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EVALUATION OF NITROGEN REMOVAL BY STEP FEEDING IN LARGE TREATMENT PLANTS

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ABSTRACT

Step feeding flow configuration is an attractive process alternative for large treatment systems designed for nitrogen removal, eliminating the need for internal recycling and optimizing organic carbon utilization for denitrification. Volume ratios of anoxic and aerobic volumes and wastewater fraction to be diverted from the inlet of the system are important parameters to be considered in the design of the step feeding process. Wastewater characterization and especially C/N ratio significantly affect the design. The effect of wastewater characterization is illustrated for the Riva Plant in Istanbul, with a capacity of 4 million population equivalent, designed as a two-stage step feeding system for biological nutrient removal. It is shown that the proposed design cannot meet the effluent standard of 10 mgl^{-1} total N for the relevant sewage characterization assessed on the basis of an extensive experimental study, totally different from the one adopted for design. Copyright © 1996 IAWQ. Published by Elsevier Science Ltd.

KEYWORDS

Step feeding; biological nitrogen removal; activated sludge; nitrification; denitrification; process kinetics; Istanbul sewage.

INTRODUCTION

Effective control of nutrients is now required for all wastewater discharges to sensitive receiving waters. Recent studies indicate that the water body in the Marmara Sea has reached a critical stage of pollution, especially with respect to nutrient concentrations, giving severe signs of future eutrophication problems (Orhon, *et al.*, 1994a). The Metropolitan Area of Istanbul, is the major polluter of the highly sensitive zone between The Marmara Sea, The Bosphorus and The Black Sea. Accordingly, a wastewater management policy has been adopted to provide biological nitrogen and phosphorus removal at all discharge points within the area. This management plan is currently under reevaluation. One of these discharge points, namely Riva Wastewater Treatment Plant is basically a step feeding system (Fig. 1). This plant has been designed without considering the necessary treatability oriented wastewater characterization, but only common unit values from the literature.

The main objective of this paper is to summarize the conceptual approach for nitrogen removal in step feeding system and in this framework, to evaluate the Riva plant designed as a step feeding process.

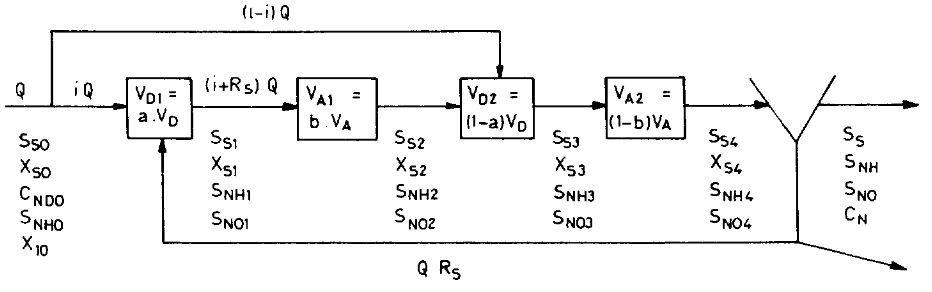

Fig. 1. Schematic diagram of the Riva Plant step feeding process

This activated sludge modification was first proposed in 1940, under the name of *step aeration*, to remedy operational problems encountered in conventional aeration systems (Gould, 1942). It is now successfully applied as an effective nutrient removal system (Schlegel, 1992). However, step feeding systems require careful design and consideration of wastewater characteristics, as the flow scheme is highly sensitive to the delicate balance reflected by the C/N ratio. The paper provides a critical appraisal for the design of the Riva plant, on the basis of pertinent wastewater characterization newly assessed as a result of an extensive experimental survey (Orhon, *et al.*, 1994b; Sözen, 1995), not confirming the previously adopted values , and emphasizes the significance of wastewater characterization in the design of such systems.

