. 53 (2006) 287–295.

[33] U. Jeppsson, M.-N. Pons, I. Nopens, J. Alex, J. Copp, K. Gernaey, C. Rosen, J.-P. Steyer, P. Vanrolleghem, Benchmark simulation model no 2: general protocol and exploratory case studies, Water Sci. Technol. 56 (8) (2007) 67–78.

[34] D. Vrecko, K. Gernaey, C. Rosén, U. Jeppsson, Benchmark simulation model no 2 in matlab-simulink: towards plant-wide wwtp control strategy evaluation, Water Sci. Technol. 54 (2006) 65–72.

[35] I. Nopens, L. Benedetti, U. Jeppsson, M.-N. Pons, J. Alex, J.B. Copp, K.V. Gernaey, C. Rosen, J.-P. Steyer, P.A. Vanrolleghem, Benchmark simulation model no 2: finalisation of plant layout and default control strategy, Water Sci. Technol. 62 (9) (2010) 1967–1974.

[36] K. Gernaey, C. Rosén, L. Benedetti, U. Jeppsson, Phenomenological modeling of wastewater treatment plant influent disturbance scenarios, in: 10th International Conference on Urban Drainage.

[37] D. Vrecko, N. Hvala, A. Stare, O. Burica, M. Strazar, M. Levstek, P. Cerar, S. Podbevsek, Improvement of ammonia removal in activated sludge process with feedforward-feedback aeration controllers, Water Sci. Technol. 53 (4–5) (2006) 125–132.

[38] A. Stare, D. Vrecko, N. Hvala, S. Strmcnick, Comparison of control strategies for nitrogen removal in an activated sludge process in terms of operating costs: a simulation study, Water Res. 41 (9) (2007) 2004–2014.

[39] D. Vrecko, N. Hvala, M. Strazar, The application of model predictive control of ammonia nitrogen in an activated sludge process, Water Sci. Technol. 64 (5) (2011) 1115–1121.

[40] I. Santín, C. Pedret, R. Vilanova, Applying variable dissolved oxygen set point in a two level hierarchical control structure to a wastewater treatment process, J. Process Control 28 (2015) 40–55.

[41] G. Klir, B. Yuan, Fuzzy Sets and Fuzzy Logic Volume 4, Prentice hall New Jersey, 1995.

[42] E. Mamdani, Application of fuzzy algorithms for control of simple dynamic plant, Proc. Inst. Electr. Eng. 121 (12) (1976) 1585–1588.