The Results of Mathematical Model and Pilot Plant Research of Wastewater Treatment

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In memoriam Prof. Emeritus Vera Johanides

Mathematical models of the activated sludge process are believed to be a useful tool for research, process optimisation and troubleshooting at full-scale treatment plants, teaching and design assistance. Every simulation model is specific, because it contains kinetic and stoichiometric coefficients, which depend on the nature of a wastewater treatment plant.

The present paper is concerned with a comparison between the practical results from a pilot wastewater treatment plant and mathematical model predictions results for steady-state conditions. A comparison of the real pilot plant quantities and model simulation was done proving the model confidence in the sense of carbon and nitrogen removal. The model simulated the real process successfully.

Keywords:
Wastewater treatment, activated sludge, pilot plant, mathematical model, calibration.

Introduction

Activated sludge is a complex process and simulation of such system must necessarily account for a large number of reactions between a large numbers of components. Successful process modeling requires good knowledge of process variables, such as the most influential kinetic, and stoichiometric quantities, and the resulting biomass composition. The activated Sludge Model No. 1 (ASM1) presented by the IAWQ Task Group on Mathematical Modelling for Design and Operation of Biological Wastewater Treatment Processes (*Hence* et al., 1987), is generally accepted as state-of-the-art and is used for simulation of waste treatment plants in many studies (*Kabouris* and *Georgakakos*, 1996; *Janning* et al., 1997; *Keesman* et al., 1998; *Vanrolleghem* et al., 1999; *Plazl* et al., 1999). However, the applications of the models are limited due to a lack of advanced input quantities values required by the models. Although the numbers of typical conversion factors and stoichiometric constants are presented in the literature, they usually depend on the nature of a specific wastewater treatment plant. The biological nature of wastewater treatment processes implies that the characteristic of the process be determined over and over again according to the local situation (*Vanrolleghem* et al., 1999).

The paper presents an overview of activated sludge experiments taking place in a pilot wastewater treatment plant for the calibration of ASM1. The calibration of the model was successfully experimentally confirmed for steady-state operational conditions.

Experimental

The raw wastewater was municipal wastewater, which flows to a central wastewater treatment plant Ljubljana, from a mixed sewage system. The laboratory at Vodovod-Kanalizacija Ltd., Ljubljana, monitors daily the activated sludge process of a pilot wastewater treatment plant with the volume of nitrification cone, V_N = 1.913 m^3, and the volume of denitrification cone, V_D = 0.707 m^3 (Figure 1). The temperature was about 22 °C. Inflow was proportional to real flow on Wastewater treatment plant of Ljubljana, regulated by pilot plant pumps. For the purpose of this work, some additional analyses were made. The concentrations of activated sludge, X_T, ammonium and NH_3 nitrogen, S_{NH}, nitrate and nitrite nitrogen, S_{NO}, total Kjeldahl nitrogen, S_{TKN}, dissolved oxygen, S_O, and the concentration of readily biodegradable substrate (in g m^{-3} COD), S_S, were determined by standard methods (Standard Methods for Water and Wastewater, 19th Edition, AWWA, Washington d.c., 1995): SIST ISO 6060, SM 4500-NH3C, SM 2540 D, SM 2540 E. The average measured values with deviations are presented in Table 1 (Drolka, 2000).

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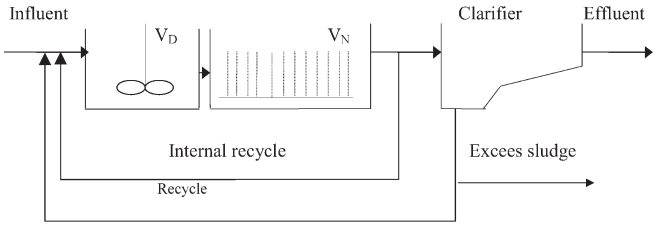


F i g . 1 – *Scheme of the wastewater pilot plant*

Simulation model

The average measured values of process parameters presented in Table 1, served as input parameters for the steady-state model based on real conditions and developed according to IAWQ model No. 1 (*Hence* et al., 1987). Biodegradable organic matter is divided into readily degradable and slowly degradable matter. For the purpose of modelling, the readily degradable material is treated as if it were soluble, whereas the slowly biodegradable substrate is treated as if it were particulate. The rate of hydrolysis of organic nitrogen is proportional to the hydrolysis of carbon matter. For the concentration determination of heterotrophic and autotrophic biomass, simplified theoretical values were observed: 96.5 % of biomass are heterotrophic microorganisms, 3.5 % of biomass are autotrophic microorganisms, and 32 % of heterotrophic biomass are also active under anoxic conditions. The model with the 'death-regeneration' concept (model includes biomass regeneration as a substrate), presupposes that there is no oxygen requirement for the death of microorganisms under anoxic conditions.