CONCEPTUAL APPROACH FOR DESIGN

The step feeding configuration, as schematically defined in Fig. 1, is basically a single sludge system and its kinetic evaluation should involve all the basic components and processes describing carbon oxidation, nitrification and denitrification. The reaction matrix commonly adopted for such an evaluation is given in Table 1 (Orhon and Artan, 1994). Its design relies on the selection of an appropriate sludge age for the autotrophic and the heterotrophic sludge biomass. The aerobic sludge age, θ_{XA} is particularly important because complete nitrification is a prerequisite for an effective nitrogen removal which takes place within the total anoxic volume, V_D. Appropriate selection of the ratio of the anoxic volume to the total reactor volume, V_D/V and θ_{XA} yields the total sludge age of the system:

$$\theta_x = \frac{\theta_{XA}}{1 - \frac{V_D}{V}} \tag{1}$$

The total reactor volume should ensure complete removal of the biodegradable COD, C_{S0}. Then the heterotrophic biomass, $V\ X_H$ may be computed as follows:

$$V X_H = \frac{Y_H\ Q\ C_{S0}\ \theta_X}{1 + b_H\ \theta_X} \tag{2}$$

It is postulated that all growth processes consume ammonia nitrogen, S_{NH} as nitrogen source. In the aerated zones, this component is converted into nitrate nitrogen, S_{NO} by means of nitrification. Furthermore, the total biodegradable organic nitrogen concentration in the influent, C_{ND0} may be considered as a potential ammonia nitrogen source assuming that the ammonification of organic nitrogen is not rate limiting. In this context, the following expression defines the mass balance for nitrogen:

$$N_{OX} = C_{NDO} + S_{NHO} - S_{NH} - N_X \tag{3}$$

where, N_X = the amount of nitrogen incorporated into biomass per unit volume of wastewater treated,
N_{OX}= the amount of nitrate nitrogen formed per unit volume of wastewater treated.

TABLE 1. PROCESS KINETICS AND STOICHIOMETRY FOR SINGLE-SLUDGE NITROGEN REMOVAL

Component →	1	2	3	4	5	6	7	8	Process Rate
Process ↓	S_S	X_S	X_H	X_A	X_P	S_{NH}	S_O	S_{NO}	
Aerobic Growth of Heterotrophs	$-\frac{1}{Y_H}$		1			$-i_{XB}$	$-\frac{1-Y_H}{Y_H}$		$\hat{\mu}_H \frac{S_S}{K_S+S_S} X_H$
Anoxic Growth of Heterotrophs	$-\frac{1}{Y_H}$		1			$-i_{XB}$		$-\frac{1-Y_H}{2.86Y_H}$	$\eta_G \hat{\mu}_H \frac{S_S}{K_S+S_S} X_H$
Growth of Autotrophs				1		$-1/Y_A-i_{XB}$	$-\frac{4.57-Y_A}{Y_A}$	$\frac{1}{Y_A}$	$\hat{\mu}_A \frac{S_{NH}}{K_{NH}+S_{NH}} X_A$
Aerobic Hydrolysis	1	-1							$K_h X_S$
Anoxic Hydrolysis	1	-1							$\eta_H K_h X_S$
Aerobic Decay of Heterotrophs			-1		f_{EX}	$i_{XB}-f_{EX}i_{XE}$	$-(1-f_{EX})$		$b_H X_H$
Anoxic Decay of Heterotrophs			-1		f_{EX}	$i_{XB}-f_{EX}i_{XE}$		$-\frac{1-f_{EX}}{2.86}$	$\eta_E b_H X_H$
Decay of Autotrophs				-1	f_{EX}		$-(1-f_{EX})$		$b_A X_A$
	COD	COD	cell COD	cell COD	cell COD	NH_3-N	O_2	NO_3^--N	

