11
Modelling of the Activated Sludge Process

11.1
Why We Need Mathematical Models

We address the need for mathematical models in this chapter only in reference to treatment processes in biological wastewater technology. The main compounds which must be removed from water during treatment are:

- Organics, dissolved molecules, colloids and solid particles.
- Inorganic, dissolved compounds containing nitrogen (NH_4^+, NO_2^-, NO_3^-) and phosphorus (PO_4^{3-}).

All these compounds are removable in the activated sludge process in different parts of the reactor (see Chapters 6 and 10):

- The organics in the anaerobic, anoxic and aerobic sections.
- NH_4^+ and NO_2^- in the aerobic section.
- NO_3^- and NO_2^- in the anoxic section.
- PO_4^{3-} in the anoxic and aerobic sections by the formation of polyphosphates or, if chemical precipitation is used, by the formation of undissolved phosphatohydroxy compounds with iron or aluminium.

Flow rates and concentrations change over time, in the aerobic part air must be dispersed, oxygen dissolved and wastewater and also sludge must be recycled. The entire process has to be controlled continously to ensure adherence with legal regulations and to minimize costs, especially for energy.

A mathematical model describing the process in whole or in part provides some of the following advantages for design and operation:

- To find the best construction for the basins, mixing and aeration system.
- To optimize the process design and the process controls.
- To develop automatic process controls.
- To use a program for training the staff.

In Chapters 5 and 6, some kinetic and reaction engineering fundamentals of modelling are discussed. In this chapter various models of the activated sludge process, their structure and their application are explained.

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11.2 Models Describing Carbon and Nitrogen Removal

11.2.1 Carbon Removal

The first model will be discussed in its simplest form, which is typified by the following assumptions:

- The reactor is completely mixed and operated in steady state.
- Oxygen is used only for carbon removal.
- The bacterial growth rate is high compared to its decay rate.
- The concentrations of HCO_3^- and CO_3^{2-} do not change during CO_2 production.
- The oxygen/carbon content of bacteria $y_{XO/XC}$ is known and constant.

The balance of substrates takes the form of:

$$0 = Q_0 (S_0 - S) - r_{SC} V \tag{11.1}$$

Substrate concentration is measured as dissolved organic carbon (DOC). From Eq. (11.1) we obtain:

$$S = S_0 - r_{SC} \frac{V}{Q_0} = S_0 - r_{SC} t_R \tag{11.2}$$

where r_{SC} is the rate of carbon (DOC) removal and t_R is the retention time.

Is it possible to calculate S by measuring O_2 and CO_2 concentrations in the effluent air?

The following two equations must be valid:

$$r_{SC} = r_{XC} + r_{CO_2\text{–}C} \tag{11.3}$$

$$r_{O_2} = 2\,r_{XO} + 2\,r_{CO_2\text{–}O} \tag{11.4}$$

where r_{XC} is the rate of carbon consumption for bacterial growth (mol L^{-1} h^{-1} C), r_{XO} is the rate of oxygen consumption for bacterial growth (mol L^{-1} h^{-1} O), r_{O_2} is the respiration rate (mol L^{-1} h^{-1} O_2), $r_{CO_2\text{–}C}$ is the rate of carbon consumption for the formation of CO_2 (mol L^{-1} h^{-1} C) and $r_{CO_2\text{–}O}$ is the rate of oxygen consumption for the formation of CO_2 (mol L^{-1} h^{-1} O).

Our aim is to calculate r_{SC} from the measured r_{O_2}. Therefore, we introduce:

$$r_{CO_2\text{–}C} = 2\,r_{CO_2\text{–}O} \tag{11.5}$$

inserting Eqs. (11.4) and (11.5) into Eq. (11.3), one obtains:

$$r_{SC} = r_{XC} + r_{O_2} - 2\,r_{XO} \tag{11.6}$$

with the C/O yield of bacteria:

$$y_{XC/XO} = \frac{r_{XC}}{r_{XO}} \tag{11.7}$$

and the true yield coefficient:

$$Y^{o}_{XC/SC} = \frac{r_{XC}}{r_{SC}} \tag{11.8}$$

r_{XC} and r_{XO} can be replaced and r_{SC} eliminated, giving:

$$r_{SC} = \frac{r_{O_2}}{1 - Y^{o}_{XC/SC}(1 - 2\,y_{XO/XC})} \tag{11.9}$$

If we know the values of the coefficients $Y^{o}_{XC/SC}$ (assumed constant) and $y_{XO/XC} = y^{-1}_{XC/XO}$, we are able to calculate r_{SC} from the measured rate r_{O2}, assuming that bacterial decay, endogenous respiration and nitrification can be neglected.

11.2.2
Carbon Removal and Bacterial Decay

Starting again from the substrate balance in Eq. (11.1), we now have to consider a carbon removal rate r_{SC} which is different from that in Eq. (11.1) as a result of the reduction of bacterial concentration by decay (bacterial death and mass reduction by endogenous respiration). In addition, the oxygen consumption rate is higher than that of Eq. (11.4) due to endogenous respiration. Instead of Eqs. (11.3) and (11.4), we must now write:

$$r_{SC} = r_{XC,\Sigma} + r_{CO_2-C,\Sigma} \tag{11.10}$$

$$r_{O_2,\Sigma} = 2\,r_{XO,\Sigma} + 2\,r_{CO_2-O,\Sigma} \tag{11.11}$$

with:

$$r_{XC,\Sigma} = r_{XC} + r_{XC,d} \tag{11.12}$$

$$r_{O,\Sigma} = r_{O_2} + r_{O_2,e} \tag{11.13}$$

where $r_{XC,d}$ is the decay rate of bacteria by bacterial death and endogenous respiration and $r_{O_2,e}$ is the rate of endogenous respiration.

Defining a real yield coefficient:

$$Y_{XC/SC} = \frac{r_{XC,\Sigma}}{r_{SC}} \tag{11.14}$$

and using:

$$Y_{XC/SC} = Y^{o}_{XC/SC} \cdot \left(1 - \frac{k_d}{\mu}\right) \tag{4.34}$$

from Chapter 4 and assuming the same C/O yield of bacteria, the result is:

$$r_{SC} = \frac{r_{O2,\Sigma}}{1 - Y^{o}_{XC/SC} \cdot \left(1 - \frac{k_d}{\mu}\right)(1 - 2\,y_{XO/XC})} \tag{11.15}$$

For the same measured $r_{O_2,\Sigma} = r_{O_2}$ compared with that of Section 11.2.1, r_{SC} must be lower compared to Eq. (11.9) as a result of bacterial decay k_d (death rate and endogenous respiration). r_{SC} can be quite low, particularly for low substrate concentrations (low specific growth rates μ), in spite of relatively high oxygen uptake rates.

11.2.3 Carbon Removal and Nitrification Without Bacterial Decay

In addition to the balance of substrate (see Eq. 11.1), we now have to consider the balance of ammonia:

$$O = Q_0 (S_{NH_4-N,0} - S_{NH_4-N}) - r_{NH_4-N} V \tag{11.16}$$

The aim of the following reflections is to replace r_{SC} and $r_{NH_4\text{-}N}$ with $r_{O_2,\Sigma}$. We will learn that we also need to measure $r_{CO_2\text{-}C,\Sigma}$ in addition to $r_{O_2,\Sigma}$.

