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Research article

New approach for regulation of the internal recirculation flow rate by fuzzy logic in biological wastewater treatments

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ABSTRACT

The internal recirculation plays an important role on the different biological processes of wastewater treatment plants because it has a great influence on the concentration of pollutants, especially nutrients. Usually, the internal recirculation flow rate is kept fixed or manipulated by control techniques to maintain a fixed nitrate set-point in the last anoxic tank. This work proposes a new control strategy to manipulate the internal recirculation flow rate by applying a fuzzy controller. The proposed controller takes into account the effects of the internal recirculation flow rate on the inlet of the biological treatment and on the denitrification and nitrification processes with the aim of reducing violations of legally established limits of nitrogen and ammonia and also reducing operational costs. The proposed fuzzy controller is tested by simulation with the internationally known benchmark simulation model no. 2. The objective is to apply the proposed fuzzy controller in any control strategy, only replacing the manipulation of the internal recirculation flow rate, to improve the plant operation.Therefore, it has been implemented in five operation strategies from the literature, replacing their original internal recirculation flow rate control, and simulation results are compared with those of the original strategies. Results show improvements with the application of the proposed fuzzy controller of between 2.25 and 57.94% in reduction of total nitrogen limit violations, between 55.22 and 79.69% in reduction of ammonia limit violations and between 0.84 and 38.06% in cost reduction of pumping energy.

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1. Introduction

Large amounts of freshwater are used daily around the world, becoming waste water. This waste water must be treated to avoid contamination of the receiving waters (rivers, lakes, etc.), which could affect aquatic life and consequently biodiversity. Due to this reason, wastewater treatment plants (WWTPs) are necessary to maintain the required levels of water quality.

Specifically, maximum concentration limits are established for discharges in the receiving environment of Total Suspended Solids (*TSS*), organic matter (Biological Oxygen Demand in 5 days (BOD_5), and Chemical Oxygen Demand (*COD*), total nitrogen (S_{Ntot}), phosphorous and ammonium and ammonia nitrogen concentration (S_{NH}). Nitrogen and phosphorus are nutrients that can cause eutrophication in the receiving water, and consequently the death of aquatic beings. S_{NH}, in addition to containing nitrogen, is toxic to aquatic life. Precisely, keeping S_{Ntot} and S_{NH} concentrations below the limits is usually one of the most difficult objectives to fulfill in WWTPs. In order to achieve all these targets, the application of operation strategies in WWTPs are very common.

Given the importance of keeping the pollutant concentration within the established limits, and achieving this with the lowest possible operational costs, several research works have been published in recent years focusing on the application of control strategies in WWTPs. In Katebi et al. [1], Santín et al. [2], i Arbós et al. [3] several control strategies applied in WWTPs are summarized.

Some works apply control strategies in the sludge treatment as in Barbu et al. [4] and Santín et al. [5], but most articles do it in the secondary treatment, which corresponds to biological treatment, whose operation is explained in Section 2. In the literature there are several works that aim to improve the control of the concentration of the dissolved oxygen (S_O) in the aerobic reactors, by manipulating the oxygen transfer coefficient (K_La), using different control techniques (Serralta et al. [6], Belchior et al. [7], Yang et al. [8], Harja et al. [9], Du et al. [10], Santín et al. [11]). The regulation of the S_O set-point in the nitrification

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List of abbreviations

AE	Aeration Energy (kWh/d)
ASM1	Activated Sludge Model no. 1
BOD_5	5-day Biological Oxygen Demand (mg/l)
BSM1	Benchmark Simulation Model no 1
BSM2	Benchmark Simulation Model no2
COD	Chemical Oxygen Demand (mg/l)
DCS	Default Control Strategy
EC	External Carbon (kg/d)
HE_{net}	Net Heating Energy (kWh/d)
HRT	Hydraulic Retention Time (s)
K_La	Oxygen transfer coefficient (d^{-1})
K_La_i	Oxygen transfer coefficient in tank i (d^{-1})
ME	Mixing Energy (kWh/d)
MET_{prod}	Methane production in the anaerobic digester (kg/d)
MPC	Model Predictive Control
OCI	Overall Cost Index
PE	Pumping Energy (kWh/d)
PI	Proportional-Integral
Q	Flow rate (m^3/d)
Q_a	Internal recycle flow rate (m^3/d)
q_{EC}	External carbon flow rate (m^3/d)
$q_{EC,1}$	External carbon flow rate in the first tank (m^3/d)
Q_{in}	Influent flow rate (m^3/d)
Q_w	Wastage flow rate (m^3/d)
$r_{S_{NH}}$	Conversion rate of ammonium and ammonia nitrogen concentration in the biological process
$r_{S_{NO}}$	Conversion rate of nitrate concentration in the biological process
S_{Ntot}	Total nitrogen concentration (mg/l)
$S_{Ntot,e}$	Total nitrogen concentration in the effluent (mg/l)
S_{NH}	Ammonium and ammonia nitrogen concentration (mg/l)
$S_{NH,0}$	Ammonium and ammonia nitrogen concentration at the input of the first reactor (mg/l)
$S_{NH,5}$	Ammonium and ammonia nitrogen concentration at the output of the fifth reactor (mg/l)
$S_{NH,in}$	Ammonium and ammonia nitrogen concentration in the influent (mg/l)
$S_{NH,po}$	Ammonium and ammonia nitrogen concentration from the primary clarifier (mg/l)
$S_{NH,e}$	Ammonium and ammonia nitrogen concentration in the effluent (mg/l)
S_{NO}	Nitrate concentration (mg/l)
$S_{NO,0}$	Nitrate concentration at the input of the first reactor (mg/l)
$S_{NO,2}$	Nitrate concentration at the output of the second reactor (mg/l)
$S_{NO,5}$	Nitrate concentration at the output of the fifth reactor (mg/l)
S_O	Dissolved oxygen concentration (mg/l)
$S_{O,i}$	Dissolved oxygen concentration in tank i (mg/l)
SP	Sludge Production (kg/d)
T_{as}	Temperature (°C)
TSS	Total Suspended Solids (mg/l)
WWTP	Wastewater Treatment Plants
$X_{B,H}$	The active heterotrophic biomass
Z	any concentration of the process
Z_i	is Z at the output of the reactor i

process has also been the goal of many articles, such as Serralta et al. [6], Vega et al. [12], Błaszkiewicz et al. [13], Santín et al. [14], Li et al. [15], Revollar et al. [16], Qiao et al. [17], Sadeghassadi et al. [18], Zhang et al. [19], Caraman et al. [20].

Another variable that can be manipulated in the biological treatment is the internal recirculation flow rate (Q_a). However, research into a new control strategy to manipulate Q_a is not common. The work Karches [21] shows the improvement obtained by adding an internal recirculation in completely stirred tank reactors. In some operation strategies of the articles cited above, Q_a is kept fixed and in others Q_a is manipulated to maintain the nitrate (S_{NO}) set-point in the last anoxic reactor. In Serralta et al. [6], Sadeghassadi et al. [18], Qiao et al. [17] and Caraman et al. [20], in addition to manipulating S_O set-point, the S_{NO} set-point in the last anoxic reactor is regulated by manipulating Q_a with different techniques. In Caraman et al. [20] by applying optimization techniques, in Sadeghassadi et al. [18] with neural network and MPC, in Qiao et al. [17] with adaptive fuzzy neural network and in Serralta et al. [6] by fuzzy controllers. In Serralta et al. [6] there are two internal recirculations in the biological treatment because anoxic and aerobic tanks are alternated. The works Revollar et al. [16] and Zhang et al. [19] apply optimization techniques to manipulate both S_O and Q_a directly, without S_{NO} control. In Santín et al. [22], the usual manipulation of Q_a is modified to avoid S_{NH} violations, but only in the periods of time when a risk of S_{NH} violation is predicted.

Within the control techniques, it is common to find papers that apply fuzzy logic in WWTPs. Some of these articles have already been referred above, which regulate the S_{NO} set-point or Q_a directly (Serralta et al. [6], Santín et al. [22], Qiao et al. [17], Caraman et al. [20]). In the case of Caraman et al. [20], the fuzzy controller is not applied to regulate S_O and S_{NO} set-points, but to differentiate the operating regime (dry, rain or storm). In addition to the articles mentioned, fuzzy controllers have also been applied in WWTPs for other purposes. For example, in Camilleri and Katebi [23] a fuzzy controller is applied for global control, taking into account not only WWTP but also the river and the sewer; and in Boiocchi et al. [24], the goal of the fuzzy controller is to reduce nitrous oxide emissions by manipulating the aeration of the aerobic reactor based on input and output values of S_{NH} and S_{NO}.

The novelty proposed in this paper is a new control strategy to manipulate Q_a by a fuzzy controller. The variation of Q_a has several effects on the nitrification and denitrification processes of the biological treatment. The analysis of these effects explains why the proposed control strategy has better results than those normally used. For the design of the Proposed Fuzzy Controller for Q_a manipulation (PFC_Q_a), the dilution or the increase of concentration of different compounds at the beginning of the biological treatment is taken into account, as well as the variation of the Hydraulic Retention Time (HRT) (a more exhaustive explanation is found in Section 3). This paper uses operation strategies from the literature, replacing only the manipulation of Q_a by PFC_Q_a,

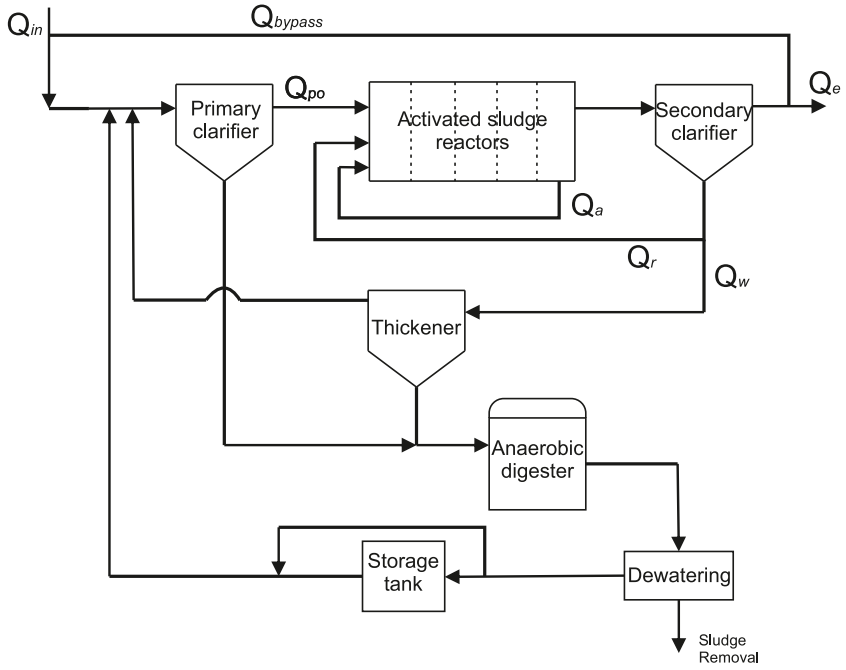


Fig. 1. BSM2 plant with notation used for flow rates.

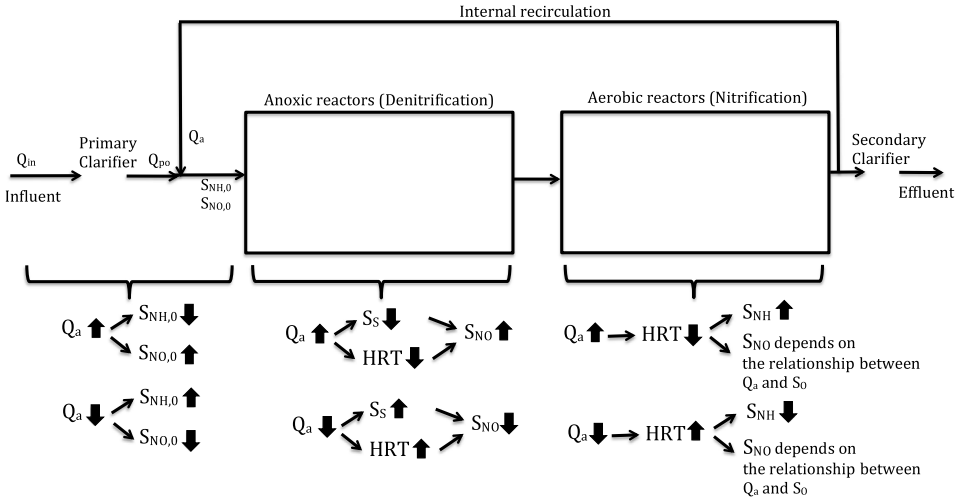


Fig. 2. Q_a effects on the biological treatment.

and shows the improvements it provides in terms of reducing violations of S_{Ntot} and S_{NH}, and operational costs.

The use of simulation models to test control strategies in WWTPs is a common practice in research. So much so that most of the previously referenced papers use the internationally known and accepted standard Benchmark Simulation Model no. 2 (BSM2)[1] (Gernaey et al. [25]), which is an extension of the Benchmark Simulation Model no. 1 (BSM1) developed by the International Association on Water Pollution Research and Control (Alex et al. [26], Copp [27]). BSM2 differs from BSM1 by including the entire cycle of a WWTP, adding the sludge treatment, and in that the simulation period is extended to one-year assessment. In this work, the simulations and evaluations of the control strategies have been carried out with BSM2.

The paper is organized as follows. First, BSM2 is presented. Next, PFC_Q_a is explained. Afterward, the simulation results are shown, as well as the discussion about them. Finally, the most important conclusions are drawn.

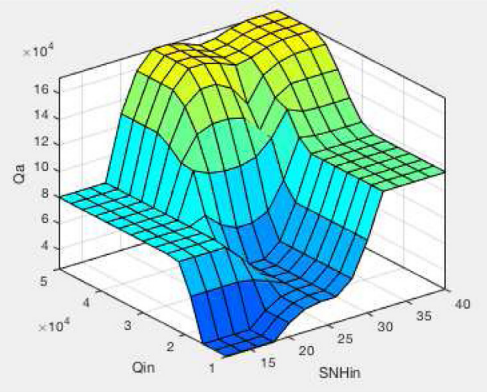
2. Materials and methods

The evaluation of the PFC_Q_a for wastewater treatment plants has been carried out using the internationally known BSM2 (Jeppsson et al. [28]), which was updated by Nopens et al. [29]. The BSM2 layout (Fig. 1) includes the biological treatment (secondary treatment) of BSM1 and, in addition, a primary settler, a sludge treatment by a thickener, a digester and a dewatering. The liquid extracted in the dewatering is stored in a regulator tank and later recirculated to the primary settler.

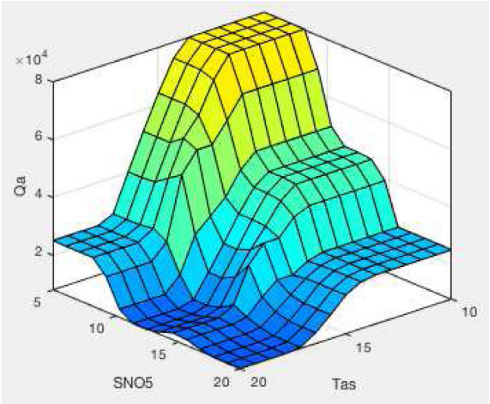
BSM2 includes dynamics of the different influent concentrations for a period of 609 days, and the data from day 245 to 609 (one year) are evaluated. These dynamics include rain events and temperature (T_{as}) variations.

