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ACTIVATED SLUDGE MODEL NO.2D, ASM2D

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ABSTRACT

The Activated Sludge Model No. 2d (ASM2d) presents a model for biological phosphorus removal with simultaneous nitrification-denitrification in activated sludge systems. ASM2d is based on ASM2 and is expanded to include the denitrifying activity of the phosphorus accumulating organisms (PAOs). This extension of ASM2 allows for improved modeling of the processes, especially with respect to the dynamics of nitrate and phosphate.

KEYWORDS

ASM2; ASM2d; nitrification; denitrification; biological phosphorus removal; PAOs; mathematical modeling; activated Sludge.

INTRODUCTION

This paper presents a mathematical model which allows for dynamic simulation of combined biological processes for chemical oxygen demand (COD), nitrogen and phosphorus removal in activated sludge systems. The model as presented here is a tool for:

- research (testing results, selecting and optimizing experiments)
- process optimization and troubleshooting at full-scale treatment plants
- teaching
- design assistance (for optimization of details, not for full design).

The model presented below is not the final answer to biological phosphorus removal models. Rather it is a compromise between complexity and simplicity, and between the many viewpoints on what the correct model would be. It is intended to be a conceptual platform and reference for further model development.

ASM2d is an extension of the Activated Sludge Model No.2 (Henze *et al.*, 1995) and the Activated Sludge Model No. 1 (ASM1) (Henze *et al.*, 1987), and uses the concepts incorporated in these models. ASM1 has long since proved to be an excellent tool for modeling nitrification-denitrification processes and has initiated further research in modeling and wastewater characterization. It is hoped that ASM2d will serve a similar function. ASM2d may be applied as presented, but based on experience, it will most likely be used as a platform for future model development. As this is the basic idea behind presenting the model, this is highly encouraged.

In ASM2 an unresolved part was the denitrification related to PAOs. Since the publication of ASM2 it has been demonstrated clearly (Mino *et al.*, 1995, Meinholt *et al.*, 1999, Kerrn-Jespersen and Henze, 1993) that PAOs in a modeling context can be considered to consist of two fractions, one of which can denitrify. This has created a need for an extension of ASM2, the result being presented here as ASM2d.

CONCEPTUAL APPROACH

An attempt has been made to limit the number of processes used in the model. The aim has, however, been to produce a model that can reasonably describe the many different activated sludge system configurations which are used for biological phosphorus removal. This has resulted in the present level of complexity. In specific cases, it will be possible to reduce the complexity of the model by omitting processes that do not play a significant role, without interfering with the predictive power of the model.

The kinetics and stoichiometry used to describe the processes have been chosen as simply as possible, mainly based on Monod kinetics for all components that can influence the reaction rates. Monod kinetics allows for smooth transitions of the processes, as experience has shown. Kinetics and stoichiometry are presented using the matrix notation, which has been introduced together with ASM1 and appears at this moment to be the most efficient method to overview the complex transformations among the components. The matrix notation also allows control of the conservation of components in the stoichiometric coefficients and thus ensures that mass balances in the calculations are correctly maintained.

THE ACTIVATED SLUDGE MODEL NO. 2d (ASM2d)

The Activated Sludge Model No. 2 (ASM2) is an extension of the Activated Sludge Model No. 1 (ASM1). ASM2 is more complex and includes many more components which are required in order to characterize the wastewater as well as the activated sludge. Additional biological processes are included, primarily in order to deal with biological phosphorus removal. The most significant change from ASM1 to ASM2 is the fact that the biomass now has cell internal structure, and therefore its concentration cannot simply be described with the distributed parameter X_{BM}. This is a prerequisite in order to include biological phosphorus removal in the model.

The Activated Sludge Model No. 2d is a minor extension of ASM2. It includes two additional processes to account for the fact that phosphorus accumulating organisms (PAOs) can use cell internal organic storage products for denitrification. Whereas ASM2 assumes PAOs to grow only under aerobic conditions, ASM2d includes denitrifying PAOs. This report is based on the previous report which introduced ASM2. All remarks made relative to ASM2 are equally valid for ASM2d. If information is given which relates specifically to ASM2d then reference will be made to this extended model.

In addition to the biological processes, ASM2 includes two 'chemical processes', which may be used to model chemical precipitation of phosphorus.

Whereas ASM1 was based entirely on COD for all particulate organic material, as well as the total concentration of the activated sludge, ASM2 includes poly-phosphates, a fraction of the activated sludge

which is of prime importance for the performance of the activated sludge system, but which does not exert any COD. For this reason, the possibility of including total suspended solids (TSS) in the model is introduced. TSS also allow for inclusion of mineral particulate solids in the influent to treatment plants, as well as generation of such solids in the context of precipitation of phosphorus.

ASM2 is introduced here in a form which is more complex than a basic version, which could still predict many of the phenomena within a biological nutrient removal plant. The complex model as presented may easily be simplified by eliminating those components which do not have a dominant effect upon the kinetics of the processes, or the aspects of performance of the plant which are of interest.

ASM2 does not distinguish between the composition (cell internal structure) of individual cells but considers only the average composition of the biomass. Since each cell has a different history, its composition will typically deviate from the population average (e.g. it may not contain storage products whereas the average cell still has storage products available). This is of importance because kinetic expressions used in ASM2 are non-linear, and therefore average behaviour may not necessarily be predicted from average properties. In view of the additional problems that population models would introduce, the Task Group took the pragmatic decision to accept these problems and to propose ASM2 based on average properties of the population.

Components in the model

All symbols for model components distinguish between soluble '$S_?$' and particulate '$X_?$'. Within the activated sludge systems, particulate components, $X_?$, are assumed to be associated with the activated sludge (flocculated onto the activated sludge). They can be concentrated by sedimentation/thickening in clarifiers whereas soluble components, $S_?$, will only be transported with the water.

All particulate model components, $X_?$, must be electrically neutral (no ionic charges), soluble components, $S_?$, may carry ionic charge.

Soluble and particulate components may not necessarily be differentiated by filtration through 0.45 μm membrane filters as is frequently assumed in the technical literature. Some of these components are defined by their interaction with the biomass and require bioassays for their analysis (see Chapter 4 of the original report on ASM2 (Henze *et al.*, 1995)).

All components are assumed to be homogeneous and distributed throughout the systems of interest.

Definition of soluble components, '$S_?$':

S_A [M(COD) L^{-3}]: Fermentation products, considered to be acetate. Since fermentation is included in the biological processes, the fermentation products must be modelled separately from other soluble organic materials. They are endproducts of fermentation. For all stoichiometric computations, it is assumed that S_A is equal to acetate; in reality a whole range of other fermentation products dominated by acetate is possible.

S_{ALK} [mol(HCO_3^-) L^{-3}]: Alkalinity of the wastewater. Alkalinity is used to approximate the conservation of electrical charges in biological reactions. Alkalinity is introduced in order to obtain an early indication of possible low pH conditions, which might inhibit some biological processes. For all stoichiometric computations, S_{ALK} is assumed to be bicarbonate, HCO_3^- only.