We start with the following equations:

$$r_{SC} = r_{XC} + r_{CO_2-C} \tag{11.3}$$

$$r_{O_2,\Sigma} = 2\,r_{XO} + 2\,r_{CO_2-O,\Sigma} + 2\,r_{NH_4-O_2} \tag{11.17}$$

$$r_{CO_2-C,\Sigma} = r_{CO_2-C} + 2\,r_{CO_2-N} \tag{11.18}$$

r_{CO_2-N} is explained a little later. We will assume that there is complete nitrification without enrichment of NO_2^- (see Chapter 10):

$$NH_4^+ + 2\,O_2 \rightarrow NO_3^- + 2\,H^+ + H_2O \tag{11.19}$$

resulting in:

$$r_{NH_4-N} = 2\,r_{NH_4-O_2} \tag{11.20}$$

The NH_4^+ needed for the nitrifiers' anabolism is neglected. The pH is stabilized by the addition of HCO_3^-:

$$2\,HCO_3^- + 2\,H^+ \rightarrow 2\,H_2O + 2\,CO_2 \tag{11.21}$$

We can assume that CO_2 is completely degassed by aeration. Therefore, we can consider:

$$2\,r_{CO_2-N} = r_{NH_4-N} \tag{11.22}$$

In Eqs. (11.5), (11.18) and (11.20), the following rates are used: $r_{NH_4-O_2}$ is the rate of oxygen consumption for the catabolism of nitrification (mol L^{-1} h^{-1} O_2), r_{CO_2-N} is the rate of CO_2 formation by neutralization of H^+ with HCO_3^- (mol L^{-1} h^{-1} C), r_{CO_2-O} is the rate of oxygen use forming CO_2 (mol L^{-1} h^{-1} O) and r_{CO_2-C} is the rate of the carbon use forming CO_2 (mol L^{-1} h^{-1} C).

With the help of Eq. (11.7), we obtain r_{SC} from Eq. (11.3) considering:

$$Y^{o}_{CO_2-C/SC} = \frac{r_{CO_2-C}}{r_{SC}} \tag{11.23}$$

$$r_{SC} = r_{XO}\, y_{XC/XO} + r_{SC}\, Y^{o}_{CO_2\text{–}C/SC} \tag{11.24}$$

$$\text{or: } r_{SC} = \frac{r_{XO}\, y_{XC/XO}}{Y^{o}_{XC/SC}} \tag{11.25}$$

r_{XO} follows from Eqs. (11.17) and (11.20):

$$r_{XO} = \frac{1}{2}\,(r_{O_2,\Sigma} - r_{CO_2\text{–}C,\Sigma} - r_{NH_4\text{–}N}) \tag{11.26}$$

and after introduction into Eq. (11.25), we obtain:

$$r_{SC} = \frac{(r_{O_2,\Sigma} - r_{CO_2\text{–}C,\Sigma} - r_{NH_4\text{–}N})\, y_{XC/XO}}{2\, Y^{o}_{X\text{–}C/SC}} \tag{11.27}$$

$r_{NH_4\text{–}N}$ is obtained using Eqs. (11.17) and (11.20):

$$r_{NH_4\text{–}N} = r_{O_2,\Sigma} - 2\, r_{XO} - 2\, r_{CO_2\text{–}C,\Sigma} = r_{O_2,\Sigma} - 2\,\frac{r_{XC}}{y_{XC/XO}} - r_{CO_2\text{–}C,\Sigma} \tag{11.28}$$

and with Eq. (11.3):

$$r_{NH_4\text{–}N} = r_{O_2,\Sigma} - 2\,\frac{r_{SC} - r_{CO_2\text{–}C}}{y_{XC/XO}} - r_{CO_2\text{–}C,\Sigma} \tag{11.29}$$

By applying Eqs. (11.17) and (11.20), Eq. (11.29) can be written as:

$$r_{NH_4\text{–}N} = \frac{r_{O_2,\Sigma}\, y_{XC/XO} - 2\, r_{SC}}{2 + y_{XC/XO}} + r_{CO_2\text{–}C,\Sigma} \tag{11.30}$$

Equations (11.27) and (11.30) are two equations with two unknown parameters r_{SC} and $r_{NH_4\text{–}N}$, which can both be solved.

As such methods have only recently become known, balances and waste gas analysis have seldom been used for the process control of activated sludge plants. However, we are convinced that the importance of such methods will increase during the next decades.

11.3 Models for Optimizing the Activated Sludge Process

11.3.1 Preface

The models discussed in Section 11.2 can only be used for process control via off-gas measurements. If we want to find the best process and equipment design with the help of models, we further have to introduce a known formula available for the specific growth rate of bacteria:

$$r_X = \mu X = \mu(S, c', T, pH)\, X \tag{11.31}$$

in bacterial balances and to couple it with the substrate removal rate:

$$r_{SC} = \frac{\mu X}{Y^{o}_{XC/SC}} \tag{11.32}$$

and the oxygen consumption rate:

$$r_{O_2} = \frac{\mu X}{Y^{o}_{XC/O_2}} \tag{11.33}$$

The next step is to find the best equation for Eq. (11.31) (see Chapters 6 and 10).

The construction of such models will be demonstrated in the next Sections 11.3.2 and 11.3.3, starting with a relative simple model consisting of only three balances and ending with the activated sludge model (ASM) 1 with 13 balances. Further models will be mentioned briefly in Section 13.3.5.

11.3.2
Modelling the Influence of Aeration on Carbon Removal

The assumptions for this model are:

- CSTR in steady state.
- Only carbon removal.
- Monod kinetics (considering S and c' as substrates).
- No bacterial decay.
- Bacteria concentration is measured as g L^{-1} COD.

Three balances must be considered, the balance for substrate (as COD; Fig. 6.3):

$$0 = \frac{Q_M (S_M - S)}{V} - \frac{\mu_{max}}{Y^{o}_{X/S}} \frac{S}{K_S + S} \frac{c'}{K' + c'} X \tag{11.34}$$

the balance for heterotrophic bacteria (here as COD; see Fig. 6.3):

$$0 = \frac{Q_M (X_M - X)}{V} + \mu_{max} \frac{S}{K_S + S} \frac{c'}{K' + c'} X \tag{11.35}$$

and the overall balance for oxygen (liquid and gas):

$$0 = \frac{Q_G (c_{O_2,o} - c_{O_2})}{V} - \frac{\mu_{max}}{Y^{o}_{X/O_2}} \frac{S}{K_S + S} \frac{c'}{K' + c'} X \tag{11.36}$$

The three reaction rates on the right-hand part of the balances differ only in the yield coefficients: in the substrate balance $Y^{o}_{X/S}$, in the oxygen balance Y^{o}_{X/O_2} and the factor 1 in the bacterial balance.