The biological treatment consists of five activated sludge reactors, followed by a secondary settler. The first two reactors

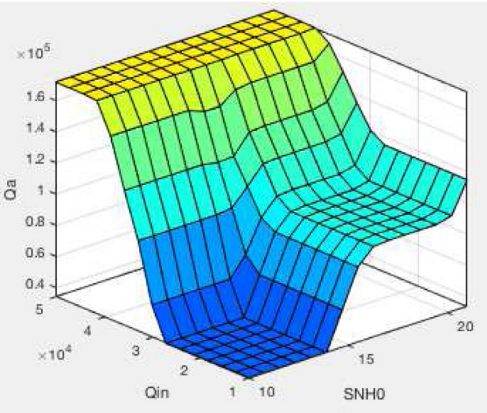
[1] http://iwa-mia.org/benchmarking



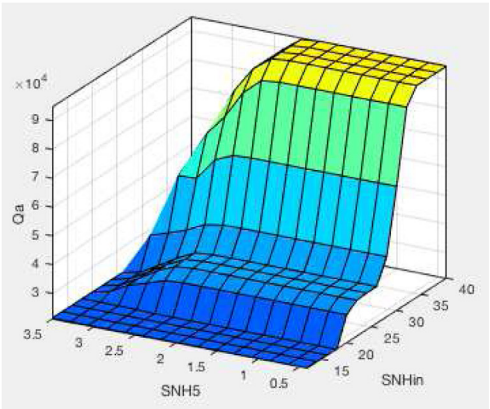
(a) X input: Q_{in}; Y input: $S_{NH,in}$; Z Output: Q_a with $S_{NH,0}$ *low*, $S_{NH,5}$ *not high*, $S_{NO,5}$ *medium* and T_{as} *low* and *high* (15°C)



(b) X input: $S_{NO,5}$; Y input: T_{as}; Z Output: Q_a with $S_{NH,in}$ *medium*, $S_{NH,0}$ *low*, $S_{NH,5}$ *not high* and Q_{in} *low*



(c) X input: Q_{in}; Y input: $S_{NH,0}$; Z Output: Q_a with $S_{NH,in}$ *medium*, $S_{NH,5}$ *not high*, $S_{NO,5}$ *medium* and T_{as} *low* and *high* (15°C)



(d) X input: $S_{NH,5}$; Y input: $S_{NH,in}$; Z Output: Q_a with $S_{NH,0}$ *low*, $S_{NO,5}$ *medium*, Q_{in} *low* and T_{as} *low* and *high* (15°C)

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

are anoxic, where the denitrification process is carried out, and the following three tanks are aerobics, where the nitrification process takes place. The influent has an average dry weather flow rate of 20,648.36 m^3/d and an average *COD* of 592.53 mg/l. The volume of each anoxic tank is 1500 m^3 and that of each aerobic tank is 3000 m^3. The HRT of the biological treatment is 14 h. There is a recirculation from the last tank to the first one (internal recirculation) and another from the underflow of the settler (external recirculation) in order to recirculate sludge.

The Activated Sludge Model No. 1 (ASM1) (Henze et al. [30]) describes the processes of the biological reactors. They define the conversion rates and the mass balance of the different variables of the biological treatment. The design of the PFC_Q_a is based on the Q_a effects on the biological treatment taking into account the conversion rates of S_{NH} ($r_{S_{NH}}$) and S_{NO} ($r_{S_{NO}}$) and the reactors mass balance.

The equations of conversion rates and mass balance are shown below:

$$r_{NH} = -0.08\rho_1 - 0.08\rho_2 - \left(0.08 + \frac{1}{0.24}\right)\rho_3 + \rho_6 \quad (1)$$

$$r_{NO} = -0.1722\rho_2 + 4.1667\rho_3 \quad (2)$$

where ρ_1, ρ_2, ρ_3, ρ_6 are four of the eight biological processes defined in ASM1. Specifically, ρ_1 is the aerobic growth of heterotrophs, ρ_2 is the anoxic growth of heterotrophs, ρ_3 is the aerobic growth of autotrophs and ρ_6 is the ammonification of soluble organic nitrogen. They are defined below:

$$\rho_1 = \mu_{HT}\left(\frac{S_S}{10 + S_S}\right)\left(\frac{S_O}{0.2 + S_O}\right)X_{B,H} \quad (3)$$

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

$$\mu_{HT} = 4 \cdot exp\left(\left(\frac{Ln\left(\frac{4}{3}\right)}{5}\right) \cdot (T_{as} - 15)\right) \quad (4)$$

$$\rho_2 = \mu_{HT}\left(\frac{S_S}{10 + S_S}\right)\left(\frac{0.2}{0.2 + S_O}\right)\left(\frac{S_{NO}}{0.5 + S_{NO}}\right)0.8 \cdot X_{B,H} \quad (5)$$

$$\rho_3 = \mu_{AT}\left(\frac{S_{NH}}{1 + S_{NH}}\right)\left(\frac{S_O}{0.4 + S_O}\right)X_{B,A} \quad (6)$$

where $X_{B,A}$ is the active autotrophic biomass and μ_{AT} is:

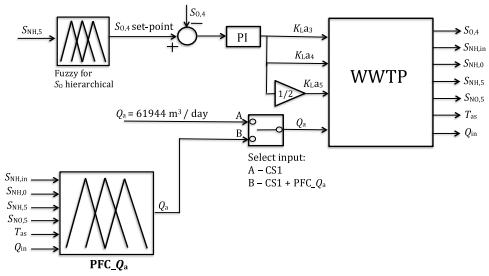
$$\mu_{AT} = 0.5 \cdot exp\left(\left(\frac{Ln\left(\frac{0.5}{0.3}\right)}{5}\right) \cdot (T_{as} - 15)\right) \quad (7)$$

$$\rho_6 = k_{aT} \cdot S_{ND} \cdot X_{B,H} \quad (8)$$

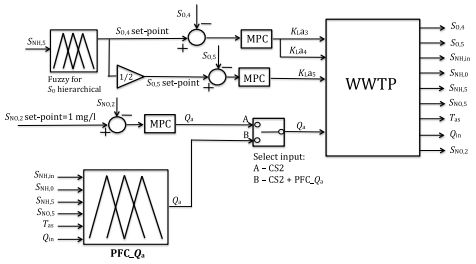
where S_{ND} is the soluble biodegradable organic nitrogen and k_{aT} is:

$$k_{aT} = 0.05 \cdot exp\left(\left(\frac{Ln\left(\frac{0.05}{0.04}\right)}{5}\right) \cdot (T_{as} - 15)\right) \quad (9)$$

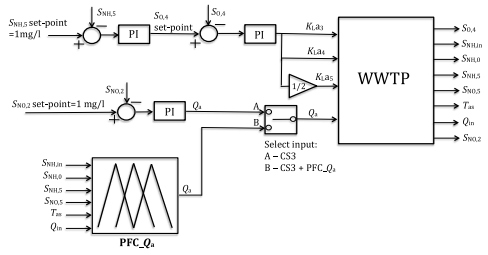
The general equations for mass balancing are:



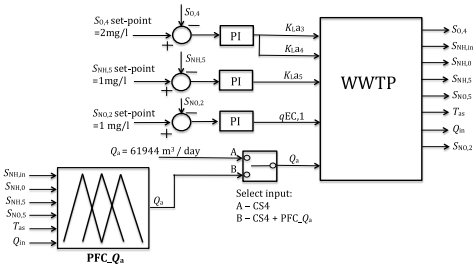
(a) CS1 (selection A) and CS1+PFC_Q_a (selection B)



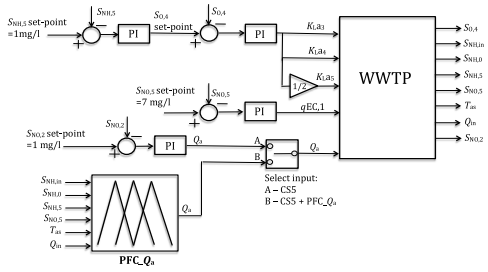
(b) CS2 (selection A) and CS2+PFC_Q_a (selection B)



(c) CS3 (selection A) and CS3+PFC_Q_a (selection B)



(d) CS4 (selection A) and CS4+PFC_Q_a (selection B)



(e) CS5 (selection A) and CS5+PFC_Q_a (selection B)

Fig. 4. Operation strategies where PFC_Q_a is tested. Selection A is the original control strategy and selection B corresponds to replace the Q_a manipulation by PFC_Q_a.

- For reactor 1:

$$\frac{dZ_1}{dt} = \frac{1}{V_1}(Q_a \cdot Z_a + Q_r \cdot Z_r + Q_{po} \cdot Z_{po} + r_{z,1} \cdot V_1 - Q_1 \cdot Z_1) \quad (10)$$

  where Z is any concentration of the process, Z_1 is Z in the first reactor, Z_a is Z in the internal recirculation, Z_r is Z in the external recirculation, Z_{po} is Z from the primary clarifier, V is the volume, V_1 is V in the first reactor, Q_{po} is the overflow from the primary clarifier and Q_1 is the flow rate in the first tank and it is equal to the sum of Q_a, Q_r and Q_{po}.

- For reactor 2 to 5:

$$\frac{dZ_k}{dt} = \frac{1}{V_k}(Q_{k-1} \cdot Z_{k-1} + r_{z,k} \cdot V_k - Q_k \cdot Z_k) \quad (11)$$

  where k is the number of reactor and Q_k is equal to Q_{k-1}

Result evaluation is carried out by the effluent quality and the operational costs. Effluent quality is evaluated by the percentage of time that the effluent concentrations of S_{Ntot}, COD, S_{NH}, TSS and BOD_5 are above the established limits, shown in Table A.6. Costs are evaluated by the Overall Cost Index (OCI) and each of its components.

OCI is defined to evaluate the operational cost as:

$$OCI = AE + PE + 3 \cdot SP + 3 \cdot EC + ME - 6 \cdot MET_{prod} + HE_{net} \quad (12)$$

where AE is the aeration energy, PE is the pumping energy, SP is the sludge production to be disposed, EC is the consumption of external carbon source, ME is the mixing energy, MET_{prod} is the methane production in the anaerobic digester and HE_{net} is the net heating energy.

AE is calculated according to the following relation:

$$AE = \frac{8}{T \cdot 1.8 \cdot 1000} \int_{t=245days}^{t=609days} \sum_{i=1}^{5} V_i \cdot K_L a_i(t) \cdot dt \quad (13)$$

where K_La_i is K_La in tank i.

PE is calculated as:

$$PE = \frac{1}{T} \int_{245days}^{609days} (0.004 \cdot Q_0(t) + 0.008 \cdot Q_a(t) + 0.06 \cdot Q_w(t) + 0.06 \cdot Q_{to}(t) + 0.004 \cdot Q_{du}(t)) \cdot dt \quad (14)$$

where Q_w is the wastage flow rate, Q_{to} is the overflow rate from the thickener and Q_{du} is the underflow rate.

SP is calculated from the total solid flow from wastage and the solids accumulated in the system over the period of time considered:

$$SP = \frac{1}{T} \cdot (TSS_a(609days) - TSS_a(245days) + TSS_s(609days) - TSS_s(245days) + 0.75 \cdot \int_{t=245days}^{t=609days} TSS_w \cdot Q_w \cdot dt) \quad (15)$$

where TSS_a is the amount of solids in the reactors, TSS_s is the amount of solids in the settler and TSS_w is the amount of solids in the wastage.

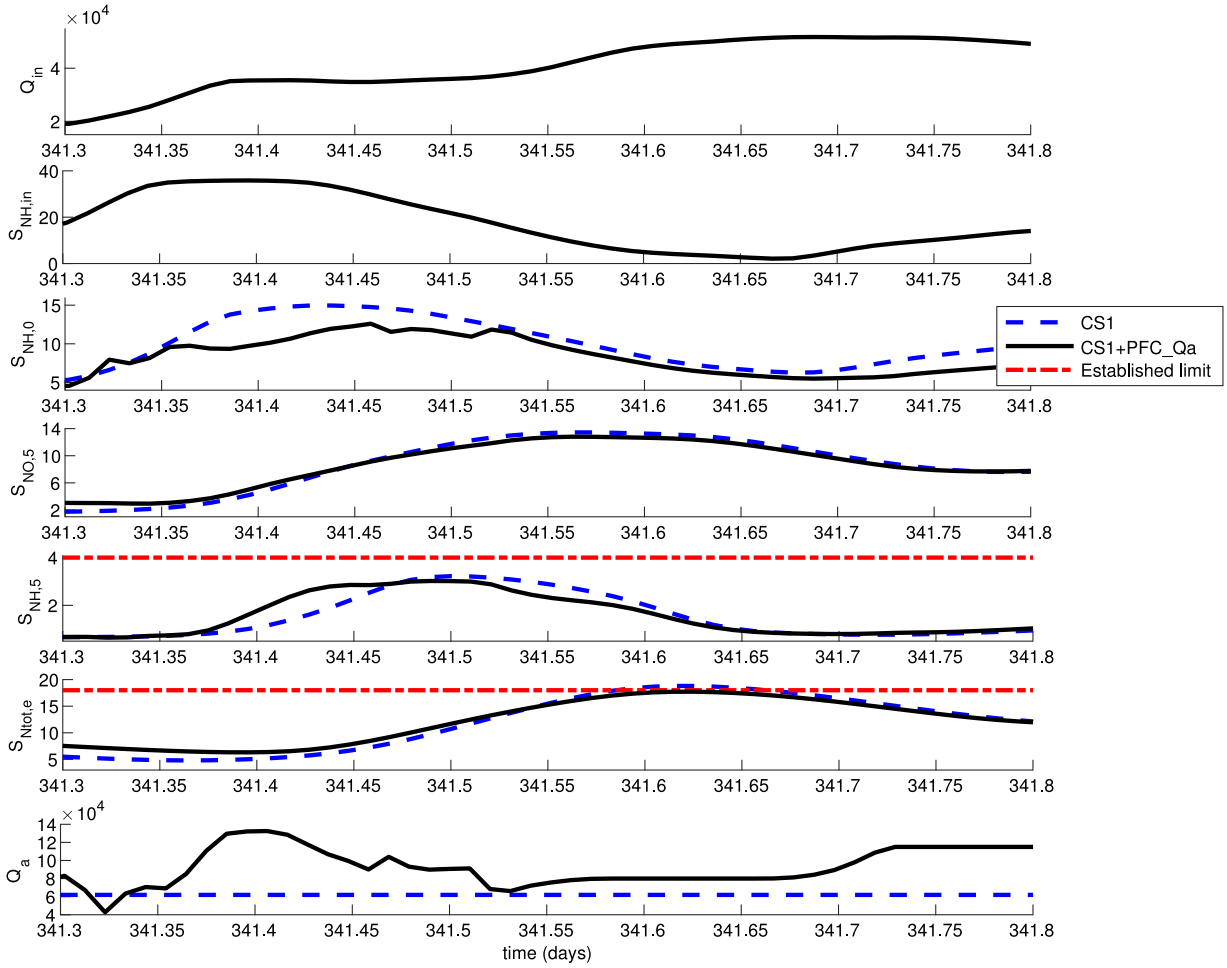


Fig. 5. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a of day 341 for CS1 and CS1+PFC_Q_a.

Table A.6
Effluent quality limits.

Variable	Value
$S_{N_{tot}}$	<18 g N m^{-3}
COD	<100 g COD m^{-3}
S_{NH}	<4 g N m^{-3}
TSS	<30 g SS m^{-3}
BOD_5	<10 g BOD m^{-3}

EC refers to the carbon that could be added to improve denitrification:

$$EC = \frac{COD_{EC}}{T \cdot 1000} \int_{t=245days}^{t=609days} \left(\sum_{i=1}^{i=n} q_{EC,i} \right) \cdot dt \tag{16}$$

where $q_{EC,i}$ is the external carbon addition (q_{EC}) added to compartment i, COD_{EC} = 400 $gCOD.m^{-3}$ is the concentration of readily biodegradable substrate in the external carbon source.

ME is a function of the compartment volume and is the energy employed to mix the anoxic tanks to avoid settling (KWh/d):

$$ME = \frac{24}{T} \int_{t=245days}^{t=609days} \sum_{i=1}^{5} \left[0.005 \cdot V_i \text{ if } K_L a_i(t) < 20 d^{-1} \text{ otherwise } 0 \right] \cdot dt \tag{17}$$

MET_{prod} is calculated as:

$$MET_{prod} = \frac{16 \cdot P_{atm}}{R \cdot T_{ad} \cdot T} \cdot \int_{t=245days}^{t=609days} \frac{Q_{gas}(t) \cdot p_{gas,ch4}(t)}{P_{gas}(t)} \cdot dt \tag{18}$$

where P_{atm} is the atmosphere pressure equal to 1.013 bar, R is the gas constant equal to 0.083145 bar m^3 K^{-1} $kmol^{-1}$, T_{ad} is the temperature in the anaerobic digester, Q_{gas} is the gas flow rate of the anaerobic digester, P_{gas} in the gas pressure of the anaerobic digester and $Qp_{gas,ch4}$ is the methane pressure of the anaerobic digester.

HE_{net} is defined as:

$$HE_{net} = max\left(0., HE - 7. \cdot MET_{prod}\right) \tag{19}$$

where *HE* is the necessary energy to heat the anaerobic digester to the operating temperature, and it is calculated as:

$$HE = \frac{100 \cdot 4186}{86,400 \cdot T} \int_{t=245days}^{t=609days} \left(T_{ad} - T_{ad,i}\right) \cdot Q_{ad}(t) \cdot dt \tag{20}$$

where $T_{ad,i}$ is the temperature in the entrance of the anaerobic digester.

The simulation conditions are the ones established in BSM2 by default to fairly compare the results with other works using the same benchmark. Thus, the variable-step solver ode45 is taken. Variable-step size is needed in order to guarantee the best numerical solution as the mathematical model includes components with very different time constants.