S_F [M(COD) L^{-3}]: Fermentable, readily bio-degradable organic substrates. This fraction of the soluble COD is directly available for biodegradation by heterotrophic organisms. It is assumed that S_F may serve as a substrate for fermentation, therefore it does not include fermentation products.

S_I [M(COD) L^{-3}]: Inert soluble organic material. The prime characteristic of S_I is that these organics cannot be further degraded in the treatment plants dealt with in this report. This material is assumed to be part of the influent and it is also assumed to be produced in the context of hydrolysis of particulate substrates X_S.

S_{N2} [M(N) L^{-3}]: Dinitrogen, N_2. S_{N2} is assumed to be the only nitrogenous product of denitrification. S_{N2} may be subject to gas exchange, parallel with oxygen, S_{O2}.

S_{NH4} [M(N) L^{-3}]: Ammonium plus ammonia nitrogen. For the balance of the electrical charges, S_{NH4} is assumed to be all NH_4^+.

S_{NO3} [M(N) L^{-3}]: Nitrate plus nitrite nitrogen (NO_3^- + NO_2^- -N). S_{NO3} is assumed to include nitrate as well as nitrite nitrogen, since nitrite is not included as a separate model component. For all stoichiometric computations (COD conservation), S_{NO3} is considered to be NO_3^- -N only.

S_{O2} [M(O_2) L^{-3}]: Dissolved oxygen. Dissolved oxygen may be subject to gas exchange.

S_{PO4} [M(P) L^{-3}]: Inorganic soluble phosphorus, primarily ortho-phosphates. For the balance of electrical charges, it is assumed that S_{PO4} consists of 50% $H_2PO_4^-$ and 50% HPO_4^{2-}, independent of pH.

S_S [M(COD) L^{-3}]: Readily biodegradable substrate. This component was introduced in ASM1. In ASM2, it is replaced by the sum of S_F + S_A.

Definition of particulate components '$X_?$':

X_{AUT} [M(COD) L^{-3}]: Nitrifying organisms. Nitrifying organisms are responsible for nitrification; they are obligate aerobic, chemo-litho-autotrophic. It is assumed that nitrifiers oxidize ammonium S_{NH4} directly to nitrate S_{NO3} (nitrifiers include both ammonium and nitrite oxidizers).

X_H [M(COD) L^{-3}]: Heterotrophic organisms. These organisms are assumed to be the 'allrounder' heterotrophic organisms, they may grow aerobically and anoxically (denitrification) and be active anaerobically (fermentation). They are responsible for hydrolysis of particulate substrates X_S and can use all degradable organic substrates under all relevant environmental conditions.

X_I [M(COD) L^{-3}]: Inert particulate organic material. This material is not degraded within the systems of interest. It is flocculated onto the activated sludge. X_I may be a fraction of the influent or may be produced in the context of biomass decay.

X_{MeOH} [M(TSS) L^{-3}]: Metal-hydroxides. This component stands for the phosphorus-binding capacity of possible metal-hydroxides, which may be in the wastewater or may be added to the system. For all stoichiometric computations, it is assumed that this component is composed of $Fe(OH)_3$. It is possible to 'replace' this component with other reactants; this would require adaptation of the stoichiometric and kinetic information.

X_{MeP} [M(TSS) L^{-3}]: Metal-phosphate, $MePO_4$. This component results from binding phosphorus to the metal-hydroxides. For all stoichiometric computations, it is assumed that this component is composed of $FePO_4$. It is possible to 'replace' this component with other precipitation products; this would require adaptation of the stoichiometric and kinetic information.

X_{PAO} [M(COD) L^{-3}]: Phosphate-accumulating organisms: PAO. These organisms are assumed to be representative for all types of poly-phosphate-accumulating organism. The concentration of X_{PAO} does not include the cell internal storage products X_{PP} and X_{PHA}, but only the 'true' biomass. In ASM2d it is assumed that these organisms may grow in an anoxic as well as an aerobic environment whereas in ASM2 only aerobic growth is considered.

X_{PHA} [M(COD) L^{-3}]: A cell internal storage product of phosphorus-accumulating organisms, PAO. It includes primarily poly-hydroxy-alkanoates (PHA). It occurs only associated with X_{PAO}; it is, however, not included in the mass of X_{PAO}. X_{PHA} *cannot be directly compared* with analytically measured PHA concentrations; X_{PHA} is only a functional component required for modelling but not directly identifiable chemically. X_{PHA} may, however, be recovered in COD analysis, where it must satisfy COD conservation. For stoichiometric considerations, PHA is assumed to have the chemical composition of poly-hydroxy-butyrate $(C_4H_6O_2)_n$.

X_{PP} [M(P) L^{-3}]: Poly-phosphate. Poly-phosphate is a cell internal inorganic storage product of PAO. It occurs only associated with X_{PAO}; it is, however, not included in the mass of X_{PAO}. It is part of the particulate phosphorus and may be analytically observed. For stoichiometric considerations, poly-phosphates are assumed to have the composition of $(K_{0.33}Mg_{0.33}PO_3)_n$.

X_S [M(COD) L^{-3}]: Slowly biodegradable substrates. Slowly biodegradable substrates are high molecular weight, colloidal and particulate organic substrates which must undergo cell external hydrolysis before they are available for degradation. It is assumed that the products of hydrolysis (S_F) may be fermented.

X_{TSS} [M(TSS) L^{-3}]: Total suspended solids, TSS. Total suspended solids are introduced into the biokinetic models in order to compute their concentration via stoichiometry. Since phosphorus removal and precipitation introduce mineral fractions into the activated sludge, prediction of TSS is important.

Basis for the introduction of ASM2

Matrix notation:

The Task Group introduced matrix notation for the presentation of biokinetic models in its report on the ASM1. The same concept will be used for the introduction of ASM2. It is assumed that the reader is familiar with this way of presenting biokinetics.

As a short summary: the components which are considered in the model and the transformation processes are characterized with the indices i and j respectively. Stoichiometric coefficients are presented in the form of a stoichiometric matrix ν_{ji}. The process rate equations form a vector ρ_j. The rate of production of the component i, r_i [$M_i\ L^{-3}\ T^{-1}$], in all parallel processes may then be computed from the sum:

$$r_i = \Sigma\ \nu_{ji} \cdot \rho_j \quad \text{over all processes j} \tag{1}$$

Within the stoichiometric matrix one stoichiometric coefficient, ν_{jk}, of each process j may be chosen as dimensionless with the value of +1 or −1. For all other stoichiometric coefficients algebraic equations may be given, which introduce conservation principles into the determination of stoichiometric coefficients. Alternatively ν_{ji} may be given in the form of absolute values with the dimension $M_i\ M_k^{-1}$, where M_k is the unit mass of the component k upon which stoichiometry is based (the component which has $\nu_{jk} = +1$ or -1).

Conservation equations:

Conservation equations are the mathematical equivalent of the principle that in chemical reactions, elements, electrons (or COD) and net electrical charges may neither be formed nor destroyed.

