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Comparison of Sludge Wastage Control Strategies

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Abstract: In order to compare whether sludge age control by wastage from the biological reactor is more efficient than wastage from the final clarifier in wastewater treatment plants by activated sludge, the Benchmark Simulation Model 1 has been modified. The secondary settler has been made reactive and the sludge settling characteristics vary as a function of the amount of gas produced by denitrification. Proportional-integral controllers were implemented with success to control the sludge age by wastage from the biological reactor or the clarifier and were tested under different dynamic situations. It was confirmed that a simple strategy of constant wastage from the biological reactor could be a good alternative when no suspended solids sensor is available.

1. INTRODUCTION

Sludge age is one of the important parameters used to maintain under control the proliferation of bacteria in wastewater treatment plants by activated sludge. For that purpose a certain amount of sludge should be wasted every day. Usually the wastage is removed from the underflow of the clarifier (Figure 1a) (Ma et al., 2006). But different researchers have advocated wastage from the biological reactor itself (Figure 1b). One of the reasons mentioned (Marais and Ekama (1976), WRC (1984)) is that the daily variations of sludge concentration in the underflow are larger than the variations observed for the mixed liquor in the biological reactor.

In order to compare both types of wastage, different sludge age control strategies should be tested. For that purpose the Benchmark Simulation Model n°1 (Copp, 2002) seems to be a perfect tool. However, in order to emphasize the effect of storage of sludge in the clarifier in case of low recycle rate, the non-reactive model used normally in BSM1 has been replaced by a reactive model. The biological reactions taking place in the reactive clarifier are modelled according to the Activated Sludge Model n°1 (ASM1) (Henze et al., 1987), which is used in the biological reactor of BSM1. Furthermore, in order to account for the effect of gas release due to denitrification in the clarifier, the settling parameters of the Takács et al.'s model (Takács et al., 1991) are modified according to the amount of gas produced by denitrification. Sludge rising due to gas bubbles entrapment in the activated sludge flocs is a sludge settling problems which causes the release of biomass across the clarifier weir. The effect of temperature, which is a key factor in nitrogen related reactions, is also taken into account.

The paper is organised as follows. In Section 2, the modifications of the BSM1 model are explicated. In Section 3, the effect under constant influent conditions of temperature, external recycle rate and wastage rate are presented. In Section 4, the open-loop system is investigated with respect to the same conditions. Finally, in Section 5, the closed loop control strategies of the activated sludge age using both types of wastage are discussed.

(a)

(b)

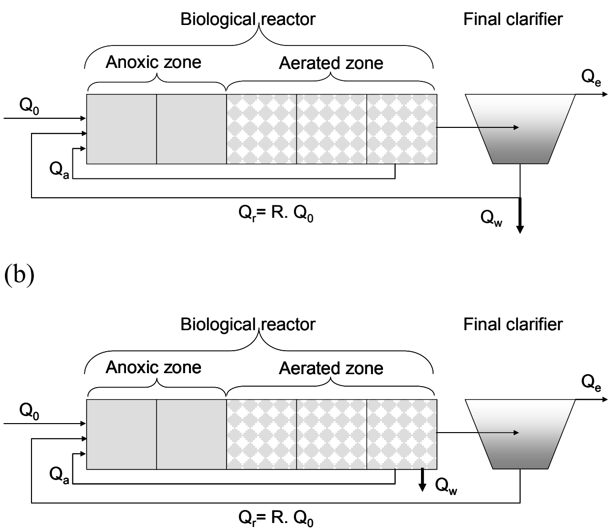

Fig. 1. Wastage from the final clarifier (a) and from the biological reactor (b) in a classical wastewater treatment plant by activated sludge

2. MODELLING

2.1 The BSM1 plant

The BSM1 plant is a classical wastewater treatment plant by activated sludge for nutrient removal. It is composed of a final clarifier (volume = 6000 m^3 and height = 4 m) and a biological reactor built with an anoxic zone (two compartments of 1000 m^3 each) and an aerated zone (three