N_X may be defined on the basis of related kinetic expressions with the assumption that the heterotrophic activity is reduced in the anoxic zones by a correction factor. Different correction factors η_G, η_H, η_E maybe are commonly defined to characterize respectively growth, hydrolysis and decay under anoxic conditions. As no substantial proof has so far been provided in the literature to show that they are significantly different, a single correction factor, η has been adopted in this study as shown in the following equations:

$$\eta_G = \eta_E = \eta$$

$$N_X = (i_{XB} + i_{XE}\, f_{EX}\, b_H\, c\, \theta_X)\, \frac{Y_H\, C_{S0}}{1 + c\, b_H\, \theta_X} \tag{4}$$

where, $$V_A + \eta V_D = c V \quad or \quad c = 1 - (1 - \eta)\, \frac{V_D}{V}$$

The total autotrophic biomass in the system may then be expressed as a function of N_{OX}:

$$V X_A = \frac{Y_A\, N_{OX}\, Q\, \theta_X}{1 + b_A\, \theta_X} \tag{5}$$

The unit amount of nitrogen incorporated into biomass, N_X is set for selected values of V_D/V and θ_X. For a desired effluent nitrate nitrogen concentration, S_{NO}, N_{OX} and the autotrophic biomass, $V X_A$ can be computed from expressions 3 and 5. Similarly, the following kinetic expressions may be derived for the particulate inert COD fractions, X_P and X_I:

$$V X_P = f_{EX}\, c\, b_H\, \theta_X\, V X_H \tag{6}$$

and,

$$V X_I = X_{I0}\, Q\, \theta_X \tag{7}$$

$$V X_T = V X_H + V X_A + V X_P + V X_I \tag{8}$$

An appropriate X_T value, selected as the average total particulate COD in the system enables the calculation of the total and the anoxic reactor volumes, V and V_D. The procedure so far described applies to all single sludge systems designed for nitrogen removal. Step feeding with a reactor configuration given in Fig. 1, additionally involves three significant design parameters: the fraction of the influent flow rate fed to the first anoxic reactor, **i**; the volume ratio of the first anoxic reactor, **a**; and the volume ratio of the first aerobic reactor, **b**. The volume ratios, **a** and **b** are defined as follows:

$$a = \frac{V_{D1}}{V_D} \quad ; \quad b = \frac{V_{A1}}{V_A} \tag{9}$$

The selection of the appropriate value for **i**, is most important for the optimum design of step feeding flow configuration, because the ammonia content of the wastewater fraction, **1–i**, diverted to the 2nd aerobic reactor, aside from the relatively small portion incorporated into biomass, will be converted into nitrate and will leave the system as nitrate nitrogen. The latter may be considered as the effluent nitrate nitrogen concentration, S_{NO}, provided that the 2nd anoxic reactor secures complete denitrification, virtually eliminating all nitrate nitrogen ($S_{NO3} = 0$). In this respect, the 2nd anoxic reactor is the key part of the whole system and should be designed to maintain the delicate balance between its denitrification potential, N_{DP2} and the nitrate nitrogen generated in the first aerobic reactor, N_{OX1}:

$$N_{OX1} = N_{DP2} \tag{10}$$

When this balance is satisfied, the amount of ammonia nitrogen nitrified in the 2nd aerobic reactor, N_{OX2} will determine the effluent nitrate nitrogen concentration. On the basis of kinetic considerations, the following expressions may be derived to define N_{OX1} and N_{DP2} :

$$N_{OX1} = b\, \frac{V_A}{Q}\, X_A \left(\frac{1}{Y_A} + i_{XB}\right) \hat{\mu}_{A1}\, \frac{S_{NH2}}{K_{NH} + S_{NH2}} \tag{11}$$

$$N_{DP2} = (1 - a)\, \frac{V_D}{Q}\, \eta\, \frac{X_H}{2.86} \left[\frac{1 - Y_H}{Y_H}\, \mu_{H3} + (1 - f_{EX})\, b_H\right] \tag{12}$$

Equation 11 shows that N_{OX1} is a function of b and S_{NH2} in the first aerobic reactor. The level of S_{NH2} is set by the selected θ_{XA}. Since **b** is computed to reach this level of S_{NH2}, the ammonia load entering the reactor determines the magnitude of nitrification. Therefore, N_{OX1} basically relates to and increases with the flow fraction, **i**. The same way, N_{DP2} varies with the heterotrophic specific growth rate at the third tank, μ_{H3} and consequently with the **(1–i)** fraction.