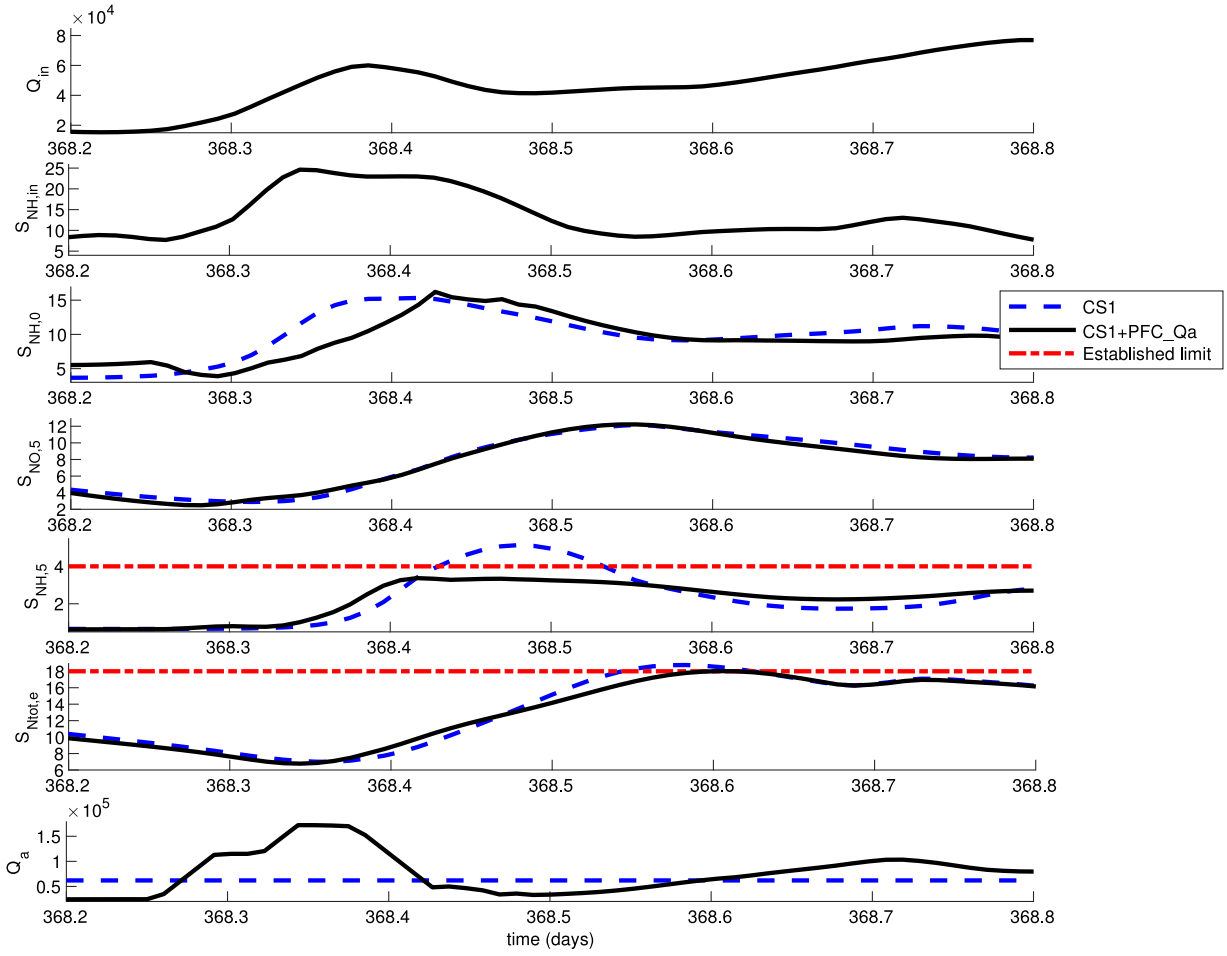


Fig. 6. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a of day 368 for CS1 and CS1+PFC_Q_a.

Table A.7
Ranges, types and parameters of the membership functions.

Variables		Range	Fuzzy sets	Type	Parameters
Inputs	$S_{NH,in}$	[12 40]	Low	Z-shaped	[12 24.2]
			Medium	Triangular	[18 25 32]
			High	S-shaped	[26 40]
	$S_{NH,0}$	[10 21]	Low	Z-shaped	[14 16.5]
			Medium	Triangular	[14 17.5 21]
			High	S-shaped	[19 21]
	$S_{NH,5}$	[0.4 3.5]	Low	Z-shaped	[0.4 1.84]
			Medium	Triangular	[0.71 1.95 3.19]
			High	S-shaped	[2.06 3.5]
	$S_{NO,5}$	[5 20]	Low	Z-shaped	[5 11.25]
			Medium	Triangular	[8.5 12 15.5]
			High	S-shaped	[13 20]
	T_{as}	[10 20]	Low	Z-shaped	[13 17.5]
			High	S-shaped	[13.5 17]
	Q_{in}	[1e+04 5e+04]	Low	Z-shaped	[1e+04 2.25e+04]
			Medium	Triangular	[1.7e+04 2.75e+04 3.75e+04]
			High	S-shaped	[2.75e+04 4.2e+04]
Output	Q_a	[0 2e+05]	Very-low	Triangular	[−2.5e+04 0 2.5e+04]
			Low	Triangular	[5000 2.5e+04 4.5e+04]
			Medium-Low	Triangular	[2.5e+04 4.54e+04 6.5e+04]
			Medium	Triangular	[4.5e+04 8e+04 1.15e+05]
			High	Triangular	[8e+04 1.15e+05 1.5e+05]
			Very-High	Triangular	[1.15e+05 2e+05 2.85e+05]

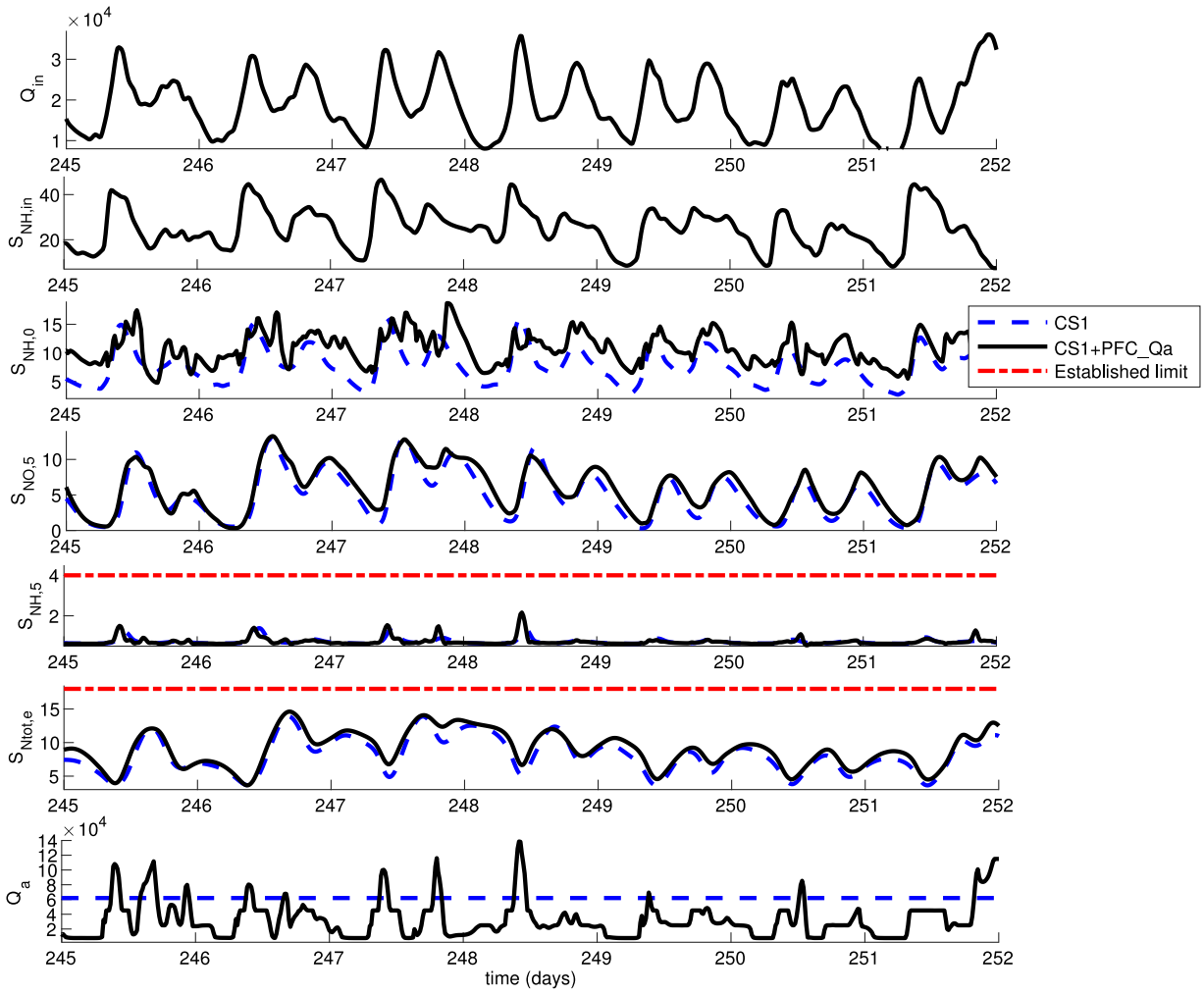


Fig. 7. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a during one week in summer for CS1 and CS1+PFC_Q_a.

3. Control approach

This article applies a new control strategy to manipulate Q_a by a fuzzy controller, with the aim of reducing limit violations of S_{Ntot} in the effluent ($S_{Ntot,e}$) and S_{NH} in the effluent ($S_{NH,e}$) as well as operational costs. The idea of the work is to add PFC_Q_a to other already tested and published operation strategies, replacing only the Q_a manipulation. The effects of Q_a on biological treatment, the design of PFC_Q_a and the operation strategies on which it is tested are detailed below.

3.1. Q_a effects on the biological treatment

The Q_a variation influences both the denitrification and the nitrification processes, as well as the dilution or increase of concentrations at the biological treatment input. Due to this fact Q_a variations have immediate effects on $S_{Ntot,e}$ and $S_{NH,e}$, but also other different effects on the same variables after some time. This complexity makes necessary an in-depth knowledge of the plant behavior for the Q_a manipulation and justify the use of a fuzzy controller.

A more detailed explanation of the Q_a influence on the biological treatment, specifically on S_{Ntot} and S_{NH}, is carried out in Fig. 2, the equations of the observed conversion rates and mass balance of the biological reactors described in Section 2 and the mixture of concentrations at the inlet of the biological treatment.

3.1.1. Q_a effect at the inlet of the biological treatment

On one hand, the S_{NH} value at the inlet of the first reactor is given by the mixture of S_{NH} from the primary clarifier ($S_{NH,po}$) and the recirculated S_{NH}, which is equal to S_{NH} in the fifth tank ($S_{NH,5}$), as can be seen in (21).

$$S_{NH,0} = \frac{Q_{in} \cdot S_{NH,po} + Q_a \cdot S_{NH,5}}{Q_{in} + Q_a} \tag{21}$$

As due to the nitrification process the $S_{NH,5}$ value is lower than $S_{NH,po}$, Q_a increases causes a dilution of S_{NH} at the input of the first reactor ($S_{NH,0}$) and, on the contrary, Q_a reductions result in $S_{NH,0}$ increases. On the other hand, since there is no S_{NO} in the influent and all S_{NO} at the inlet of the first tank comes from Q_a, which is equal to S_{NO} in the fifth tank ($S_{NO,5}$), Q_a increases cause S_{NO} at the input of the first reactor ($S_{NO,0}$) increases (22).

$$S_{NO,0} = \frac{Q_{in} \cdot S_{NO,po} + Q_a \cdot S_{NO,5}}{Q_{in} + Q_a} \tag{22}$$

The $S_{NH,0}$ and $S_{NO,0}$ values affect $S_{NH,e}$ and $S_{Ntot,e}$ values after a period of time that depends on HRT and therefore on the flow rate.

3.1.2. Q_a effect on the denitrification process

In the denitrification process that takes place in anoxic reactors, S_{NO} is reduced to molecular nitrogen, which is harmless. The active heterotrophic biomass ($X_{B,H}$) consume S_S using oxygen from S_{NO} (due to the absence of S_O). Thus, as it can be seen in the

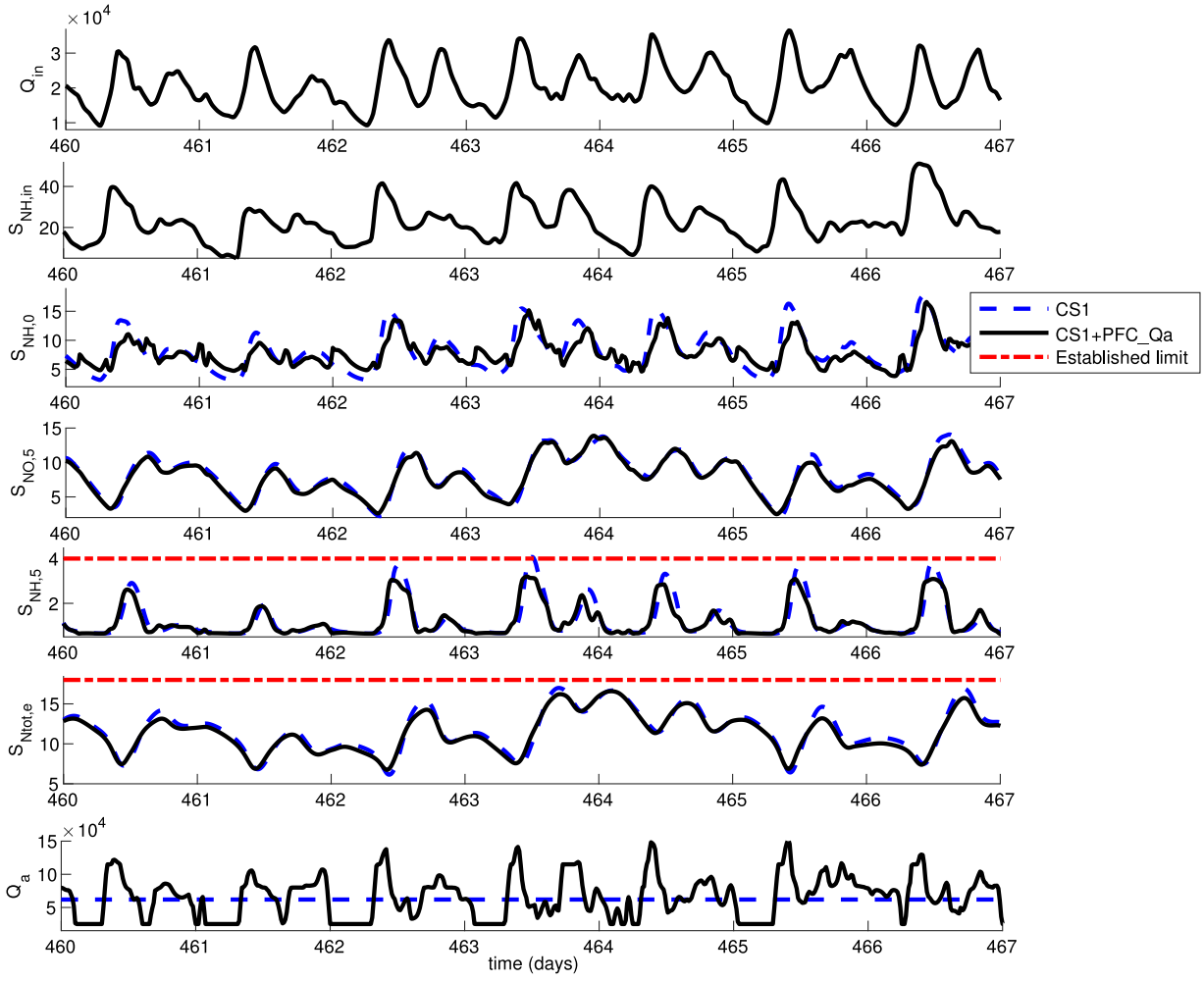


Fig. 8. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a during one week in winter for CS1 and CS1+PFC_Q_a.

$r_{S_{NO}}$ Eqs. (2), (5), the greater the amount of S_S, the greater the S_{NO} reduction. Due to the fact that S_S is reduced during the biological treatment, an increase in Q_a reduces S_{NO} in the anoxic reactors, worsening denitrification.