T a b l e 1 – *The average measured values of process quantities for the period of one month (source: JP Vo-Ka Ltd., Ljubljana).*

Q_0	= 205 ± 10 L^3 h^{-1}
Q_{ir}	= 290 ± 10 L^3 h^{-1}
Q_r	= 158 ± 10 L^3 h^{-1}
S_O	= 1.9 ± 1 mg L^{-3} O_2
$S_{S,0}$	= 419 ± 200 mg L^{-3} COD
$S_{TKN,0}$	= 28 ± 8 mg L^{-3}
$S_{NH,0}$	= 16.3± 3.5 mg L^{-3} N
$S_{NO,0}$	= 0.58± 0.25 mg L^{-3} N
X_T	= 3500± 400 mg L^{-1} MLSS

0 – inlet

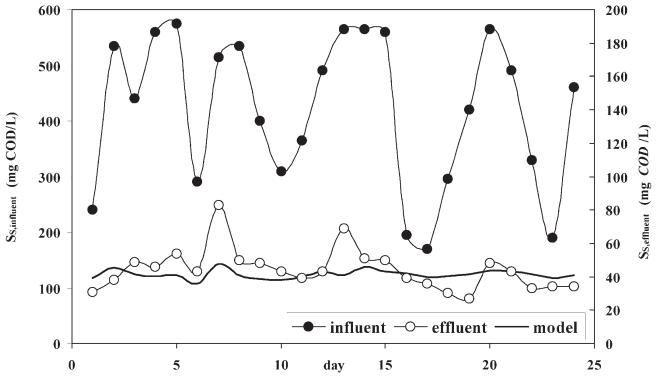
Results and Discussion

On the basis of the average experimental values of sludge process variables the estimation of kinetic and stoichiometric parameters can be obtained by steady-state model calibration, using an appropriate numerical method, built in a mathematical package (Mathematica 4.0). The comparison between calibrated parameters and typical literature values, are presented in Table 2.

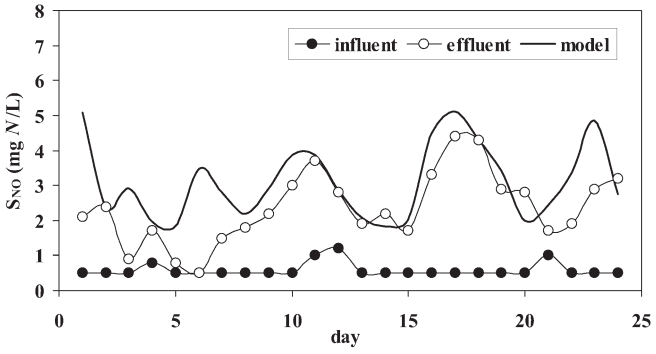
The calibrated kinetic and stoichiometric parameters can now be used for process simulation of activated sludge process taking place in pilot wastewater treatment plant.

The comparison between measured values of process parameters in the effluent for each day of period of 25 days and the model predictions, based on estimated kinetic and stoichiometric coefficients (Table 2), are presented in Figures 2–5. Despite the relatively high fluctuations of process parameters in the influent, it is quite remarkable that the model predictions are in agreement with the experimental data in the effluent.

The average measured wastewater treatment efficiency for concentration of substrate, γ_S, was



F i g . 2 – *Influent substrate concentration and the comparison between measured and predicted effluent substrate concentration.*



F i g . 3 – *Influent nitrate and nitrite nitrogen concentration and the comparison between measured and predicted effluent S_{NO} concentration.*

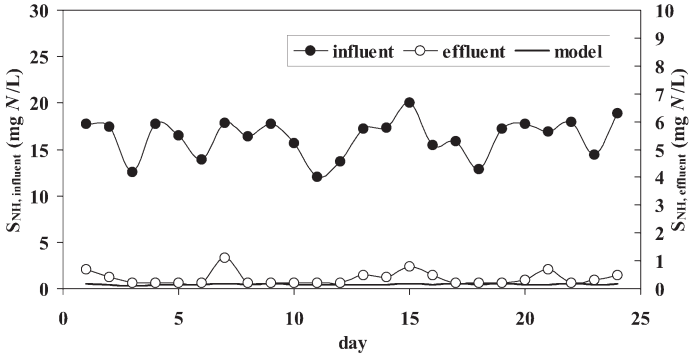


Fig. 4 – *Influent ammonium and NH_3 nitrogen concentration and the comparison between measured and predicted effluent S_{NH} concentration.*

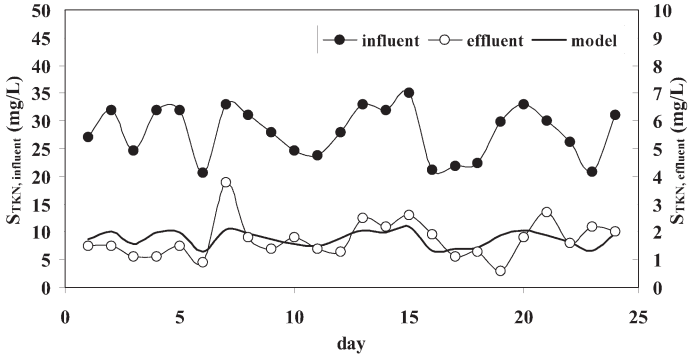


Fig. 5 – *Influent total Kjeldahl nitrogen concentration and the comparison between measured and predicted effluent S_{TKN} concentration.*

