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Modeling and simulation of a carousel for long-term operation

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Abstract: Following the directions set by the International Water Association for the development of benchmarks to compare control strategies and fault detection methods in activated sludge plants, a carousel benchmark has been developed. It is based on a real plant (Golbey-Epinal, France), on which wastewater characteristics were measured. The model incorporate sludge bulking effects based in the ratio ammonia-to-nitrate in the effluent and inhibition effects due to the possible presence of toxicants in the influent.

Keywords: activated sludge, bulking, carousel, inhibition, sludge volume index;

1. INTRODUCTION

Carousels or oxidation ditches are widely used for the treatment of wastewater by activated sludge. These large-size reactors are subject to large disturbances due to the variability of wastewater flow rate and composition. Within the framework of international projects (COST, IWA) the problem of long-term monitoring protocol assessment and control strategies comparison has been addressed by the development of benchmarks (BSM1, BSM1_LT and BSM2) (Copp, 2002; Nopens et al., 2008). The layout of the virtual wastewater treatment plants incorporated in these benchmarks is a classical nitrification-denitrification scheme. In order to test biological fault detection schemes for an existing wastewater treatment plant (Epinal, France, 60 000 person-equivalents) of the carousel type, a model has been developed, the BSM methodology being used as background. This provided a good basis to initiate a benchmark based on the carousel technology. Similar work has been conducted previously but for larger oxidation ditches, equipped with surface aerators (Abusam et al., 2002) and for control strategies evaluation. The biological faults under consideration here are toxicants in the wastewater and problems of sludge bulking in the final clarifier. These are practical problems that plant operators are regularly facing.

2. CASE STUDY

The design is based on the urban wastewater treatment plant of Epinal-Golbey, in the North-East of France. After the grit and grease removal stage, the 60 000 persons-equivalent plant has two parallel biological lines (with a carousel and a clarifier for each) and a final chemical phosphorous removal stage.



Fig. 1. Aerial view of the Epinal-Golbey wastewater treatment plant.

In each line, the carousel and the circular clarifier have volumes of 5000 m³ and 3000 m³, respectively. A primary settler has been built but is not used currently. The aeration is provided by fine bubbles diffusers located on the carousel floor. Aeration and anoxia phases are controlled via a redox potential sensor, with constraints on the minimal and maximal duration of the phases. Phosphorous is removed by chemical precipitation but this will not be taken into consideration in the present paper.

3. MODELLING

3.1 Carousel

Figure 2 presents the plant layout that has been selected for modelling a carousel. The carousel is represented by a set of eight well-mixed compartments, which can be aerated or not. In comparison, 10 CSTRs were used by Abusam et al. (2001) to model a 13 000 m³ oxidation ditch. As it was not practical

to simulate the redox potential in the system, the on-off aeration in the eight compartments is controlled by the dissolved oxygen concentration and the nitrate concentration in compartment 8. The sludge recycled from the final clarifier is injected in the first compartment when the raw (or primary settled wastewater if the primary settler is in operation) and the reject water from the wasted sludge treatment are injected in the fourth compartment. An external carbon source can be added if necessary in compartment 4.

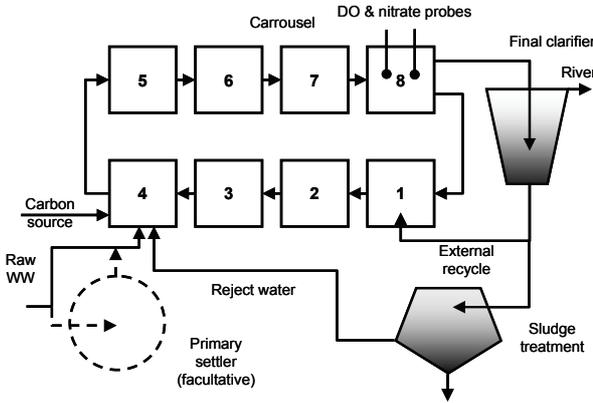


Fig. 2. Plant layout

For any state variable except oxygen, the mass balance for compartment i , $i = 2, 3, 5, 6$ and 7 is