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compartments of 1333 m^3 each). Part of the mixed liquor is recycled to the inlet of the biological reactor (flow rate = Q_a) while the remaining part is directed towards the final clarifier. The clarifier underflow is recycled to the inlet of the biological reactor (flow rate = Q_r) but a part of it is wasted (flow rate Q_w). The bioreactions taking place in the biological reactor are modelled according to ASM1, while the Takács et al.'s model is used to simulate the non-reactive behaviour of the clarifier, which is divided into 10 layers. The full description of BSM1 can be found in Copp (2002). The effect of temperature is considered on the bioreaction rates, the dissolved oxygen concentration at saturation and the oxygen mass transfer coefficients. The sludge age θ is calculated as:

$$\theta = \left(TX_{reac} + TX_{clarif}\right)/(\phi_w + \phi_{eff}) \quad (1)$$

where TX_{reac} and TX_{clarif} are the total amount of solids (biomass, particulate pollution) in the biological reactor and in the clarifier respectively, ϕ_w and ϕ_w are the loss of total solids due to wastage and in the clarifier overflow respectively. The biological sludge age (θ_{bio}) is calculated as θ by considering the biomass (heterotrophs and autotrophs) instead of the total solids. The biological sludge age is more related to the actual biomass activity, but only θ can be practically measured in a plant.

2.2 Introducing a reactive settler

To transform the settler into a reactive unit, each layer has been considered as a well-mixed reactor from the point of view of the soluble and the insoluble components. The ASM1 bioreactions are taking place in each layer. The fate of the total solids concentration is tracked from one layer to the other to fulfil the mass balance. The settling velocity in each layer is a function of its total solids concentration. The gas production rate ($q_{n2,i}$) in a layer i is directly related to the denitrification rate, r_{denit}:

$$q_{n2,i} = -r_{denit,i} = \frac{1-Y_H}{2.86\,Y_H}\rho \quad (2)$$

where ρ is the anoxic growth rate of heterotrophs, which is a function of soluble biodegradable substrate, dissolved oxygen concentration, nitrate and heterotrophic biomass concentrations in the layer. Y_H is the anoxic growth yield. The volume specific mass flow rate of gas entrapped in the settler is given by:

$$Q_{n2} = \frac{1}{v_{settler}} \sum_{i=1}^{10} q_{n2,i} \cdot v_{layer,i} \quad (3)$$

A volume-specific mass flow rate of gas of 8.19 g N/m^3/h has been obtained at 15°C with the reactive settler model. This value is used as a reference to modify the Takács et al.'s settling model with the efficiency factor f_{n2}:

$$v_s(X) = f_{n2} \cdot \max\left[0, \min\left\{v_0', v_0\left(e^{-r_h(X-X_{\min})} - e^{-r_p(X-X_{\min})}\right)\right\}\right] \quad (4)$$

where $X_{\min} = f_{ns} \cdot X_f$ $f_{n2} = \min\left(1.,8.19/Q_{n2}\right)$ and X_f the total suspended solids concentration in the settler feed (Table 1). Using this simple formulation an increase of the denitrification rate due to temperature will decrease the settling velocity, resulting in an increase of the suspended solids discharged at the clarifier weir.

Table 1. Settling parameters

	Parameter	Units	Value
Maximum settling velocity	v_0'	m.d^{-1}	250.0
Maximum Vesilind settling velocity	v_0	m.d^{-1}	474
Hindered zone settling parameter	r_h	m^3.(g SS)$^{-1}$	0.000576
Flocculant zone settling parameter	r_p	m^3.(g SS)$^{-1}$	0.00286
Non-settleable fraction	f_{ns}	dimensionless	0.00228

3. WASTAGE FROM CLARIFIER UNDERFLOW

3.1 Steady-state open loop

The system was first evaluated in open loop with constant influent composition and flow rate (Q_0= 18446 m^3/d). Q_a (= 55338 m^3/d), Q_r (= 18446 m^3/d) and Q_w (= 385 m^3/d) are kept constant. Sludge is wasted at a constant rate (385 m^3/d) from the clarifier underflow. In Figures 2 and 3, some of the characteristics of the plant effluent are presented. The influence on residual ammonia is low. As expected, a lower concentration of nitrate is observed in the plant effluent with the reactive settler, due to the denitrification taking place in this unit. The decrease of nitrate as temperature increases is due to the strong effect of temperature on nitrogen metabolism.