A more important effect of Q_a on the denitrification process is its influence on HRT, since when the flow is higher, HRT decreases and vice versa. As can been observed in the mass balance equation (11), an increase in Q_a diminishes the effect of r_Z and therefore worsens the denitrification process, increasing S_{NO} and consequently $S_{Ntot,e}$.

3.1.3. Q_a effect on the nitrification process

The nitrification process takes place in aerobic reactors, where the active autotrophic biomass ($X_{B,A}$) oxidize S_{NH} into S_{NO}. In the same way as in the denitrification process, Q_a increases attenuate the effect of r_Z (11), worsening in this case the nitrification process, which causes S_{NH} increase and S_{NO} decrease. However, S_O is often regulated in the aerobic reactors based on S_{NH}. In this case, Q_a increases can result in an S_O increase to improve the nitrification process, which reduces S_{NH} and increases S_{NO}. In conclusion, the best way to reduce S_{NH} is to reduce Q_a. Regarding S_{Ntot}, as its main components are S_{NH} and S_{NO}, a trade-off solution must be found between both to reduce S_{Ntot}.

3.2. Fuzzy controller design

Fuzzy logic can be defined as a control 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 [31]. The FIS[2] Editor from Matlab is used in this work for the implementation of PFC_Q_a.

As explained in Section 3.1, to assess the Q_a effects on the biological treatment requires an exhaustive knowledge of the plant behavior. Due to this reason, a fuzzy controller has been proposed for the Q_a manipulation.

PFC_Q_a has been initially tuned based on the knowledge of the biological processes described by the extended ASM1 and on a specific analysis of the evolution over time of the fuzzy controller inputs. After that, the range of values of the membership functions have been adjusted by trial and error to optimize the results. PFC_Q_a is conceived here with 6 inputs, 1 output and 30 rules. As shown in Fig. 4, the inputs are S_{NH} in the influent ($S_{NH,in}$), $S_{NH,0}$, $S_{NH,5}$, $S_{NO,5}$, T_{as} and influent flow rate (Q_{in}) and the output is Q_a. Mamdani (Mamdani [32]) is the method of inference

[2] FIS: Fuzzy Inference System.

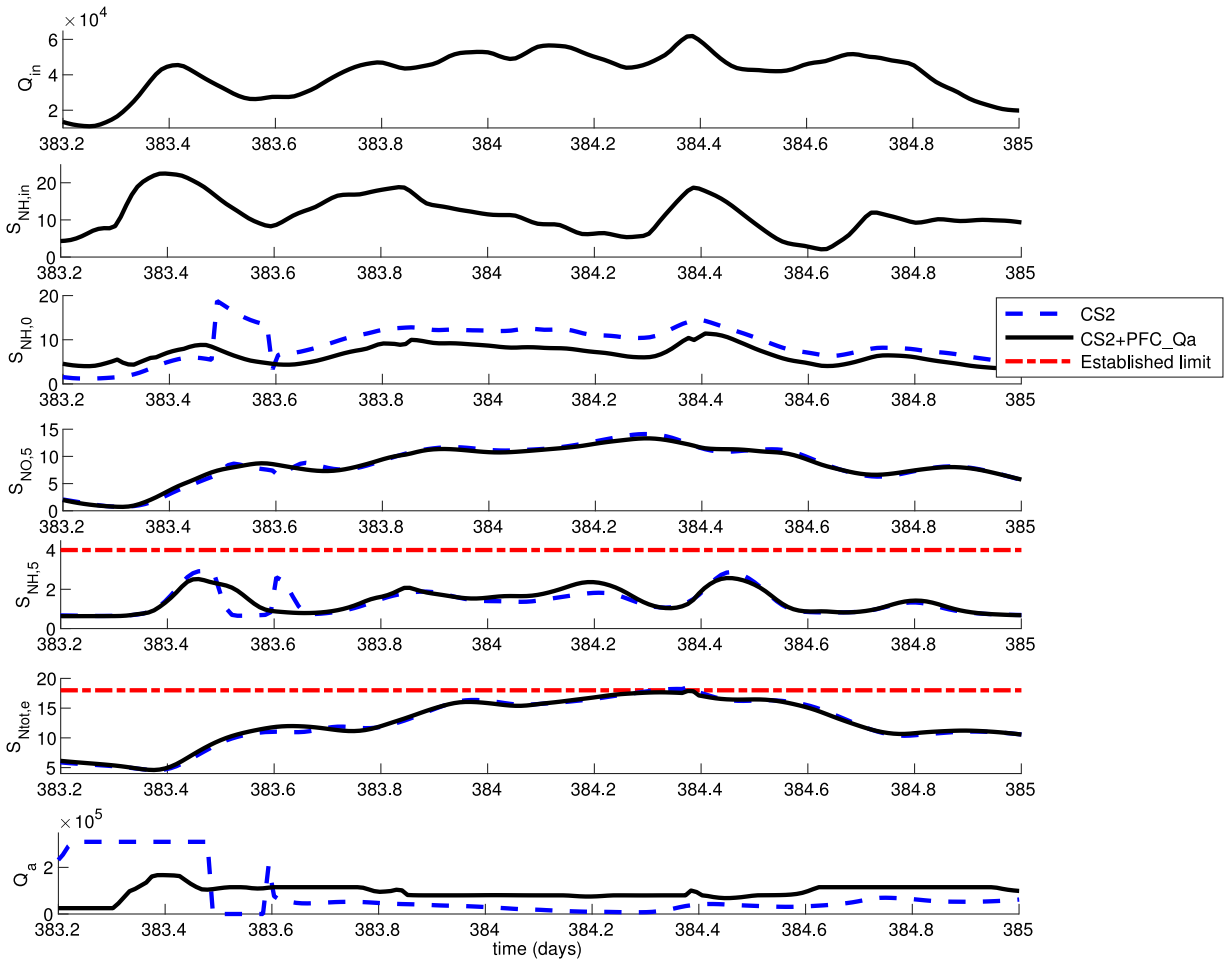


Fig. 9. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a of day 384 for CS2 and CS2+PFC_Q_a.

Table A.8
Rules of PFC_Q_a.

Rule number	$S_{NH,in}$	$S_{NH,0}$	$S_{NH,5}$	$S_{NO,5}$	T_{as}	Q_{in}	Q_a
1	If is Low	and is not High	–	–	and is Low	and is Low	Then is Low
2	If is Low	and is not High	–	–	and is High	and is Low	Then is Very-Low
3	If is Low	–	and is not High	and is Low	–	and is Medium	Then is High
4	If is Low	–	and is not High	and is Low	–	and is High	Then is High
5	If is Low	–	and is not High	and is Medium	–	and is Medium	Then is Medium
6	If is Low	–	and is not High	and is Medium	–	and is High	Then is Medium
7	If is Low	–	and is not High	and is High	and is High	–	Then is Very-Low
8	If is Low	–	and is not High	and is High	and is Low	–	Then is Low
9	If is Medium	and is not High	and is not High	and is Low	and is High	and is not High	Then is Low
10	If is Medium	and is not High	and is not High	and is Medium	and is High	and is not High	Then is Very-Low
11	If is Medium	–	and is not High	and is High	and is High	and is not High	Then is Very-Low
12	If is Medium	and is Low	and is not High	and is Low	and is Low	and is not High	Then is Medium
13	If is Medium	and is Low	and is not High	and is Medium	and is Low	and is not High	Then is Medium-Low
14	If is Medium	–	and is not High	and is High	and is Low	and is not High	Then is Low
15	If is Medium	–	and is not High	and is Low	–	and is High	Then is Very-High
16	If is Medium	–	and is not High	and is Medium	–	and is High	Then is Very-High
17	If is Medium	–	and is not High	and is High	–	and is High	Then is Medium-Low
18	If is High	and is not High	and is not High	and is Low	and is High	and is not High	Then is Medium-Low
19	If is High	and is not High	and is not High	and is Medium	and is High	and is not High	Then is Medium-Low
20	If is High	–	and is not High	and is High	and is High	and is not High	Then is Very-Low
21	If is High	and is Low	and is not High	and is Low	and is Low	and is not High	Then is High
22	If is High	and is Low	and is not High	and is Medium	and is Low	and is not High	Then is High
23	If is High	–	and is not High	and is High	and is Low	and is not High	Then is Medium-Low
24	If is High	–	and is not High	and is Low	–	and is High	Then is Very-High
25	If is High	–	and is not High	and is Medium	–	and is High	Then is Very-High
26	If is High	–	and is not High	and is High	–	and is High	Then is Medium-Low
27	–	–	If is High	–	and is Low	–	Then is Low
28	–	–	If is High	–	and is High	–	Then is Very-Low
29	–	If is not Low	and is not High	and is not High	and is Low	and is not High	Then is High
30	–	If is High	and is not High	and is not High	and is High	and is not High	Then is High

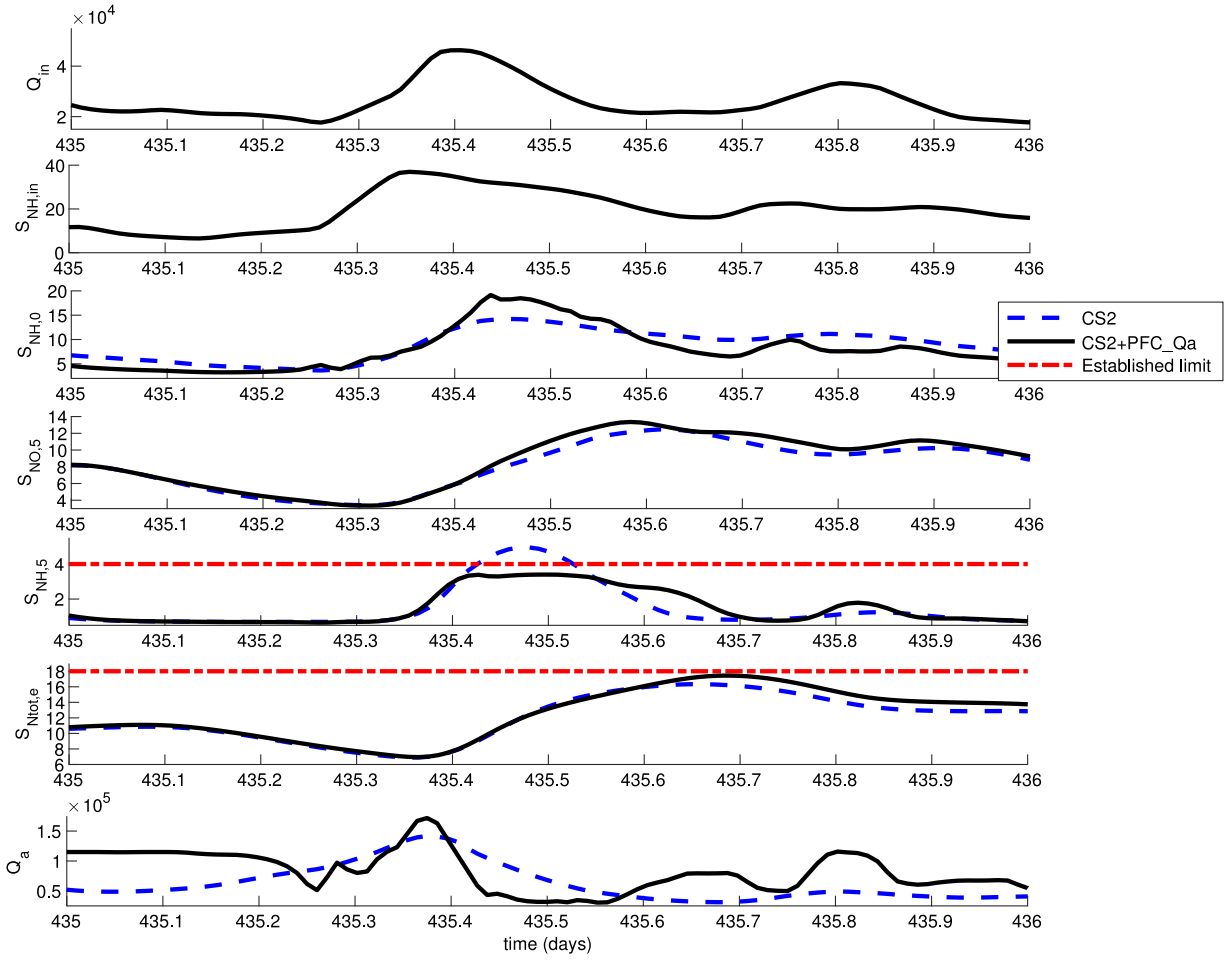


Fig. 10. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a of day 435 for CS2 and CS2+PFC_Q_a.

Table A.9
Parameters of PFC_Q_a that affects the computational complexity.

Number of inputs	Number of input fuzzy sets	Number of rules	Number of output fuzzy sets
6	17	30	6

Table A.10
CPU time and elapsed time in the 609-day simulation of all the operation strategies with and without PFC_Q_a.

Indicators	CS1	CS1+PFC_Qa	Difference	CS2	CS2+PFC_Qa	Difference	CS3	CS3+PFC_Qa	Difference	CS4	CS4+PFC_Qa	Difference	CS5	CS5+PFC_Qa	Difference
CPU time (hours)	1.218	1.529	25.534%	10.239	9.372	−8.467%	7.982	7.591	−4.898%	7.819	8.074	3.258%	8.084	7.911	−2.131%
Elapsed time (hours)	1.214	1.512	24.547%	10.095	9.175	−9.117%	7.945	7.469	−5.982%	7.671	7.924	3.291%	7.955	7.757	−2.490%

used in this paper. The range, parameter values and types of all the membership functions of the inputs and output of the fuzzy controller are shown in Table A.7 and the rules in Table A.8. In addition the fuzzy controller code is listed in the appendix.

In the Simulink model, Q_a variations are limited to a rising and falling slew rates of 2,500,000 and −2,500,000 respectively, with flow rate units in m^3/s and time units in days.

The sample time of the controller applied in a real scenario could take any fixed value that was considered the most suitable to meet the plants' requirements. The lowest possible discretization could also be adopted, but other requirements might make larger values convenient. Applying a sample time based on the maximum response time of the sensors could be an option. Following the BSM2 recommendations on the type of sensors to be applied, Q_{in} and T_{as} sensors have a one-minute response time, while S_{NH} and S_{NO} sensors have a 10-minute response time. Thus, an option in a real scenario could be to apply a sample time of 10 min (0.0069 days).

The rules are based on the effects of Q_a on the biological treatment explained in Section 3.1 and are detailed below. Some of them are also shown in the surface graphs (Fig. 3).

In dry weather, the ratio of Q_{in} to $S_{NH,in}$ remains stable, and consequently when there is an increase in this ratio due to an increase in Q_{in} it is considered that a rain event is taking place. During dry weather, when $S_{NH,in}$ is *low*, Q_a is decreased to reduce pumping energy costs and improve nitrification and denitrification processes, and if $S_{NH,in}$ increases, Q_a is also increased in order to dilute $S_{NH,0}$. In the case that a rain event is detected, Q_a is increased to dilute $S_{NH,0}$, as long as there is no risk of $S_{NH,5}$ or $S_{NO,5}$ increase. Fig. 3a shows the relationship between Q_{in} and $S_{NH,in}$.

