Modelling of a Pilot Wastewater Treatment Plant Operated With Variable Inflows

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The nitrification-denitrification process was studied on suspended activated sludge in a CSTR pilot plant of 15 l. The system was operated in the single sludge mode and was fed with artificial wastewater. The experiments were carried out under steady and non-steady-state operational conditions in order to assess the reliability of mathematical simulations based on a modified ASM1 model that was successfully calibrated at the starting steady-state conditions. The dynamic model predictions and the measured responses of the real process yielded the initial values when the initial steady-state operational conditions were restored after stepped changes in the input flow. Although, relatively good correlations were obtained between the experimental data and the model predictions, in some cases large differences were observed under non-steady-state operational conditions. This reflects the discrepancy between the complex nature of the real activated sludge processes and the model's macroscopic descriptions of these processes.

Key words:
ASM1, calibration, validation, artificial wastewater, nutrient removal

Introduction

Efficient treatment of wastewater requires not only the right technology, but also an understanding of the biological processes and recognition of the factors influencing these processes. A dynamic mathematical model can be a valuable tool for improving our understanding of wastewater treatment processes (*Orhon* et al., 1994; *Olsson* et al., 1999). Many authors have described the use of various Activated Sludge Models (ASM) in wastewater treatment plants (*Makinia* et al., 2000; *Brdjanovic* et al., 2000; *Henze* et al., 2000, *Petersen* et al., 2002). In recent years dynamic models, including commercial software (*Olsson* et al., 1999), have increasingly been used for optimization of activated sludge processes, process control (*Coen* et al., 1997; *Hvala* et al., 2002), and as a decision and detection tool (*Makinia* et al., 2005, *Comas* et al., 2005). The Activated Sludge Model No.1 (ASM1) is generally accepted as state-of-the-art (*Henze* et al., 2000). It was primarily developed for municipal activated sludge wastewater treatment plants (WWTP's), to describe the removal of organic carbon substances and nitrogen with simultaneous consumption of oxygen and nitrate as electron acceptors, and to yield a prediction of sludge production. ASM1 has been extended to include a description of biological phosphorus removal, resulting in ASM2 and ASM2d (*Henze* et al., 2000). Recently, some of the model concepts behind ASM1 have been altered in ASM3 (*Gujer* et al., 1999), which allows the introduction of processes describing the storage of biopolymers under transient conditions.

Koch et al. (2000) pointed out that simulation of a dynamic model based on different stationary states could show large errors. Our previous studies (*Plazl* et al., 1999, 2001) confirmed these observations. Although, the mathematical model was successfully calibrated for one set of experiments at steady state conditions and the calibrated parameters were within or close to the range of values presented in the literature, the calculational results of the same model showed disagreements with the second set of experimental data. These latter data were gathered at different times but under the same conditions, with the exceptions of the concentration of active biomass and the composition of the inflow. The term "successfully calibrated model" simply means that the dynamic form of a particular model can exactly predict all of the process variables measured under steady-state conditions.

This paper presents a study of the nitrification-denitrification process performed in a laboratory pilot plant with the aim of studying the various possibilities for improvement. The system was operated in the single sludge mode under specified process conditions (temperature, dissolved oxygen, flow, recycle ratio), and was fed with artificial wastewater. The model experiment consisted of a

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stationary phase and a double-step input flow disturbance with a return to the stationary phase. The simulation results of a simple dynamic model, previously successfully calibrated at steady-state conditions, were then compared with the observed experimental data.

Experimental

The nitrification-denitrification process studied was tested in a laboratory pilot plant of 15 litres on suspended activated sludge. The continuous CSTR pilot plant was operated under the following volumetric relations: anoxic stage $V_1 = 5$ l, aerobic stage $V_2 = 10$ l, settler $V_3 = 5$ l (Figure 1). Whereas real wastewater, in the Domžale-Kamnik WWTP, often shows great variation in influent quality (inhibitory substances are also occasionally present), we used synthetic wastewater of known chemical composition (yeast extract, meat extract, casein peptone, sodium acetate, ammonium chloride, potassium hydrogen phosphate, some inorganic compounds such as magnesium carbonate, sodium chloride, etc., and up to $\varphi = 20$ % of settled municipal wastewater) (*Landeka*, 1995). After preparation the concentrated synthetic wastewater was filtered through a 1.0 μm filter in order to remove particulate substances and then diluted with tap water.