Table 2 – *Estimated and typical literature values for kinetic and stoichiometric coefficients (Hence et al., 1994).*

Parameter (Units)	Calibrated	Typical values
$\mu_{H,max}$ – Maximum specific growth rate for heterotrophic biomass, (day^{-1})	7.4	6
$\mu_{A,max}$ – Maximum specific growth rate for autotrophic biomass, (day^{-1})	1.04	0.8
K_S – Half-saturation coefficient for heterotrophic biomass, (g *COD* m^{-3})	60	20
K_{NH} – Ammonia half-saturation coefficient for autotrophic biomass, (g *N* m^{-3})	0.75	1.0
K_{NO} – Nitrate nitrogen half-saturation coefficient, (g *N* m^{-3})	0.5	0.5
K_X – Half-saturation coefficient for hydrolysis of slowly degradable substrate, (g *COD* g COD_c^{-1})	0.01	
k_h – Maximum specific hydrolysis rate, (g *COD* (g COD_c *day*)$^{-1}$)	10	3
$K_{O,H}$ – Oxygen half-saturation coefficient for heterotrophic biomass, (g O_2 g^{-1} m^{-3})	0.1	0.2
$K_{O,A}$ – Oxygen half-saturation coefficient for autotrophic biomass, (g O_2 g^{-1} m^{-3})	0.4	1.0
$b_{H,a}$ – Decay coefficient for heterotrophic biomass (aerobic conditions), (day^{-1})	0.63	0.62
$b_{H,d}$ – Decay coefficient for heterotrophic biomass (anoxic conditions), (day^{-1})	0.2	
$b_{A,n}$ – Decay coefficient for autotrophic biomass (aerobic conditions), (day^{-1})	0.01	0.05-0.15
$b_{A,d}$ – Decay coefficient for autotrophic biomass (anoxic conditions), (day^{-1})	0.03	
k_a – Ammonification, (m^3 (g *COD* day)$^{-1}$)	0.095	0.08
$Y_{H,a}$ – Yield for heterotrophic biomass (aerobic conditions), (g COD_c g COD^{-1})	0.75	0.67
$Y_{H,d}$ – Yield for heterotrophic biomass (anoxic conditions), (g COD_c g COD^{-1})	0.24	
$Y_{A,n}$ – Yield for autotrophic biomass (aerobic conditions), (g COD_c g^{-1} N^{-1})	0.24	0.24
f_B – Biomass fraction in the activated sludge, (g *VSS* / g *MLSS*)	0.62	
f_{CS} – *COD/VSS* ratio of the activated sludge, (g COD_c / g *VSS*)	1.45	
η_h – Coefficient to reduction reaction rate of hydrolysis (anoxic conditions), (/)	0.4	0.5
i_{XB} – Nitrogen fraction in the active biomass, (g *N* / g COD_c)	0.086	0.086
f_{PX} – Fraction of active biomass leading to particulate products, (/)	0.055	
α_R _ Soluble inert product formation coefficient, (/)	0.01	
η_g – Coefficient to reduction reaction rate of heterotrophic (anoxic conditions), (/)	0.8	0.8
f_{EX} – Fraction of inert biomass, (/)	0.2	0.2

85.2 % and predicted with the model 83.8 %. The experimental efficiency for ammonium and NH_3 nitrogen, S_{NH}, was 97.5 % and predicted 98.9%. Similarly, acceptable agreement between measured and calculated wastewater treatment efficiency was observed for total Kjeldahl nitrogen, S_{TKN}, (92.1 % / 93.8 %).

Conclusions

A nitrifying and denitrifying activated sludge process of Ljubljana municipal wastewater, taking place in a pilot wastewater plant, was calibrated by the IAWPRC Activated Sludge Model 1 in order to estimate the kinetic and stoichiometric parameters. The model calibration was successfully experimentally confirmed for steady-state operational conditions at real fluctuations of wastewater quality in the influent.

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Symbols

b – decay coefficient, d^{-1}

K – half-saturation coefficient, –

k_a – ammonification, $m^3 \cdot g_{COD}^{-1} \cdot d^{-1}$

k_h – maximum specific hydrolysis rate, $g_{COD} \cdot g_{CODc}^{-1} \cdot d^{-1}$

Q – volume flow rate, $m^3 \cdot h^{-1}$

w – mass fraction, –

Y – yield, –

Greek letters

α_R – soluble inert product formation coefficient, –

γ_S – substrate concentration, $mg \cdot m^{-3}$

γ_X – biomass concentration, $mg \cdot m^{-3}$

ρ – mass ratio of the activated, $g_{CODi} \cdot g_{VSS}^{-1}$

η_h – coefficient to reduction rate of hydrolisis, –

μ – specific growth rate, d^{-1}

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