During both dry and rainy weather (except when $S_{NH,in}$ is *low* in dry weather), Q_a values are inversely based on the $S_{NO,5}$ values, so the higher $S_{NO,5}$, the lower Q_a (Fig. 3b). This is because PFC_Q_a is applied with control strategies that regulate S_O set-point based on S_{NH}, since they give better results than keeping S_O set-point fixed (Santín et al. [14]). So, decreasing Q_a, $S_{NH,5}$ is reduced and

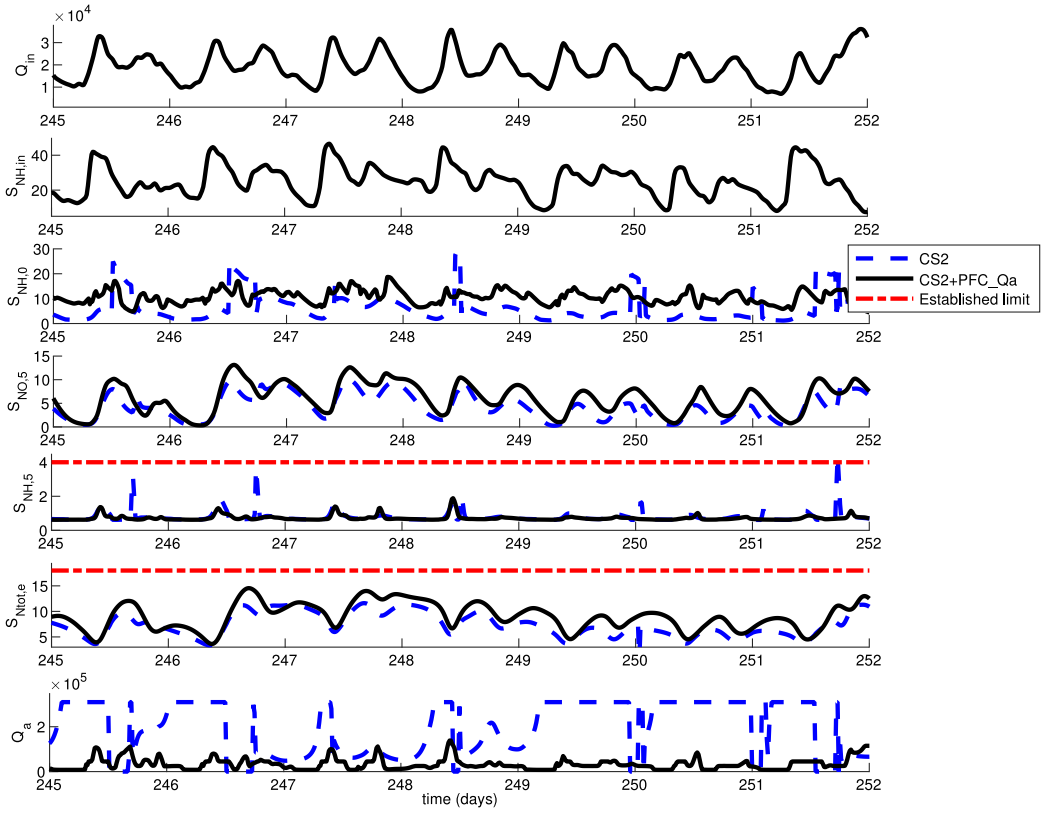


Fig. 11. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a during one week in summer for CS2 and CS2+PFC_Q_a.

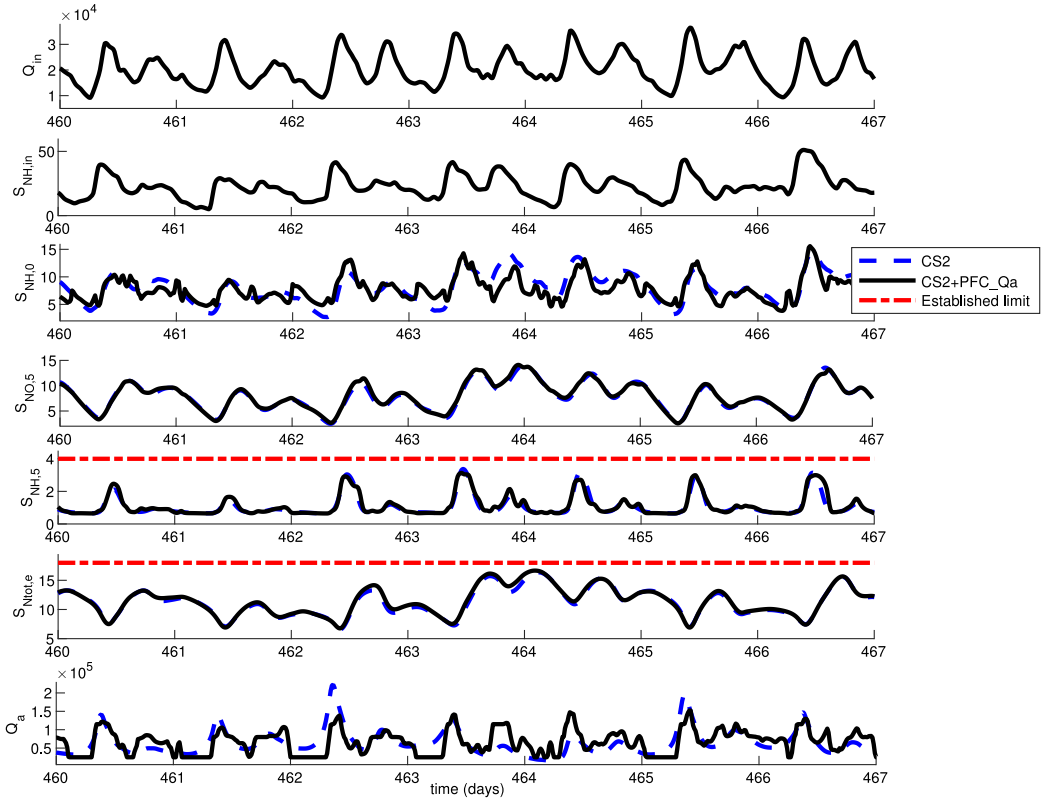


Fig. 12. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a during one week in winter for CS2 and CS2+PFC_Q_a.

consequently also S_O and $S_{NO,0}$. It should be noted that this fact does not happen in the case that $S_{NH,5}$ is so high that the value of $S_{O,5}$ reaches its maximum value defined by the controller that regulates it, even if Q_a is reduced. In the case of control strategies

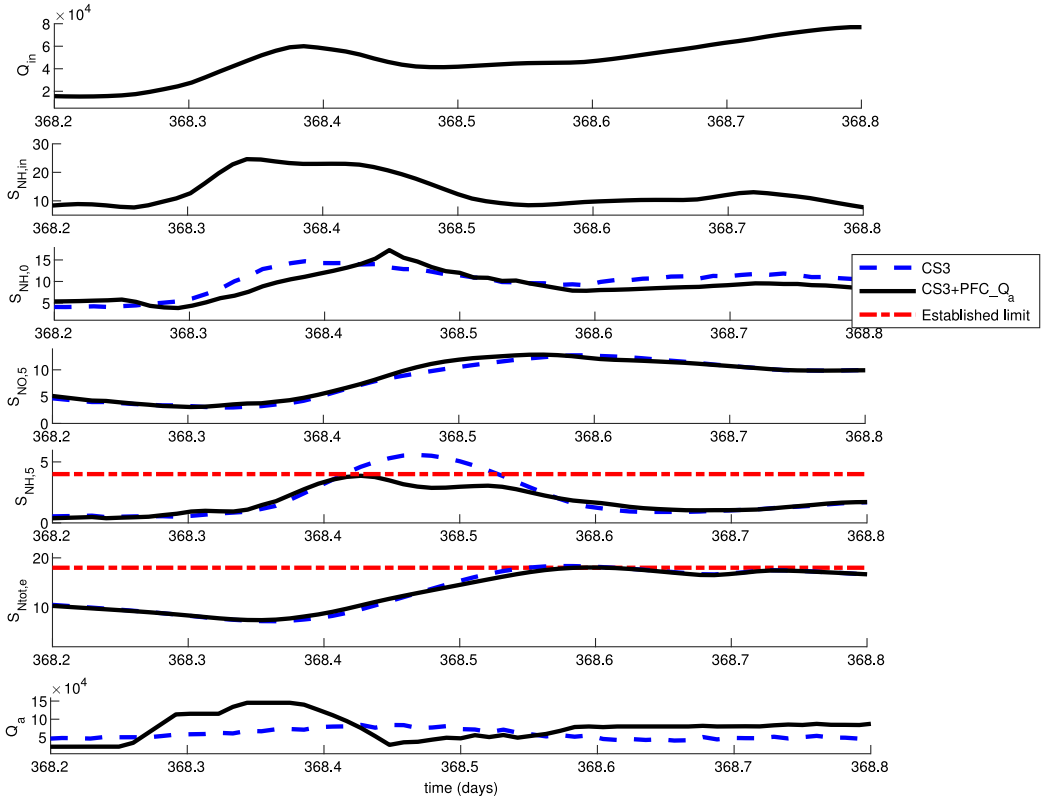


Fig. 13. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a of day 368 for CS3 and CS3+PFC_Q_a.

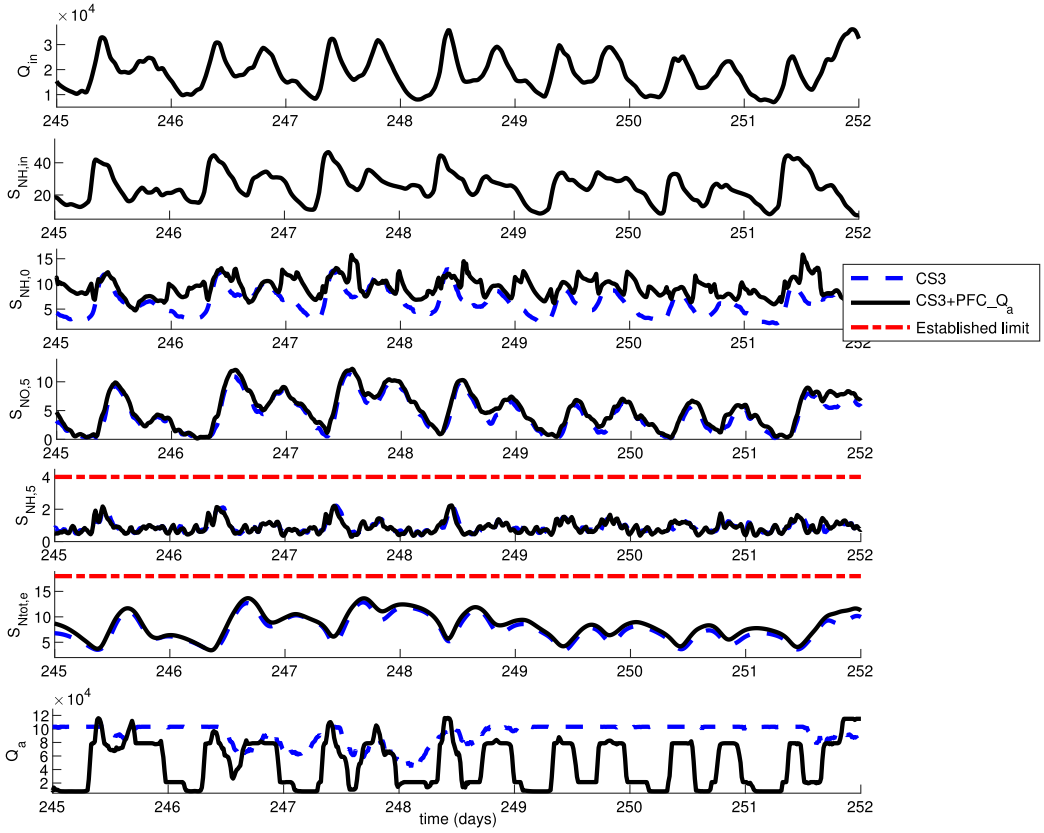


Fig. 14. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a during one week in summer for CS3 and CS3+PFC_Q_a.

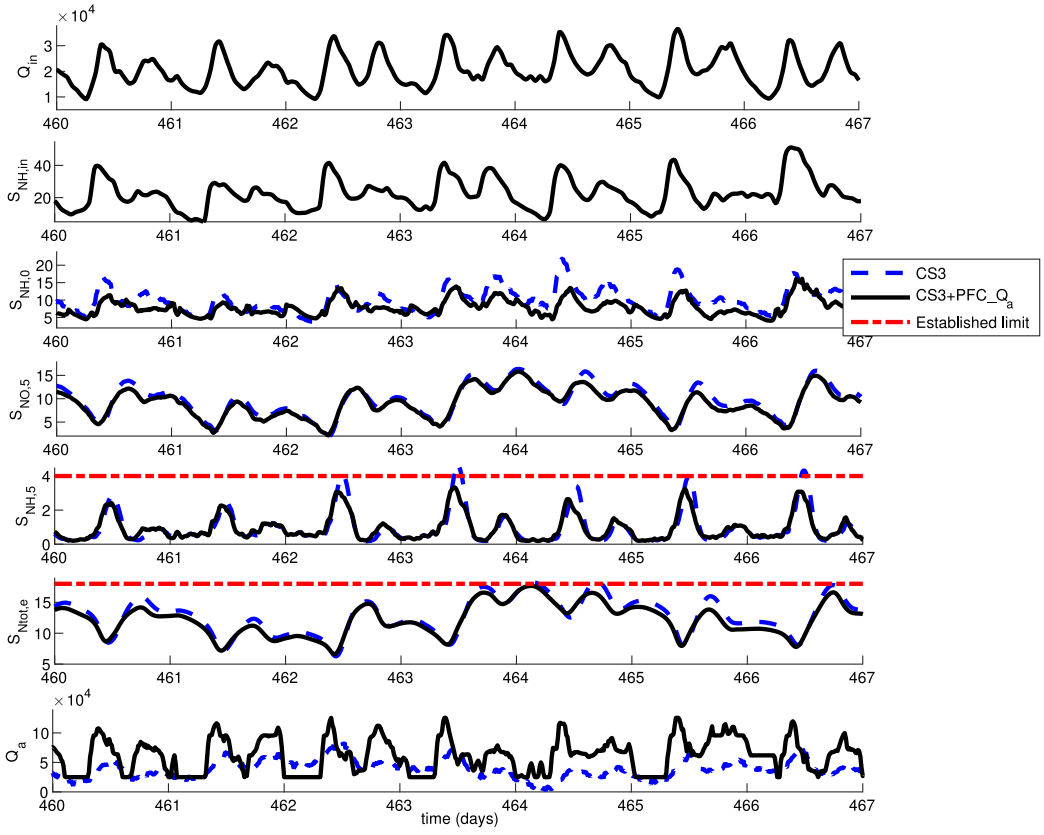


Fig. 15. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a during one week in winter for CS3 and CS3+PFC_Q_a.

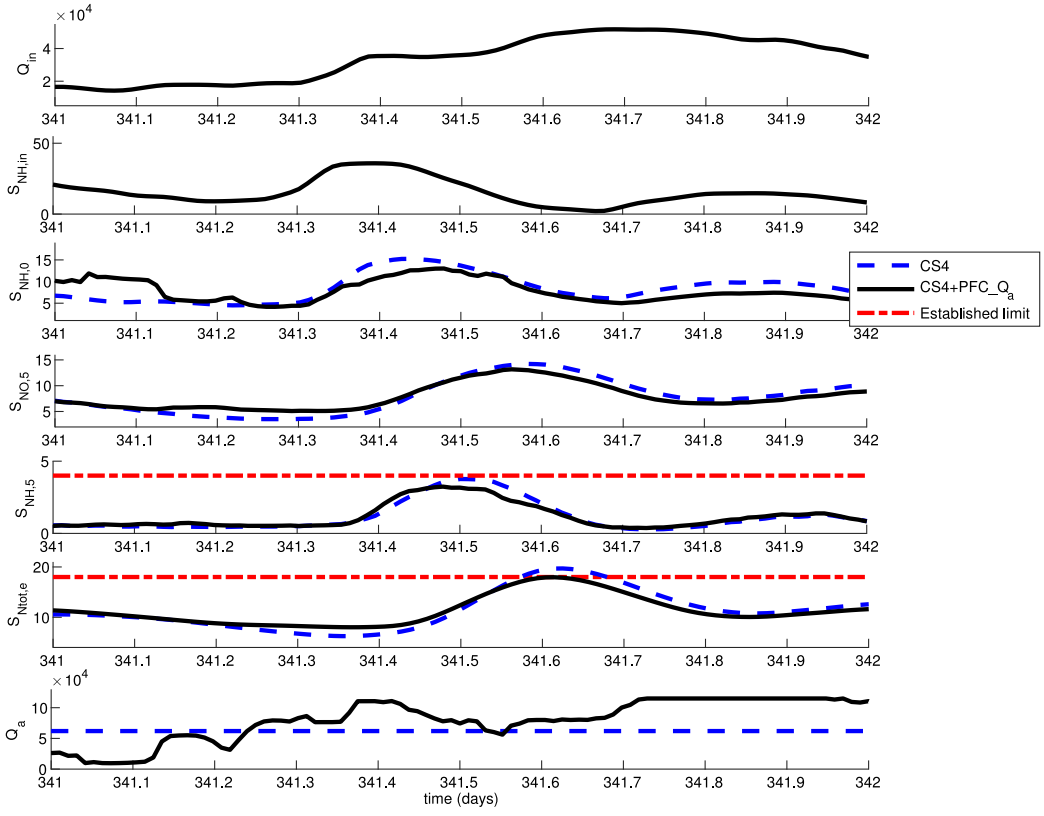


Fig. 16. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a of day 341 for CS4 and CS4+PFC_Q_a.