The stoichiometry of ASM1 is implicitly based on three conservation considerations for COD, electrical charges and nitrogen. ASM2 adds phosphorus conservation to these three. Further, an equation is introduced which converts the different solid components $X_?$ from their unit of measurement, to total suspended solids, X_{TSS}.

A conservation equation, which is valid for all processes j and all materials c subject to conservation, may be written as:

$$\Sigma\ \nu_{ji} \cdot i_{ci} = 0 \quad \text{over all components I} \tag{2}$$

where

ν_{ji} = stoichiometric coefficient for component i in process j [$M_i\ M_k^{-1}$],

i_{ci} = conversion factor to convert the units of component i to the units of the material c, to which conservation is to be applied [$M_c\ M_i^{-1}$].

Each conservation equation contains *a priori* information and may be applied to each process. Each conservation equation allows the prediction of one stoichiometric coefficient without performing an experiment, provided the other coefficients are known.

In ASM2, these equations are used to estimate the stoichiometric coefficients of S_{O2} (S_{NO3} and S_{N2} in denitrification) from COD, S_{NH4} from nitrogen, S_{PO4} from phosphorus, S_{ALK} from charge and X_{TSS} from total solids conservation. Table 1 is a summary of the conversion factors i_{ci} which must be applied in equation 2. These conversion factors are, wherever possible, obtained from chemical stoichiometry. 'COD' as a conservative property is defined as closely as possible to the analytically obtained COD. Examples are:

$i_{COD,5} = -64$ g O_2 / 14 g NO_3^--N from:

$NO_3^- + H_2O + 2\ H^+ \rightarrow NH_4^+ + 2\ O_2$

Table 1. Conversion factors i_{ci} to be applied in the conservation equation of ASM2. Missing values are equal to 0. The units of i_{ci} are $M_c\ M_i^{-1}$, e.g. $i_{N,2} = i_{NSF}$ g N g^{-1} COD or $i_{Charge,3}$ = -1/64 $moles^+\ g^{-1}$ COD

Index c:	Conservation for		COD	N	P	Charge	Mass
Factor			$i_{COD,i}$	$i_{N,i}$	$i_{P,i}$	$i_{Charge,i}$	$i_{TSS,i}$
Index i:	Component	Units	g COD	g N	g P	$mole^+$	g TSS
1	S_{O2}	g O_2	-1				
2	S_F	g COD	1	i_{NSF}	i_{PSF}		
3	S_A	g COD	1			-1/64	
4	S_{NH4}	g N		1		+1/14	
5	S_{NO3}	g N	-64/14	1		-1/14	
6	S_{PO4}	g P			1	-1.5/31	
7	S_I	g COD	1	i_{NSI}	i_{PSI}		
8	S_{ALK}	mole HCO_3^-				-1	
9	S_{N2}	g N	-24/14	1			
10	X_I	g COD	1	i_{NXI}	i_{PXI}		i_{TSSXI}
11	X_S	g COD	1	i_{NXS}	i_{PXS}		i_{TSSXS}
12	X_H	g COD	1	i_{NBM}	i_{PBM}		i_{TSSBM}
13	X_{PAO}	g COD	1	i_{NBM}	i_{PBM}		i_{TSSBM}
14	X_{PP}	g P			1	-1/31[b]	3.23
15	X_{PHA}	g COD	1				0.60
16	X_{AUT}	g COD	1	i_{NBM}	i_{PBM}		i_{TSSBM}
17	X_{TSS}	g TSS					-1[a]
18	X_{MeOH}	g TSS					1
19	X_{MeP}	g TSS			0.205		1

a) Since TSS are counted twice, this factor must be negative

b) Since ASM2 does not account for K^+ and Mg^{2+} this factor must compensate for their charge.

All absolute numbers are obtained based on the chemical composition of the component (see definition of component). All factors i_{ci} are model parameters and must be obtained from experiments (See also Table 9).

Or, one mole of nitrate (14 g N) has a negative oxygen demand ('liberates oxygen') of two moles of oxygen (64 g O_2). Similar arguments lead to:

$$i_{COD,9} = -24\ g\ O_2 / 14\ g\ N_2 \text{ from:}$$
$$2\ N_2 + 6\ H_2O + 4\ H^+ \rightarrow 4\ NH_4^+ + 3\ O_2$$

All conversion factors given with absolute numbers in Table 1 may be obtained from chemical stoichiometry, based on the definition of the compounds. All factors identified with a symbol i_{ci} must be obtained from chemical analysis. Since ASM2 does not account for potassium (K^+) and magnesium ions (Mg^{2+}) X_{PP} must include these counterions. This is taken care of by the conversion factor $i_{Charge,14} = -1/31$.

As an example, the stoichiometric coefficient for component 2 (i = 2) in the third process (j = 3) may be obtained from the conservation equation for COD based on equation 2 according to:

$$\nu_{3,2} = -(\nu_{3,1} \cdot i_{COD,1} + \nu_{3,3} \cdot i_{COD,3} + \ldots + \nu_{3,n} \cdot i_{COD,n}) / i_{COD,2}$$

or

$$\nu_{3,2} = -[\Sigma_i (\nu_{3,i} \cdot i_{COD,i}) - \nu_{3,2} \cdot i_{COD,2}] / i_{COD,2}$$

The introduction of the conservation equations in an abstract form may at first appear to be complicated. However, the concept is directed towards its application in computer programs and helps to simplify the development of program code.

Biological processes, stoichiometry and kinetics

The biological processes of ASM2 are introduced here. A full stoichiometric matrix using typical stoichiometric coefficients is presented in Table 11.

Biological processes, general remarks:
Microorganisms have a complex cell internal structure and respond to different environmental conditions with adjustment of this structure. A frequently observed phenomenon is unbalanced growth, a situation where not all fractions of the cells are reproduced at an equal rate. Modelling such shifts of cell internal structure would require modelling of the different fractions of the biomass, a task which would be most fruitful if the behaviour of axenic cultures were described. Here, only three groups of microorganisms represent a vast variety of unknown species; each biological process described in ASM2 represents a large number of processes which act upon a variety of substances, which in the model are summarized in terms of COD.

Process descriptions in ASM2 are therefore based on the average behaviour of these different microorganisms, and are described in the way balanced growth processes would be modelled.

Table 2. Stoichiometry of hydrolysis processes. The stoichiometric parameters are defined in Table 9

	Process	S_F	S_{NH4}	S_{PO4}	S_I	S_{ALK}	X_S	X_{TSS}
1	Aerobic hydrolysis	$1-f_{SI}$	$\nu_{1,NH4}$	$\nu_{1,PO4}$	f_{SI}	$\nu_{1,ALK}$	-1	$\nu_{1,TSS}$
2	Anoxic hydrolysis	$1-f_{SI}$	$\nu_{2,NH4}$	$\nu_{2,PO4}$	f_{SI}	$\nu_{2,ALK}$	-1	$\nu_{2,TSS}$
3	Anaerobic hydrolysis	$1-f_{SI}$	$\nu_{3,NH4}$	$\nu_{3,PO4}$	f_{SI}	$\nu_{3,ALK}$	-1	$\nu_{3,TSS}$

The stoichiometric coefficients for S_{NH4}, S_{PO4}, S_{ALK} and X_{TSS} may be computed from Conservation equation 2 with the aid of Table 1. As an example $\nu_{1,PO4} = -[(1-f_{SI})\cdot i_{PSF} + f_{SI}\cdot i_{PSI} - 1\cdot i_{PXS}]/1$.