$$\frac{dZ_i}{dt} = \frac{1}{V_i} (Q_{i-1}Z_{i-1} + r_{Z,i}V_i - Q_iZ_i) \quad (1)$$

$$\text{With } Q_{i-1} = Q_i \quad (2)$$

For $i = 1$

$$\frac{dZ_1}{dt} = \frac{1}{V_1} (Q_a Z_8 + Q_{rec} Z_{rec} + r_{Z,1}V_1 - Q_1 Z_1) \quad (3)$$

$$\text{With } Q_1 = Q_a + Q_r \quad (4)$$

For $i = 4$

$$\frac{dZ_4}{dt} = \frac{1}{V_4} \left(Q_3 Z_3 + Q_{raw} Z_{raw} + Q_{rej} Z_{rej} + Q_{prim} Z_{prim} + r_{Z,4} V_4 - Q_4 Z_4 + Q_{ec} Z_{ec} \right) \quad (5)$$

$$\text{with } Q_4 = Q_3 + Q_{raw} + Q_{rej} + Q_{prim} + Q_{ec} \quad (6)$$

For $i = 8$

$$\frac{dZ_8}{dt} = \frac{1}{V_i} (Q_7 Z_7 + r_{Z,8} V_i - Q_a Z_8 - Q_8 Z_8) \quad (7)$$

$$\text{With } Q_8 = Q_7 - Q_a \quad (8)$$

For oxygen, Eq. (1) is modified as follows:

$$\frac{dS_{O,i}}{dt} = \frac{1}{V_i} \left(\frac{Q_{i-1} S_{O,i} + r_{O,i} V_i + (K_L a)_i V_i (S_O^{sat} - S_{O,i})}{(K_L a)_i} - Q_i S_{O,i} \right) \quad (9)$$

The other mass balances related to oxygen are modified similarly.

$K_L a$ and S_O^{sat} are temperature dependant:

$$K_L a(T) = 1.024^{(T-15)} \cdot K_L a(15^\circ C) \quad (10)$$

$$S_O^{sat}(T_{as}) = 0.9997743214 \cdot \frac{8}{10.5} \cdot 6791.5 \cdot K(T_K) \quad (11)$$

$$\text{With } K(T_K) = 56.12 e^{A+B/T^*+C \ln T^*} \quad (12)$$

where $T^* = T_K/100$ (K), $T_K = T_i$ ($^\circ C$) + 273.15, $A = -66.7354$, $B = 87.4755$ $C = 24.4526$.

The Activated Sludge Model N^o1 (ASM1) (Henze et al., 1987), with temperature effect, is used to describe the biological reactions. The modification proposed by Pons (2007) to take into account the effect of toxicants has been implemented. The inhibition parameters are used as additional state variables to represent the variability of the toxicant nature. The classical Monod equations are modified by adding two steps describing the behaviour of an inhibitor (I). The general expression for biomass growth rate:

$$r_X = \mu S X / (K_s + S) \text{ is replaced by:} \quad (13)$$

$$r_X = \frac{\mu S X}{(1 + [I]/K_{I1})K_s + (1 + [I]/K_{I2})S}$$

The biomass decay rate $r_d = -bX$ becomes:

$$r_d = -bX(1 + [I]/K_{I1})^\alpha (1 + [I]/K_{I2})^\beta \quad (14)$$

Finally the toxicant can be (bio)degraded:

$$r_{deg} = -d \cdot [I]^\gamma \quad (15)$$

As an example the mass balance for K_{I1} is, for compartment i , $i = 2, 3, 5, 6$ and 7 :

$$\frac{dK_{I1,i}}{dt} = \frac{1}{V_i} (Q_i K_{I1,i} - Q_{i-1} K_{I1,i-1}) \quad (16)$$

The other mass balances are deduced accordingly.

