A Modified ASM3 Model for a Trickling Filter

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Abstract

This paper aims to determine and analyze a model for a biological filter that is part of an intensive recycled aquaculture plant. The biological filter used in this plant is a biofilm filter of trickling type. In this filter only the nitrification processes take place. In order to determine a model that can be used in real-time control a global model for the nitrification filter is recommended. Consequently, a modified ASM3 (Activated Sludge Model No. 3) model is proposed in order to include only the nitrification processes and to consider the nitrite and the nitrate as distinct state variables. In this model the quality variables are the ammonium and the nitrite concentrations, the command variables are the aeration and recycled volume and the disturbance variable is the ammonium concentration from the fish tanks. The simulation results of the model are also presented in the paper. These results are obtained for different functioning conditions of the technological plant. The simulation results show that the model offers a good description of the main state variables: ammonium, nitrite and nitrate.

Keywords: Activated sludge modeling, Process modelling and control, Nitrification, Trickling filter.

Introduction

The modern technologies for fish super-intensive growth ask for water recycled plants that require the use of high performance specific systems for water treatment [1]. These systems aim the ammonium removal from the wastewater so that the maximum limit, $1\ \text{mgN/l}$, be not exceeded. This fact, together with the existence of large flows that have to be treated and the small spaces existent for treatment is the reason for that, in the case of these systems, the option taken into consideration was the use of particular solutions for wastewater treatment. Thus a combination of biological filters with biofilm for the nitrification process and chemical filters for the denitrification process is used. The nitrification filters with biofilm have the advantage that offer a higher efficiency than the classic solution for wastewater treatment, but the modelling and control problem of these systems becomes more complex.

The mathematical modelling of the systems with biofilm leads to extremely complex models, the biofilm being treated as a dynamic system with distributed parameters with respect to two spatial coordinates [2]: a) the coordinate corresponding to the trace of the processed water and b) the spatial coordinate corresponding to the processes from biofilm. Obviously, the scales of the two spatial coordinates differ through many size orders. An alternative to the local models that are very complex, based on the micrometric scale description of the processes from biofilm, is the consideration of biofilter model in which the nitrification processes are globally treated. In this case, the existent models for the classic wastewater treatment can be used. The most known models in the literature are ASM 1, ASM2, ASM 2d and ASM3. These models are proposed by IWA (International Water Association) [3]. An improved variant of the models mentioned before is ASM3_2N, in witch the ammonium decomposition in the nitrification-denitrification processes is treated on the two components, nitrites and nitrates [4].

Materials and methods

An intensive aquaculture recycled system contains the following units:

- *The unit for the fish growth*: the organic substance produced by the fish metabolism is decomposed through an aerobe process by the heterotrophs bacteria in simpler organic products, the final product being the ammonium. The goal followed by the wastewater treatment system is to ensure the removal of the organic substances and the intermediary products (the ammonium compounds);
- *The mechanic filter*: it aims to remove the big particles existent in the water eliminated from the fish growth tanks;
- *The biologic nitrification filter*: a nitrification biofilm of „trickling" type is considered in the paper. Regardless the configuration of the filter, the nitrification is achieved in two oxidation phases. In the first phase, the ammonium is oxidized by the autotrophs bacteria (*Nitrosomonas*), in nitrites – (NO_2^-), through the reaction (1):

$$NH_4^+ + \frac{3}{2}O_2 \xrightarrow{\text{Ammonium oxidizers}} NO_2^- + 2H^+ + H_2O + 66\text{kcal/M} \qquad (1)$$

  The nitrites are oxidized by another category of autotrophs bacteria (*Nitrobacter*), in nitrates – (NO_3^-), through the reaction (2):

$$NO_2^- + \frac{1}{2}O_2 \xrightarrow{\text{Nitrite oxidizers}} NO_3^- + 18\text{kcal/M} \qquad (2)$$

- *The denitrification filter*: it is used to transform the nitrate resulted in the nitrification filter in gaseous ammonium. Within the plant studied in the paper, the denitrification filter is based on chemical principles and it has a constant efficiency.