This fact can be written using a simple matrix (Henze et al. 1987a), considering (see Table 11.1):

$$\frac{1}{Y^{o}_{X/O_2}} = \frac{Y^{o}_{O_2/S}}{Y^{o}_{X/S}} = \frac{1 - Y^{o}_{X/S}}{Y^{o}_{X/S}} \tag{11.37}$$

Table 11.1 Simple model matrix for an activated sludge reactor, only carbon removal, see Eqs. (11.34) to (11.36).

Component	**X**	**S**	**c′**	**Kinetic formation**
Process	Bacteria	Substrate	Dissolved O_2	Growth rate
Aerobic growth of heterotrophs	1	$\frac{1}{Y^{o}_{X/S}}$	$\frac{1-Y^{o}_{X/S}}{Y^{o}_{X/S}}$	$\mu_{max}\frac{S}{K_S+S}\frac{c'}{K'+c'}X$

with:

$$1 = Y^{o}_{O_2/S} + Y^{o}_{X/S}{}^{1)} \tag{11.38}$$

Equation (11.38) means that the substrate is partly used for catabolism ($Y^{o}_{O_2/S}$) and for anabolism ($Y^{o}_{X/S}$)

We want to discuss some solutions to Eqs. (11.34) to (11.36). We replace the oxygen consumption rate $Q_G\ (c_{O_2,o}-c_{O_2})/V$ by the specific oxygen mass transfer rate using an oxygen balance of the dispersed air:

$$Q_G\,(c_{O_2,o}-c_{O_2})/V = k_L a\,(c^*-c') \tag{11.39}$$

With Eqs. (11.36), (11.37) and (11.39), the balance of oxygen is:

$$0 = k_L a\,(c^*-c') - \frac{1-Y^{o}_{X/S}}{Y^{o}_{X/S}}\,\mu_{max}\,\frac{S}{K_S+S}\cdot\frac{c'}{K'+c'}\,X \tag{11.40}$$

It is possible to define dimensionless numbers which provide several advantages: to minimize the number of parameters and to be free of units. We will use:

- The dimensionless concentration of dissolved O_2, $C' = \frac{c'}{K'}$ (11.41)
- The dimensionless concentration of the substrate, $S^* = \frac{S}{K_S}$ (11.42)
- The dimensionless concentration of bacteria, $X^* = \frac{X}{K'}$ (11.43)

Introducing Eqs. (11.41) to (11.43) into Eq. (11.40), we obtain:

$$0 = \frac{k_L a}{\mu_{max}}\left(\frac{c^*}{K'} - C'\right) - \frac{1-Y^{o}_{X/S}}{Y^{o}_{X/S}}\,\frac{S^*}{1+S^*}\cdot\frac{C'}{1+C'}\,X^* \tag{11.44}$$

with:

$$\frac{k_L a}{\mu_{max}} = Sm \triangleq \text{Semenow number} \tag{11.45}$$

and $\frac{c^*}{K'}$ as the dimensionless oxygen saturation concentration.

1) Note: X is measured as g L^{-1} COD.

For high Sm numbers, there is only a very low concentration gradient of dissolved O_2 near the bubble surface and the reaction is controlled by growth kinetics of bacteria; for low Sm numbers, c' is very low ($c^* - c' \approx c^*$) and the reaction is controlled by the mass transfer rate. In a similar manner, the balances of substrate in Eq. (11.34) and bacteria in Eq. (11.35) can be written in dimensionless form (see Section 6.2), with $Da = \mu_{max} t_R$ as the Damköhler number, $n_R = Q_R/Q_0$ as the recirculation of sludge, $n_E = X_D/X_a$ as the thickening ratio and $Mo = S_0/K_S$ as the Monod number (Mehring, 1979).

Figure 11.1 demonstrates some solutions as:

$$S/K_S = f\,(Da,\ Sm = \text{parameter}) \qquad (11.46)$$

for Mo = 10 (K_S = 50 mg L^{-1} COD, S_0 = 500 mg L^{-1} COD). The other constant parameters are given in Figure 11.1.

For $Da \le 0.2$ ($S^* = Mo = 10$), the mean retention time is low and all bacteria are washed out, even though the substrate concentration is high. Due to the low oxygen consumption rate (low t_R), no influence of Sm (or $k_L a$) can be observed for $0.2 < Da < 0.25$.

For $Da > 2.5$, the oxygen consumption rate is again very low because of the very low substrate concentration. Only in the middle region ($0.25 < Da < 2.5$) can a large influence of Sm (or $k_L a$) be observed. For $Sm \ge 100$, carbon removal and bacterial growth are not dependent on aeration intensity.

For Sm = 25 and a substrate removal of 90% ($S^* = 1$ for $S_0^* = Mo = 10$), a Da = 0.5 is needed if an aeration system is to be used effectively (Fig. 11.1). The reaction is limited by dissolved oxygen. Using pure oxygen ($c^*/K' = 475$), the mean retention time t_R can be reduced by about a factor of 2 and oxygen limitation is avoided nearly completely (Fig. 11.2).

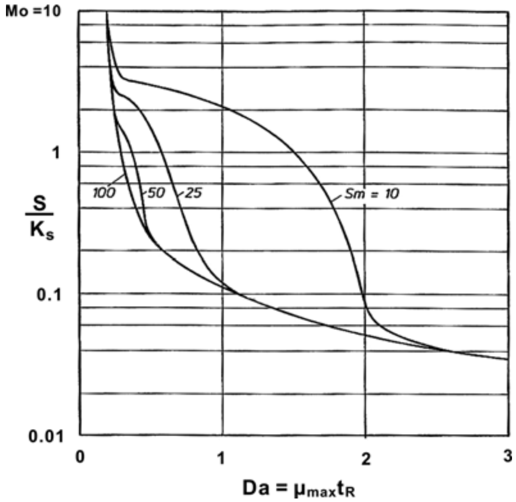

Fig. 11.1 Influence of dimensionless mean retention time $Da = \mu_{max} t_R$ and dimensionless specific mass transfer rate $Sm = k_L a/\mu_{max}$ on dimensionless effluent substrate concentration S/K_S. Constant parameters: $Mo = S_0/K_2 = 10$, $n_R = 0.45$, $n_E = 3$, $c^*/K' = 95$ (aeration).

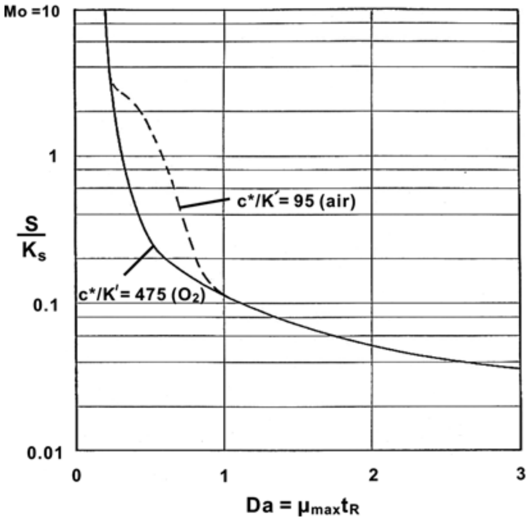

Fig. 11.2 Influence of dimensionless mean retention time $Da = \mu_{max} t_R$ and dimensionless saturation concentration $c^*/K' = 95$ (air) and 475 (pure oxygen) on dimensionless effluent substrate concentration S/K_S. Constant parameters: $Mo = S_0/K_S = 10$, $n_R = 0.45$, $n_E = 3$, $Sm = 25$.