The anoxic stage was completely mixed and deoxygenated to a dissolved oxygen mass concentration ($\gamma_{O_2,1}$) < 0.1 mg O_2 l^{-1}, while in the aerobic stage the oxygen concentration was ($\gamma_{O_2,2}$) 5.5 mg l^{-1}. The temperature during the whole experiment was kept at 20.0 ± 0.8 °C.

We analyzed the influent, the effluent, and the water of the anoxic and, oxic reactors for the following compounds: chemical oxygen demand (COD) ($\gamma_{S_{COD}} + \gamma_{X_S} + \gamma_{S_I}$), ammonium nitrogen ($\gamma_{N-NH_4}$), Kjeldahl nitrogen ($\gamma_{N-NH_4} + \gamma_{N-org} + \gamma_{N-org,1}$) and nitrate nitrogen ($\gamma_{N-NO_3}$) according to ISO standards. Fractionation of wastewater was simplified as described in the literature (*Makinia* et. al., 2005). The soluble part ($\gamma_{S_{COD}}, \gamma_{S_I}, \gamma_{N-org}, \gamma_{N-org,1}$) was determined after filtration through a 0.45 μm filter. Inert soluble material ($\gamma_{S_I}, \gamma_{N-org,1}$) was determined by a prolonged aeration batch test. The influent and effluent values were based on averaged daily samples, whereas water from the anoxic and oxic stages and settler were analyzed as single samples; these samples were also analyzed for mixed liquor suspended solids (MLSS), total COD and total *N*-Kjeldahl for calculation of the biomass ($\gamma_{COD_C,A}, \gamma_{COD_C,H}, \zeta_{N/COD_C}$) concentration.

The pilot plant was operated under steady-state conditions for four months at a flow rate of 1.5 l h^{-1}. For steady state calibration we took the data of the last five days before changing the flow to the plant. Then the input flow rate was increased from 1.5 l h^{-1} to 2.5 l h^{-1} for two days, then increased further to 3.5 l h^{-1} for two days, and then decreased to the original value of 1.5 l h^{-1} (Figure 2). The daily averaged experimental data with estimated ex-