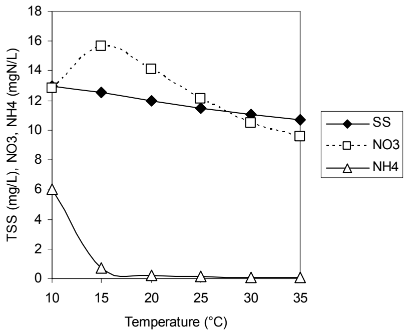
The suspended solids concentration decreases as temperature increases in the case of the non reactive settler but is almost constant with the reactive settler: in the latter case this is due to the carry-over of particulate pollution due to the gas produced by denitrification. These observations are in agreement with practical observations on full-scale wastewater plants and confirm that the model is able to represent real situations. It can be seen in Figure 3 that the sludge ages are not affected by the reactivity of the settler and decrease slightly as temperature increases.

3.2 Dynamic open loop

For dynamic open loop simulations, an 84-days influent file with varying characteristics in terms of composition and flow rate has been built as a series of 12 dry weather weeks, using as a basis the 2 weeks dry-weather file available on the internet (http://www.benchmarkwwtp.org) for BSM1.

In Fig. 4, the variations of ammonia, nitrate and suspended solids in the effluent are shown with respect to time for a temperature of 20°C, Q_a = 55338 m^3/d, Q_r = 18446 m^3/d and Q_w = 385 m^3/d , a reactive settler and wastage from the clarifier underflow. The first 50 days are run with constant influent composition and flow rate (Q_0= 18446 m^3/d).

(a)



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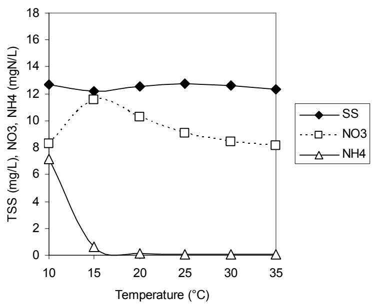


Fig. 2. Variations, as function of temperature, of ammonia, nitrate and suspended solids concentrations in the overflow of the clarifier with a non-reactive (a) and a reactive (b) clarifier.

In Fig. 5, the flow-average concentrations in suspended solids, ammonia and nitrates in the effluent over the last 70 days of the dynamic open loop simulations with a reactive clarifier are plotted versus temperature and for various external recycle strategies: Q_r = 18446 m^3/d or $R = Q_r/Q_0$ = constant. Globally the trends observed during the steady-state open loop tests with respect to temperature (Fig.2) are also observed in the dynamic open loop case (Fig. 3a, b). Q_r = constant and R = 1 give similar results, which could be expected as Q_r was set equal to the average influent flow rate. The range of variations for the sludge age is larger in the case where Q_r = cst than when R =1. Small R values increase the average nitrate concentration in the effluent and decrease the average sludge age.

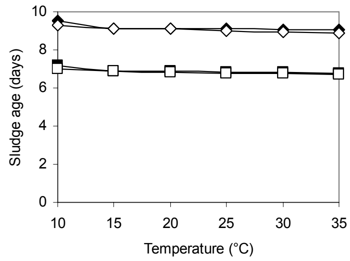
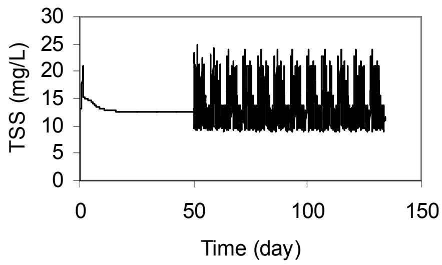


Fig. 3. Variations of the sludge age (□, ■) and the biological sludge age (◊, ♦) for non reactive (closed symbols) and reactive (open symbols) clarifier

(a)



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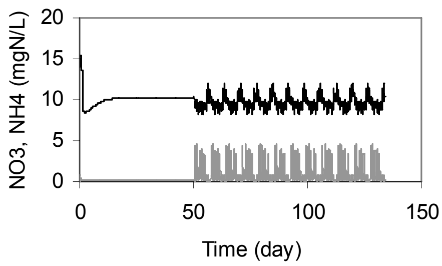


Fig. 4. Variations of suspended solids (a), ammonia (grey line) and nitrate (dark line) (b) with a reactive settler at 20°C (dynamic open loop)

In Fig. 6, the variations of influent flow rate, mixed liquor concentration in the biological reactor and suspended solids in the clarifier underflow are plotted with respect to time over one day. The mixed liquor concentration variations are smoother than the underflow suspended solids concentration. The daily standard deviations and coefficient of variations are 42 mg/L and 2% for the mixed liquor concentration and 197 mg/L respectively and 3.2% for the underflow suspended solids concentration. This is in agreement with experimental observations on full-scale plants.