Hydrolysis processes:
Many high molecular weight, colloidal or particulate organic substrates cannot be utilized directly by microorganisms. These substrates must be made available by cell external enzymatic reactions which are called hydrolysis processes. It is unclear whether the products of hydrolysis ever exist in true solution or whether they are taken up directly by the organisms which catalyse hydrolysis. Typically hydrolysis processes are considered to be surface reactions, which occur in close contact between the organisms which provide the hydrolytic enzymes and the slowly biodegradable substrates themselves.

Parallel with hydrolysis the activity of protozoa contribute to phenomena which are assigned to hydrolysis. Whereas it is difficult to distinguish between true hydrolysis and protozoan activity it is becoming more and more evident that the effect of electron acceptors upon the 'hydrolysis' process may actually be due to the inactivity of protozoa under anoxic and anaerobic conditions. Experimental evidence that 'hydrolysis' reactions depend on the available electron acceptors, leads to the differentiation of three hydrolysis processes in ASM2. It is, however, a difficult task to estimate hydrolysis rate constants under different electron acceptor conditions.

1. Aerobic hydrolysis of slowly biodegradable substrate characterizes hydrolysis under aerobic conditions ($S_{O2} > 0$).
2. Anoxic hydrolysis of slowly biodegradable substrate characterizes hydrolysis under anoxic conditions ($S_{O2} \approx 0$, $S_{NO3} > 0$). This process is typically slower than aerobic hydrolysis.
3. Anaerobic hydrolysis of slowly biodegradable substrate characterizes hydrolysis under anaerobic conditions ($S_{O2} \approx 0$, $S_{NO3} \approx 0$). This process is not well characterized and is probably slower than aerobic hydrolysis. Its rate remains to be studied.

Table 2 summarizes the stoichiometry of the hydrolysis processes. It is assumed that slowly biodegradable substrate X_S is degraded to readily degradable substrate S_F whereby a small fraction f_{SI} of inert organic material S_I is released. The stoichiometric coefficients for S_{NH4}, S_{PO4} and S_{ALK} may be computed from conservation equation 2. These three coefficients are typically positive.

The proposed rate equations for the hydrolysis processes 1–3 are presented in Table 7. They are similar to those of ASM1: hyperbolic switching functions for S_{O2} and S_{NO3} consider the environmental conditions; a surface-limited reaction $(X_S/X_H) / (K_X+X_S/X_H)$ is assumed for the hydrolysis process itself. It is proposed that only heterotrophic organisms may catalyse hydrolysis. Typically hydrolysis is slower under denitrifying or anaerobic (fermentation) than under aerobic conditions. The rate for anoxic and anaerobic hydrolysis is therefore reduced by the factors η_{NO3} and η_{fe} respectively.

The hydrolysis of particulate, biodegradable organic nitrogen is included as a separate process in ASM1 but not in ASM2. This process is necessary if the nitrogen content of X_S is variable. In order to simplify ASM2, it is assumed that X_S contains a constant fraction of nitrogen i_{NXS} and phosphorus i_{PXS}. Without this simplifying assumption, six more hydrolysis processes and two more particulate components would be required.

The process of ammonification is included in ASM1 in order to describe the release of ammonium, S_{NH4}, from soluble, biodegradable organic nitrogen. In ASM2 it is assumed that the fermentable substrates, S_F, contain a constant fraction of nitrogen and phosphorus, i_{NSF} and i_{PSF} respectively. This allows the process of ammonification to be ignored. Without this simplifying assumption, two more processes (ammonification as well as phosphatification, the release of phosphate S_{PO4} from an organic fraction), and two more components (soluble, degradable organic nitrogen and phosphorus) would have to be introduced.

Table 3. Stoichiometry of the facultative heterotrophic organisms X_H. The stoichiometric parameters are defined in Table 9. Stoichiometry for S_{O2}, S_{NH4}, S_{PO4}, S_{ALK} and X_{TSS} may be computed from conservation

	Process	S_{O2}	S_F	S_A	S_{NO3}	S_{N2}	X_I	X_S	X_H
4	Aerobic growth on S_F	$1-\frac{1}{Y_H}$	$-\frac{1}{Y_H}$						1
5	Aerobic growth on S_A	$1-\frac{1}{Y_H}$		$-\frac{1}{Y_H}$					1
6	Anoxic growth on S_F		$-\frac{1}{Y_H}$		$-\frac{1-Y_H}{2.86\cdot Y_H}$	$\frac{1-Y_H}{2.86\cdot Y_H}$			1
7	Anoxic growth on S_A, Denitrification			$-\frac{1}{Y_H}$	$-\frac{1-Y_H}{2.86\cdot Y_H}$	$\frac{1-Y_H}{2.86\cdot Y_H}$			1
8	Fermentation		-1	1					
9	Lysis						f_{XI}	$1-f_{XI}$	-1

Processes of facultative heterotrophic organisms:
The heterotrophic organisms X_H are responsible for the hydrolysis of slowly biodegradable substrate X_S (see above), the aerobic degradation of fermentable organic substrates S_F and of fermentation products S_A (aerobic growth), anoxic oxidation of S_F and S_A and reduction of nitrate S_{NO3} (denitrification), and anaerobic fermentation of S_F to S_A. In addition these organisms are subject to decay and lysis. The stoichiometry and the kinetics of the processes described below are presented in Table 3 and Table 7 respectively.

4. and 5. Aerobic growth of heterotrophic organisms on fermentable substrates S_F and on fermentation products S_A. These processes are modelled as two parallel processes, which consume the two degradable organic substrates S_F and S_A. For both processes identical growth rates μ_m and yield coefficients Y_H are assumed. The rate equations are designed such that the maximum specific growth rate of the heterotrophic organisms does not increase above μ_m even if both substrates, S_F and S_A, are present in high concentrations. These processes require oxygen, S_{O2}, nutrients, S_{NH4} and S_{PO4}, and possibly alkalinity, S_{ALK}, and they produce suspended solids, X_{TSS}.

6. and 7. Anoxic growth of heterotrophic organisms on fermentable substrates, S_F, and on fermentation products, S_A; denitrification. These two processes are similar to the aerobic growth processes, but they

require nitrate, S_{NO3}, as the electron acceptor rather than oxygen. The stoichiometry for nitrate is computed based on the assumption that all nitrate, S_{NO3}, is reduced to dinitrogen, S_{N2}. Denitrification releases alkalinity, the stoichiometry of which is predicted from charge conservation. Denitrification is assumed to be inhibited by oxygen S_{O2} and the maximum growth rate μ_m is reduced relative to its value under aerobic conditions, by the factor η_{NO3}. This accounts for the fact that not all heterotrophic organisms X_H may be capable of denitrification or that denitrification may only proceed at a reduced rate.