11.3.3
Activated Sludge Model 1 (ASM 1)

This model describes the relatively complex process of aerobic and anoxic C and N removal from municipal wastewater. It is based on the post-doctoral work of Gujer (1985) and the work of Henze et al. (1987a, b). In order to present the model in its fundamental form, it is shown as a matrix which contains only reaction terms as sources (positive) or sinks (negative). This matrix is normally published without further explanations or is explained only briefly (Grady et al. 1999; Henze et al. 2000). In this section, we try to give an introduction to provide a better understanding.

The model can be fit to:

- Primary models describing different kinds of reactor configurations (anoxic/aerobic; aerobic/anoxic).
- Models describing different kinds of reactors (CSTR in one stage or as a cascade, plug flow or flow with axial dispersion, see Chapter 6).

The very simple matrix in Table 11.1 consists of only three different substances (bacteria, substrate and oxygen) and only one process (aerobic growth of heterotrophs and removal of organic substrates). ASM 1 consists of 13 different substances and eight different processes. At the beginning, we will give an overview of these 13 substances (Table 11.2).

Table 11.2 The 13 substance concentrations of ASM 1. Units for symbols 1–7: mol L^{-1} COD; units for symbol 8: –mol L^{-1} COD; units for symbols 9–12: mol L^{-1} N; units for symbol 13: mol L^{-1}.

No.	Symbol	Substance
1	S_i	Soluble inert organic matter
2	S_S	Readily biodegradable substrate
3	X_i	Particulate inert organic matter
4	X_S	Slowly biodegradable substrate
5	X_H	Active heterotrophic biomass
6	X_A	Active autotrophic biomass
7	X_P	Particulate products from biomass decay
8	c'	Dissolved oxygen
9	S_{NO}	Nitrate and nitrite nitrogen
10	S_{NH_4}	Ammonium and amonia nitrogen
11	S_{NS}	Soluble degradable organic nitrogen
12	X_{ND}	Particulate degradable organic nitrogen
13	S_{Alk}	Alkalinity

It should be emphasized that, besides the readily biodegradable substances S_S, slowly biodegradable substances X_S are considered as solid particles, which must first be hydrolyzed by exoenzymes. X_i is the corresponding inert organic matter which cannot be disregarded, as we will see below. Particulate products X_P result from the lysis of bacteria or remain as insoluble solids.

The eight processes are summarized in Table 11.3.

The matrix of the ASM 1 model consists, therefore, of a 13×8 matrix for the 13 substances in the columns and eight processes in the rows.

For a CSTR in non-steady condition, 13 balances must be taken into account, each of which is written in the same way as Eq. (11.47):

$$\frac{dS}{dt} = \frac{Q_M}{V}(S_M - S) + r_S \tag{11.47}$$

eight for different dissolved components (7 S + c′) and five for different undissolved components X. Only the reaction terms r_{Si} are arranged in the matrix.

The reaction terms should be discussed in some detail before the matrix is constructed (see Table 11.4).

We will begin with the reaction terms for soluble inert organic matter.

Table 11.3 The eight processes of ASM 1.

No.	Process
1	Aerobic growth of heterotrophs
2	Anoxic growth of heterotrophs
3	Aerobic growth of autotrophs
4	Decay of heterotrophs
5	Decay of autotrophs
6	Ammonification of soluble organic nitrogen
7	Hydrolysis of particulate organics
8	Hydrolysis of particulate organic nitrogen

Table 11.4 Process kinetics and stoichiometric parameters of the activated sludge model ASM 1 plotted in a matrix form (13 parameters, 8 processes; Henze et al. 2000)

Component (i) →	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	
j ↓ Process (j)	S_i	S_S	X_i	X_S	X_H	X_A	X_P	c'	S_{NO_3}	S_{NH_4}	S_{ND}	X_{ND}	S_{Alk}	Process rate $r_j\,[ML^{-3}T^{-1}]$
1 Aerobic growth of heterotrophs		$\frac{1}{Y^o_{XH/SS}}$			1			$\frac{1-Y^o_{XH/SS}}{Y^o_{XH/SS}}$		i_{XB}			$\frac{i_{XB}}{14}$	$\mu_{max,H}\frac{S_S}{K_S+S_S}\frac{c'}{K'_H+c'}X_H$
2 Anoxic growth of heterotrophs		$\frac{1}{Y^o_{XH/SS}}$			1				$\frac{1-Y^o_{XH/SS}}{2.86\,Y^o_{XH/SS}}$	i_{XB}			$\frac{1-Y^o_{XH/SS}}{14\cdot 2.86\,Y^o_{XH/SS}}$ $\frac{i_{XB}}{14}$	$\mu_{max,H}\,\eta\frac{S_S}{K_S+S_S}\frac{K_{i0}}{K_{i0}+c'}\frac{S_{NO_3}}{K_{NO}+S_{NO_3}}X_H$
3 Aerobic growth of autotrophs						1		$\frac{4.57-Y^o_{XA/NH_4}}{Y^o_{XA/NH_4}}$	$Y^o_{NO_3/XA}$	$i_{XB}-\frac{1}{Y^o_{XA/NH_4}}$			$\frac{i_{XB}}{14}-\frac{1}{7\,Y^o_{XA/NH_4}}$	$\mu_{max,A}\frac{S_{NH_4}}{K_{SA}+S_{NH_4}}\cdot\frac{c'}{K'_A+c'}X_A$
4 Decay of heterotrophs				$1-f_i$	−1		f_P					$i_{XB}-f_P\,i_{XP}$		$k_{dH}X_H$
5 Decay of autotrophs				$1-f_i$		−1	f_P					$i_{XB}-f_P\,i_{XP}$		$k_{dA}X_A$
6 Ammonification of soluble organic nitrogen										1	1		$\frac{1}{14}$	$k_a\,S_{ND}\,X_H$
7 Hydrolysis of particulate organics				1										$k_H\frac{X_S/X_H}{K_X+(X_S/X_H)}\left(\frac{c'}{K'_H+c'}+\eta_n\frac{K_{i0}}{K_{i0}+c'}\frac{S_{NO_3}}{K_{NO}+S_{NO_3}}\right)X_H$
8 Hydrolysis of particulate organic nitrogen											1	1		$k_{en}(X_{ND}/X_S)$

i = 1, S_i – Soluble Inert Organic Matter

$$r_{Si} = 0$$

This assumption is a simplification made by ASM 1. In reality, such dissolved inert substances (non-biodegradable) can be formed by the hydrolysis or lysis of solid particles or other dissolved substances or they can be adsorbed on solid surfaces.

i = 2, S_S – Readily Biodegradable Substrate

$$r_{SS} = -\frac{1}{Y^{o}_{XH/SS}}\,\mu_{max,H}\,\frac{S_S}{K_S+S_S}\left(\frac{c'}{K'_H+c'}+\eta\,\frac{K_{i0}}{K_{i0}+c'}\,\frac{S_{NO_3}}{K_{NO}+S_{NO_3}}\right)X_H \tag{11.48}$$

r_{SS} is the rate of COD removal by aerobic and anoxic bacteria.

