Algae based wastewater treatment model using the RWQM1

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Abstract: In this paper, we propose a model describing the dynamics of an algae based wastewater treatment process in an activated sludge environment. As the basis for the process modelling, the River Water Quality Model no. 1 (RWQM1) is chosen. In order to evaluate the applicability of the model to an activated sludge process, the proposed model is compared to the Activated Sludge Model no. 1 (ASM1) since is a model extensively used to describe activated sludge processes. The study involves the evaluation of the RWQM1 considering changes in some process rates such as the hydrolysis and the algae growth on ammonium and nitrate. Results shows that these changes make it possible for the RWQM1 to mimic the results given by the ASM1.

Keywords: algae; activated sludge process; wastewater treatment; RWQM1; ASM1.

Introduction

The focus of wastewater management is now focused on the sustainability of the wastewater treatment process itself. Algae based wastewater treatment is an alternative to conventional wastewater treatment since it has the potential to yield an acceptable effluent quality at a lower ecological cost. The process has been investigated for more than 50 years. Some important overviews of this process have been provided by Hoffmann (1998) and de la Noüe et al. (1992).

Algae based wastewater treatment has the potential to overcome several of the problems encountered in conventional wastewater treatment. The oxygen produced during algal photosynthesis reduces the need for energy intensive aeration. It might even make the aeration redundant. Carbon dioxide is consumed during photosynthesis. Hence, an algae based wastewater treatment plant may potentially work as a carbon dioxide sink mitigating global warming. It has been shown that algae based wastewater treatment is sufficient for high level reductions of organic matter, nitrogen and phosphorous, as discussed by Hoffmann (1998). The large nutrient uptake of algae may replace the usage of chemical precipitation and the processes of nitrification and denitrification. This would make the extensive usage of precipitation chemicals and external carbon redundant. Also, the sludge produced in an algae based wastewater treatment process would be rich in both nitrogen and phosphorous, and hence a potentially valuable fertilizer.

The aim of this work is to propose a model describing the dynamics of algae based wastewater treatment. To the best of the authors knowledge such a study is novel and would increase the understanding of this kind of processes.

Material and Methods

The River Water Quality Model no. 1 (RWQM1) (see Reichert et al. (2001) for details of the model description) was chosen as the basis for modelling the algae based wastewater treatment since it includes the state variables and processes necessary to describe the dynamics of bacteria, algae and pH.

Since the RWQM1 was originally developed to describe a river system, it was important to evaluate if the model is applicable to an activated sludge environment.

Therefore, some adaptations of the RWQM1 model were assessed. Also, a comparison was made between the system dynamics of the RWQM1 and the Activated Sludge Model no. 1 (ASM1), which is a model extensively used to describe an activated sludge process accurately.

To get a straightforward comparison between the RWQM1 and the ASM1, the study involved two main scenarios: (i) RWQM1 without algae dynamics, and (ii) RWQM1 with algae dynamics.

For scenario (i), two tasks were performed: change in the hydrolysis process rate assuming predefined values for some parameters, and non-linear system identification so to get the optimization of parameters. For the non-linear system identification, the Matlab function *fmincon* was used to minimize the cost function $V(\theta)$ defined as

$$V(\theta) = \sum_{i=1}^{N} \sum_{j=1}^{J} e_{rel}^{2}, \quad e_{rel} = \frac{y_{sim,asm1}^{j}(i) - y_{sim,rwqm1}^{j}(i)}{\bar{y}_{sim,asm1}^{j}(i)}, \qquad i=1,2,\ldots,N \tag{1}$$

where $y_{sim,rwqm1}$ denoting the values from the RWQM1 and $y_{sim,asm1}$ denoting the values from the ASM1, with j denoting the state variable and i denoting the discrete time step. Supplementary results can be found in Pierong (2014), where parameter optimization through linear system identification has also been studied.

For scenario (ii), two versions of the RWQM1 were considered. The first version assumes the default parameters of this model (cf. Reichert et al. (2001)). The second version used the results of the parameter optimization obtained in scenario (i). Both versions included the updated expression for the hydrolysis, and some additional changes in the algae growth on ammonia and nitrate.

Both the RWQM1 and the ASM1 were simulated over 1000 days using constant influent data, where only the last 500 days were used for evaluation. Matlab/Simulink® environment was used for the model implementation.

Results and Discussions

- Scenario (i): No algae dynamics included

The algae dynamics of RWQM1 were excluded in order to have a simple comparison between models. The original RWQM1 set-up failed in describing an activated sludge process (results not shown). Therefore, it was decided to modify its kinetics, specifically the hydrolysis process rates by merging the curretn expression with the one given in the ASM1. Therefore, a new expression for the hydrolysis was defined as follows

$$k_{hyd} \cdot e^{\beta_{hyd} \cdot (T - T_0)} \cdot \frac{X_S / X_H}{K_X + X_S / X_H} \cdot \left(\frac{S_{O2}}{K_{O2} + S_{O2}} + \eta_h \cdot \frac{K_{O2}}{K_{O2} + S_{O2}} \cdot \frac{S_{NO3}}{K_{NO} + S_{NO3}} \right) \cdot X_H \tag{2}$$

with β_{hyd} = 0.7 ºC^{-1} and T_0 = 20 ºC, as suggested by Reichert et al. (2001). η_h was set to 0.8 and the half-saturation coefficients K_x, K_{o2} and K_{NO} were set to 0.1, 0.2 gO/m^3 and 0.5 gN/m^3, respectively, as in the BSM1 framework (Alex et al. 2008).