8. Fermentation. Under anaerobic conditions ($S_{O2} \approx 0$, $S_{NO3} \approx 0$) it is assumed that heterotrophic organisms are capable of fermentation, whereby readily biodegradable substrates S_F are transformed into fermentation products S_A. Although this process may possibly cause growth of heterotrophic organisms, it is introduced here as a simple transformation process. A growth process would require more complex kinetics, more kinetic and stoichiometric parameters which are difficult to obtain, and possibly different yield coefficients for S_F and S_A in processes 4 to 7. Fermentation releases negatively charged fermentation products, S_A, and therefore has a requirement for alkalinity, S_{ALK}. This is predicted from charge conservation.

Fermentation is a process which, up to now, has not been well characterized. Little is known about the kinetics of this process, which may lead to a large range of kinetic parameters for modelling experimental results. Reliable application of ASM2 requires that research is directed towards characterizing what is described here with the process of fermentation.

9. Lysis of heterotrophic organisms. This process represents the sum of all decay and loss processes of the heterotrophic organisms: endogenous respiration, lysis, predation etc. It is modelled in analogy to ASM1; its rate is independent of environmental conditions.

Table 4. Stoichiometry of the phosphorus-accumulating organisms, PAO, for ASM2d. The stoichiometric parameters are defined in Table 9. Stoichiometry for S_{O2}, S_{NH4}, S_{N2}, S_{NO3}, S_{PO4}, S_{ALK} and X_{TSS} may be computed from conservation. ASM2 does not include processes 12 and 14

	Process	S_{O2}	S_A	S_{N2}	S_{NO3}	S_{PO4}	X_I	X_S	X_{PAO}	X_{PP}	X_{PHA}
10	Storage of X_{PHA}		-1			Y_{PO4}				$-Y_{PO4}$	
11	Aerobic storage of X_{PP}	$-Y_{PHA}$				-1				1	$-Y_{PHA}$
12	Anoxic storage of X_{PP}			$-v_{12,NO3}$	$v_{12,NO3}$	-1				1	$-Y_{PHA}$
13	Aerobic growth of X_{PAO}	$v_{13,O2}$				$-i_{PBM}$			1		$-1/Y_H$
14	Anoxic growth of X_{PAO}			$-v_{14,NO3}$	$v_{14,NO3}$	$-i_{PBM}$			1		$-1/Y_H$
15	Lysis of X_{PAO}					$v_{15,PO4}$	f_{XI}	$1-f_{XI}$	-1		
16	Lysis of X_{PP}					1				-1	
17	Lysis of X_{PHA}		1								-1

Processes of phosphorus-accumulating organisms:
Some organisms, X_{PAO}, are known for their potential to accumulate phosphorus in the form of poly-phosphate X_{PP}. Currently these organisms are not well characterized; historically it was assumed that they would all be part of the Acinetobacter genus. However, today it is clear that Acinetobacter may contribute to, but by far do not dominate, biological phosphorus removal. Initially it was assumed that phosphorus-accumulating organisms, PAO, could not denitrify; now evidence has become available that some of them can denitrify. Phosphate release is sometimes slower in the presence of nitrate; this observation is not predicted with ASM2 but is included in ASM2d. Glycogen is found to be an important carbon storage material of PAO but is not considered in ASM2 in order to reduce model complexity. This restriction leads to limitations of the applicability of ASM2d which will be discussed later.

The greater the attempts to characterize PAO, the more complex this group of organisms becomes. The Task Group is well aware that the time has come when biological phosphorus removal is being designed and used in actual plants. The introduction of a very detailed mechanistic model for the processes responsible for biological phosphorus removal is, however, premature. The Task Group therefore has chosen to suggest a simple model,

which allows prediction of biological phosphorus removal, but does not yet include all observed phenomena. The model proposed may be the base for further development. With the introduction of ASM2d the most important criticism — that PAO contribute significantly to denitrification which is not described in ASM2 — is taken care of.

The following model for the behaviour of phosphorus-accumulating organisms, X_{PAO}, is valid for ASM2d only, it assumes that these organisms can grow under aerobic ($S_{O2} > 0$) as well as anoxic ($S_{O2} \approx 0$, $S_{NO3} > 0$) conditions. They can only grow on cell internal stored organic materials, X_{PHA}. This assumption is a severe restriction of ASM2d and may lead to further extensions. The stoichiometry and the kinetics of the processes described below are presented in Tables 4 and 7 respectively.

10. Storage of X_{PHA}. It is assumed that PAO may release phosphate, S_{PO4} from poly-phosphate, X_{PP}, and utilize the energy which becomes available from the hydrolysis of X_{PP}, in order to store cell external fermentation products S_A in the form of cell internal organic storage material X_{PHA}. The process is primarily observed under anaerobic conditions. However, since the process has also been reported to occur under aerobic and anoxic conditions, the kinetic expression does not include inhibition terms for S_{O2} and S_{NO3}. Experimental observation of this process is easy if the release of phosphorus is observed rather than the organics which are stored. Experience indicates, however, that the rate of storage of organics is relatively constant, whereas the release of phosphorus varies, indicating a variable stoichiometric relationship. The base for the stoichiometry of this process was therefore chosen to be the organics which are taken up, S_A and X_{PHA}. Reliable estimation of the rate constant, q_{PHA}, and the stoichiometric parameter, Y_{PO4}, requires independent measurement of both S_A removal and S_P release. It has been shown that Y_{PO4} depends on pH.

11 and 12. Aerobic and anoxic storage of poly-phosphate. Storage of ortho-phosphate, S_{PO4}, in the form of cell internal poly-phosphates, X_{PP}, requires the PAO to obtain energy, which may be gained from the aerobic or anoxic respiration of X_{PHA}. The regeneration of poly-phosphates is a requirement for the growth of PAO, because the organic substrates, S_A, are stored only upon the release of poly-phosphate. Storage of X_{PP} is observed to stop if the phosphorus content of the PAO becomes too high. This observation leads to an inhibition term of X_{PP} storage, which becomes active as the ratio X_{PP}/X_{PAO} approaches the maximum allowable value of K_{MAX}. Under anoxic conditions the maximum rate of storage of poly-phosphate q_{PP} is reduced relative to its value under aerobic conditions, by the factor η_{NO3}. This accounts for the fact that not all PAO (X_{PAO}) may be capable of denitrification or that denitrification may only proceed at a reduced rate. Process 12 is contained in ASM2d but not in ASM2.