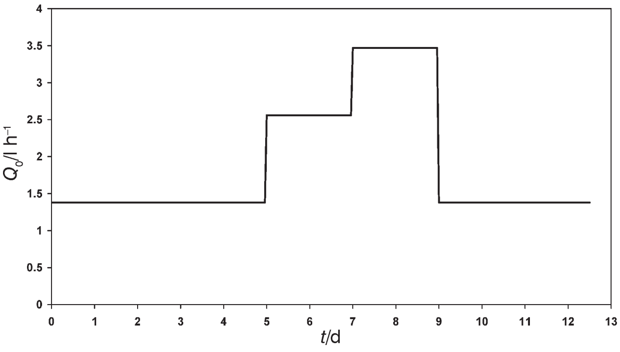

Fig. 2 – *Inflow change during the experiment*

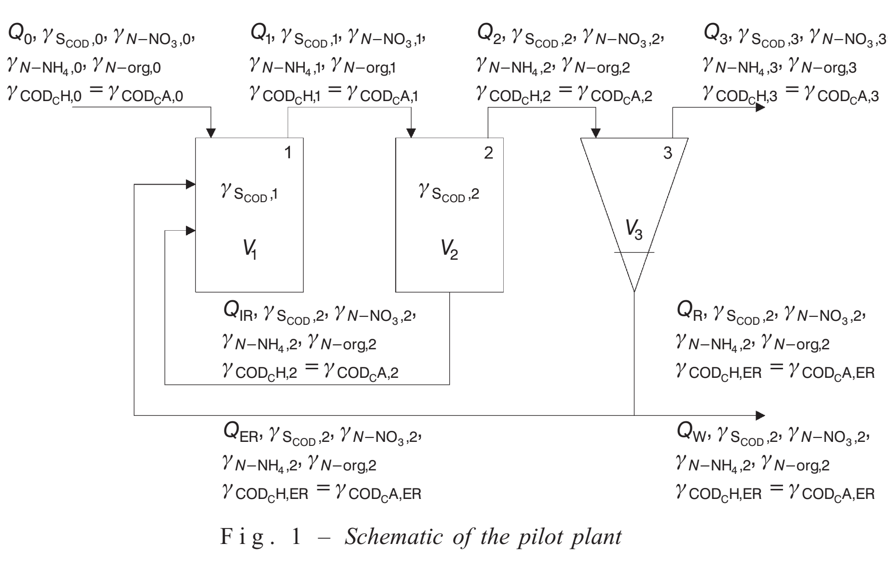

Fig. 1 – *Schematic of the pilot plant*

Table 1 – *Matrix used in the mathematical model*

Component → i		1	2	3	4	5	6	Process rate Γ/mg l^{-1} h^{-1}
j	Process ↓	$\gamma_{S_{COD}}$	γ_{N-NO_3}	γ_{N-NH_4}	γ_{N-org}	$\gamma_{COD_C,H}$	$\gamma_{COD_C,A}$	
1	anoxic growth of heterotrophs	$-\frac{1}{Y_H}$	$-\frac{1-Y_H}{2.86 \cdot Y_H}$	$-\zeta_{N/COD_c}$		1		$\hat{\mu}H \cdot \left(\frac{\gamma_{S_{COD}}}{K_{S_{COD}}+\gamma_{S_{COD}}}\right) \cdot \left(\frac{K_{O_2H}}{K_{O_2H}+\gamma_{O_2}}\right) \cdot \left(\frac{\gamma_{N-NO_3}}{K_{NO}+\gamma_{N-NO_3}}\right) \cdot n_g \cdot \gamma_{COD_C,H} = \Gamma_{COD_C,1}$
2	aerobic growth of heterotrophs	$-\frac{1}{Y_H}$		$-\zeta_{N/COD_c}$		1		$\hat{\mu}H \cdot \left(\frac{\gamma_{S_{COD}}}{K_{S_{COD}}+\gamma_{S_{COD}}}\right) \cdot \left(\frac{K_{O_2H}}{K_{O_2H}+\gamma_{O_2}}\right) \cdot \gamma_{COD_C,H} = \Gamma_{COD_C,2}$
3	aerobic growth of avtotrophs		$\frac{1}{Y_A}$	$-\zeta_{N/COD_c} - \frac{1}{Y_A}$			1	$\hat{\mu}H \cdot \left(\frac{\gamma_{S_{COD}}}{K_{N-NH_4}+\gamma_{N-NH_4}}\right) \cdot \left(\frac{K_{O_2H}}{K_{O_2A}+\gamma_{O_2}}\right) \cdot \gamma_{COD_C,A} = \Gamma_{COD_C,2}$
4	"decay" of heterotrophs	ξ			$\xi \cdot \zeta_{N/COD_c}$	-1		$b_H \cdot \gamma_{COD_C,H}$
5	"decay" of avtotrophs	ξ			$\xi \cdot \zeta_{N/COD_c}$		-1	$b_A \cdot \gamma_{COD_C,A}$
6	ammonification of soluble ogranic nitrogen			1	-1			$\gamma_{N-org} \cdot \gamma_{COD_C,H}$

perimental errors are presented in Table 2. At that time COD mass balance together with sludge retention time (SRT) was checked for consistency (*Makinia* et al., 2005). The calculated SRT of the plant was 27.0 days. These experimental results served for model calibration (steady-state operational conditions) and validation (dynamic operational conditions).

Simulation model

A mathematical model was built, according to ASM1 for activated sludge, including nitrogen removal. For each reactor we wrote mass balance equations (Table 1) based on the known mass concentrations ($\gamma_{S_{COD}}$, γ_{N-NO_3}, γ_{N-NH_4}, γ_{N-org}, $\gamma_{COD_C H}$, $\gamma_{COD_C A}$).

Calibration can be done with different calibration procedures. According to a critical comparison of systematic calibration protocols for activated sludge models (swot analyses), presented by *Sin* et at., 2005, the STOWA protocol appears to be the most straightforward, practical and easy to follow.

Our calibration calculations, employing appropriate numerical methods, were performed using *Mathematica 5.0* at steady state according to a logical stepwise procedure (sludge production, nitrification and denitrification). We followed the STOWA calibration protocol (*Hulsbeek* et al., 2002). The amount of active biomass was calibrated. The experimentally determined ζ_{N/COD_c} was $\zeta_{N/COD_c} = 0.07$ and showed good correlation with the calibrated value (0.077), as shown in Table 3.