In this scenario, two differeent cases were evaluated in order to observe different aspects of the system dynamics. The first case was focused on the aerobic growth of both autotrophic and heterotrophic bacteria. The second case was focused on the anoxic growth of heterotrophic bacteria. Systen dynamics were observed by 50% step increase in the influent. Results are shown in Figure 1.

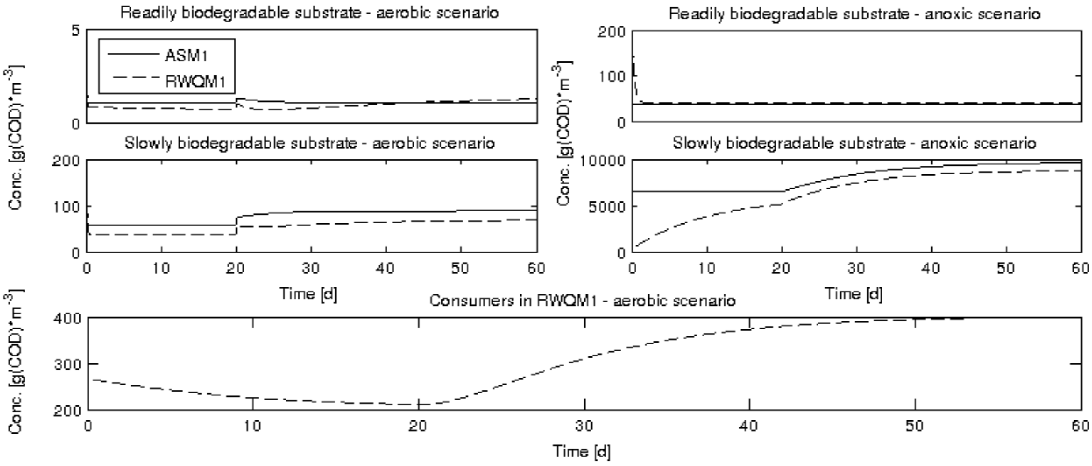

Figure 1 Comparison between ASM1 (solid) and RWQM1 (dashed) including an updated hydrolysis process. Scenario with 50% increase in the inflow magnitude.

Results from simulations shown that the adjustment of the hydrolysis improved the consistency between the RWQM1 and the ASM1 in terms of readily and slowly biodegradable substrate. Nevertheless, the adjustment of the hydrolysis did not give significat changes in other state variables.

Next, a non-linear system identification was performed to improve the RWQM1. The optimization was applied to seven kinetic parameters: $k_{gro,H,aer}$ (in aerobic growth of heterotrophic with NH_4), $k_{resp,H,aer}$ (in aerobic endogenous respiration of heterotrophs), $k_{gro,N1,aer}$ (growth of 1st stage nitrifiers) $k_{resp,N1}$ (aerobic endogenous respiration for 1st stage nitrifiers), $k_{resp,CON}$ (aerobic endogenous respiration of consumers), $k_{death,CON}$ (death of consumers), k_{hyd} (hydrolysis); and nine state variables: readily and slowly biodegradable substate, ammonium plus ammonia, particulate inorganic matter, heterotrophic bacteria, autotrophic bacteria, dissolved oxygen, nitrate plus nitrite and consumers. The updated hydrolysis given by expression (2) was included. Results are shown in Figure 2.

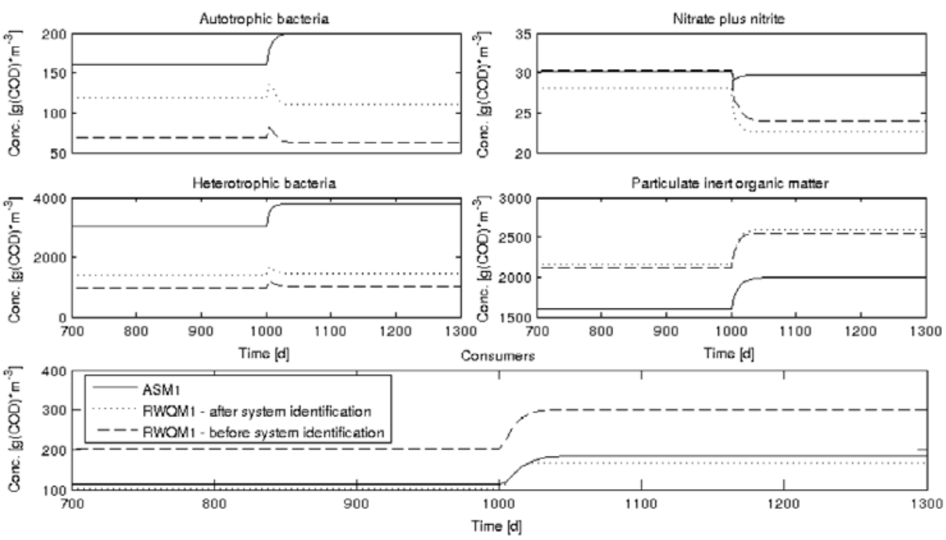

Figure 2 Comparison between ASM1 (solid) and RWQM1 with default parameters (dashed) and parameters based on non-linear system identification (dotted). The updated hydrolysis was included.