The key function of the 2nd anoxic reactor is illustrated in Fig. 2, which plots the variation of N_{OX1}, N_{DP2} and S_{NO} as a function of the wastewater flow fraction entering the system, **i**, for selected constant values of θ_X and V_D/V. As shown in this Fig., for low **i** values, the amount of available organic carbon in the 2nd anoxic reactor stays beyond the required level to remove the existing nitrate and consequently, $N_{DP2} > N_{OX1}$, indicating an excess of wasted denitrification potential. Conversely, as the value of **i** increases, the amount of available organic carbon drops and becomes insufficient in removing the steadily increasing amount of nitrate entering the reactor. Therefore the lowest effluent nitrate concentration, S_{NO} is obtained when the denitrification potential is balanced with the amount of available nitrate nitrogen. This balance also yields the optimum value of **i** for a constant sludge age selected for the operation of the system.

Fig. 2 also indicates that S_{NO} cannot be reduced below a limit dictated by the selected θ_X or V_D/V. To lower this level is only possible by increasing the V_D/V ratio. It should be noted that the amount of nitrate recycled to the first anoxic tank by means of sludge return, R_S Q S_{NO} determines the volume of this reactor or **a**. One of the attractive features of the step feeding configuration is the elimination of internal recycling and the sludge return is practically constant. Therefore a higher V_D/V ratio basically affects the volume of the 2nd anoxic reactor and increases N_{DP2}. This lowers the achievable effluent nitrate nitrogen concentration, S_{NO} and increases the optimum value of the flow fraction, **i**, or in other words, reduces the wastewater flow to be diverted as a step feed, as illustrated in Fig. 3. The variation of S_{NO} with **i** shows the previously explained trend, decreasing to a minimum value as the amount of nitrogen entering to the 2nd anoxic tank drops for higher **i** values, then increasing for insufficient N_{DP2} levels.

Finally, kinetic evaluations indicate that the selection of the volume ratio of the first aerobic reactor, **b** should best be in proportion to the ammonia nitrogen loads; thus **b** may be given the same value as **i**.