The measured COD is:

$$S_{S\Sigma} = S_i + S_S \tag{11.49}$$

and S_S can only be determined if S_i is known. η is the ratio of $\mu_{max,H}$ values for anoxic and aerobic bacteria (Henze 1986).

i = 3, X_i – Particulate Inert Organic Matter

$$r_{Xi} = 0$$

Nearly the same remarks are valid as those above (see $i = 1$, S_i). Nevertheless, X_i is needed for the definition of f_i (see Eq. 11.52) and for the formation of the balance describing non-steady state transport:

$$\frac{dX_i}{dt} = \frac{Q_M}{V}\,(X_{iM}-X_i) \tag{11.50}$$

i = 4, X_S – Slowly Biodegradable Substrate

$$r_{XS} = \underbrace{(1-f_i)\,k_{dH}X_H}_{\substack{\text{formation from}\\ \text{decay of heterotrophs}}} + \underbrace{(1-f_i)\,k_{dA}X_A}_{\substack{\text{formation from}\\ \text{decay of autotrophs}}}$$
$$\underbrace{-\,k_H\,\frac{X_S/X_H}{K_X+X_S/X_H}\left(\frac{c'}{K'_H+c'}+\eta\,\frac{K_{i0}}{K_{i0}+c'}\cdot\frac{S_{NO_3}}{K_{NO}+S_{NO_3}}\right)X_H}_{\text{hydrolysis of entrapped organics by aerobic and anoxic bacteria}} \tag{11.51}$$

$$f_i = \frac{X_i}{X_H+X_A+X_i+X_S} \tag{11.52}$$

$$1-f_i = \frac{X_H+X_A+X_S}{X_H+X_A+X_i+X_S} \tag{11.53}$$

$$\eta = \frac{r_{H,Ax}}{r_{H,Ae}}\;\frac{\text{hydrolysis by anoxic bacteria}}{\text{hydrolysis by aerobic bacteria}} \tag{11.54}$$

***i* = 5, X_H – Active Heterotrophic Biomass**

$$r_{XH} = \underbrace{\mu_{max,H} \frac{S_S}{K_S + S_S} \left(\frac{c'}{K'_H + c'} + \eta \frac{K_{i0}}{K_{i0} + c'} \frac{S_{NO_3}}{K_{NO} + S_{NO_3}} \right) X_H}_{\text{growth of aerobic and anoxic bacteria}}$$

$$\underbrace{- k_{dH} X_H}_{\text{decay of heterotrophs}} \tag{11.55}$$

***i* = 6, X_A – Active Autotrophic Biomass**

$$r_{XA} = \underbrace{\mu_{max,A} \frac{S_{NH_4}}{K_{SA} + S_{NH_4}} \frac{c'}{K'_A + c'} X_A}_{\text{growth of autotrophs}} - \underbrace{k_{dA} X_A}_{\text{decay of autotrophs}} \tag{11.56}$$

***i* = 7, X_P – Particulate Products from Biomass Decay**

$$r_{XP} = \underbrace{f_P k_{dH} X_H + f_P k_{dA} X_A}_{\text{production rate by decay}} \tag{11.57}$$

$$f_P = \frac{X_P}{X_H + X_A} \tag{11.58}$$

***i* = 8, c' – Dissolved Oxygen**

$$\begin{aligned} r_{O_2} = &- Y^o_{O_2/XH} \mu_{max,H} \frac{S_S}{K_S + S_S} \frac{c'}{K'_H + c'} X_H \\ &- Y^o_{O_2/XA} \mu_{max,A} \frac{S_{NH_4}}{K_{SA} + S_{NH_4}} \frac{c'}{K'_A + c'} X_A \end{aligned} \tag{11.59}$$

reflects oxygen consumption (or COD removal) by aerobic heterotrophs and autotrophs. Therefore, the units of r_{O_2} are g m^{-3} h^{-1} COD.

$Y^o_{O_2/XH}$ follows from:

$$\underbrace{Y^o_{XH/SS}}_{\text{anabolism}} + \underbrace{Y^o_{O_2/SS}}_{\text{catabolism}} = 1^{1)} \tag{11.60}$$

$$\text{and: } Y^o_{O_2/XH} = \frac{Y^o_{O_2/SS}}{Y^o_{XH/SS}} = \frac{1 - Y^o_{XH/SS}}{Y^o_{XH/SS}} \tag{11.61}$$

---

1) See remarks on Eq. (11.38).

For autotrophic nitrifiers one can write:

$$Y^o_{O_2/XA} = \frac{Y^o_{O_2/NH_4}}{Y^o_{XA/NH_4}} \tag{11.62}$$

and:

$$\underbrace{Y^o_{O_2/NH_4}}_{\text{catabolism}} = Y^o_{O_2/NH_4-N,\Sigma} - \underbrace{Y^o_{XA/NH_4}}_{\text{anabolism}} \tag{11.63}$$

as well as:

$$Y^o_{O_2/NH_4-N,\Sigma} = \frac{r_{O_2}}{r_{NH_4-N,\Sigma}} = \frac{64}{14} = 4.57 \frac{g\ O_2}{g\ NH_4-N} \tag{11.64}$$ [2]

$$\text{and: } Y^o_{O_2/XA} = \frac{4.57 - Y^o_{XA/NH_4}}{Y^o_{XA/NH_4}} \tag{11.65}$$

Finally, Eqs. (11.61) and (11.65) are introduced into the matrix of Table 11.4 (space i = 8 for j = 1, j = 3).

***i* = 9, S_{NO_3} – Nitrate Nitrogen**

As already assumed for nitrifier growth (i = 6), where nearly no NO_2 is produced, denitrification goes directly to nitrogen and the denitrification of NO_2 is not considered (Chapter 10).

$$r_{NO_3} = \underbrace{- Y^o_{NO_3/XH}\, \mu_{max,H}\, \eta \frac{S_S}{K_S + S_S} \frac{K_{i0}}{K_{i0} + c'} \frac{S_{NO_3}}{K_{NO} + S_{NO_3}} X_H}_{\text{reduction of } NO_3 \text{ by denitrification}}$$

$$\underbrace{+ Y^o_{NO_3/XA}\, \mu_{max,A} \frac{S_{NH_4}}{K_{SA} + S_{NH_4}} \frac{c'}{K'_A + c'} X_A}_{\text{formation of } NO_3 \text{ by nitrification}} \tag{11.66}$$

Writing:

$$Y^o_{NO_3/XH} = \frac{Y^o_{O_2/XH}}{\Delta Y^o_{O_2/NO_3}} \tag{11.67}$$

$\Delta Y^o_{O_2/NO_3}$ is the oxygen savings by denitrification after nitrification and can be calculated using:

$$\Delta Y^o_{O_2/NO_3} = Y^o_{O_2/NH_4} - Y^o_{O_2/NO_3} \tag{11.68}$$

$Y^o_{O_2/NH_4-N,\Sigma} = 4.57\ g\ O_2\ (g\ NH_4-N)^{-1}$ follows from Eq. (11.64).