Table 1. Process rate equations for the ASM3_2N modified model

j	Process	Rate equation r_j
1	Hydrolysis	$k_H \frac{X_S / X_H}{K_X + (X_S / X_H)} X_H$
2	Aerobic storage of S_S	$k_{STO} \frac{S_{O_2}}{K_{O_2} + S_{O_2}} \frac{S_S}{K_S + S_S} X_H$
3	Aerobic growth	$\mu_H \frac{S_{O_2}}{K_{O_2} + S_{O_2}} \frac{S_{NH_4}}{K_{NH_4} + S_{NH_4}} \frac{X_{STO} / X_H}{K_{STO} + (X_{STO} / X_H)} X_H$
4	Aerobic endogenous respiration	$b_{H,O_2} \frac{S_{O_2}}{K_{O_2} + S_{O_2}} X_H$
5	Aerobic respiration of X_{STO}	$b_{STO,O_2} \frac{S_{O_2}}{K_{O_2} + S_{O_2}} X_{STO}$

6	Aerobic growth of X_{ns}	$\mu_{ns}\dfrac{S_{O_2}}{K_{A,O_2}+S_{O_2}}\dfrac{S_{NH_4}}{K_{A,NH_4}+S_{NH_4}}X_{ns}$
7	Aerobic growth of X_{nb}	$\mu_{nb}\dfrac{S_{O_2}}{K_{A,O_2}+S_{O_2}}\dfrac{K_{I,NH_4}}{K_{I,NH_4}+S_{NH_4}}\dfrac{S_{NO_2}}{K_{NO_2}+S_{NO_2}}X_{nb}$
8	Aerobic endogenous respiration of X_{ns}	$b_{ns,O_2}\dfrac{S_{O_2}}{K_{A,O_2}+S_{O_2}}X_{ns}$
9	Aerobic endogenous respiration of X_{nb}	$b_{nb,O_2}\dfrac{S_{O_2}}{K_{A,O_2}+S_{O_2}}X_{nb}$

The model proposed in the paper is a modified variant of the model ASM3_2N. Thus, taking into account the fact that within the intensive aquaculture plant there is only an aerobe biologic filter, a model in which are included the aerobe phenomena containing in the model ASM_2n is proposed. It results a model in which only 9 phenomena that take place in the filter and 12 state variables are considered. The phenomena considered in the model, together with the corresponding reaction rates are presented in Table 1. Table 2 shows the values of the kinetic parameters used in the model.

Table 2. Kinetic and stoichiometric parameters values used in the ASM3_2N modified model

Symbol	Characterization	Value	Units
k_H	Hydrolysis rate constant	3	$gCOD_{X_S}(gCOD_{X_H})^{-1}d^{-1}$
K_X	Hydrolysis saturation constant	1	$gCOD_{X_S}(gCOD_{X_H})^{-1}$
k_{STO}	Storage rate constant	7.38	$gCOD_{X_S}(gCOD_{X_H})^{-1}d^{-1}$
K_{O_2}	Saturation constant for S_{O_2}	0.1	gO_2m^{-3}
K_S	Saturation constant for S_S	3	$gCOD_{S_S}m^{-3}$
μ_H	Heterotrophic maximum growth rate for X_H	1	d^{-1}
K_{NH_4}	Saturation constant for S_{NH_4}	0.01	gNm^{-3}
K_{STO}	Saturation constant for X_{STO}	1	$gCOD_{X_{STO}}(gCOD_{X_H})^{-1}$
b_{H,O_2}	Aerobic endogenous respiration rate of X_H	0.1	d^{-1}
b_{STO,O_2}	Aerobic respiration rate of X_{STO}	0.2	d^{-1}
μ_{ns}	Maximum growth rate of X_{ns}	0.6313	d^{-1}
K_{A,O_2}	Oxygen saturation for nitrifiers	0.5	gO_2m^{-3}
K_{A,NH_4}	Ammonium substrate saturation for nitrifiers	2	gNm^{-3}
μ_{nb}	Maximum growth rate of X_{nb}	1.0476	d^{-1}
K_{I,NH_4}	Ammonia inhibition of nitrite oxidation	5	$gNH_4^-Nm^{-3}$
K_{NO_2}	Saturation constant for S_{NO_2}	0.5	$gNO_2^-Nm^{-3}$

b_{ns,O_2}	Aerobic endogenous respiration rate of X_{ns}	0.061	d^{-1}
b_{nb,O_2}	Aerobic endogenous respiration rate of X_{nb}	0.061	d^{-1}