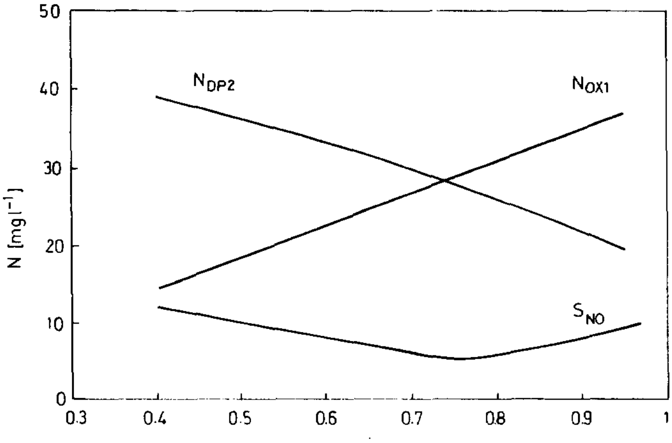

Fig. 2. Variation of N_{OX1}, N_{DP2} and S_{NO} with the flow fraction **i**

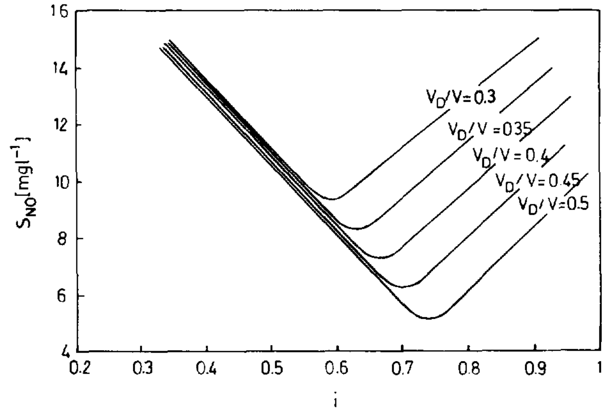

Fig. 3. Relationship between S_{NO} and **i** for different V_D/V values

EVALUATION OF PROPOSED DESIGN

The Riva plant is planned for a wastewater flow rate of 1.160.000 m^3d^{-1}, corresponding to a capacity of 4 million population equivalent. The design proposes to meet the 10 mgl^{-1} total N effluent standard at 10 °C with a total reactor volume of 658.000 m^3, computed on the basis of a θ_{XA} of 12.5 d and a θ_X of 26 d. The resulting V_D/V ratio is 0.52, slightly over the 0.50 limit recommended for good settling conditions. The wastewater fraction, **i** is choosen as 0.8 with a compatible **b** value of 0.78 and the volume of the first anoxic tank is only 29.000 m^3, or 8% of the total anoxic volume (**a** = 0.08). The system is designed for a settled biodegradable COD and TKN concentrations of 271 mgl^{-1} and 44 mgl^{-1}, corresponding to a COD/TKN ratio of 6.15 (TBP and UBM, 1993).

After the design, a comprehensive research study has been carried out for a period of more than two years to characterize the sewage likely to be treated at the Riva Plant and to assess major kinetic parameters for heterotrophic and autotrophic growth (Orhon, *et al.*, 1994b; Sözen, 1995). The results are outlined in Tables 2 and 3. The study indicates a much stronger wastewater than what has been adopted for design, with a C_{S0} = 366 mgl^{-1} and a C_{TKN} = 57 mgl^{-1}.

The proposed model is evaluated by means of a modelling procedure recently developed by Görgün (1995) on the basis of the fundamental kinetic principles described in the previous section. Kinetic and stoichiometric parameters, mostly assessed as part of the experimental evaluation and listed in Table 3, are used in model simulations. The simulation results for 10 °C and 20 °C are outlined in Table 4.

TABLE 2. PREVIOUSLY ADOPTED AND EXPERIMENTALLY ASSESSED WASTEWATER CHARACERISTICS FOR THE RIVA PLANT

Parameter	Unit	Sözen (1995)	TBP and UBM (1993)
C_{T0}	mgCODl^{-1}	406	300
S_{S0}	mgCODl^{-1}	50	37
S_{I0}	mgCODl^{-1}	25	18
X_{I0}	mgCODl^{-1}	15	11
C_{S0}	mgCODl^{-1}	366	271
X_{S0}	mgCODl^{-1}	316	234
C_{TKN}	mgNl^{-1}	57	44
C_{ND0}	mgNl^{-1}	12	11
S_{NH0}	mgNl^{-1}	43	31
P	mgPl^{-1}	9	6.6

TABLE 3. STOICHIOMETRIC AND KINETIC PARAMETERS USED IN MODEL SIMULATION

Parameter	Unit	20 °C	10 °C
$\hat{\mu}_H$	d^{-1}	4.6	3
$\hat{\mu}_A$	d^{-1}	0.43	0.2
b_H	d^{-1}	0.24	0.18
b_A	d^{-1}	0.05	0.05 (default)
η_G	-	0.6	0.6
η_H	-	0.9	0.9
K_S	mgl^{-1}	20	20 (default)
K_{NH}	mgl^{-1}	1	1 (default)
K_h	d^{-1}	50	50 (default)
Y_H	mg COD(mg COD)$^{-1}$	0.6	0.6 (default)
Y_A	mg COD(mg N)$^{-1}$	0.2	0.2 (default)