Results and Discussion

Different types of models, namely classical ASM1, modified ASM1, and ASM3 were used to perform the calibration procedure. The averaged experimental values of the process variables, collected under steady-state operational conditions for the first five days (Table 2), were used for this procedure. The applied models were based on the following assumptions: the biomass is homogeneous and does not undergo changes in species diversity with time; there are no biological processes ocurring in the settler; the filtered artificial wastewater is composed of only readily biodegradable organic substrates; inert soluble material in all stages of the pilot plant was $\gamma_{S_{COD},1} = 15$ mg l^{-1} and $\gamma_{N-org} = 2.0$ mg l^{-1} was subtracted from the experimental values.

As we expected, the steady-state form of the classical ASM1 model, where the same kinetic and stoichiometric parameters appear in both anoxic and aerobic reactors, failed to achieve successful calibration. The differences between simplified mathematical models, based on a macroscopic description of the processes and the complex nature of the real activated sludge processes, are reflected in the kinetic and stoichiometric parameters that appear in the models. It is understandable that the different process characteristics in the anoxic and aerobic reactors cannot be properly described by the same parameters in both reactors. It was impossible to complete the calibration with experimentally determined kinetic and stoichiometric data, probably for the same reasons. The use of the ASM3 model in the calibration procedure was also not successful. Although this type of model presents a more de-

Table 2 – *Averaged experimental values of process variables and flow rates during the whole experiment*

Symbol	Unit	Day					
		1 … 5	6	7	8	9	10
Q_0	l h^{-1}	1.42 ± 0.02	2.56	2.56	3.47	3.47	1.42
Q_{IR}	l h^{-1}	3.79 ± 0.23					
Q_{ER}	l h^{-1}	2.38 ± 0.07					
Q_W	l h^{-1}	0.017 ± 0.003					
$\gamma_{COD_C H} + \gamma_{COD,A}(1\&2)$	mg l^{-1}	4990 ± 509					
$\gamma_{COD_C H} + \gamma_{COD_C,A}(ER)$	mg l^{-1}	11103 ± 4060					
$\gamma_{S_{COD},0} + \gamma_{S_{COD}} + \gamma_{S_{COD},I}$	mg l^{-1}	526 ± 30					
$\gamma_{S_{COD},0}$	mg l^{-1}	454 ± 26					
$\gamma_{S_{COD},1}$	mg l^{-1}	18.9 ± 1.9	47.2	48.7	117	109	22.9
$\gamma_{S_{COD},2} = \gamma_{S_{COD},3}$	mg l^{-1}	1.3 ± 0.8	13.4	13.4	21.9	24	0.8
$\gamma_{N-NO_3,0}$	mg l^{-1}	3.0 ± 0.8					
$\gamma_{N-NO_3,1}$	mg l^{-1}	0.0 ± 0.0	0.0	0.0	0.0	0.0	0.0
$\gamma_{N-NO_3,2} = \gamma_{N-NO_3,3}$	mg l^{-1}	9.0 ± 0.8	11.2	13.0	14.3	16.1	10.7
$\gamma_{N-NH_4,0}$	mg l^{-1}	20.6 ± 2.2					
$\gamma_{N-NH_4,1}$	mg l^{-1}	7.6 ± 0.3	9.6	9.1	18.3	22.6	8.7
$\gamma_{N-NH_4,2} = \gamma_{N-NH_4,3}$	mg l^{-1}	0.4 ± 0.3	0.3	0.4	10.5	10.1	0.3
$\gamma_{N-org,0} + \gamma_{COD_C,0} + \gamma_{N-org,I}$	mg l^{-1}	55.7 ± 3.2					
$\gamma_{N-org,0}$	mg l^{-1}	50.2 ± 4.1					
$\gamma_{N-org,1}$	mg l^{-1}	2.2 ± 0.9					
$\gamma_{N-org,2} = \gamma_{N-org,3}$	mg l^{-1}	0.2 ± 0.2					

Table 3 – *Kinetic and stoichiometric constants obtained by the calibration procedure and compared to the literature values (Henze et al., 2000)*