3.2 Secondary clarifier

The secondary clarifier (diameter = 31 m, volume = 3 000 m³) is modelled according to the solid flux theory with 10 layers. It is non-reactive and based on the Takács et al. (1991) settling velocity model. The hindered zone settling parameter (r_h), the flocculant zone settling parameter (r_p) and the non-settleable fraction (f_{ns}) are kept constant and equal to 0.000576, 0.00286 and 0.00228 respectively. The settling velocity (v_s) in a layer, where the total solid concentration is X_{sc} , is calculated as:

$$v_s(X_{sc}) = \max \left[0, \min \left\{ v_0', v_0 \left(e^{-r_h(X_{sc} - X_{\min})} - e^{-r_p(X_{sc} - X_{\min})} \right) \right\} \right] \quad (17)$$

$$\text{with } X_{\min} = f_{ns} X_f \quad (18)$$

where

$$X_f = 0.75(X_{S,8} + X_{P,8} + X_{I,8} + X_{B,H,8} + X_{B,A,8}) \quad (19)$$

To take into account the effect of bulking on the settling parameters, the model suggested by Hartley (2008) is used (Fig. 3):

$$SSVI = \frac{SSVI_{\min} + (SSVI_{\max} - SSVI_{\min})}{(1 - \exp(-\kappa |\log N_{r,ave} - \log N_{r,opt}|))} \quad (20)$$

Where $SSVI$ is the stirred sludge volume index, N_r is the effluent ammonia to nitrate ratio and κ a constant. N_r is a surrogate for the process anoxic fraction. $N_{r,ave}$ is a time-averaged value of N_r , calculated over 3 days, and $N_{r,opt}$ is the optimal value, set to 1 in the present application. Hartley based his model on data collected on actual carousel plants. The correlation provided by Ozinsky and Ekama (1995) is used to relate $SSVI$ to SVI , the sludge volume index measured in a simple cylinder (settling of a mixed liquor sample for 30 min).

$$v_o = \xi \cdot \exp(-\zeta \cdot SSVI) \quad (21)$$

The maximum settling velocity is taken as $v_o/2$. The sludge volume settling test is modelled in order to provide on-line information on sludge settleability (SVI):

$$SVI = H_{30} / (X_0 \cdot H_0) \quad (22)$$

Where H_0 and H_{30} are the sludge height in the cylinder at time 0 and 30 min respectively, and X_0 the initial sludge concentration in the cylinder

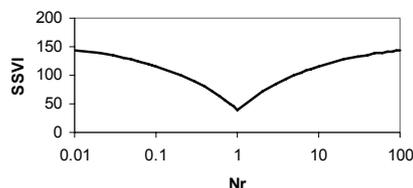


Fig. 3: Variation of the stirred sludge volume index ($SSVI$) in function of N_r .

3.3. Sludge treatment

An ideal model is assumed for the sludge treatment by dewatering. The percentage of suspended solids in the underflow of the dewatering (i.e. the reject water which is recycled to compartment 4 of the carousel) is 28%. The percentage of suspended solids removed is 98%.

3.4 Influent files

Influent files have been created based on Epinal wastewater plant data. Daily variability for COD, nitrogen and suspended solids has been measured by specific sampling campaigns. An automated sampler has been set to collect raw wastewater samples on a hourly basis. Non-filtrated samples were analysed for total COD (Hach micro-method n°8000), total nitrogen (Hach micro-method n°10072) and turbidity (at 450nm on a Hach spectrophotometer DR2500, calibrated with formazin suspensions). Filtrated (1.5µm paper filter)

samples were analysed for N-NH₄ (Nessler method). UV-visible spectra were collected on a Anthelie Light spectrophotometer (Secomam, Domont, France) and A₂₅₄ was used as a surrogate for soluble COD (Wu et al., 2006). Synchronous fluorescence spectra were collected on a Hitachi FL2500 fluorometer. The tryptophan-like fluorescence read at λ_{exc} = 280 nm - λ_{em} = 330 nm was used as a surrogate for soluble organic nitrogen (Wu et al., 2006). Figure 4 gives the example of one wastewater influent characterization campaign.