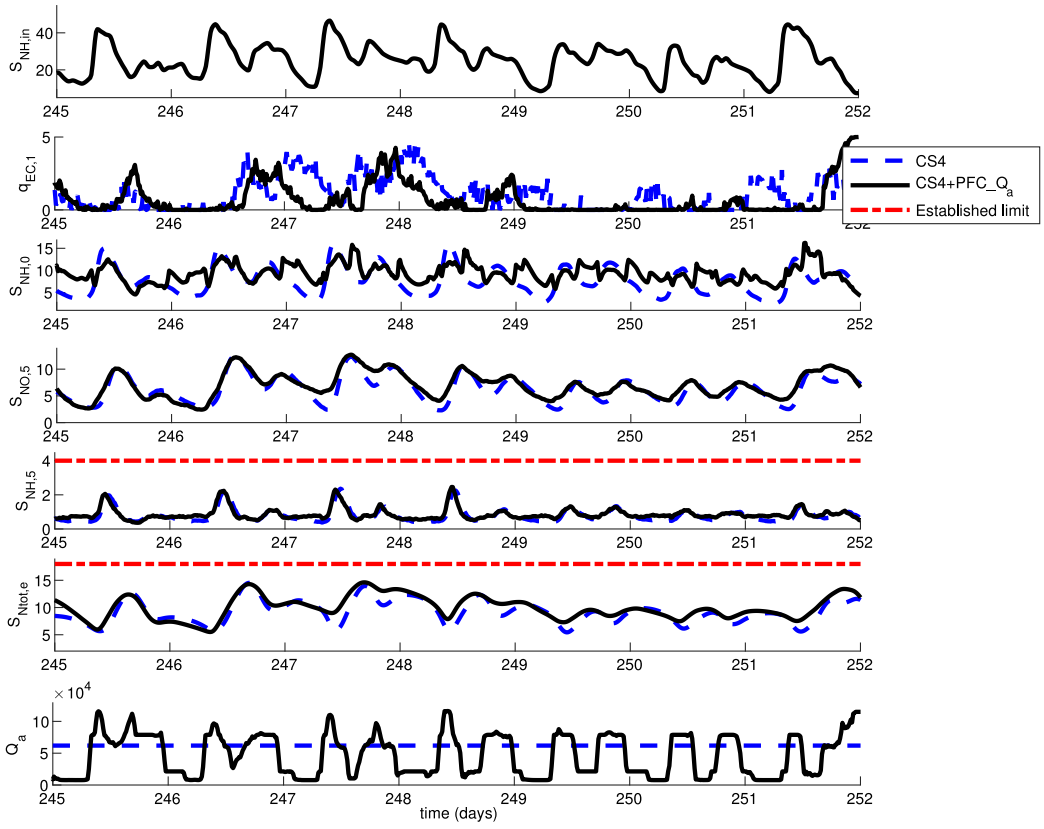


Fig. 17. Time evolution of $S_{NH,in}$, $q_{EC,1}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a during one week in summer for CS4 and CS4+PFC_Q_a.

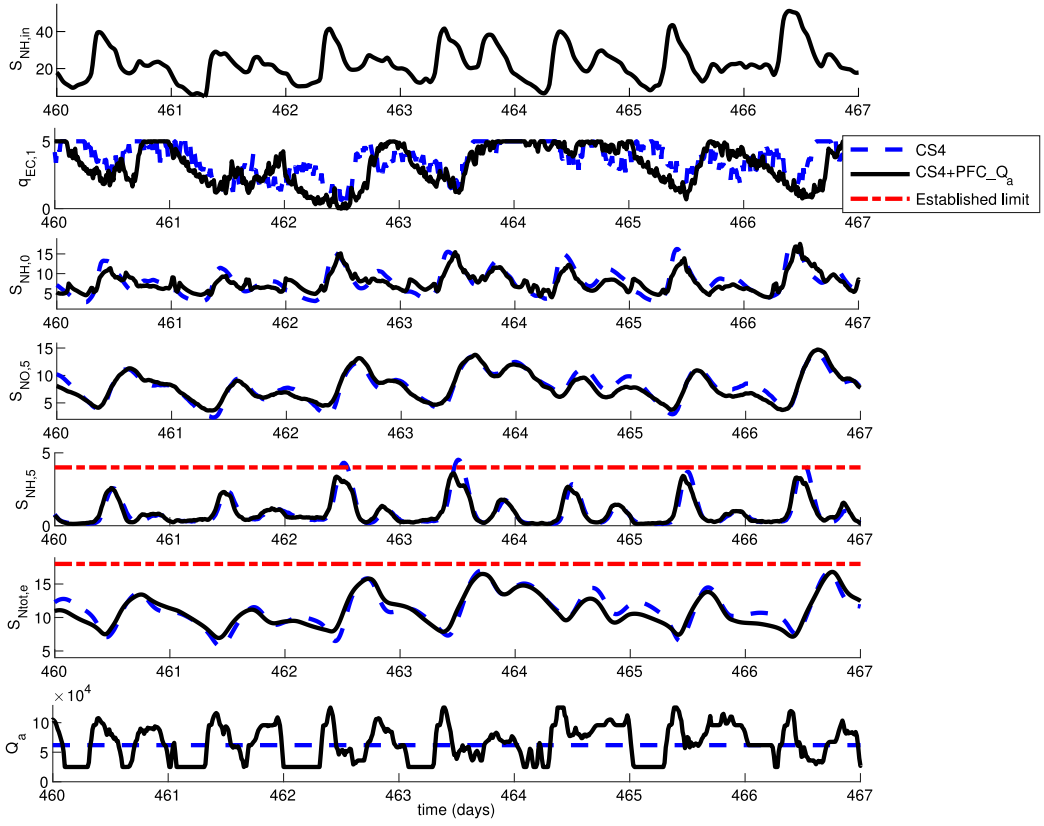


Fig. 18. Time evolution of $S_{NH,in}$, $q_{EC,1}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a during one week in winter for CS4 and CS4+PFC_Q_a.

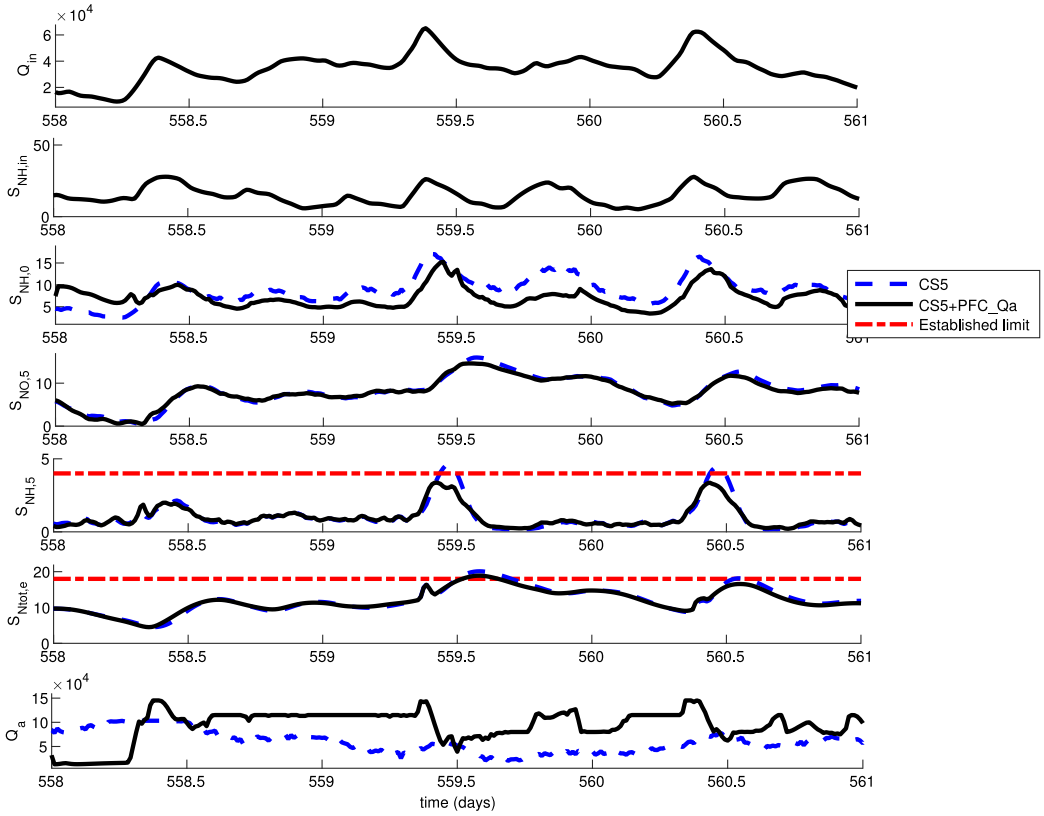


Fig. 19. Time evolution of Q_{in}, $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a of days 558, 559 and 560 for CS5 and CS5+PFC_Q_a.

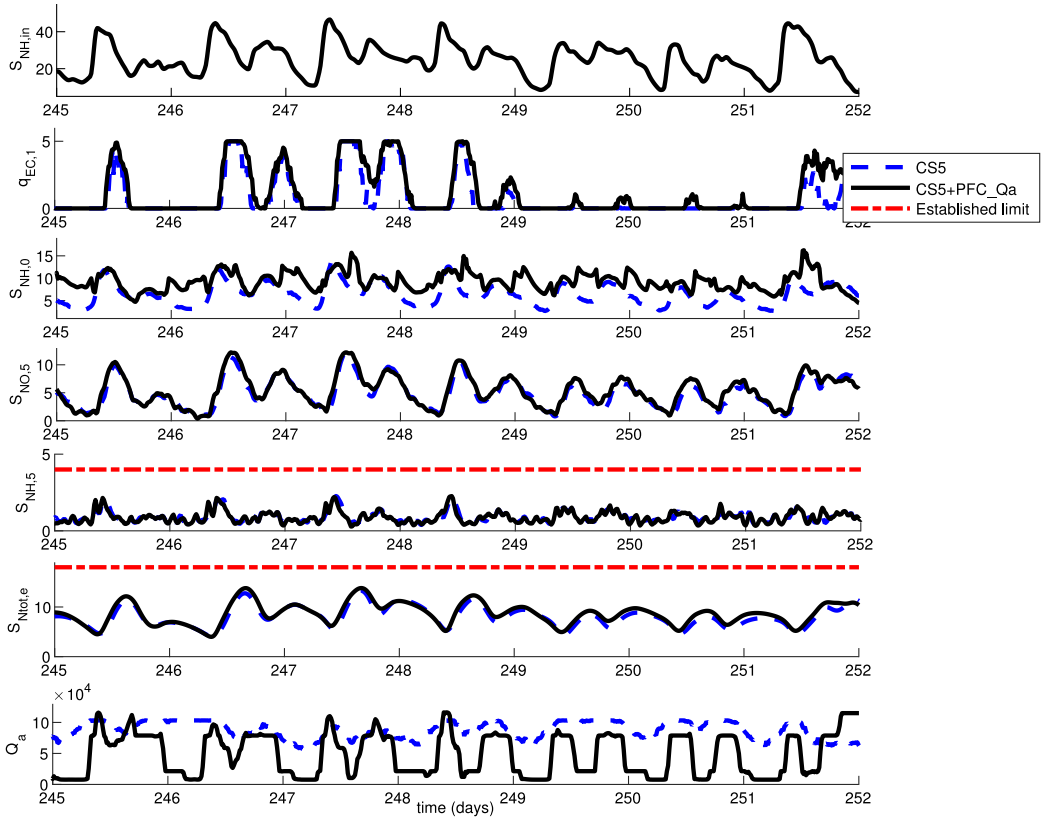


Fig. 20. Time evolution of $S_{NH,in}$, $q_{EC,1}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a during one week in summer for CS5 and CS5+PFC_Q_a.

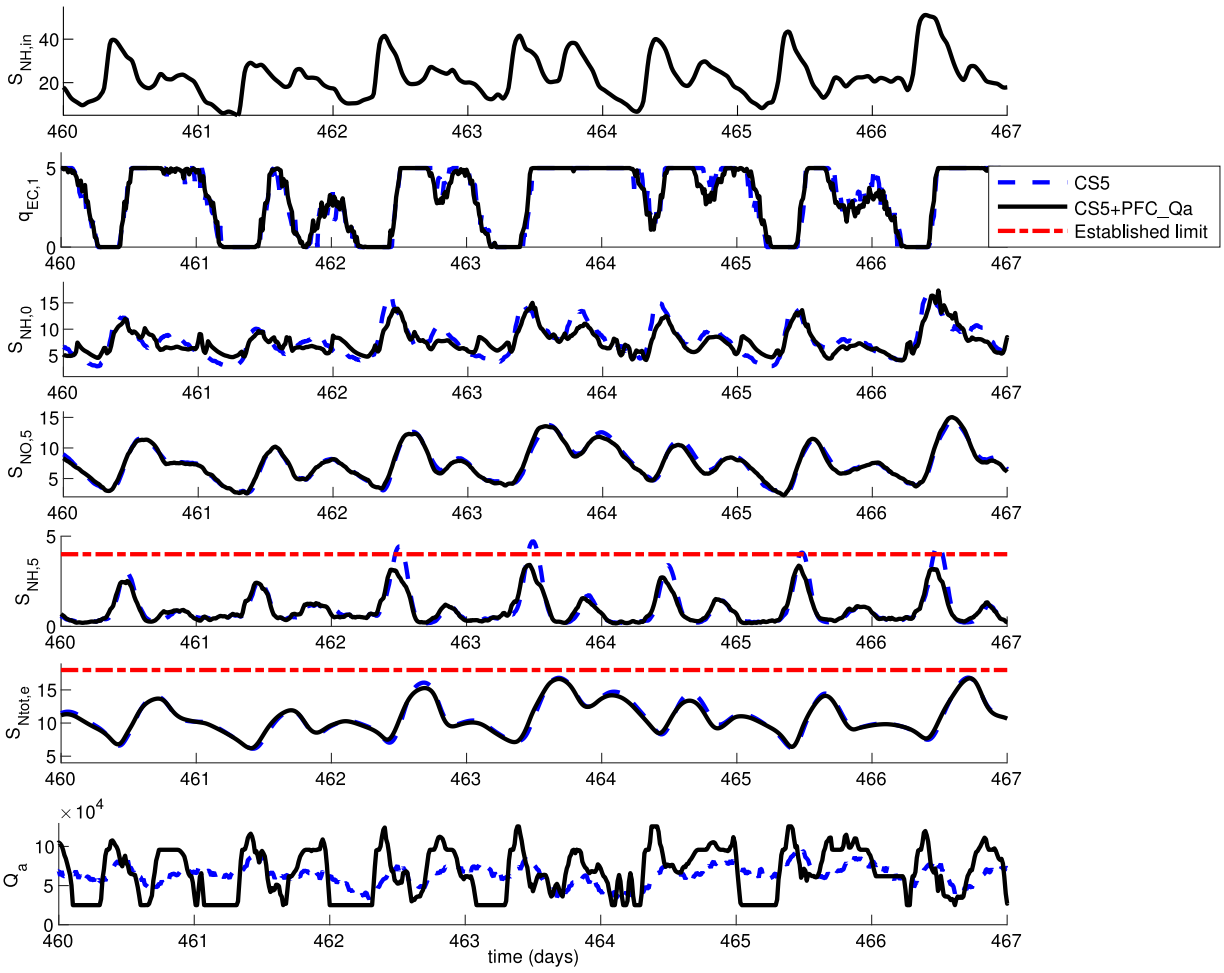


Fig. 21. Time evolution of $S_{NH,in}$, $q_{EC,1}$, $S_{NH,0}$, $S_{NO,5}$, $S_{NH,5}$, $S_{Ntot,e}$ and Q_a during one week in winter for CS5 and CS5+PFC_Q_a.

with fixed S_O set-point, the fuzzy controller design should be modified by adding S_O as input.

Q_a values depend on T_{as}, with both dry and rainy weather, because T_{as} affects the denitrification and nitrification processes. When T_{as} decreases, these processes worsen, as shown in the equations of observed conversion rates ((2), (1), (5), (6), (4) and (7)). Therefore, Q_a is higher when T_{as} is lower with the aim of diluting more $S_{NH,0}$ (Fig. 3b).

Q_a reduction is always limited by $S_{NH,0}$. When it is not necessary to dilute S_{NH}, Q_a is reduced to reduce pumping costs and to improve nitrification and denitrification processes. The $S_{NH,0}$ value limits the Q_a reduction, since there must be a minimum S_{NH} dilution in order to make possible to reduce it in the nitrification process to levels below the established limits (Fig. 3c).

Finally, $S_{NH,5}$ always plays a priority role in the rules, so that the Q_a increase is always limited by it, because when $S_{NH,5}$ is *high*, Q_a is *low* or *very low* (depending on T_{as}) (Fig. 3d).