Parameter	Unit	Calibrated values (modified ASM1)	Lit. data (ASM1)	Lit. data (ASM3)
$Y_{H,1}$	mg mg^{-1}	0.73	0.67	0.43
$Y_{H,2}$	mg mg^{-1}	0.67	0.67	0.54
$Y_{A,2}$	mg mg^{-1}	0.14	0.24	0.24
$\mu_{H,1}$	h^{-1}	0.49	0.25	0.083
$\mu_{H,2}$	h^{-1}	0.32	0.25	0.083
η_g	–	1	0.8	0.6
$\zeta_{N/COD}$	mg N/mg CODc	0.077	0.086	0.07
$K_{S,1}$	mg COD/l	20	20	2
$K_{S,2}$	mg COD/l	180	20	2
$b_{H,1}$	h^{-1}	0.0042	0.026	0.0042
$b_{H,2}$	h^{-1}	0.0196	0.026	0.0083
$\mu_{A,2}$	h^{-1}	0.0365	0.033	0.042
$b_{A,1}$	h^{-1}	0.0021	0.0021	0.0021
$b_{A,2}$	h^{-1}	0.006	0.0021	0.0063
$k_{a,1}$	l mg^{-1} h^{-1}	0.00254	0.003	-
$k_{a,2}$	l mg^{-1} h^{-1}	0.00366	0.003	-
K_{OH}	mg l^{-1}	0.2	0.2	0.2
K_{OA}	mg l^{-1}	0.4	0.4	0.5
K_{NO}	mg l^{-1}	0.5	0.5	0.5
K_{NH}	mg l^{-1}	1.0	1.0	1.0

tailed description of the activated sludge processes on the macroscopic level, at the same time it requires knowledge of the additional stoichiometric and kinetic constants that appear in such very sensitive parametric mathematical models.

Calibration was successfully performed when the modified ASM1 model was used. These simple modifications in the ASM1 model are based on the different value of the same parameters (Y_H, b_H, K_s, b_A) applied in anoxic and aerobic reactors as in the ASM3 model. In Table 3 the calibration results are presented and are compared to the most often published values of kinetic and stoichiometric constants in connection with ASM1 and ASM3 models (*Henze* et al., 2000).

The calibrated kinetic and stoichiometric values were then used for calculations and process simulations, based on the dynamic form of the modified ASM1 model. A comparison between the model predictions and the experimental responses of the real system to the double-step inflow change is presented in Figures 3–8. Some general conclusions can be drawn from these graphs. First, the dynamic model predictions and the measured responses of the real process, within experimental error, followed the expected return to the stationary state, when the initial steady-state operational conditions were restored after the dynamic input flow disturbances. Secondly, the agreements between the dynamic calculations and the measurements for the periods of steady-state conditions confirm the calibration procedure. A larger difference between the predictions and the experimental data can be observed in some cases for the non-steady-state operational conditions. The steep responses of the model predictions at the positions of flow changes are due to the numerical responses of the step function F_0 introduced into the system of model equations.

Conclusions

A comparison of the mathematical calculations and the measured responses of the real process to the described non-steady-state operational conditions led us to these conclusions:

Both, the dynamic model predictions, and the measured responses of the real system to substantial changes in the operational conditions, showed a return to the stationary state when the initial steady-state operational conditions were restored.

Although, the agreement between the dynamic calculations and measurements for the periods of steady-state conditions confirm successful calibration, at the non-steady-state operational conditions larger differences between the predictions and the experimental data are still observed in some cases (*Sin* et. al., 2005).

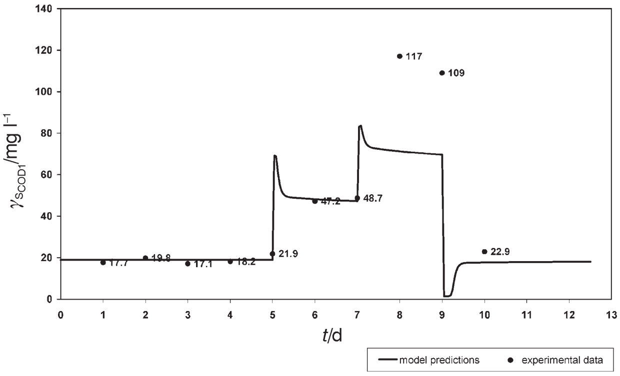

Fig. 3 – *Dynamic model prediction of COD mass concentration in the first anoxic reactor*