13. and 14. Aerobic and anoxic growth of phosphorus-accumulating organisms. These organisms are assumed to grow only at the expense of cell internal organic storage products X_{PHA}. As phosphorus is continuously released by the lysis of X_{PP}, it is possible to assume that the organisms consume ortho-phosphate, S_{PO4}, as a nutrient for the production of biomass. It is known that PAO may grow at the expense of soluble substrates (e.g. S_A), but it is unlikely that such substrates ever become available under aerobic or anoxic conditions in a biological nutrient removal plant. The Task Group therefore suggests this possibility be ignored at this time. Under anoxic conditions the maximum growth rate of PAO μ_{PAO} is reduced relative to its value under aerobic conditions, by the factor η_{NO3}. This accounts for the fact that not all PAO (X_{PAO}) may be capable of denitrification or that denitrification may only proceed at a reduced rate. Process 13 is contained in ASM2d but not in ASM2.

15, 16. and 17. Lysis of phosphorus-accumulating organisms and their storage products. Death, endogenous respiration and maintenance all result in a loss or decay of all fractions of PAO. Since the storage products X_{PP} and X_{PHA} are accounted for separately from the biomass X_{PAO}, all three components must be subject to separate decay processes. ASM2 includes three lysis processes which are all first-order relative to the component which is lost. If all three rate constants are equal, the composition of the organisms does not change due to decay. There is experimental evidence that X_{PP} decays faster than X_{PAO} and X_{PHA}. This additional loss of poly-phosphates may be modelled by the choice of an increased rate, b_{PP}, for the lysis of this component. The products of lysis are chosen in analogy to the lysis of heterotrophic organisms; storage products are assumed

to decay to ortho-phosphate S_{PO4} and fermentation products S_A.

Nitrification processes:
Nitrification is assumed to be a one-step process, from ammonium S_{NH4} directly to nitrate S_{NO3}. The intermediate component, nitrite, is not included as a model component. In the context of nitrification, modelling nitrite production and consumption would be relatively easy. However, nitrite is also produced and consumed in the context of denitrification where the Task Group felt that the required addition to the model complexity does not warrant its inclusion at the present time. Modelling nitrite in nitrification but not in denitrification would, however, not be consistent and could lead to erroneous model predictions.

Table 5. Stoichiometry of the growth and decay processes of nitrifying organisms X_{AUT}. The stoichiometric parameters are defined in Table 9. Stoichiometry for S_{O2}, S_{NH4}, S_{PO4}, S_{ALK} and X_{TSS} may be computed from conservation

	Process	S_{O2}	S_{NH4}	S_{NO3}	S_{PO4}	X_I	X_S	X_{AUT}
18	Aerobic growth of X_{AUT}	$-\frac{4.57-Y_A}{Y_A}$	$v_{18,NH4}$	$\frac{1}{Y_A}$	$-i_{PBM}$			1
19	Lysis		$v_{19,NH4}$		$v_{19,PO4}$	f_{XI}	$1-f_{XI}$	-1

The stoichiometry and the kinetics of the processes described below, are presented in Table 5 and Table 7 respectively.

18. Growth of nitrifying organisms. Nitrifying organisms are obligate aerobic, they consume ammonium as a substrate and a nutrient, and produce nitrate. Nitrification reduces alkalinity. The process is modelled as proposed in ASM1 with the exception of a phosphorus uptake into the biomass.

19. Lysis of nitrifying organisms. The process of lysis of nitrifiers is modelled in analogy to ASM1 and to the process of lysis of heterotrophic organisms. Since the decay products of lysis (X_S and ultimately S_F) are available substrates for heterotrophic organisms only, endogenous respiration of nitrifiers becomes manifest as an increased growth and oxygen consumption of heterotrophs. This is in analogy to ASM1.

Table 6. Stoichiometry of the processes describing sumultaneous precipitation of phosphorous. The absolute values of stoichiometry (and kinetics in Table 10) are based on the assumption that $Fe(OH)_3$ is used to precipitate S_{PO4} in the form of $FePO_4$ + $Fe(OH)_3$. Stoichiometry for S_{ALK} and X_{TSS} may be computed from conservation

	Process	S_{PO4}	S_{ALK}	X_{MeOH}	X_{MeP}	X_{TSS}
20	Precipitation	-1	$v_{20,ALK}$	-3.45	4.87	1.42
21	Redissolution	1	$v_{21,ALK}$	3.45	-4.87	-1.42

Chemical precipitation of phosphates

In biological nutrient removal systems, metals, which are naturally present in the wastewater (e.g. Ca^{2+}), together with the high concentration of released soluble ortho-phosphate, S_{PO4}, may result in chemical precipitation of phosphorus (e.g. in the form of apatite or calcium phosphate).

Further, simultaneous precipitation of phosphorus via the addition of iron or aluminium salts is a very common process for phosphorus removal worldwide. Simultaneous precipitation may be used in combination with biological phosphorus removal if the carbon to phosphorus ratio is unfavourably small.

In order to model the low effluent concentrations of ortho-phosphate, S_{PO4}, which are observed in practice and which are partly due to chemical precipitation, the Task Group suggests a very simple precipitation model, which may be calibrated for a variety of situations. For this purpose, two processes (precipitation and redissolution) and two more components (X_{MeOH} and X_{MeP}) are added to ASM2. If chemical precipitation is not of any interest, these additions may be deleted from the model.

20. and 21. Precipitation and redissolution of phosphate S_{PO4}. The precipitation model is based on the assumption that precipitation and redissolution are reverse processes, which at steady state would be in equilibrium according to:

$$X_{MeOH} + S_{PO4} \leftrightarrow X_{MeP}$$

Precipitation and redissolution may be modelled with the following process rates respectively:

$\rho_{20} = k_{PRE} \cdot S_{PO4} \cdot X_{MeOH}$

$\rho_{21} = k_{RED} \cdot X_{MeP}$

Table 7. Process rate equations for ASM2d. The kinetic parameters are defined in Table 10