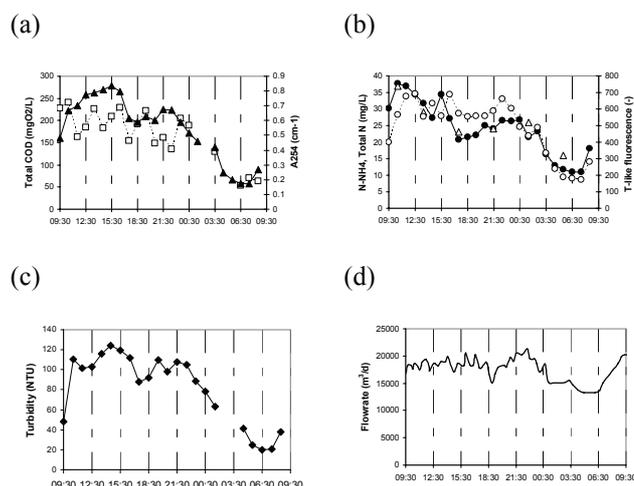


Fig. 4: Golbey-Epinal wastewater characteristics over 24hr (a) Total COD (□) and A₂₅₄ (▲), (b) N-NH₄ (●), total nitrogen (▲) and T-like fluorescence (○), (c) turbidity, (d) total flowrate

Based on these variations, the relative daily variations of Figure 5 have been applied for the state variables related to pollution and for flowrate. ASM1 fractionation was supposed to be similar to the one observed in Nancy (Lourenço da Silva, 2008).

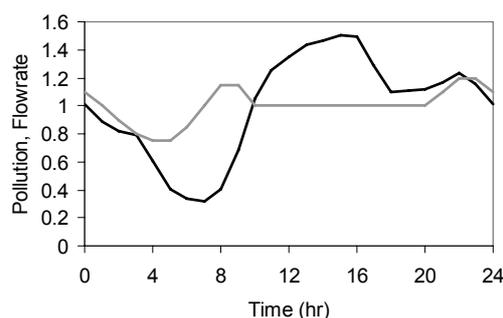


Fig. 5: Relative daily variation for pollution state variables (black line) and flowrate (grey line).

Historical data are available daily for flow rate, rainfall and temperature (effluent), every 3 days for total COD and suspended solids, every 5 days for BOD₅, nitrogen (ammonia, Kjeldahl and total). Data have been analyzed over five years (2000-2005). Figure 6 depicts the variations of the flowrate at the inlet of the plant between 2000 and 2005. The flowrate incorporates the effect of rainfall on the watershed

(combined sewer network). The weather in Epinal is quite rainy and wastewater is diluted by run-off. The water temperature at the plant outlet varies between 8°C and 20°C. It is therefore expected that the nitrification will not be very efficient during winter.

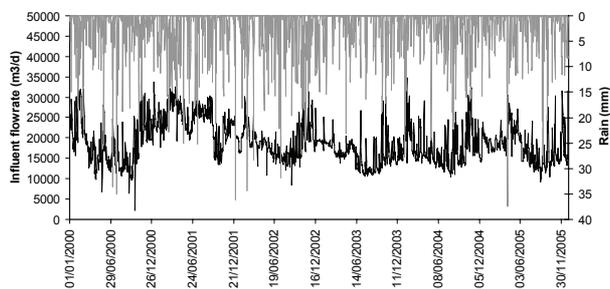


Fig. 6: Golbey-Epinal wastewater total flowrate (black line) and rainfall (grey line) feeding the two caroussels

As an example of the variations of the wastewater characteristics that are used for the simulations, Figure 7 shows the N-NH₄ content and temperature of the carousel influent simulated for a period of 609 days with one data point every 15 min.