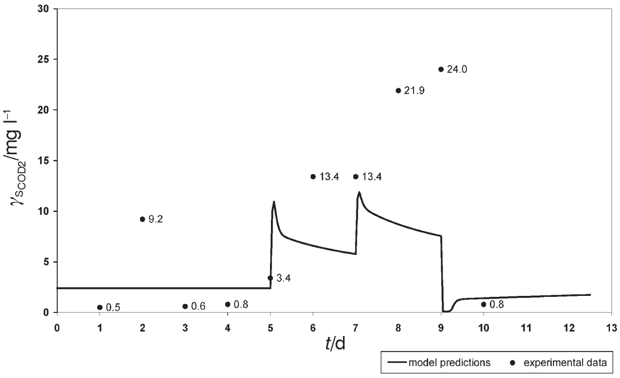

Fig. 4 – *Dynamic model prediction of COD mass concentration in the second aerobic reactor*

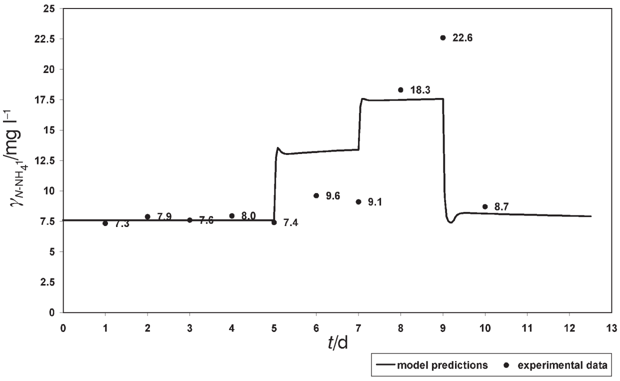

Fig. 5 – *Dynamic model prediction of ammonia mass concentration in the first anoxic reactor*

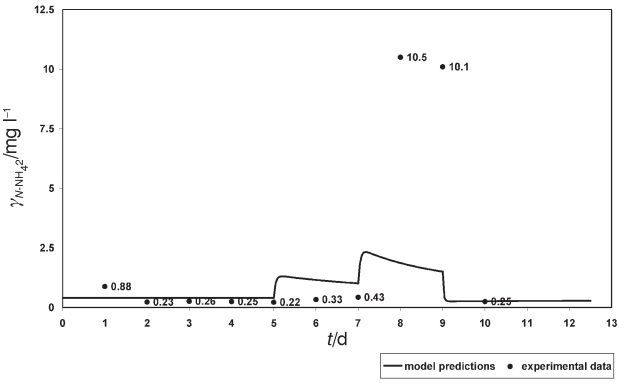

Fig. 6 – *Dynamic model prediction of ammonia mass concentration in the second aerobic reactor*

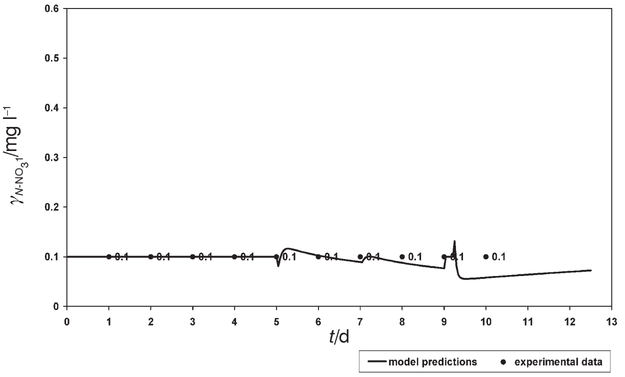

Fig. 7 – *Dynamic model prediction of nitrate mass concentration in the first anoxic reactor*