j	Process	Process rate equation ρ_j, $\rho_j \geq 0$ $[M_I L^{-3} T^{-1}]$
Hydrolysis Processes:		
1	Aerobic Hydrolysis	$K_h \cdot \frac{S_{O2}}{K_{O2}+S_{O2}} \cdot \frac{X_S/X_H}{K_X+X_S/X_H} \cdot X_H$
2	Anoxic Hydrolysis	$K_h \cdot \eta_{NO3} \cdot \frac{K_{O2}}{K_{O2}+S_{O2}} \cdot \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \cdot \frac{X_S/X_H}{K_X+X_S/X_H} \cdot X_H$
3	Anaerobic Hydrolysis	$K_h \cdot \eta_{fe} \cdot \frac{K_{O2}}{K_{O2}+S_{O2}} \cdot \frac{K_{NO3}}{K_{NO3}+S_{NO3}} \cdot \frac{X_S/X_H}{K_X+X_S/X_H} \cdot X_H$
Heterotrophic organisms: X_H.		
4	Growth on fermentable substrates, S_F	$\mu_H \cdot \frac{S_{O2}}{K_{O2}+S_{O2}} \cdot \frac{S_F}{K_F+S_F} \cdot \frac{S_F}{S_F+S_A} \cdot \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \cdot \frac{S_{PO4}}{K_P+S_{PO4}} \cdot \frac{S_{ALK}}{K_{AIK}+S_{ALK}} \cdot X_H$
5	Growth on fermentation products, S_A	$\mu_H \cdot \frac{S_{O2}}{K_{O2}+S_{O2}} \cdot \frac{S_A}{K_A+S_A} \cdot \frac{S_A}{S_F+S_A} \cdot \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \cdot \frac{S_{PO4}}{K_P+S_{PO4}} \cdot \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \cdot X_H$
6	Denitrification with fermentable substrates, S_F	$\mu_H \cdot \eta_{NIO3} \cdot \frac{K_{O2}}{K_{O2}+S_{O2}} \cdot \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \cdot \frac{S_F}{K_F+S_F} \cdot \frac{S_F}{S_F+S_A} \cdot \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \cdot \frac{S_{PO4}}{K_P+S_{PO4}} \cdot \frac{S_{ALK}}{S_{AIK}+S_{ALK}} \cdot X_H$
7	Denitrification with fermentation products, S_A	$\mu_H \cdot \eta_{NIO3} \cdot \frac{K_{O2}}{K_{O2}+S_{O2}} \cdot \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \cdot \frac{S_A}{K_A+S_A} \cdot \frac{S_A}{S_F+S_A} \cdot \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \cdot \frac{S_{PO4}}{K_P+S_{PO4}} \cdot \frac{S_{ALK}}{S_{AIK}+S_{ALK}} \cdot X_H$
8	Fermentation	$q_{fe} \cdot \frac{K_{O2}}{K_{O2}+S_{O2}} \cdot \frac{K_{NO3}}{K_{NO3}+S_{NO3}} \cdot \frac{S_F}{K_F+S_F} \cdot \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \cdot X_H$
9	Lysis	$b_H \cdot X_H$
Phosphorus accumulating organisms (PAO): X_{PAO}		
10	Storage of X_{PHA}	$q_{PHA} \cdot \frac{S_A}{K_A+S_A} \cdot \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \cdot \frac{X_{PP}/X_{PAO}}{K_{PP}+X_{PP}/X_{PAO}} \cdot X_{PAO}$
11	Aerobic storage of X_{PP}	$q_{PP} \cdot \frac{S_{O2}}{K_{O2}+S_{O2}} \cdot \frac{S_{PO4}}{K_{PS}+S_{PO4}} \cdot \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \cdot \frac{X_{PHA}/X_{PAO}}{K_{PHA}+X_{PHA}/X_{PAO}} \cdot \frac{K_{MAX}-X_{PP}/X_{PAO}}{K_{IPP}+K_{MAX}-X_{PP}/X_{PAO}} \cdot X_{PAO}$
12	Anoxic storage of X_{PP}	$\rho_{12} = \rho_{11} \cdot \eta_{NO3} \cdot \frac{K_{O2}}{S_{O2}} \cdot \frac{S_{NO3}}{K_{NO3}+S_{NO3}}$
13	Aerobic growth on X_{PHA}	$\mu_{PAO} \cdot \frac{S_{O2}}{K_{O2}+S_{O2}} \cdot \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \cdot \frac{S_{PO4}}{K_P+S_{PO4}} \cdot \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \cdot \frac{X_{PHA}/X_{PAO}}{K_{PHA}+X_{PHA}/X_{PAO}} \cdot X_{PAO}$
14	Anoxic growth on X_{PHA}	$\rho_{14} = \rho_{13} \cdot \eta_{NO3} \cdot \frac{K_{O2}}{S_{O2}} \cdot \frac{S_{NO3}}{K_{NO3}+S_{NO3}}$
15	Lysis of X_{PAO}	$b_{PAO} \cdot X_{PAO} \cdot S_{ALK}/(K_{ALK}+S_{ALK})$
16	Lysis of X_{PP}	$b_{PP} \cdot X_{PP} \cdot S_{ALK}/(K_{ALK}+S_{ALK})$
17	Lysis of X_{PHA}	$b_{PHA} \cdot X_{PHA} \cdot S_{ALK}/(K_{ALK}+S_{ALK})$
Nitrifying organisms (autotrophic organisms): X_{AUT}		
18	Aerobic Growth of X_{AUT}	$\mu_{AUT} \cdot \frac{S_{O2}}{K_{O2}+S_{O2}} \cdot \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \cdot \frac{S_{PO4}}{K_P+S_{PO4}} \cdot \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \cdot X_{AUT}$
19	Lysis of X_{AUT}	$b_{AUT} \cdot X_{AUT}$
Simulataneous precipitation of phosphorus with ferric hydroxide $Fe(OH)_3$		
20	Precipitation	$k_{PRE} \cdot S_{PO4} \cdot X_{MeOH}$
21	Redissolution	$k_{RED} \cdot X_{MeP} \cdot S_{ALK}/(K_{ALK}+S_{ALK})$

If both processes are in equilibrium ($\nu_{20,i} \cdot \rho_{20} = \nu_{21,i} \cdot \rho_{21}$) then an equilibrium constant may be derived as:

$$K_{eq} = \frac{\nu_{21,i} \cdot k_{RED}}{\nu_{20,i} \cdot k_{PRE}} = \frac{S_{PO4} \cdot X_{MeOH}}{X_{MeP}}$$

Processes 20 and 21 are introduced here based on the assumption that X_{MeOH} and X_{MeP} are composed of ferric-hydroxide, $Fe(OH)_3$, and ferric-phosphate, $FePO_4$, respectively. This leads to the stoichiometry indicated in Table 6. The indicated rates of the processes result in residual ortho-phosphate concentrations, S_P, which at steady state are typical for simultaneous precipitation with the addition of $FeCl_3$. In this case, the addition of Fe^{3+} to the influent of a treatment plant may be modelled by the choice of X_{MeOH} in the influent recognizing that 1 g Fe^{3+} m^{-3} leads to 1.91 g $Fe(OH)_3$ m^{-3} = 1.91 g MeOH m^{-3} (which also increases influent X_{TSS} and decreases influent alkalinity S_{ALK}).

TYPICAL WASTEWATER CHARACTERISTICS AND KINETIC AND STOICHIOMETRIC CONSTANTS

It is the responsibility of the user of the Activated Sludge Model No. 2 (ASM2 and ASM2d) to determine the concentrations of relevant components in the wastewater, as well as the stoichiometric and kinetic parameters which apply to the specific case to be dealt with. Absolute numbers of these parameters are neither part of ASM2 nor of ASM2d, but are necessary for the application of the model to a specific case.