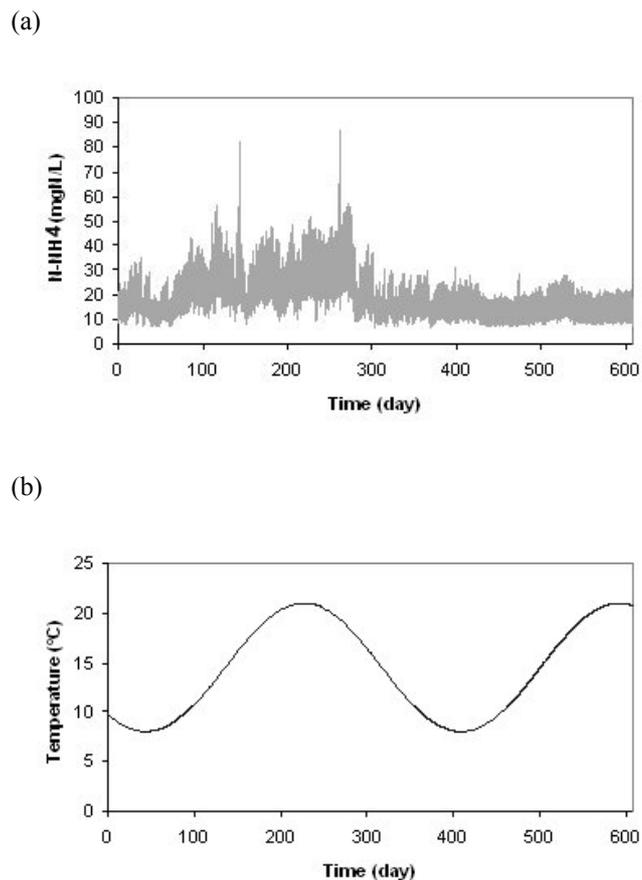


Fig. 7: Influent N-NH₄ concentration (a) and temperature (b) used for the simulation.

4. RESULTS

The models have been implemented in FORTRAN and the simulation methodology applied in BSM1 (Copp, 2002) has been used. The BSM1 parameter values for the ASM1 section have been adopted, without calibration on the actual plant. The influent data file corresponds to 609 days. The first 245 days are used for dynamic stabilization of the process and the final assessment of the plant performance is done on the final 364 days. Based on the actual settings of the Golbey-Epinal plant, the minimal and maximal duration for the anoxic and oxic phases have been set to 1 hour and 3 hours, respectively. The high limit for oxygen (which triggers the start of an anoxic period) is 7 mg O₂/L. The low limit for nitrate concentration (which triggers the start of an oxic period) is 0.5 mg N-NO₃/L. The average flowrate for one carousel is 10 000 m³/d. The external recycle has been set to 10 000 m³/d, the internal recycle (Q_a) to 30 000 m³/d, and the wastage flowrate to 200 m³/d (i.e. 2% of the average influent flowrate in one carousel). The ratio between the internal recycle flowrate and the average influent flowrate is much lower than in Abusam et al. (2001) (3 instead of 83).

Figure 8 presents the variations of N-NH₄ and N-NO₃ at the outlet of the plant during the final assessment period, in absence of toxicant. As expected, nitrification is very low in winter. The total suspended solids concentration remains around 20 mg/L, except at the beginning of the assessment period (Fig. 9). This is due to a good settling velocity (Fig. 10). The settling velocity is maximal when the N_r ratio is close to 1 (Fig. 3).