In the case of taking into account all the inputs in all the rules with the condition "is", the minimum number of rules should be 486 to always assign a value to the output. However, due to the priorities of different situations, there are rules where the value given to the output does not depend on some inputs and there are cases where the input condition is "is not" instead of "is". This fact results in a reduction of the computational complexity, and a value is always assigned to the output with only 30 rules. The cases where some inputs are not included in the rules or the condition "is not" is established are explained below:

- $S_{NH,5}$ input:
  - During dry weather, when $S_{NH,in}$ "is Low", while $S_{NH,0}$ "is not High" Q_a is defined as "Low" or "Very Low" (depending on T_{as}) and the $S_{NH,5}$ input is not taken into account because it is restrictive when its value is "High" and when that happens Q_a must be "Low" or "Very Low" (depending also on T_{as}).
  - *When Q_a is assigned a higher value than "Low" or "Very Low", it is restricted to $S_{NH,5}$ "is not High".*
- $S_{NO,5}$ input:
  - For the same reason as $S_{NH,5}$ input explained above, during dry weather, when $S_{NH,in}$ "is Low", while $S_{NH,0}$ "is not High", the $S_{NO,5}$ input is not taken into account.
  - The $S_{NO,5}$ input is neither taken into account when $S_{NH,5}$ "is High", and then Q_a is "Low" or "Very Low".
  - When $S_{NH,0}$ "is not Low", Q_a is increased with the restriction of $S_{NO,5}$ "is not High".
- $S_{NH,0}$ input:
  - $S_{NH,0}$ restriction is given when it increases to dilute S_{NH}. Then, if Q_a is increased due to a rain event, $S_{NH,0}$ does not need to be taken into account.
  - $S_{NH,5}$ and $S_{NO,5}$ are more restrictive than $S_{NH,0}$. Therefore, if some of them are "High", Q_a is decreased without taken into account $S_{NH,0}$

  - During dry weather, when T_{as} is "High" and the situation is not of $S_{NH,5}$ or $S_{NO,5}$ "High", the decrease of Q_a is restricted to the condition of $S_{NH,0}$ "is not High".

- $S_{NH,0}$ input:
  - When Q_a is increased due to a $S_{NH,0}$ increase, $S_{NH,in}$ input is not taken into account
  - When Q_a is decreased because $S_{NH,5}$ "is High", $S_{NH,in}$ input is neither taken into account

- Q_{in} input:
  - If $S_{NH,in}$ "is Low" and $S_{NO,5}$ "is High" Q_a is "Low" or "Very Low" (depending on T_{as}) without taking into account Q_{in} input
  - When Q_a is decreased because $S_{NH,5}$ "is High", Q_{in} input is neither taken into account
  - When $S_{NH,in}$ is "Medium" or High", Q_a value depends on $S_{NO,5}$ and T_{as} inputs and restricted to Q_{in} "is not High".

- T_{as} input:
  - If a rain event is considered, the Q_a value does not depend on T_{as} input

Regarding the computational complexity of PFC_Q_a, the parameters that most influence it are shown in Table A.9. As specified in Kim et al. [33], the number of rules greatly affect the number of operations. Therefore, the reduction of the number of rules to 30 instead of 486 has an important effect on reducing the number of operations and consequently on computational complexity.

The rest of the parameters in Table A.9 do not excessively affect the fuzzy controller complexity and not cause any computation time problem, which is confirmed by the simulation times, shown in Section 4.

3.3. Operation strategies where PFC_Q_a is tested

PFC_Q_a is applied in five already tested and published operation strategies. The objective is to modify only the Q_a manipulation and compare the results obtained in different scenarios, as shown in Fig. 4. The operation strategies with which the fuzzy controller has been tested are detailed below.

As mentioned in Section 1, Serralta et al. [6], Sadeghassadi et al. [18], Qiao et al. [17], Caraman et al. [20], Revollar et al. [16] and Zhang et al. [19] also apply operation strategies that regulate Q_a, among other control approaches. However, none of them use BSM2 as working scenario and the controllers should be adapted to the new plant's requirements. In addition, although Serralta et al. [6], Sadeghassadi et al. [18], Qiao et al. [17] and Caraman et al. [20] apply different control techniques, the control approach to manipulate Q_a is the S_{NO} control, which is already applied in three operation strategies where PFC_Q_a is tested. In Revollar et al. [16] and Zhang et al. [19], MPC is applied to regulate both K_La and Q_a, and it is not possible to replace only the Q_a manipulation without modifying the controller.

3.3.1. Default control strategy with S_O hierarchical control (CS1)

The original BSM2 definition (Jeppsson et al. [28]) proposes a Default Control Strategy (DCS). The closed-loop control configuration consists of a Proportional-Integral (PI) controller that controls the S_O in the fourth reactor ($S_{O,4}$) at a set-point of 2 mg/l by K_La in the third tank (K_La_3), K_La in the fourth tank (K_La_4) and K_La in the fifth tank (K_La_5) with K_La_5 set to the half value of K_La_3 and K_La_4. q_{EC} in the first reactor ($q_{EC,1}$) is added at a constant flow rate of 2 m^3/d. Two different Q_w values are imposed depending on time of the year: from 0 to 180 days and from 364 to 454 days Q_w is set to 300m^3/d; and for the remaining time periods Q_w is set to 450m^3/d. Finally, Q_a is kept fixed to 61,944 m^3/d.

As explained in Section 3.2, PFC_Q_a is designed for control strategies with regulated S_O set-point. For this reason, a hierarchical control for $S_{O,4}$ set-point manipulation is added to DCS by means of a fuzzy controller designed and tested in Santín et al. [14] for BSM1 and adapted to the BSM2 characteristics in Santín et al. [22]. This referred paper shows that better results are obtained by regulating S_O based on S_{NH}, instead of trying to keep S_O at a fixed set-point.

For testing PFC_Q_a, it has been added to this control strategy, to regulate Q_a, instead of keeping it fixed (CS1+PFC_Q_a) (Fig. 4a).

3.3.2. Higher level fuzzy controller in Santín et al. [14] (CS2)

The control strategy applied in Santín et al. [14] is based on three Model Predictive Control (MPC) controllers and a fuzzy controller. A MPC controls the $S_{O,5}$ set-point by manipulating KLa5 and another MPC controls the $S_{O,4}$ set-point by manipulating K_La_3, and K_La_4. The fuzzy controller is the same as the one applied in CS1, which manipulates the $S_{O,4}$ and $S_{O,5}$ set-points (with $S_{O,5}$ set-point set to half of the value of $S_{O,4}$ set-point). As in CS1, the hierarchical fuzzy controller configuration is the one established in Santín et al. [22] because it is adapted to BSM2. The third MPC introduces the greatest difference with respect to CS1, controlling S_{NO} at the output of the second reactor ($S_{NO,2}$) at a set-point of 2mg/l by manipulating Q_a, instead of keeping Q_a constant. The values of Q_w and $q_{EC,1}$ are the same as in DCS.

PFC_Q_a is applied replacing the MPC that controls $S_{NO,2}$ (CS2+PFC_Q_a) (Fig. 4b).

3.3.3. Control strategy WL-S2 in Barbu et al. [4] (CS3)

The WL-S2 control strategy of Barbu et al. [4] applies three PI controllers. As in DCS, one PI controller controls SO,4 by manipulating K_La_3, K_La_4 and K_La_5, with K_La_5 set to half of the value of K_La_3 and K_La_4. Another PI controller tries to keep $S_{NH,5}$ at a set-point of 1mg/l by manipulating the $S_{O,4}$ set-point and the last PI controller controls $S_{NO,2}$ at a set-point of 1mg/l by manipulating Q_a. The Q_w and $q_{EC,1}$ values are the same as in DCS.

PFC_Q_a is tested by replacing the $S_{NO,2}$ control (CS3+PFC_Q_a) (Fig. 4c).

3.3.4. Control strategy WL-S3 in Barbu et al. [4] (CS4)

The WL-S3 control strategy of Barbu et al. [4] consists of three PI controllers. One PI controller controls $S_{O,4}$ at a fixed set-point of 2 mg/l by manipulating K_La_3 and K_La_4. Another PI controller controls $S_{NH,5}$ at a fixed set-point of 1 mg/l by manipulating K_La_5. Finally, the third PI controller aims to maintain $S_{NO,2}$ at a fixed set-point of 1mg/l by manipulating $q_{EC,1}$. Q_a and Q_w maintain the same values as in DCS.

PFC_Q_a is tested with this control strategy by replacing the Q_a fixed value of 61944 m^3/d (CS4+PFC_Q_a) (Fig. 4d).

3.3.5. Control strategy WL-S4 in Barbu et al. [4] (CS5)

The WL-S4 control strategy of Barbu et al. [4] applies the same control loops as in CS3 and adds another PI controller to control $S_{NO,5}$ at a set-point of 7 mg/l by manipulating $q_{EC,1}$. Q_w maintains the same values as in DCS.

As in CS3, PFC_Q_a is tested by replacing the $S_{NO,2}$ control (CS5+PFC_Q_a) (Fig. 4e).

4. Simulation results and discussion

Table A.11 shows the results obtained with the original operation strategies explained in Section 3.3 and also those obtained by

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Table A.11
Simulation results of CS1, CS2, CS3, CS4 and CS5 and the same operation strategies adding PFC_Q_a.

Evaluation Criteria		CS1	CS1+PFC_Qa	% of improvement	CS2	CS2+PFC_Qa	% of improvement	CS3	CS3+PFC_Qa	% of improvement	CS4	CS4+PFC_Qa	% of improvement	CS5	CS5+PFC_Qa	% of improvement
Effluent Quality	$S_{Ntot,e}$ limits violations (% of time)	0.309	0.237	23.301	0.255	0.246	3.529	0.607	0.529	12.850	0.252	0.106	57.937	0.149	0.114	23.392
	$S_{NH,e}$ limits violations (% of time)	0.229	0.0715	68.777	0.134	0.06	55.224	0.335	0.069	79.493	0.338	0.080	76.293	0.352	0.071	79.687
	COD limits violations (% of time)	0.057	0.057	0	0.057	0.057	0	0.057	0.057	0	0.057	0.054	4.999	0.054	0.054	0
	TSS limits violations (% of time)	0.343	0.343	0	0.349	0.343	1.638	0.352	0.343	2.438	0.386	0.381	1.380	0.352	0.349	0.849
	BOD_5 limits violations (% of time)	0.226	0.226	0	0.226	0.226	0	0.226	0.226	0	0.226	0.226	0	0.226	0.226	0
Operational Costs	*PE* (kWh/day)	445.454	427.899	3.941	692.241	428.803	38.056	492.031	439.319	10.713	445.457	441.700	0.843	491.873	445.064	9.516
	SP (kg SS/day)	2707.477	2708.854	−0.051	2709.218	2708.909	0.011	2707.572	2708.867	−0.048	2708.759	2701.251	0.277	2687.241	2698.786	−0.430
	AE (kWh/day)	3601.86	3593.732	0.226	3596.126	3591.647	0.125	3672.740	3663.750	0.245	3989.417	3961.181	0.708	3818.602	3632.194	−0.376
	EC (kg COD/day)	2400	2400	0	2400	2400	0	2400	2400	0	2441.519	2293.758	6.052	1989.907	2219.619	−11.544
	ME (kWh/day)	769.113	768.464	0.084	770.524	768.773	0.227	776.798	778.426	−0.210	970.036	967.605	0.251	778.694	779.425	−0.094
	HE_{net} (kWh/day)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	MET_{prod} (kg CH4/day)	1086.239	1085.851	0.036	1085.659	1085.849	−0.018	1086.164	1085.963	0.019	1086.911	1085.214	0.156	1082.418	1084.545	−0.197
	OCI	8821.425	8.801.551	0.225	9072.589	8800.853	2.995	8947.298	8892.318	0.614	9451.240	9256.709	2.058	8446.291	8665.387	−2.594

replacing in these strategies the Q_a manipulation by PFC_Q_a. Thus, the improvements provided by this controller can be observed.

Regarding the effluent quality, improvements in the reduction of $S_{NH,e}$ and $S_{Ntot,e}$ limit violations are achieved in all the operation strategies explained in Section 3.3 (from CS1 to CS5) using PFC_Q_a. The greatest improvements are obtained in the reduction of $S_{NH,e}$ limit violations, from 55.22% in CS2+ PFC_Q_a to 79.69% in CS5+PFC_Q_a. The reductions in $S_{Ntot,e}$ limit violations are lower than in $S_{NH,e}$ with a maximum reduction of 57.94% in CS4+PFC_Q_a and a minimum reduction of 3.53% in CS2+PFC_Q_a. The percentages of time of limit violations of *COD*, *TSS* and BOD_5 remain the same, except minor variations in *TSS* limit violations in CS2, CS3 and CS4. The number of times of limit violations are also the same. This is understable given that the proposed fuzzy controller is designed only to reduce limit violations of $S_{NH,e}$ and $S_{Ntot,e}$. It should be mentioned that *COD*, *TSS* and BOD_5 limit violations happen when the bypass is active, due to a significant Q_{in} increase that the plant cannot assume.

By manipulating Q_a with PFC_Q_a, costs due to *PE* are reduced in all the operation strategies described in 3.3. The maximum reduction of *PE* is 38.06% in CS2+PFC_Q_a, which results in a reduction of 96,154 kWh in one year. The smallest reduction of *PE* is obtained in CS4+PFC_Q_a, but in this case there is also a reduction of *EC* of 6.05%. In CS5+PFC_Q_a, the *PE* decrease is 9.52%, at the expense of an OCI increase of 2.59%, mainly due to an *EC* increase of 11.54%.

The reasons for the results obtained are discussed below. Specific days have been chosen for the analysis of the PFC_Q_a effects in each one of the operation strategies, where there are $S_{NH,e}$ limit violations (Figs. 6, 10 and 13), $S_{Ntot,e}$ limit violations (Figs. 5, 9, 16 and 19), one summer week (Figs. 7, 11, 14 and 17) and one week in winter (Figs. 8, 12, 15, 18 and 21). The comparison between summer and winter weeks allows to observe the T_{as} effects on the nitrification and denitrification processes and analyze how the Q_a manipulation can affect the pumping energy costs. In some operation strategies, the winter week has also been used for the analysis of $S_{NH,e}$ or $S_{Ntot,e}$ limit violations.

To illustrate the computational burden of the PFC_Q_a application, Table A.10 shows the CPU time used and the elapsed time in the 609-day simulation of all the operation strategies with and without PFC_Q_a, using a 7 GHz. Intel Core i7 processor. These values have been obtained with "cputime" and "tic/toc" functions of Matlab, respectively. As can be seen, in the operation strategies in which PFC_Q_a replaces a fixed Qa value (CS1 and CS4), PFC_Q_a results in an increase in elapsed time and CPU time of between approximately 15 and 19 min in the 609-day simulation. In the case of CS1, as it is a less complex operation strategy, the simulation time is lower, and the PFC_Q_a application results in a higher percentage of increase, of 24.547% in elapsed time and 25.534% in CPU time. In CS4, the percentages of increase are smaller, 3.258% and 3.291% in elapsed time and CPU time, respectively. However, in the operation strategies where PFC_Q_a replaces the nitrate control (CS2, CS3 and CS5), the application of PFC_Q_a results in a decrease in elapsed time and CPU time. In CS2, the percentage of decrease is higher (9.117% and 8.437% in elapsed time and CPU time, respectively) because PFC_Q_a replaces an MPC. In CS3 and CS5, PFC_Q_a replaces PI controllers, but even so, elapsed time and CPU time are reduced, showing that the proposed method does not result in a large computational burden.

4.1. $S_{NH,e}$ limit violations

With PFC_Q_a, when there is a $S_{NH,in}$ increase, Q_a is increased to dilute $S_{NH,0}$. On the other hand, Q_a is reduced when $S_{NH,5}$ is *high*, to improve the nitrification process.

The greatest difference between applying PFC_Q_a and keeping Q_a fixed (CS1 and CS4) is the $S_{NH,0}$ dilution when $S_{NH,in}$ increases. Fig. 6 corresponds to day 368 with CS1 and with CS1+ PFC_Q_a. In this day, there is an increase in the Q_{in} to $S_{NH,in}$ ratio that is representative of a rain event and causes a Q_a increase, which takes place earlier in CS1+PFC_Q_a. The subsequent $S_{NH,5}$ increase results in a Q_a decrease in CS1+PFC_Q_a, which is reduced to even lower levels than in CS1.

Fig. 18 shows a winter week with CS4 and with CS4+PFC_Q_a. The worsening of the nitrification process with low T_{as} results in $S_{NH,e}$ limit violations on days 462, 463 and 466 with CS4. There is no rain event during this period, but the $S_{NH,in}$ increase produces a Q_a increase in CS4+PFC_Q_a, which is higher due to low T_{as}. As happens in 6 by CS1+PFC_Q_a, the previous $S_{NH,0}$ dilution and the subsequent Q_a reduction when $S_{NH,5}$ increases allows to avoid $S_{NH,e}$ limit violations by CS4+PFC_Q_a.