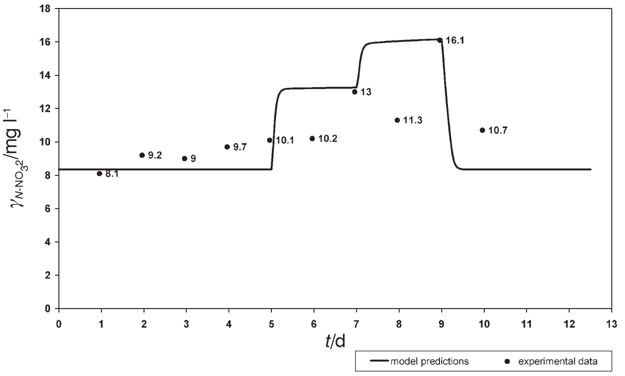

Fig. 8 – *Dynamic model prediction of nitrate mass concentration in the second aerobic reactor*

It is shown again how very difficult, and in a way problematical, is the role of the kinetic and stoichiometric constants in the modelling of wastewater treatment plants. Most of these constants, which in fact are treated as modelling parameters, actually cover the gap between the complex nature of activated sludge processes and the mathematical models based on macroscopic descriptions of the real processes (*Koch* et al., 2000, *Plazl* et al., 1999, 2001).

However, in spite of the rather simplified mathematical model containing many assumptions, we obtained relatively good correlations with the experimental data. The application of the dynamic ASM models for optimization of activated sludge processes requires well-considered evaluations of the kinetic and stoichiometric constants, from both the experimental and mathematical points of view.

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Abbreviations and notation

μ_H – max. specific growth rate of heterotrophic biomass, h^{-1}
μ_A – max. specific growth rate of autotrophic biomass, h^{-1}
η_g – correction factor for mH under anoxic conditions
ξ – portion of particulate decay into soluble substrate
b_A – decay coeff. for autotrophic biomass, h^{-1}
b_H – decay coeff. for heterotrophic biomass, h^{-1}
Q – volumetric flow rate, l h^{-1}
t_{HRT} – hydraulic residence time, h
ζ_{N/COD_C} – mass ratio in biomass, m_N/m_{COD_C}, mg mg^{-1}
k_a – ammonification rate coefficient, l mg^{-1} h^{-1}
K_{NH} – ammonia half-saturation constant for autotrophic biomass, mg l^{-1}
K_{NO} – nitrate half-saturation constant for heterotrophic biomass, mg l^{-1}
$K_{O_2,A}$ – oxygen half-saturation constant for autotrophic biomass, mg l^{-1}
$K_{O_2,H}$ – oxygen half-saturation constant for heterotrophic biomass, mg l^{-1}
$K_{S_{COD}}$ – Substrate half-saturation constant for heterotrophic biomass, mg l^{-1}
MLSS – mixed liquor suspended solids, mg l^{-1}
$\Gamma_{COD_C,A}$ – process rate of aerobic growth for autotrophs, mg l^{-1} h^{-1}
$\Gamma_{COD_C,H1}$ – process rate of anoxic growth for heterotrophs, mg l^{-1} h^{-1}
$\Gamma_{COD_C,H2}$ – process rate of aerobic growth for heterotrophs, mg l^{-1} h^{-1}
γ_{N-org} – soluble organic nitrogen concentration after filtration through 0.45 mm pore diameter, mg l^{-1}
$\gamma_{N-org,I}$ – inert soluble organic nitrogen concentration after filtration through 0.45 mm pore diameter, mg l^{-1}
γ_{N-NH_4} – ammonia nitrogen mass concentration, mg l^{-1}
γ_{N-NO_3} – nitrate nitrogen mass concentration, mg l^{-1}
γ_{O_2} – dissolved oxygen mass concentration, mg l^{-1}
$\gamma_{S_{COD}}$ – readily biodegradable (soluble) substrate mass concentration after filtration through 0.45 mm pore diameter, mg l^{-1}
$\gamma_{S_{COD},1}$ – inert soluble substrate mass concentration after filtration through 0.45 mm pore diameter, mg l^{-1}
V – volume of the reactor, l
$\gamma_{COD_C,A}$ – active autotrophic biomass concentration in COD units,
$\gamma_{COD_C,H}$ – active heterotrophic biomass concentration in COD units,
$\gamma_{S_{COD}}$ – particulate biodegradable substrate mass concentration, mg l^{-1}
Y_A – autotrophic yield, mg mg^{-1}
Y_H – heterotrophic yield, mg mg^{-1}

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IR – internal recycle
ER – external recycle
W – waste
R – effluent from the settler
1 – anoxic reactor
2 – aerobic (oxic) reactor
3 – settler

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