The model of the process is determined based on the stoichiometric matrix corresponding to the 9 phenomena and the 12 state variables mentioned in Table 2. Further on is presented the significance of the state variables: S_{O_2} - dissolved oxygen concentration, S_S - readily biodegradable substrates concentration, S_{NH_4} - ammonium concentration, S_{NO_2} - nitrite nitrogen concentration, S_{NO_3} - nitrate nitrogen concentration, S_I - soluble inert organics concentration, X_I - inert particulate organics concentration, X_S - slowly biodegradable substrates, X_H - heterotrophic biomass, X_{STO} - organics stored by heterotrophs, X_{ns} - ammonia-oxidizing autotrophs, X_{nb} - nitrite-oxidizing autotrophs. The stoichiometric parameter values that appear in the model are presented in Table 4.

On the basis of the reaction rates presented in Table 1, the stoichiometric matrix described in Table 3 and the parameters values given in Tables 2 and 4, the model of the nitrification filter can be built. The model that results is one in which the evolution of the state variables, considering the closed system, without inputs and outputs is described. In this model the evolution of the state variables is determined only by the reaction rates, corresponding to the 9 aerobe phenomena presented in Table 1.

Table 3. Stoichiometric matrix of the ASM3_2N modified model

Variable / Process	S_{O_2}	S_S	S_{NH_4}	S_{NO_2}	S_{NO_3}	S_I	X_I	X_S	X_H	X_{STO}	X_{ns}	X_{nb}
1	-	$1-f_{S_I}$	$-i_{N,S_S}(1-f_{S_I})-f_{S_I}i_{N,S_I}+i_{N,X_S}$	-	-	f_{S_I}	-	-1	-	-	-	-
2	$Y_{STO,O_2}-1$	-1	i_{N,S_S}	-	-	-	-	-	-	Y_{STO,O_2}	-	-
3	$1-(1/Y_{H,O_2})$	-	$-i_{N,BM}$	-	-	-	-	-	1	$-1/Y_{H,O_2}$	-	-
4	$f_{X_I}-1$	-	$i_{N,BM}-f_{X_I}i_{N,X_I}$	-	-	-	f_{X_I}	-	-1	-	-	-
5	-1	-	-	-	-	-	-	-	-	-1	-	-
6	$1-(3.43/Y_{ns})$	-	$-(1/Y_{ns})-i_{N,BM}$	$1/Y_{ns}$	-	-	-	-	-	-	1	-
7	$1-(3.43/Y_{nb})$	-	$-i_{N,BM}$	$-1/Y_{nb}$	$1/Y_{nb}$	-	-	-	-	-	-	1
8	$f_{X_I}-1$	-	$i_{N,BM}-f_{X_I}i_{N,X_I}$	-	-	-	f_{X_I}	-	-	-	-1	-
9	$f_{X_I}-1$	-	$i_{N,BM}-f_{X_I}i_{N,X_I}$	-	-	-	f_{X_I}	-	-	-	-	-1