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[2] Note: $NH_4^+ + 2\,O_2 = NO_3^- + H_2O + 2\,H^+$ and $Y^o_{O_2/NH4} = Y^o_{O_2/XA} \cdot Y^o_{XA/NH_4}$

For the calculation of $Y^o_{O_2/NO_3}$ we have to use the catabolic production of NO_3^- by nitrification:

$$6\,NH_4^+ + 12\,O_2 \rightarrow 6\,NO_3^- + 6\,H_2O + 12\,H^+ \tag{11.69a}$$

and the consumption of NO_3^- by denitrification using methanol as an energy source:

$$6\,NO_3^- + 5\,CH_3OH \rightarrow 3\,N_2 + 5\,CO_2 + 7\,H_2O + 6\,OH^- \tag{11.69b}$$

in comparision with the aerobic oxydation of methanol:

$$7.5\,O_2 + 5\,CH_3OH \rightarrow 5\,CO_2 + 10\,H_2O \tag{11.70}$$

For nitrification of 6 NH_4^+ (using $5\,CH_3OH$ for denitrification), 24 moles O are needed; for aerobic oxydation of the same amount of $5\,CH_3OH$, 15 moles O must be used. Therefore, the difference of both follows to:

$$Y^o_{O_2/NO_3} = \frac{24-15}{6} = 1.5\ \frac{g\ O}{g\ NO_3^-} = 1.5\ \frac{16}{14}\ \frac{mol\ O}{mol\ N} = 1.71\ \frac{mol\ O}{mol\ N}$$

Considering Eq. (11.68), one obtains:

$$\Delta Y^o_{O_2/NO_3} = Y^o_{O_2/NH_4} - Y^o_{O_2/NO_3} = 4.57 - 1.71 = 2.86\ g\ O_2\ (g\ NO_3 - N)^{-1}$$

From Eqs. (11.67) and (11.61), it follows (i = 9, j = 2):

$$Y^o_{NO_3/XH} = \frac{1 - Y^o_{XH/SS}}{2.86\,Y^o_{XH/SS}} \tag{11.71}$$

i = 10, S_{NH_4} – Ammonium Nitrogen

$$\begin{aligned} r_{NH_4} = \; & \underbrace{-\,i_{XB}\,\mu_{max,H}\,\frac{S_S}{K_S+S_S}\,\frac{c'}{K'_H+c'}\,X_H}_{\text{NH}_4\text{ uptake by aerobic heterotrophs}} \\ & \underbrace{-\,i_{XB}\cdot\eta\,\mu_{max,H}\,\frac{S_S}{K_S+S_S}\,\frac{K_{i0}}{K_{i0}+c'}\,\frac{S_{NO_3}}{K_{NO}+S_{NH_3}}\,X_H}_{\text{NH}_4\text{ uptake by anoxic heterotrophs}} \\ & \underbrace{-\left(i_{XB} + \frac{1}{Y^o_{XA/NH_4}}\right)\mu_{max,A}\,\frac{S_{NH4}}{K_{SA}+S_{NH_4}}\,\frac{c'}{K'_A+c'}\,X_A}_{\text{NH}_4\text{ uptake and NH}_4\text{ oxidation by autotrophs}} \\ & \underbrace{+\,k_a\,S_{ND}\,X_H}_{\text{NH}_4\text{ formation by anoxic hydrolysis of heterotrophs}} \end{aligned} \tag{11.72}$$

i = 11, S_{ND} – Soluble Degradable Organic Nitrogen

$$r_{ND} = \underbrace{-k_a S_{ND} X_H}_{\substack{NH_4 + NH_3 \\ \text{uptake by} \\ \text{heterotrophs}}} + \underbrace{k_{en} X_{ND}/X_S}_{\substack{\text{formation of} \\ \text{organic nitrogen} \\ \text{by hydrolysis}}} \tag{11.73}$$

i = 12, X_{ND} – Particulate Degradable Organic Nitrogen

$$r_{ND} = \underbrace{(i_{XB} - f_P i_{XP})\, k_{dH} X_H}_{\substack{\text{formation from} \\ \text{decay of heterotrophs}}} + \underbrace{(i_{XB} - f_P i_{XP})\, k_{dA} X_A}_{\substack{\text{formation from} \\ \text{decay of autotrophs}}} - \underbrace{k_{en} X_{ND}/X_S}_{\text{hydrolysis}} \tag{11.74}$$

$$i_{XB} = \frac{X_N}{X_H + X_A + X_S} = \frac{\text{nitrogen in bacteria}}{\text{mass of bacteria + slowly biodegradable substrate}} \tag{11.75}$$

$$i_{XP} = \frac{X_N}{X_i} = \frac{\text{nitrogen in bacteria}}{\text{particulate inert organic matter in bacteria}} \tag{11.76}$$

$$i_{XB} - f_P i_{XP} = \frac{\text{biodegradable organic nitrogen}}{\text{particulate organic matter}} \tag{11.77}$$

f_P see Eq. (11.58).

i = 13, S_{Alk} – Alkalinity

$$S_{Alk} = S_{HCO_3^-} + S_{CO_3^{2-}} + S_{NO_3^-} + S_{OH^-} \tag{11.78}$$

S_{Alk} is the concentration of anions (alkalinity). The balance:

$$\frac{dS_{Alk}}{dt} = \frac{Q_M}{V}\,(S_{Alk,o} - S_{Alk}) \pm r_{Alk} \tag{11.79}$$

describes the change of pH. For $S_{Alk} \gg S_{Alk,o}$ the pH increases and vice versa. The pH influences some equilibria (NH_4^+/NH_3, NO_3^-/HNO_3) and the activity of bacteria. In wastewater with a low $S_{Alk,o}$ and nitrification, r_{Alk} cannot be neglected. The balance of anions is written in moles.

$$r_{Alk} = \underbrace{-\frac{i_{XB}}{14}\,\mu_{max,H}\,\frac{S_S}{K_S + S_S}\,\frac{c'}{K'_H + c'}\,X_H}_{\text{use of } NO_3^- \text{ for growth of aerobic heterotrophs}}$$

$$\underbrace{-\left(\frac{i_{XB}}{14} - \frac{1 - Y^o_{XH/SS}}{14 \cdot 2.86\, Y^o_{XH/SS}}\right)\mu_{max,H} \cdot \eta\,\frac{S_S}{K_S + S_S}\,\frac{K_{i0}}{K_{i0} + c'}\,\frac{S_{NO_3}}{K_{NO} + S_{NO_3}}\,X_H}_{\substack{\text{use of } NO_3^- \text{ for growth of heterotrophs and production} \\ \text{of } HCO_3^- \text{ by denitrification}}}$$

$$-\underbrace{\left(\frac{i_{XB}}{14}+\frac{1}{7\,Y^{o}_{XA/NH_4}}\right)\mu_{max,A}\,\frac{S_{NH_4}}{K_{SA}+S_{NH_4}}\,\frac{c'}{K'_A+c'}\,x_A}_{\substack{\text{use of } NO_3^- \text{ for growth of autotrophs}\\ \text{and use of } HCO_3^- \text{ for } H^+ \text{ uptake}\\ \text{during nitrification}}}+\underbrace{\frac{1}{14}\,k_{en}\,\frac{X_{ND}}{X_S}}_{\substack{\text{production of } NO_3^-\\ \text{by hydrolysis of par-}\\ \text{ticular orgaic nitrogen}}} \tag{11.80}$$

The production of HCO_3^- during denitrification is described by the stoichiometry for catabolism and anabolism using CH_3OH as an energy source (see Eqs. 10.43 and 10.44).