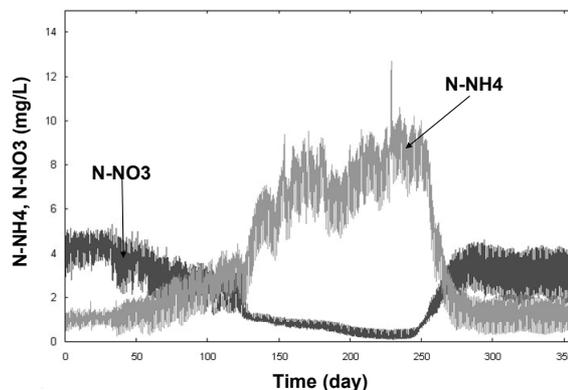


Fig. 8 N-NO₃ and N-NH₄ in the effluent during the assessment period

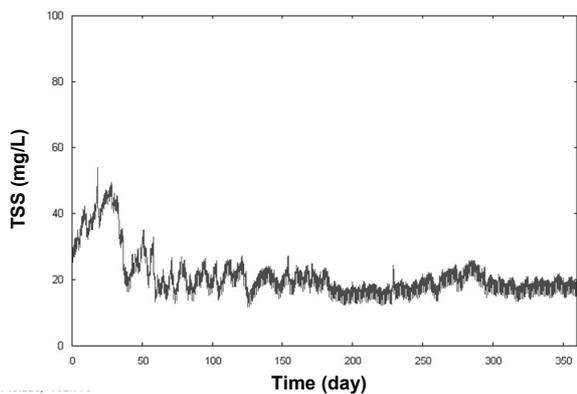


Fig. 9: N-NO₃ and N-NH₄ in the effluent during the assessment period

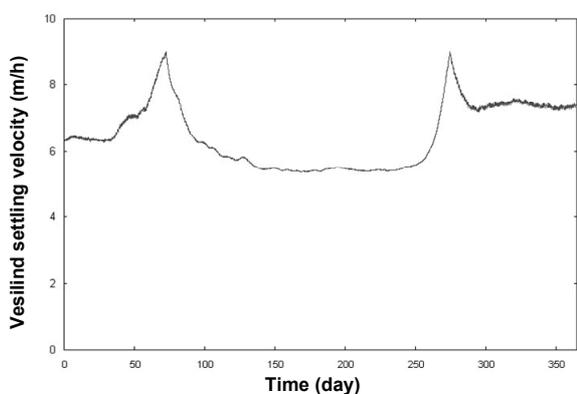


Fig. 10: Vesilind settling velocity variations during the assessment period

Finally a test has been run in presence of toxicant. Figure 11 depicts the variations of the inhibition constant $K_{I,1}$ used for heterotrophs and nitrifiers. Their average values are 10 L/ μ g and 5 L/ μ g respectively, except for two periods of 6 hours. $K_{I,2}$ are kept constant and equal to 10 L/ μ g and 5 L/ μ g for heterotrophs and nitrifiers respectively. $\alpha = 1$ (0.1) and $\beta = 1$ (0.1) for heterotrophs (nitrifiers). The toxicant is not degradable. The toxicant average concentration is 0.25 μ g/L, which is used to mimic the usual toxics that can receive a urban wastewater treatment plant due to the various activities of the city. To simulate an acute toxicity incident, the toxicant concentration has been increased to 10 μ g/L for a period of 6 hours.

As shown in Figure 12, the presence of toxicant affects globally the nutrient removal efficiency, with a decrease of the N-NO₃ concentration and an increase of the N-NH₄ concentrations in the effluent. The effect of the change of the toxicant characteristics (change in the $K_{I,1}$ values) is not noticeable. The pulse of toxicant has an effect on nitrification with an increase of the N-NH₄ concentration in the effluent.