Table 4. Stoichiometric parameters values used in the ASM3_2N modified model

Symbol	Characterization	Value	Units
Y_{STO,O_2}	Aerobic yield of stored product for S_S	0.85	$\text{gCOD}_{X_{STO}}(\text{gCOD}_{S_S})^{-1}$
Y_{H,O_2}	Aerobic yield of heterotrophic biomass	0.835	$\text{gCOD}_{X_H}(\text{gCOD}_{X_{STO}})^{-1}$
f_{X_I}	Production of X_I in endogenous respiration	0.2	$\text{gCOD}_{X_I}(\text{gCOD}_{X_{BM}})^{-1}$
Y_{ns}	Aerobic yield of X_{ns}	0.1	$\text{gCOD}_{X_{ns}}(\text{gN}_{\text{NO}_2})^{-1}$
Y_{nb}	Aerobic yield of X_{nb}	0.14	$\text{gCOD}_{X_{nb}}(\text{gN}_{\text{NO}_3})^{-1}$
f_{S_I}	Production of S_I in hydrolysis	0	$\text{gCOD}_{S_I}(\text{gCOD}_{X_S})^{-1}$
i_{N,S_S}	N content of S_S	0.03	$\text{gN}(\text{gCOD}_{S_S})^{-1}$
i_{N,S_I}	N content of S_I	0.01	$\text{gN}(\text{gCOD}_{S_I})^{-1}$
i_{N,X_S}	N content of X_S	0.04	$\text{gN}(\text{gCOD}_{X_S})^{-1}$
$i_{N,BM}$	N content of biomass (X_H , X_{ns} and X_{nb})	0.07	$\text{gN}(\text{gCOD}_{X_{BM}})^{-1}$
i_{N,X_I}	N content of X_I	0.02	$\text{gN}(\text{gCOD}_{X_I})^{-1}$

The complete model of the nitrification filter assumes the consideration of some supplementary elements besides the reaction rates: the inflow (the water loaded with ammonium provided by the tanks for the fish growth), the output flow (the water that goes out from the trickling filter and enters in the denitrification filter) and the biofilm aeration (the air is introduced for achieving an increasing of the oxygen concentration from the wastewater, that is to accelerate the oxidizing processes). The model will have the expression (3) for all the equations, excepting the one of the dissolved oxygen.

$$\frac{dx}{dt} = \frac{1}{V}\left(Q_{in}x_{in} - Q_{out}x + rV\right) \tag{3}$$

where x is the state variable, V - the trickling filter volume, Q_{in} - the inflow, x_{in} - the concentration of the component x in the influent, Q_{out} - the outflow and r represents the vector of the conversion rates. For making easy the model implementation it assumes that the output flow from the biofilm is equal to the input one, neglecting the hydraulic dynamics.

For the dissolved oxygen concentration the following equation is used:

$$\frac{dSO_2}{dt} = \frac{1}{V}\left(Q_{in}SO_{2,in} - Q_{out}SO_2 + rV\right) + \alpha W(SO_{2,sat} - SO_2) \tag{4}$$

where: α is the oxygen transfer rate, W - aeration rate and SO_2 is the saturation concentration of the dissolved oxygen concentration.

Results and Discussion

The nitrification process with biofilm of trickling type considered in the present paper has as input variables the biofilm aeration rate, the recycling flow from the intensive aquaculture system (the biofilm inflow) and the ammonium concentration from the inflow. The first two are command variables that can be modified by the operator aiming to improve the effluent quality, while the third is a disturbance variable those evolution depends on the following factors: the quantity and the age of the fish from the growth units, the food quantity, the temperature etc. The quality variables of the process are the ammonium and nitrites concentrations at the biofilter output. Further on the results obtained by numerical simulation of the model proposed in the previous section are presented. The simulations have shown how the variation of the command variables and of the disturbances influences the evolution of the quality variables.

The first simulation had in view the study of the influence of the aeration on the nitrification processes. Figure 1 presents the results of the simulation. The following cases were considered: $W = 40$ lpm (solid line), $W = 20$ lpm (dashed line) and $W = 2$ lpm (dotted line). In the simulation the dissolved oxygen concentration from the influent has been considered equal to zero, the necessary oxygen for the nitrification processes being provided only through aeration. It can be also observed that in the case of an insufficient aeration (the dissolved oxygen concentration is closed to zero), the oxidizing processes cannot take place, their efficiency being very small (the ammonium concentration in the effluent is almost equal to the one from the inflow: 1 mgN/l. Along with the growth of the dissolved oxygen concentration, the process efficiency also increases very much in the presence of the aeration. In order to establish more clearly the importance of the dissolved oxygen concentration from the wastewater on the nitrification processes a new simulation in which the dissolved oxygen from the influent was varied and it has been considered that there is not aeration has been done. Figure 2 presents the simulation results. They have been obtained considering the following cases: $SO_{2,in} = 4$ mgO$_2$/l (solid line), $SO_{2,in} = 2$ mgO$_2$/l (dashed line) and $SO_{2,in} = 0$ mgO$_2$/l (dotted line). It results very clearly that the nitrification processes could have a high efficiency only in the case when a sufficient dissolved oxygen concentration is assured. In both cases it can be observed that if the ammonium concentration from the effluent decreases, than the nitrites and nitrates concentrations increase, the most significant being the nitrate one.