Results show that the non-linear system identification improved the model performance, in particular for the case of autotrophic bacteria, heterotrophic bacteria and consumers. However, the model performance did not improve in terms of the state variables representing nitrate plus nitrite and particulate inert inorganic matter

- Scenario (ii): Incorporating algae dynamics

Processes describing algal growth were by default included in RWQM1 to describe the algae dynamics of a river system. It was considered unlikely that they would describe the algae dynamics of an activated sludge process accurately because of the differences between the systems. Therefore, an alternative description of algal growth was developed.

Algal growth was divided into two processes, growth on ammonium and growth on nitrate. Both processes were defined as functions of temperature, pH and several limiting substrates. For the case of the algal growth on ammonium, the new process rate was defined as

$$\frac{dX_A}{dt} = k_{gro,ALG} \cdot e^{\beta_{ALG}\cdot(T-T_0)} \cdot \frac{K_{pH}}{K_{pH}+y(pH)} \cdot \frac{S_{NH4}}{K_{N,ALG}+S_{NH4}} \cdot \frac{S_{HPO4}+S_{H2PO4}}{K_{PO4,ALG}+S_{HPO4}+S_{H2PO4}} \cdot \frac{S_{CO2}}{K_{CO2}+S_{CO2}} \cdot X_{ALG} \tag{3}$$

while the corresponding process for algal growth on nitrate was defined as

$$\frac{dX_A}{dt} = k_{gro,ALG} \cdot e^{\beta_{ALG}\cdot(T-T_0)} \cdot \frac{K_{pH}}{K_{pH}+y(pH)} \cdot \frac{S_{NO3}}{K_{N,ALG}+S_{NO3}} \cdot \frac{K_{N,ALG}}{K_{N,ALG}+S_{NH4}} \cdot \frac{S_{HPO4}+S_{H2PO4}}{K_{PO4,ALG}+S_{HPO4}+S_{H2PO4}} \cdot \frac{S_{CO2}}{K_{CO2}+S_{CO2}} \cdot X_{ALG}. \tag{4}$$

Introducing algae into the model affected the system dynamics in terms of most state variables. Table 1 summarizes the steady-state values for the activated sludge model based on RWQM1 for scenario (i) and (ii), i.e. model without algae dynamics and model with algae dynamics, respectively.

Table 1 Steady-state values of activated sludge model based on RWQM1 with and without algae.

State variable	**Default parameters**	**Updated parameters**	**Default parameters**	**Updated parameters**	**Unit**
	no algae		**with algae**		
Readily biodegradable substrate	69	69	32	69	[g(COD) m^{-3}]
Slowly biodegradable substrate	6300	6300	1000	1200	[g(COD) m^{-3}]
Inert organic matter	1600	1600	3000	3600	[g(COD) m^{-3}]
Dissolved oxygen	0.00013	0.00024	0.37	0.68	[g(O) m^{-3}]
Carbon dioxide	20	20	12	13	[g(C) m^{-3}]
Heterotrophic bacteria	890	890	44	37	[g(COD) m^{-3}]
Autotrophic bacteria	0	0	0	0	[g(COD) m^{-3}]
Consumers	0	0	4000	2900	[g(COD) m^{-3}]
Algae	0	0	930	1100	[g(COD) m^{-3}]
pH	7.0	7.0	7.2	7.2	[-]

Two distinct changes were found in the increased dissolved oxygen concentration and the decreased carbon dioxide concentration. Both changes were expected as a result of algal photosynthesis. The carbon dioxide concentration was decreased from 20 $g(C)\cdot m^{-3}$ to 12 $g(C)\cdot m^{-3}$ with default parameter values, or to 13 $g(C)\cdot m^{-3}$ with parameter values from the non-linear system identification. The new concentrations were above the water-atmosphere saturation level of 0.11 $g(C)\cdot m^{-3}$ and also above the carbon dioxide injection saturation level of 11.7 $g(C)\cdot m^{-3}$. The increase of dissolved oxygen enabled a stable population of consumers that in turn made the concentrations of heterotrophic bacteria and slowly biodegradable substrate decrease through predation and consumption. The concentration of autotrophic bacteria reached value equal to zero even though the oxygen concentration increased, which could be a consequence of the high predation rate.

Conclusions

The model structure of the River Water Quality Model no. 1 might be considered as a possibility for future modelling of the algae based activated sludge process. A major obstacle in this study was the fact that no algae-based activated sludge system has been running prior to the beginning of this work. Then, a better system understanding and the analysis of experimental data is needed in order to increase the model development and to perform model calibration.

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