The first simulation basically tests the proposed design with the adopted sewage character, volumes and operational parameters. As shown in Table 4, the effluent stream is computed to include an S_{NH} and S_{NO} of 5.3 and 5.7 mgl^{-1}, not in compliance with the required limit in the case where the effluent organic N remains above 1.0 mgl^{-1}. S_{NH} profile clearly indicate that the selected θ_{XA} is not sufficient for complete nitrification. No major improvements in the effluent quality is expected in summer conditions as the reduction in S_{NH} due to higher nitrification rate is somewhat balanced by an increase in S_{NO}. The second simulation run evaluates the effect of the experimentally assessed sewage character on the proposed design. The results clearly indicate the weakness of the plant in handling the stronger sewage, as the effluent total N concentration stays markedly higher than the acceptable limit both in winter and summer conditions. The third run attempts to optimize the system for the new sewage characteristics, without changing so much the total volume and the sludge age. Adjustments of the anoxic volumes to yield no nitrate nitrogen in the respective reactor effluents provides a slight but insufficient improvement in the effluent quality as depicted in Table 4, for V_T = 700.000 m^3, **i** = 0.78, and **a** = 0.03 at 10 °C. Under summer conditions the optimization is shown to provide an acceptable effluent total N concentration. The negative S_{NO} values in Table 4 is a clear indication that carbon distribution between the two anoxic zones is not adequately adjusted to maintain the required

TABLE 4. MODEL SIMULATION FOR TWO-STAGE STEP FEEDING

Process Components	Values of Reactor Effluents 10 °C				20 °C			
	1	2	3	4	1	2	3	4
I	Proposed Sewage Characterization - Process Design							
S_S	40	1.4	1.2	0.1	36	1.1	0.9	0.06
X_S	73	8.4	3.8	1.3	75.5	8.2	3.8	1.2
S_{NH}	21.3	4.4	8.8	5.3	22	0.7	6	0.9
S_{NO}	-4.7	15.9	1.7	5.7	-4.6	20.4	4.6	10.3
II	New Sewage Characterization - Previous Process Design							
S_S	32.5	1.6	1.2	0.09	30	1.2	1	0.05
X_S	89.5	12.7	6	2.4	94	14.5	6	2.2
S_{NH}	22.9	3.5	8.5	4.3	24.5	0.7	6.5	0.9
S_{NO}	-2.8	17.9	2.7	7.4	-3.4	22.4	5.2	11.5
III	New Sewage Characterization - Optimum Process Design							
S_S	33	2.1	1.3	0.09	27.1	1.6	1.2	0.06
X_S	111.3	15.6	5.8	2.3	100.6	15.7	7.5	2.6
S_{NH}	23.5	3.5	9	4.8	22	0.7	7.6	0.9
S_{NO}	0	17.4	0.3	4.9	0	19.3	0	7.4

TABLE 5. MODEL SIMULATION FOR THREE-STAGE STEP FEEDING (10 °C)

Process Components	Values of Reactor Effluents					
	1	2	3	4	5	6
IV	New Sewage Characterization - Optimum Process Design					
S_S	16.6	1.3	7.8	0.2	2.6	0.1
X_S	62.5	11.8	32	7.3	12.6	4.4
S_{NH}	14.3	2.2	11.8	3	5.5	1.7
S_{NO}	0	11.5	0.1	9.8	0.4	5
V	New Sewage Characterization - Previously Proposed Reactor Volumes					
S_S	23.3	2.1	10.7	0.3	0.8	0.09
X_S	106.5	17	38.1	7.8	4.3	2.1
S_{NH}	20.2	3	14.3	3.8	0.01	0.1
S_{NO}	0	14.8	0	11.5	0	0.33

carbon/nitrate balance in the first anoxic zone. Process optimization effectively solves this problem as shown in the same table.