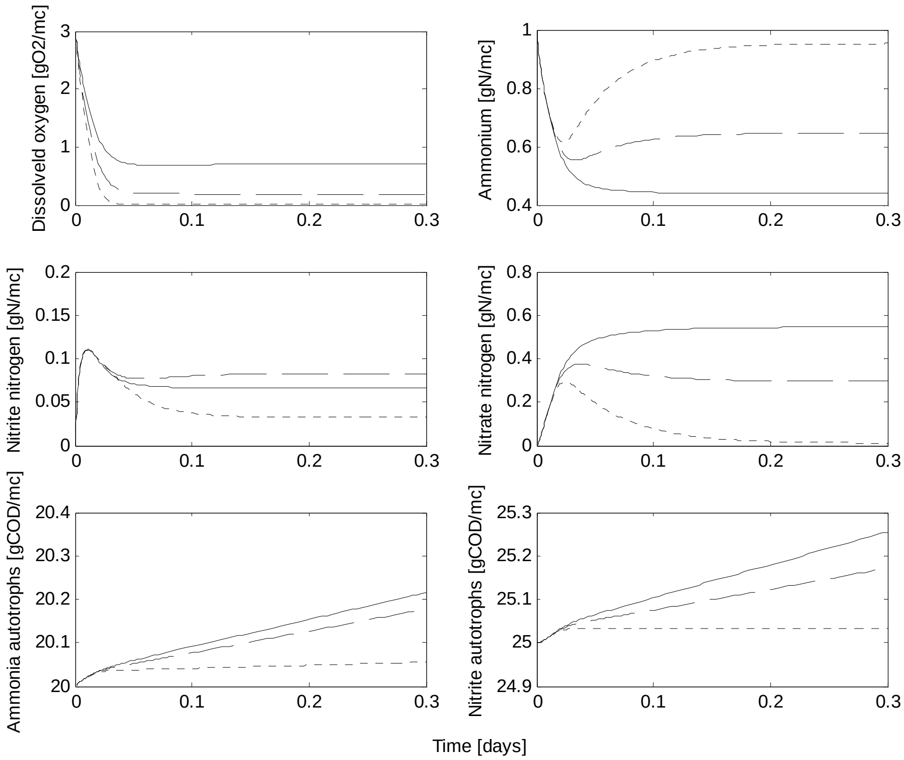

Figure 1. The influence of the aeration on the nitrification processes: $W = 40$ lpm - solid line, $W = 20$ lpm - dashed line and $W = 2$ lpm - dotted line