In the case of the operation strategies that manipulate Q_a to control $S_{NO,2}$ at the set-point of 1 mg/l (CS2, CS3 and CS5), when $S_{NO,5}$ is lower Q_a is increased to increase S_{NO} in the anoxic zone, and, inversely, when $S_{NO,5}$ is greater Q_a is decreased. CS2 applies an MPC with a higher gain than the PI controllers of CS3 and CS5, and the Q_a variations are greater. Furthermore, in CS3 and CS5 the value of Q_a is limited to 103,240 m^3/d, which is less than the maximum allowed (309,720 m^3/d). In Fig. 10, it is observed that in CS2, in the period of time when $S_{NO,5}$ is reduced and Q_a is increased, there is a coincidental increase of $S_{NH,in}$, which is diluted thanks to the Q_a increase. Although on this day Q_a is increased a little more in CS2+PFC_Q_a than in CS2, this is not the main difference between both, but the subsequent Q_a decrease when $S_{NH,5}$ increases. In CS2 Q_a is decreased later than in CS2+PFC_Q_a because it is caused by the $S_{NO,5}$ increase and not by the $S_{NH,5}$ increase. Finally, the $S_{NH,e}$ limit violation that take place on day 435 with CS2 are avoided with CS2+PFC_Q_a. It should be noted that CS2 does not aim to dilute $S_{NH,0}$ when $S_{NH,in}$ increases, but the Q_a increase, due to a $S_{NO,5}$ decrease, coincides with the $S_{NH,in}$ increase due to the influent dynamics. In Fig. 13 and Fig. 19, it is observed how violations in the $S_{NH,e}$ limits on day 368 with CS3 and on days 559 and 560 with CS5 are avoided with CS3+PFC_Q_a and CS5+PFC_Q_a, respectively. In CS3 and CS5 the Q_a variations are lower than in CS2. In these operation strategies, there is an important difference in the $S_{NH,0}$ dilution with the Q_a increase with respect to CS3+PFC_Q_a and CS5+PFC_Q_a, respectively. As in CS2, Q_a is reduced later in CS3 and CS5 than in CS3+PFC_Q_a and CS5+PFC_Q_a, respectively, and is caused by the increase of $S_{NO,5}$ instead of by the increase of $S_{NH,5}$.

4.2. $S_{Ntot,e}$ limit violations

As explained in the previous section, when there is a $S_{NH,in}$ increase, Q_a is increased to dilute $S_{NH,0}$. When $S_{NO,5}$ increases, Q_a is slightly reduced, which improves the denitrification process, which results in a $S_{NO,5}$ reduction in a first period of time. However, the reduction of Q_a also improves the nitrification process, whose effect in $S_{NO,5}$ depends on the S_O required. It should be noted that an excessive Q_a reduction would probably cause a subsequent $S_{NO,5}$ increase by improving the nitrification process.

As previously discussed, there is a reduction of $S_{Ntot,e}$ limit violations by applying PFC_Q_a in all tested operation strategies, but these reductions are lower than the reductions of $S_{NH,e}$ limit violations. The reason for this is that when there is a simultaneous increase in $S_{Ntot,e}$ and $S_{NH,5}$, the $S_{NH,5}$ increase requires a stronger and earlier Q_a reduction, which is detrimental to reduce the $S_{NO,5}$ peak. The best option is to reduce Q_a when $S_{NO,5}$ is greater, and thus to reduce the $S_{NO,5}$ peak to improve the denitrification process without an excessive generation of $S_{NO,5}$ by improving nitrification.

In Fig. 5 and in Fig. 16, the effects on $S_{Ntot,e}$ by applying PFC_Q_a can be compared to those obtained by keeping Q_a fixed. As with $S_{NH,e}$ limit violation reduction, the main difference in this case is the Q_a increase, when $S_{NH,in}$ increases, to dilute $S_{NH,0}$. Although the $S_{NH,5}$ increase results in Q_a decrease before $S_{NO,5}$ reaches high values, Fig. 5 and Fig. 16 show how CS1+PFC_Q_a and CS4+PFC_Q_a avoid $S_{Ntot,e}$ limit violation on day 341 unlike CS1 and CS4.

The Q_a effect in CS3 and in CS5 is similar to that obtained in CS1 and CS4. As explained in Section 4.1, although there is a Q_a regulation to control $S_{NO,2}$, the low gain of the PI controllers in CS1 and CS4 results in a smaller and slower Q_a increase when $S_{NO,5}$ decreases, which in turn results in a lower dilution of $S_{NH,0}$. This fact is observed in Fig. 15 where $S_{Ntot,e}$ limit violations with CS3 on days 463, 464 and 466 are avoided with CS3+PFC_Q_a.

In addition, controlling $S_{NO,2}$ by manipulating Q_a in CS2, CS3, and CS5 has another detrimental effect on $S_{Ntot,e}$ limit violations when there is a long rain period. In these cases, the denitrification process worsens due to a HRT decrease, and the S_{NO} level increases. The $S_{NO,2}$ control excessively reduces Q_a, which improves the denitrification process, but also improves the nitrification process, generating more S_{NO}. Q_a decrease affects especially $S_{NH,0}$ that is increased. This effect can be seen, for instance, in Fig. 9 and in Fig. 19.

In the case of CS2+PFC_Q_a, the reduction of $S_{Ntot,e}$ limit violations with respect to CS2 is lower than in the other operation strategies because CS2 dilutes $S_{NH,0}$ when there is a $S_{NH,in}$ increase. In addition, the subsequent reduction of Q_a is performed when $S_{NO,5}$ is greater since it does not take into account $S_{NH,5}$. However, CS2 has an increase in $S_{Ntot,e}$ limit violations mainly due to long rain periods.

4.3. Operational costs

The cost reduction is mainly due to the saving in pumping energy thanks to a lower average Q_a. It occurs mainly in summer when T_{as} is *high*, nitrification and denitrification processes improve and therefore the $S_{NH,0}$ dilution to keep both $S_{Ntot,e}$ and $S_{NH,e}$ below the established limits is less necessary. The Q_a regulation has the objective of reducing the $S_{NH,e}$ and $S_{Ntot,e}$ peaks although the $S_{NH,0}$ dilution is lower.

Figs. 7, 11, 14, 17 and 20 show how most of the time Q_a is lower with the PFC_Q_a than with the original control strategies. This difference is greater in CS2, CS3 and CS5, which manipulate Q_a to control $S_{NO,2}$, coinciding with the *PE* costs in Table A.11. In these control strategies, Q_a is increased more in summer than in winter because $S_{NO,5}$ is lower and it is necessary to recirculate more S_{NO} to maintain $S_{NO,2}$ at the set-point of 1 mg/l. However, in summer, this Q_a increase is unnecessary to keep $S_{NH,e}$ and $S_{Ntot,e}$ below the limits. The Q_a increase is greater in CS2 than in CS3 and CS5 because the maximum Q_a limit is greater. This fact also results in higher *PE* costs, shown in Table A.11.

Figs. 8, 12, 15, 18 and 21 show a week in which T_{as} is *low*. As in this case the nitrification and denitrification processes worsen, PFC_Q_a increases more Q_a in order to dilute $S_{NH,0}$ when $S_{NH,in}$ increases. The $S_{Ntot,e}$ and $S_{NH,e}$ peaks are higher than in summer and closer to the established limits. In fact, there are $S_{NH,e}$ limit violations in CS1, CS3, CS4 and CS5 and $S_{Ntot,e}$ limit violations in CS3, while with the application of PFC_ Q_a they are avoided. In all tested operation strategies, except in CS2, the Q_a average in winter is higher with the application of PFC_Q_a, but the Q_a reduction in summer, explained above, results in a reduction of *PE* annual costs.

In CS5+PFC_Q_a compared to CS5, although there is a decrease of *PE* costs, there is an OCI increase mainly due to an increase of *EC* costs. CS5 manipulates $q_{EC,1}$ to control $S_{NO,5}$ at a set-point of 7 mg/l. The application of PFC_Q_a reduces Q_a in summer most of the time to reduce *PE* costs because the values of $S_{Ntot,e}$ and $S_{NH,e}$ are far from the established limits. However, in CS5+PFC_Q_a, when $S_{NO,5}$ is greater than 7 mg/l, there is a higher $q_{EC,1}$ increase than in CS5, although $S_{NO,5}$ values are not considered dangerous for a possible $S_{Ntot,e}$ limit violation, as can be observed in Fig. 20.

In CS4, there is also a $q_{EC,1}$ regulation, but in this case to control $S_{NO,2}$, instead of $S_{NO,5}$, at the set-point of 1 mg/l. As in CS4+PFC_Q_a Qa is usually lower than in CS4, $S_{NO,2}$ is also lower and therefore less $q_{EC,1}$ is added, as can be seen in Fig. 17. Thus, *EC* costs are reduced by CS4+PFC_Q_a compared to CS4.

It must be taken into account that the PFC_Q_a application requires the addition of sensors for the $S_{NH,in}$, $S_{NH,0}$, $S_{NO,5}$, T_{as} and Q_{in} measurements to the operation strategies, in which PFC_Q_a is tested, except in CS5 that already uses a $S_{NO,5}$ sensor. These sensors are commonly used in WWTPs and do not require excessive investment. With only the reduction of pumping energy costs, the investment would be recovered in less than a year in CS2 and a little more time in the rest. If the reduction of fines due to the reduction of nutrient limit violations is taken into account, the return on investment would be in a shorter time. In addition, regardless of the PFC_Q_a application, the added sensors provide important information to the plant. Specifically, the T_{as}, Q_{in} and $S_{NH,in}$ measurements are quite essential, and it is very common to have these sensors, even though they are not used in the operation strategy.

5. Conclusions

This article has presented a new control strategy to manipulate Q_a taking into account its effects in the different areas of the biological treatment of a wastewater treatment plant, by applying a fuzzy controller. PFC_Q_a has been tested in five already tested and published operation strategies, replacing the original Q_a manipulation and comparing results. The PFC_Q_a application has reduced $S_{NH,e}$ and $S_{Ntot,e}$ limit violations and *PE* costs in all tested operation strategies. The only exception is CS5, where there is an OCI increase due to a $q_{EC,1}$ increase. The graphs of evolution over time of the most important concentrations show the effects of Q_a, corroborating that the objectives of PFC_Q_a are met . The main conclusions of the PFC_Q_a application and its comparison with the original control strategies are:

- The Q_a increase to dilute $S_{NH,0}$, when $S_{NH,in}$ or Q_{in} increases, has an important effect in reducing $S_{Ntot,e}$ and $S_{NH,e}$ peaks to avoid limit violations
- The Q_a decrease, when it is not necessary to dilute $S_{NH,0}$ due to low $S_{NH,in}$ levels and especially in summer, reduces *PE* costs.
- The Q_a reduction, when $S_{NH,5}$ increases, generates a HRT increase that improves the nitrification process, reducing the $S_{NH,e}$ peaks and avoiding limit violations
- The Q_a reduction, when $S_{NO,5}$ increases, reduces it in a first period of time due to the denitrification process improvement, which allows to avoid $S_{Ntot,e}$ limit violations. However, a large and/or too premature Q_a reduction can generate a subsequent increase of $S_{NO,5}$. A fact that happens in the PFC_Q_a application if there is a large increase in $S_{NH,5}$ and $S_{NO,5}$ on the same day.
- Keeping Q_a fixed, as in CS1 and CS4, results in a poor $S_{NH,0}$ dilution when $S_{NH,in}$ or Q_{in} increase and does not improve the nitrification process when the $S_{NH,5}$ increase requires it. The average value of Q_a in summer is excessively high, which increases *PE* costs.
- The Q_a manipulation to control $S_{NO,2}$, as in CS2, CS3 and CS5, excessively increases Q_a in summer, when less dilution is required, to try to keep $S_{NO,2}$ at the set-point of 1 mg/l,

generating an increase of *PE* costs. When there is an increase in $S_{NH,5}$, Q_a is not reduced, and during long rain periods Q_a is excessively reduced.
- The combination of the PFC_Q_a application with the $S_{NO,5}$ control by manipulating $q_{EC,1}$ can generate increases of *EC* costs in the summer period, especially with low $S_{NO,5}$ set-points.
- The combination of the PFC_Q_a application with the $S_{NO,5}$ control by manipulating $q_{EC,1}$ can generate increases of *EC* costs in the summer period, especially with low $S_{NO,5}$ set-points.

It is worth mentioning that Q_a has effects on the amount of S_O in the aerobic zone and therefore also on nitrous oxide emissions. However, the current PFC_Q_a has not been designed to take into account nitrous oxide emissions or any other greenhouse gas. Updating the approach of the Q_a regulation to take this effect into account is planned as future work.

Also, in the case of WWTPs that carry out the biological phosphorus removal, the effects of PFC_Q_a application must be analyzed.

Finally, the present work constitutes the first step of the study to be completed by further tests in pilot or real plants.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

```
[System]
Name='PFC_Qa'
Type='mamdani'
Version=2.0
NumInputs=6
NumOutputs=1
NumRules=30
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='SNHin'
Range=[12 40]
NumMFs=3
MF1='Low':'zmf',[12 24.2]
MF2='Medium':'trimf',[18 25 32]
MF3='High':'smf',[26 40]

[Input2]
Name='SNH0'
Range=[10 21]
NumMFs=3
MF1='High':'smf',[19 21]
MF2='Low':'zmf',[14 16.5]
MF3='Medium':'trimf',[14 17.5 21]

[Input3]
Name='SNH5'
Range=[0.4 3.5]
NumMFs=3
MF1='Low':'zmf',[0.4 1.84]
MF2='Medium':'trimf',[0.71 1.95 3.19]
MF3='High':'smf',[2.06 3.5]

[Input4]
Name='SNO5'
Range=[5 20]
NumMFs=3
MF1='Low':'zmf',[5 11.25]
MF2='Medium':'trimf',[8.5 12 15.5]
MF3='High':'smf',[13 20]

[Input5]
Name='Tas'
Range=[10 20]
NumMFs=2
MF1='Low':'zmf',[13 17.5]
MF2='High':'smf',[13.5 17]

[Input6]
Name='Qin'
Range=[10000 50000]
NumMFs=3
MF1='Low':'zmf',[10000 22500]
MF2='Medium':'trimf',[17000 27500 37500]
MF3='High':'smf',[27500 42000]

[Output1]
Name='Qa'
Range=[0 200000]
NumMFs=6
MF1='Low':'trimf',[5000 25000 45000]
MF2='Medium low':'trimf',[25000 45400 65000]
MF3='Medium':'trimf',[45000 80000 115000]
MF4='Very High':'trimf',[115000 200000 2.67e+55]
MF5='Very low':'trimf',[10000000 0 25000]
MF6='High':'trimf',[80000 115000 150000]

[Rules]
1 1 0 0 1 1, 1 (1) : 1
1 1 0 0 2 1, 5 (1) : 1
1 0 3 1 0 2, 6 (1) : 1
1 0 3 1 0 3, 6 (1) : 1
1 0 3 2 0 2, 3 (1) : 1
1 0 3 2 0 3, 3 (1) : 1
1 0 3 3 2 0, 5 (1) : 1
1 0 3 3 1 0, 1 (1) : 1
2 1 3 1 2 3, 1 (1) : 1
2 1 3 2 2 3, 5 (1) : 1
2 0 3 3 2 3, 5 (1) : 1
2 2 3 1 1 3, 3 (1) : 1
2 2 3 2 1 3, 2 (1) : 1
2 0 3 3 1 3, 1 (1) : 1
2 0 3 1 0 3, 4 (1) : 1
2 0 3 2 0 3, 4 (1) : 1
2 0 3 3 0 3, 2 (1) : 1
3 1 3 1 2 3, 2 (1) : 1
```

```
3  1  3 2 2  3, 2 (1) : 1
3 0  3 3 2  3, 5 (1) : 1
3 2  3 1 1  3, 6 (1) : 1
3 2  3 2 1  3, 6 (1) : 1
3 0  3 3 1  3, 2 (1) : 1
3 0  3 1 0 3, 4 (1) : 1
3 0  3 2 0 3, 4 (1) : 1
3 0  3 3 0 3, 2 (1) : 1
0 0 3 0 1 0, 1 (1) : 1
0 0 3 0 2 0, 5 (1) : 1
0  2  3  3 1  3, 6 (1) : 1
0 1  3  3 2  3, 6 (1) : 1
```

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