4. WASTAGE FROM THE BIOLOGICAL REACTOR

Up to this point the sludge wastage has always been from the clarifier underflow. We will now consider that sludge is wasted from the end of the biological reactor. A simple relation can be used to control the sludge age (Marais and Ekama, 1976; WRC, 1984). If it is assumed that at a first approximation the volume of sludge stored in the clarifier can be neglected, as well as the suspended solids escaping the plant through the clarifier weir, the sludge age can be written as:

$$\theta_{set} = V \cdot X_{rec} / (Q_w \cdot X_{reac}) = V / Q_w \tag{5}$$

where V is the total biological reactor volume (= 6 000 m^3) and X_{reac} the average suspended solids concentration in the mixed liquor.

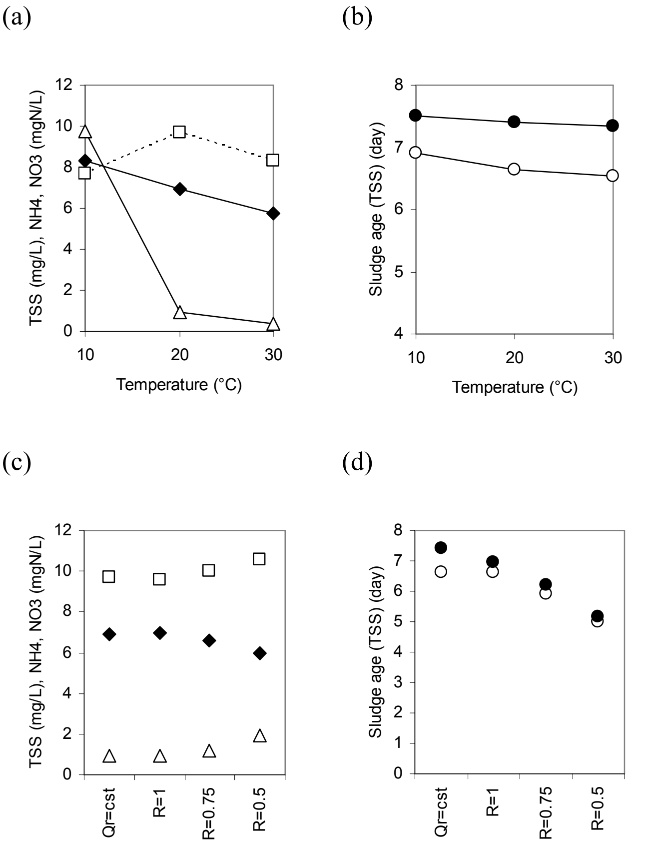


Fig. 5. Suspended solids (♦), ammonia (Δ) and nitrate (□) in the effluent (a, c), min (○) and max (•) sludge ages (b, d) with respect to temperature (a, b) and external recycle control (c, d)

Table 2 compares the observed sludge age ($\theta_{observed}$) calculated with Eq 1. with the theoretical sludge age (θ_{set}) calculated through Eq 5. for different values of Q_w and temperature, with Q_r = 18446 m^3/d under steady state open loop conditions. Under dynamic open loop conditions, the observed sludge age varies between 10.6 and 11.3 days for R = 1 and 12.8 and 13.5 when R = 0.5. This worse performance of the hydraulic control of the sludge age can be expected at low R as more sludge is stored in the clarifier.

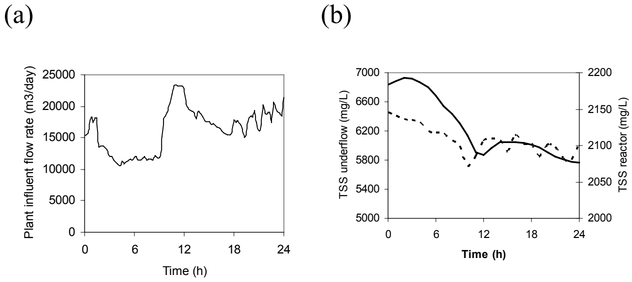


Fig. 6. Variations of influent flow rate (a), suspended solids in the underflow (dotted line) and in the reactor (solid line) (b) over 24 hours

Table 2. Comparison between the set and observed sludge ages for different operating conditions with fixed wastage from the reactor. TSS and nitrate in plant effluent.