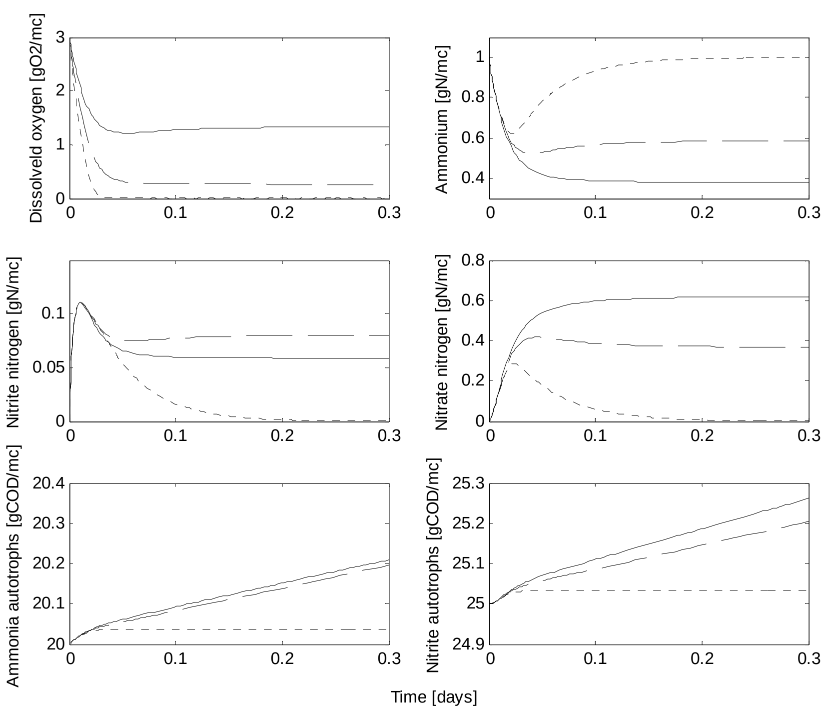

Figure 2. The influence of the dissolved oxygen concentration on the nitrification processes: $SO_{2,in} = 4$ mgO_2/l - solid line, $SO_{2,in} = 2$ mgO_2/l - dashed line and $SO_{2,in} = 0$ mgO_2/l - dotted line

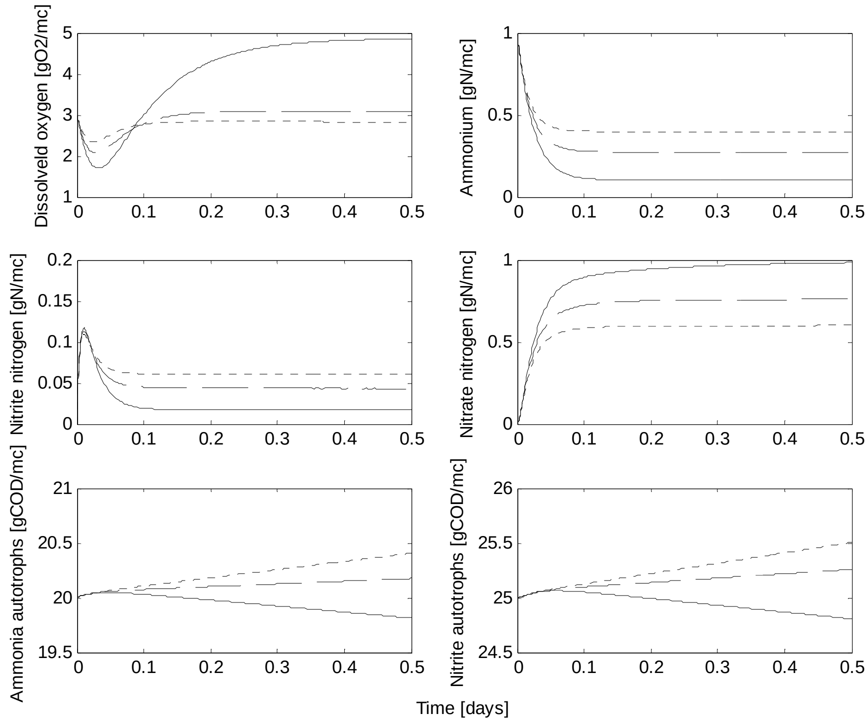

Figure 3. The influence of the recycled flow on the nitrification processes: $Q_{in} = 1\ \text{m}^3/\text{h}$ - solid line, $Q_{in} = 2\ \text{m}^3/\text{h}$ - dashed line and $Q_{in} = 4\ \text{m}^3/\text{h}$ - dotted line