Model evaluations outlined above give a clear indication that the proposed flow configuration as a 2-stage step feeding process is not likely to be the best choice and can only meet the effluent limits at the expense of exceedingly high sludge age values. Consequently, 3-stage step feeding alternatives, providing better C/N balance, are also evaluated with the same procedure. The results obtained are listed in Table 5. A search for optimum flow configuration for the new sewage characteristics yielded $S_{NH} = 1.7$ mgl^{-1}, $S_{NO} = 5.0$ mgl^{-1} for a total volume of 560.000 m^3, a total sludge age of 19.8 d and a V_D/V ratio of 0.37, with $i_1 = i_2 = 0.38$; $i_3 = 0.24$; $a_1 = 0.07$, $a_2 = 0.31$ and $a_3 = 0.62$. Results in Table 5 also show that using the total volume, the total sludge age and the V_D/V ratio of the proposed design and only changing the plant configuration into a 3-stage step feeding system is enough to yield an effluent quality with $S_{NH} = 0.1$ mgl^{-1} and $S_{NO} = 0.33$ mgl^{-1}.

CONCLUSIONS

Step feeding flow configuration is an attractive process alternative for large treatment plants designed for nitrogen removal, eliminating the need for internal recycling and optimizing organic carbon utilization for denitrification. The effect of wastewater characterization, as illustrated for the Riva plant in Istanbul, is crucially important for an appropriate design: Model simulations indicate that the Riva plant designed for an adopted set of major parameters describing settled wastewater, can no longer meet the effluent requirement of 10 mgl^{-1} when tested for a stronger sewage quality determined on the basis of experimental studies. Kinetic evaluations provide an acceptable justification for system sensitivity to wastewater characteristics, on the basis of comparative evaluations of the denitrification potential and the available nitrate nitrogen around the anoxic reactors which are the critical zones for the balance between carbonaceous and nitrogenous components.

An appropriate design procedure is used to show that a 3-stage step feeding system is likely to yield the optimum effluent quality with minimum reactor volume at the Riva plant, while the proposed 2-stage system does not provide the required C/N balance for an effective nitrogen removal for the expected sewage characteristics.

NOMENCLATURE

a,b	Volume fractions of anoxic and aerobic tanks
b_A,b_H	Decay coefficients of autotrophic and heterotrophic biomass, $[d^{-1}]$
C_{S0}	Total biodegradable substrate concentration, $[mgCODl^{-1}]$
C_{TKN}	Total Kjeldahl nitrogen, $[mgNl^{-1}]$
f_{EX}	Inert fraction of active biomass
i	Flow fraction
i_{XB},i_{XE}	Nitrogen contents of active and endogenous fractions, $[mgN(mgCOD)^{-1}]$
K_h	Hydrolysis rate constant, $[d^{-1}]$
K_S,K_{NH}	Half saturation constants for autotrophic $[mgNl^{-1}]$ and heterotrophic $[mgCODl^{-1}]$ growth.
S_{NH}	Ammonia concentration, $[mgNl^{-1}]$
S_{NO}	Nitrate and nitrite concentration, $[mgNl^{-1}]$
S_O	Oxygen concentration, $[mgl^{-1}]$
S_S	Readily biodegradable soluble substrate concentration, $[mgCODl^{-1}]$
X_A,X_H	Active autotrophic and heterotrophic biomass concentration, $[mg(cellCOD)l^{-1}]$
X_P	Inert biomass concentration, $[mg(cellCOD)l^{-1}]$
X_S	Slowly biodegradable substrate concentration, $[mgCODl^{-1}]$
Y_A	Autotrophic yield coefficient, $[mg(cellCOD)(mgN)^{-1}]$
Y_H	Heterotrophic yield coefficient, $[mg(cellCOD)(mgCOD)^{-1}]$
$\hat{\mu}_A,\hat{\mu}_H$	Maximum specific growth rate of autotrophic and heterotrophic biomass, $[d^{-1}]$
η_G,η_H,η_E	Correction factor of growth, hydrolysis and decay for denitrification
θ_{XA},θ_X	Aerobic and total sludge age, [d]

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