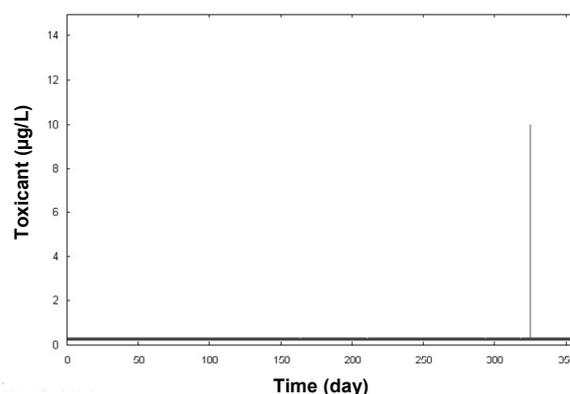
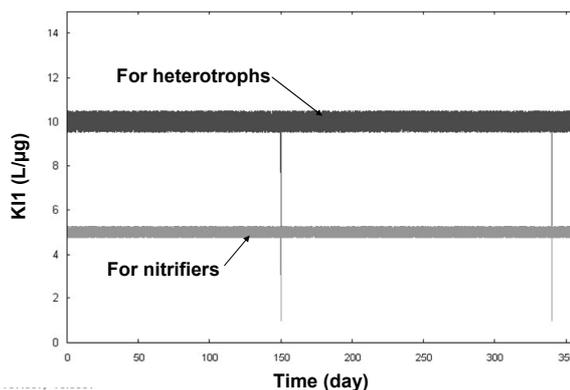


Fig. 11: Variations of (a) the inhibition constants $K_{I,1}$ and of (b) the toxicant concentration.

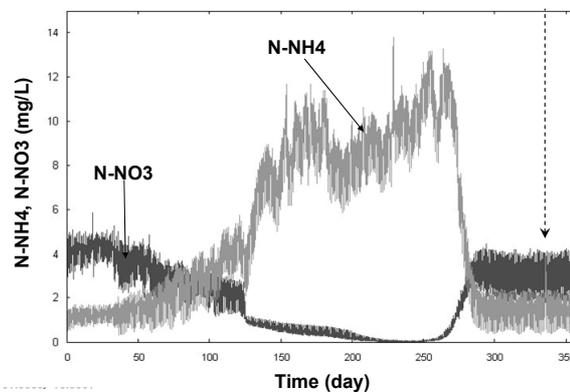


Fig. 12: N-NO₃ and N-NH₄ in the effluent during the assessment period in presence of toxicant

CONCLUSIONS

A long-term dynamic model of a carousel plant has been set up. It takes into account two types of incidents which can occur on such a process, namely the bad settling of the sludge in the final clarifier due to bulking and the presence of toxicant in the wastewater. Although the influence of the internal flowrate, which was difficult to measure experimentally, should be better investigated, it has been considered that the virtual plant provides a realistic representation of a real plant. It can be used to compare control strategies, to test the behaviour of the plant under these control strategies with influent exhibiting different

characteristics (in terms of flowrate, concentration and temperature) and to test fault detection procedures.

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NOMENCLATURE

ASM1 state variables

S_I	Soluble inert organic matter
S_S	Readily biodegradable substrate
X_I	Particulate inert organic matter
X_S	Slowly biodegradable substrate
$X_{B,H}$	Active heterotrophic biomass
$X_{B,A}$	Active autotrophic biomass
X_P	Particulate products arising from biomass decay
S_O	Oxygen
S_{NO}	Nitrate and nitrite nitrogen
S_{NH}	$NH_4^+ + NH_3$ nitrogen
S_{ND}	Soluble biodegradable organic nitrogen
X_{ND}	Particulate biodegradable organic nitrogen
S_{ALK}	Alkalinity

Other variables

b	death rate
I	inhibitor
$K_{I,j}$	inhibition parameter, $j = 1, 2$
K_{La}	oxygen transfer rate
Q	flow rate
r_{deg}	degradation rate of the toxicant
r_b	decay rate
r_X	growth rate
S_O^{sat}	saturation concentration of oxygen
S	substrate
T	temperature
V	volume
X	biomass
Z	state variable
α, β, γ	constant in inhibition model

Indices

a	internal recycle
ec	external carbon
i	compartment number
$prim$	primary settler
raw	raw wastewater
rec	clarifier recycle
rej	reject water from sludge treatment
w	wastage

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