T (°C)	Q_w (m^3·d^{-1})	TSS (mg/L)	Nitrate (mg/L)	$\theta_{observed}$ (d)	θ_{set} (d)
10	600	15.69	9.79	11.85	10
20	600	14.30	9.38	11.01	10
30	600	12.99	8.2	10.65	10
30	500	13.63	8.06	12.53	12
30	700	12.50	8.34	9.27	8.57

5. CLOSED LOOP

5.1 Dry weather conditions

The closed loop behaviour was first tested under dynamic dry weather conditions, using the influent file of the open loop case. A discrete PI controller was implemented. At time $k{\cdot}\Delta t$, the manipulated variable u (i.e. wastage flow rate from the clarifier or the reactor) is calculated according to:

$$u(k) = Du + u(k-1) \text{ with } Du = K\left\{\left[e(k) - e(k-1)\right] + \frac{\Delta t}{T_i} e(t)\right\}$$

where the error $e(t) = y^{set} - y(k)$ and under the constrains:

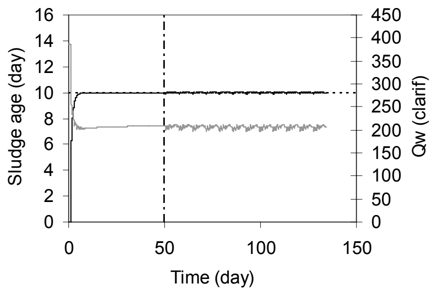
$u_{\min} \le u(k) \le u_{\max}$ and $|Du| \le Du_{\max}$. $y(k)$ is the actual value taken by the controlled variable (i.e. sludge age) and y^{set} the setpoint. To make the interpretation simple, no other closed loop was implemented on the system under study. The sludge age setpoint was fixed at 10 days. The external recycle ratio and the temperature are kept constant (R = 0.5 and T = 20°C). Table 3 summarizes the values of the PI parameters obtained after tuning.

Figure 7 presents the results obtained when the sludge age is computed using Eq. 1. The system is stabilized under constant influent conditions for 50 days before the dynamic influent file is activated. Satisfactory dynamic behaviour is observed for both wastage types. If a constant wastage from the reactor would have been used (600 m^3/d for a setpoint of 10 days according to Eq. 5), the actual sludge age would have been about 13 days: R = 0.5 induces sludge storage in the clarifier, which is not taken into account in Eq. 5.

Table 3. PI controller parameters for the closed loop tests

Wastage type	Clarifier	Reactor
K	-72 m^3/d	-43.2 m^3/d
T_i	0.83 /d	0.83 /d
u_{min}	0. m^3/d	0. m^3/d
u_{max}	500 m^3/d	1000 m^3/d
Du_{max}	5 m^3/d	20 m^3/d

(a)



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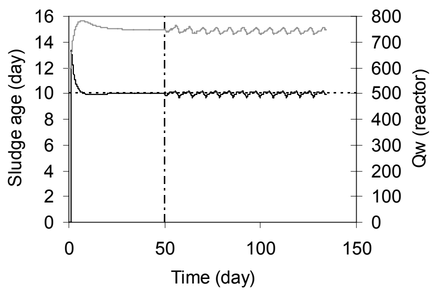

Fig. 7. Closed-loop behaviour with wastage from clarifier (a) and from reactor (b). Dark line = measured sludge age, grey line = wastage flow rate, dotted line = sludge age setpoint.

5.2 Variable weather conditions

Finally a more complex influent file was tested (Fig. 8) where rain events are taking place and temperature varies with respect to time between 17°C and 30°C. The rain and storm event influent files available on Internet were used for that purpose (http://www.benchmarkwwtp.org). Furthermore, the measured sludge age was estimated from a simple TSS measurement in the biological reactor and in the clarifier underflow: $\hat{\theta} = V \cdot X_{reac} / (Q_w \cdot X_{under})$, where X_{under} is the TSS concentration in the clarifier underflow. In practice an exact sludge age determination is difficult and costly as it requires several sensors (TSS, sludge blanket height). R was set to 1. in this example, which means that less sludge will be stored in the clarifier than in the previous example.