As follows from the catabolism of nitrification without NO_2^- enrichment:

$$NH_4^+ + 2\,O_2 \rightarrow NO_3^- + H_2O + 2\,H^+ \tag{10.6}$$

and with the use of HCO_3^- as an electron acceptor:

$$2\,H^+ + 2\,HCO_3^- \rightarrow 2\,H_2CO_3 \tag{11.81}$$

$12\,HCO_3^-$ are needed for $6\,NH_4^+$, these are 6 more moles anions than those recovered by denitrification (see Eq. (11.69) and consider $OH^- + CO_2 = HCO_3^-$).

Because: $Y^{o}_{HCO_3^-/NH_4^+} = 2$, we write for the rate of HCO_3^- consumption by nitrification (Table 11.4, space i = 13, j = 3 in the matrix):

$$\frac{Y^{o}_{HCO_3^-/NH_4^+}}{14\,Y^{o}_{XA/SS}}\,r_{NH_4} = \frac{1}{7\,Y^{o}_{XA/SS}}\,r_{NH_4} \tag{11.82}$$

The ASM 1 model makes it possible to simulate different loadings of municipal activated sludge plants in steady and non-steady state without biological phosphorous removal. It can be used as the basis for a training program for the staff of wastewater treatment plants and for design calculation of the plant and optimization of the processes.

After intensive study of the model, the reader of the matrix (see Table 11.4) will see the advantage in using the matrix in combination with a computer program.

11.3.4
Application of ASM 1

Grady et al. (1999) published some examples for applications of the ASM 1. It is necessary to first determine values for all 19 coefficients compiled in Table 11.5.

Some of them have been chosen from mean values from many kinetic measurements; some of them are still unreliable. The processes 6 (ammonification of soluble organic nitrogen) and 8 (hydrolysis of entrapped organic nitrogen) are neglected.

In addition to the parameters in Table 11.5, some characteristics of a domestic wastewater following primary sedimentation were considered (Table 11.6).

A large number of questions can be answered using this model. One interesting question is: what is the oxygen requirement $Q_G\,\Delta c_{O_2}$ in dependence on sludge retention time t_{RX}? The model was calculated for a steady-state condition and $X_A + X_H$; and then X_H and $Q_G\,\Delta c_{O_2}$ were both plotted versus sludge age (Fig. 11.3).

Table 11.5 Typical parameter values at neutral pH and 20 °C for domestic wastewater (Grady et al. 1999, p. 199).

Symbol	Units	Value
Stoichiometric coefficients		
$Y^{o}_{XH/SS}$	mg biomass COD formed per mg COD removed	0.60
f_P	mg debris COD (mg biomass COD)$^{-1}$	0.08
i_{XB}	mg N (mg COD)$^{-1}$ in active biomass	0.086
i_{XP}	mg N(mg COD)$^{-1}$ in biomass debris	0.06
Y^{o}_{XA/NH_4}	mg biomass COD formed per mg N oxidized	0.24
Kinetic parameters		
$\mu_{max,H}$	h^{-1}	0.25
K_S	mg L^{-1} COD	20
K'_H	mg L^{-1} O_2	0.10
K_{NO}	mg L^{-1} N	0.20
k_{dH}	h^{-1}	0.017
η	Dimensionless	0.8
η_h	Dimensionless	0.4
k_a	L (mg biomass COD h)$^{-1}$	0.0067
k_H	mg COD (mg biomass COD h)$^{-1}$	0.092
K_X	mg COD (mg biomass COD)$^{-1}$	0.15
$\mu_{max,A}$	h^{-1}	0.032
K_{NO}	mg L^{-1} N	1.0
K'_A	mg L^{-1} O_2	0.75
k_{dA}	h^{-1}	0.004

Table 11.6 Characteristics of a domestic wastewater of the USA after primary sedimentation (Grady et al. 1999, p. 214; Bidstrup and Grady 1988).

Symbol	Component	Concentration (mg L^{-1})
X_i	Inert particulate organic matter (COD)	35.0
X_S	Slowly biodegradable substrate (COD)	150.0
S_S	Readily biodegradable substrate (COD)	115.0
c'	Oxygen (O_2)	0.0
S_{NO}	Soluble nitrate N	0.0
S_{NH}	Soluble ammonia N	25.0
S_{NS}	Soluble biodegradable organic N	6.5
X_{ND}	Particulate biodegradable organic N	8.5

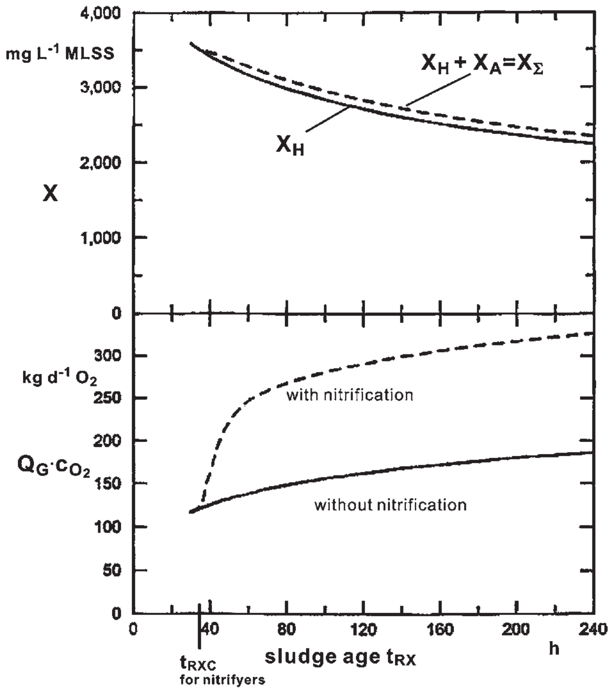

Fig. 11.3 Effect of sludge age t_{RX} on bacterial concentration X_H and $X_H + X_A$ as well as oxygen demand in a CSTR with $t_{RX}/t_R = 20$. Parameter values given in Tables 11.5 and 11.6. $c' = 4.0$ mg L^{-1} (Grady et al. 1999, p. 214).

The sludge age can be calculated using:

$$t_{RX} = \frac{V\,(X_A + X_H)}{Q_{ex} X_R} \tag{11.83}$$

where Q_{ex} is the excess sludge flow rate ($m^3\ d^{-1}$) and X_R is the concentration of excess sludge (kg m^{-3}).

For a sludge age of $t_{RX} \leq 35$ h, the nitrifiers are washed out. Their growth rate is too low compared with their dilution time in the system consisting of reactor and secondary clarifier. For $t_{RX} \geq 148$ h = 7 d, the oxygen demand increases mainly as a result of endogenous respiration; nitrogen and carbon are removed to a greater extent.