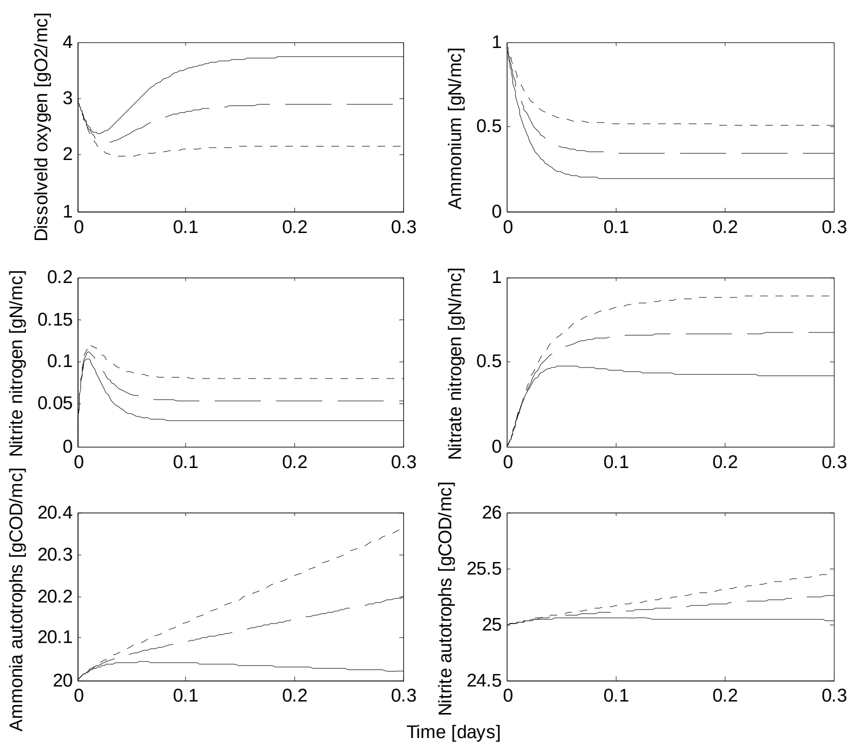

Figura 4. The influence of the ammonium concentration from the influent on the effluent quality: $S_{NH_4,in} = 0.6$ mgN/l - solid line, $S_{NH_4,in} = 1$ mgN/l - dashed line and $S_{NH_4,in} = 1.4$ mgN/l - dotted line

Further on the influence of the recycled flow was verified (the inflow in the trickling filter) on the efficiency of the nitrification processes. Figure 3 presents the simulation results, they being obtained in the following cases: $Q_{in} = 1\ \text{m}^3/\text{h}$ (solid line), dashed line $Q_{in} = 2\ \text{m}^3/\text{h}$ and dotted line $Q_{in} = 4\ \text{m}^3/\text{h}$. In Figure 3 it can be observed that the process efficiency increases along with the decreasing of the recycled flow. This is due to the fact that through the amount of a small quantity of water, the aeration is able to reach a bigger dissolved oxygen concentration, that is the oxidizing processes have a better efficiency. In the same time, the recycling flow being smaller, the ammonium quantity that needs to be treated decreases, that is the ammonium concentration from the effluent also decreases. A last study has been achieved considering the influence of the ammonium concentration on the effluent quality. Figure 4 presents the simulation results, they being obtained in the following conditions: $S_{NH_4,in} = 0.6\ \text{mgN/l}$ (solid line), dashed line $S_{NH_4,in} = 1\ \text{mgN/l}$ and dotted line $S_{NH_4,in} = 1.4\ \text{mgN/l}$. As it was expected, the ammonium concentration from the input flow directly influences the one from the effluent. Moreover, unlike the other previous cases, a small ammonium concentration in the influent involves smaller nitrites and nitrates concentrations.

Conclusions

Within the paper, for the description of the nitrification filter, a modified version of the model ASM3_2N in which the nitrite and the nitrate are considered distinct variables has been proposed. Taking into account that only the nitrification filter is a biologic filter, only the aerobe phenomena that appear in the case of the ammonium removal are included in the model. The model simulations aimed the analysis of the way of how the variation of the command variables (the aeration rate and the recycling flow) and also of the disturbances influences the evolution of the quality variables (ammonium and nitrites). In all cases it can be observed that a sufficient dissolved oxygen concentration for the nitrification processes and a corresponding flow lead to good results from the point of view of the ammonium concentration (values under $0.4\ \text{mgN/l}$) and the nitrite concentration (values under $0.05\ \text{mgN/l}$), the two variables being the most important variables in the case of the water quality from the intensive recycling aquaculture systems. This study creates good premises for the design of control system of the ammonium concentration level, aiming to increase the efficiency of the intensive growth of the fish in recycling plants.

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