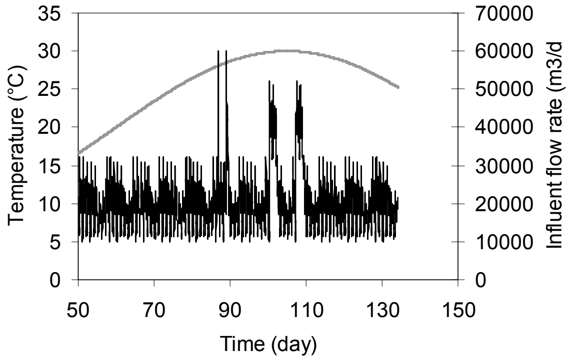

Fig. 8. Influent flow rate and temperature variations in the variable weather influent file

In Fig. 9, the sludge age and the wastage flow rate are plotted for two wastage scenarios: PI control w.r.t. clarifier wastage (a) and constant wastage from the biological reactor (b). The calculation of the sludge age based only on the sludge contained in the reactor and in the clarifier underflow underestimates the actual sludge age. The setpoint is correctly maintained when wastage from the clarifier is used, in spite of the strong system disturbances due to the rain events (Fig. 10). Rain events induce hydraulic disturbances in the clarifier and cause suspended solids to escape the system in the overflow.

The simple strategy of constant wastage from the biological reactor produces a behaviour which is very similar to what is obtained with the PI control from the clarifier wastage, which needs two sensors.

6. CONCLUSIONS

In order to compare whether sludge age control by wastage from the biological reactor is more efficient than wastage from the final clarifier in wastewater treatment plants by activated sludge, the Benchmark Simulation Model 1 has been modified. The secondary settler has been made reactive and the sludge settling characteristics vary as a function of the amount of gas produced by denitrification. Based on these modifications a realistic behaviour is observed. Proportional-integral controllers were then implemented to control the sludge age by wastage from the biological reactor or the clarifier and were tested under different dynamic situations (dry weather, variable weather conditions). It was confirmed that a simple strategy of constant wastage from the biological reactor could be a good alternative when no suspended solids sensor is available. It should be reminded however that this strategy produces low-concentrated wastage sludge, which can be more difficult to deal with that wastage sludge from a secondary clarifier.

In further work, the effect of the combination with other control loops such as dissolved oxygen by air flow rate, ammonium and nitrate by internal recycle rate and external carbon addition, mixed liquor concentration by external recycle rate, will be investigated on longer dynamic simulations to analyze the long-time effects.

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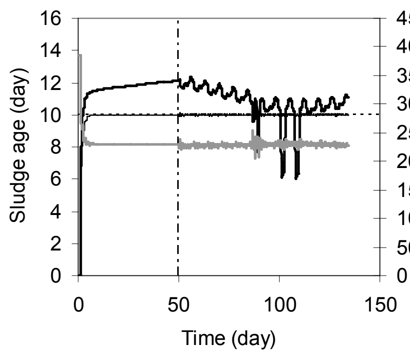
DISCLAIMER

The content of the paper reflects the sole ideas of the authors and is not endorsed by the IWA Task Group on Benchmarking of Control Strategies.

(a)



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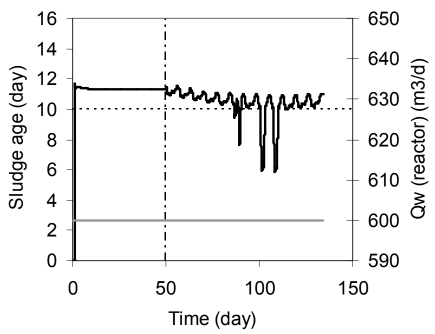

Fig. 9: Sludge age (thin line = estimated sludge age, thick line = real sludge age, grey line = wastage flow rate, dotted line = sludge age set point)

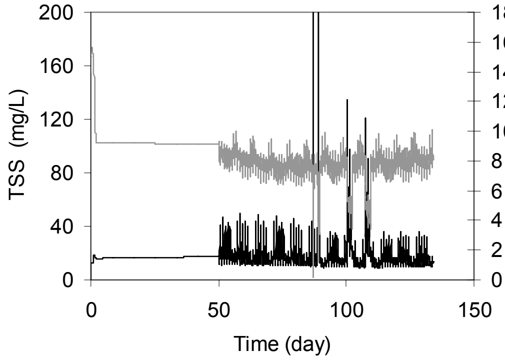

Fig. 10: Nitrate and TSS concentrations in the clarifier overflow under variable weather conditions (black line = TSS, grey line = nitrate)

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