11.3.5
More Complicated Models and Conclusions

ASM 1 does not describe biological or chemical phosphorus removal. It was necessary to expand it to 19 balances for 19 components and 12 processes. The reaction terms consist of up to 7 Monod parts. The expanded model, called ASM 2 (Henze et al. 2000), will not be described here. ASM 2 models biological phosphorous accumulation by organisms of two fractions, one of which is able to nitrify.

ASM 3 was developed to correct some ASM 1 problems:

- Limitations of nitrogen and alkalinity on growth rate of heterotrophic organisms.
- Inclusion of soluble and particulate organic nitrogen.
- The elimination of a differentiation between inert organic material, inert particles, influent or biomass decay compared to ASM 1.

All together, ten points were mentioned (Henze et al. 2000), showing that the ASM 1 model is too simple to accurately describe the activated sludge process. Therefore, a completely new model was generated, ASM 3, which will not be described or discussed here.

There is no single model which describes all the qualities and properties of a plant-scale activated sludge process. The power of modern computer systems tempts us to construct more and more complex models. But we should not forget that an activated sludge plant in non-steady operation is not only influenced by the complicated reaction terms of the ASM models. The fluid dynamics and the mass transfer in activated sludge plants influence the substrate removal and nitrification just as much if not more than do the micro-kinetics. We model completely mixed tanks and nothing else. Frequently, it is not easy to describe the measurements of retention time distributions mathematically. But there are only a few plants that have been studied with such measurements. For most basins, we do not have these results and we are not able to conclude whether we need a cascade model with six stages or only two. We should never forget such considerations when applying simple models or one of the ASM models!

PROBLEM 11.1

In a completely mixed activated sludge reactor with an influent concentration of $S_0 = 200\ \mathrm{g\ m^{-3}}$ DOC, a 95% DOC reduction should be realized within $t_R = 6$ h. Calculate the necessary oxygen uptake rate r_{O_2}.

Given:

$$y_{XO/XC} = \frac{20}{50}\ \frac{\mathrm{g\ O}}{\mathrm{g\ C}} = \frac{20}{50}\ \frac{12}{16}\ \frac{\mathrm{mol\ O}}{\mathrm{mol\ C}} = 0.3\ \frac{\mathrm{mol\ O}}{\mathrm{mol\ C}}$$

and:

$$Y^{o}_{XC/SC} = 0.5\ \frac{\mathrm{mol\ X-C}}{\mathrm{mol\ S-C}}$$

Solution

The carbon removal rate r_{SC} follows from the C balance in Eq. (11.2):

$$r_{SC} = \frac{S_0 - S}{t_R} = \frac{190}{6} = 31.67\ \mathrm{g\ m^{-3}\ h^{-1}}\ \mathrm{DOC}$$

Using Eq. (11.9), we obtain the oxygen uptake rate:

$$r_{O_2} = r_{SC}\,(1 - Y^{o}_{XC/SC}\,(1 - 2\,y_{XO/XC}))$$

$$= 31.67\left(1 - 0.5\,\frac{\text{mol C}}{\text{mol C}}\left(1 - 2\cdot 0.3\,\frac{\text{mol O}}{\text{mol C}}\right)\right)$$

$$= 31.67\cdot 0.8\ \text{g m}^{-3}\,\text{h}^{-1}\ \text{DOC}\ \frac{\text{mol O}}{\text{mol C}}$$

$$= 25.34\cdot 0.5\ \text{g m}^{-3}\,\text{h}^{-1}\ \text{DOC}\ \frac{\text{mol } O_2}{\text{mol C}} = 12.67\ \text{g m}^{-3}\,\text{h}^{-1}\ \text{DOC}\ \frac{32\ \text{g } O_2}{12\ \text{g C}}$$

$$r_{O2} = 33.78\ \text{g m}^{-3}\,\text{h}^{-1}\ O_2$$

PROBLEM 11.2

The same wastewater described in Problem 11.1 is to be nitrified. The NH_4-N concentration of $S_{NH_4-N,o} = 50$ mg L^{-1} must be reduced down to 1 mg L^{-1}. Oxygen utilization in the airflow is about 20%, $c_{O_2,0} = 0.232$ kg m^{-3} O_2, $V = 5000$ m^3. We will assume that the nitrifiyers are not washed out.

1. Calculate the oxygen uptake rate and the required air flow rate.
2. Calculate the needed specific mass transfer coefficients with ($c' = 2$ mg L^{-1}) and without nitrification ($c' = 1$ mg L^{-1}).

Solution

1. To calculate the required air flow rate, we start with an oxygen balance:

$$Q_G\,(c_{O_2,0} - c_{O_2}) = r_{O_2,\Sigma}\,V$$

$$Q_G = \frac{r_{O_2,\Sigma}\,V}{c_{O_2,0} - c_{O_2}}$$

with 20% oxygen utilization $c_{O_2,0} - c_{O_2} = 0.046$ kg m^{-3}. Starting from an NH_4 balance:

$$r_{NH_4-N} = \frac{(S_{NH_4-N,0} - S_{NH_4-N})}{t_R} = \frac{49}{6} = 8.17\ \text{mg L}^{-1}\,\text{h}^{-1}$$

$$= \frac{8.17}{14} = 0.584\ \text{mmol L}^{-1}\,\text{h}^{-1}\ NH_4\text{-N}$$

can be calculated.

As $NH_4^+ + 2\,O_2 \rightarrow NO_3^- + 2\,H^+ + H_2O$, the oxygen consumption rate of nitrification is:

$$r_{O_2,N} = 2 \cdot 0.584 = 1.17 \text{ mmol L}^{-1}\text{ h}^{-1}$$
$$= 1.17 \cdot 32 = 37.44 \text{ mg L}^{-1}\text{ h}^{-1}\text{ O}_2$$

$$r_{O_2,\Sigma} = r_{O_2,N} + r_{O_2,C}$$
$$= 37.44 + 33.78 \text{ (see: problem 11.1)}$$
$$= 71.22 \text{ g m}^{-3}\text{ h}^{-1}\text{ O}_2$$

For the flow rate we obtain:

$$Q_G = \frac{71.22 \cdot 5000}{0.046} = \frac{\text{g m}^3\text{ m}^3}{\text{m}^3\text{ h kg}} = 7741 \text{ m}^3\text{ h}^{-1}$$

2. The concentration of dissolved oxygen must be increased from $c' = 1$ mg L^{-1} (only carbon removal) to 2 mg L^{-1} (carbon removal with nitrification).

What is the old and what do we select for the new specific mass transfer coefficient k_La of the aeration system? Saturation concentration $c^* = 9$ mg L^{-1} O_2.

(a) Only C-removal

$$k_L a\,(c^* - c') = r_{O_2}$$

$$k_L a = \frac{33.78}{8} = 4.2 \text{ h}^{-1}$$

(b) C-removal with nitrification

$$k_L a\,(c^* - c') = r_{O_2\Sigma}$$

$$k_L a = \frac{71.22}{7} = 10.2 \text{ h}^{-1}$$

The aeration system must be selected according to these requirements.

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