Table 8. Short definition of model components and typical wastewater composition (primary effluent), considering the composition of the different model components as indicated in Table 9

COD_{tot} = 260 g COD m^{-3}, TKN = 25 g N m^{-3}, TP = 6 g P m^{-3}			
Dissolved components:			
S_{O2}	Dissolved oxygen	0	g O_2 m^{-3}
S_F	Readily biodegradable substrate	30	g COD m^{-3}
S_A	Fermentation products (acetate)	20	g COD m^{-3}
S_{NH4}	Ammonium	16	g N m^{-3}
S_{NO3}	Nitrate (plus nitrite)	0	g N m^{-3}
S_{PO4}	Phosphate	3.6	g P m^{-3}
S_I	Inert, bon-biodegradable organics	30	g COD m^{-3}
S_{ALK}	Bicarbonate alkalinity	5	Mole HCO_3^- m^{-3}
S_{N2}	Dinitrogen (N_2), 0.78 atm at 20°C	15	g N m^{-3}
Particulate components:			
X_I	Inert, non-biodegradable organics	25	g COD m^{-3}
X_S	Slowly biodegradable substrate	125	g COD m^{-3}
X_H	Heterotrophic biomass	30	g COD m^{-3}
X_{PAO}	Phosphorus-accumulating organisms, PAO	0	g COD m^{-3}
X_{PP}	Stored poly-phosphate of PAO	0	g P m^{-3}
X_{PHA}	Organic storage products of PAO	0	g COD m^{-3}
X_{AUT}	Autotrophic, nitrifying biomass	0	g COD m^{-3}
X_{MeOH}	'Ferric-hydroxide', $Fe(OH)_3$	0	g $Fe(OH)_3$ m^{-3}
X_{MeP}	'Ferric-phosphate', $FePO_4$	0	g $FePO_4$ m^{-3}
X_{TSS}	Particulate material as model component[a)]	180[a)]	g TSS m^{-3}

a) This value is larger than TSS which may be measured analytically, since it includes the fraction of X_S, which would pass the filter in the TSS analysis. X_{TSS} may also include some inert mineral material, which is contained in the influent but not accounted for by other components. If this is the case, then X_{TSS} in the influent will be larger than predicted from the conservation equation, which for the above values and based on the conversion factors given in Table 9 would result in 140 g TSS m^{-3}. Analytically measured TSS (0.45 µm) would be approximately 120 g TSS m^{-3}.

In this section, the Task Group suggests a list of typical concentrations of model components in a primary effluent as well as a set of model parameters. This neither indicates that ASM2 or ASM2d is meant to be reliable with these parameters in any case, nor that these parameters are the state of the art. They are merely presented as a reference for testing computer code and a first estimate for the design of possible experiments which are proposed to determine these parameters more accurately.

Table 8 contains a list of all model components and typical concentrations in a primary effluent. This wastewater contains a total COD of 260 g COD m^{-3}, a total nitrogen content of 25 g N m^{-3} and approximately 140 g TSS m^{-3}. The analytically measured TSS are lower than the value of X_{TSS} = 180 g TSS m^{-3}, since a fraction of X_S in the influent would pass through membrane filters but must be included in the model component X_{TSS} since it will later adsorb onto the activated sludge. The total nitrogen (and phosphorus) in the influent may be computed with the aid of all influent concentrations multiplied with the relevant conversion factors from Table 1 and Table 9.

Table 9. Definition and typical values for the stoichiometric coefficients of ASM2

Typical conversion factors for conservation equation			
Nitrogen:			
Soluble material:			
i_{NSI}	N content of inert soluble COD S_I	0.01	g N g^{-1} COD
i_{NSF}	N content of fermentable substrates S_F	0.03	g N g^{-1} COD
Particulate material:			
i_{NXI}	N content of inert particulate COD X_I	0.02	g N g^{-1} COD
i_{NXS}	N content of slowly biodegradable substrate X_S	0.04	g N g^{-1} COD
i_{NBM}	N content of biomass, X_H, X_{PAO}, X_{AUT}	0.07	g N g^{-1} COD
Phosphorus:			
Soluble material:			
i_{PSI}	P content of inert soluble COD S_I	0.00	g P g^{-1} COD
i_{PSF}	P content of fermentable substrates S_F	0.01	g P g^{-1} COD
Particulate material:			
i_{PXI}	P content of inert particulate COD X_I	0.01	g P g^{-1} COD
i_{PXS}	P content of slowly biodegradable substrate X_S	0.01	g P g^{-1} COD
i_{PBM}	P content of biomass, X_H, X_{PAO}, X_{AUT}	0.02	g P g^{-1} COD
Total suspended solids TSS:			
i_{TSSXI}	TSS to COD ratio for X_I	0.75	g TSS g^{-1} COD
i_{TSSXS}	TSS to COD ratio for X_S	0.75	g TSS g^{-1} COD
i_{TSSBM}	TSS to COD ratio for biomass, X_H, X_{PAO}, X_A	0.90	g TSS g^{-1} COD
Typical stoichiometric parameters			
Hydrolysis:			
f_{SI}	Production of S_I in hydrolysis	0	g COD g^{-1} COD
Heterotrophic biomass: X_H			
Y_H	Yield coefficient	0.625	g COD g^{-1} COD
f_{XI}	Fraction of inert COD generated in biomass lysis	0.10	g COD g^{-1} COD
Phosphorus-accumulating organisms: X_{PAO}			
Y_{PAO}	Yield coefficient (biomass / PHA)	0.625	g COD g^{-1} COD
Y_{PO4}	PP requirement (PO_4 release) per PHA stored	0.40	g P g^{-1} COD
Y_{PHA}	PHA requirement for PP storage	0.20	g COD g^{-1} P
f_{XI}	Fraction of inert COD generated in biomass lysis	0.10	g COD g^{-1} COD
Nitrifying organisms: X_{AUT}			
Y_A	Yield of autotrophic biomass per NO_3^--N	0.24	g COD g^{-1} N
f_{XI}	Fraction of inert COD generated in biomass lysis	0.10	g COD g^{-1} COD

Table 10. Definition and typical values for the kinetic parameters of ASM2d

	Temperature	20°C	10°C	Units
Hydrolysis of particulate substrate: X_S				
K_h	= Hydrolysis rate constant	3.00	2.00	d^{-1}
η_{NO3}	= Anoxic hydrolysis reduction factor	0.60	0.60	-
η_{fe}	= Anaerobic hydrolysis reduction factor	0.40	0.40	-
K_{O2}	= Saturation/inhibition coefficient for oxygen	0.20	0.20	g O_2 m^{-3}
K_{NO3}	= Saturation/inhibition coefficient for nitrate	0.50	0.50	g N m^{-3}
K_X	= Saturation coefficient for particulate COD	0.10	0.10	g X_S g^{-1} X_H
Heterotrophic organisms: X_H				
μ_H	= Maximum growth rate on substrate	6.00	3.00	g X_S g^{-1} X_H d^{-1}
q_{fe}	= Maximum rate for fermentation	3.00	1.50	g S_F g^{-1} X_H d^{-1}
η_{NO3}	= Reduction factor for denitrification	0.80	0.80	-
b_H	= Rate constant for lysis and decay	0.40	0.20	d^{-1}
K_{O2}	= Saturation / inhibition coefficient for oxygen	0.20	0.20	g O_2 m^{-3}
K_F	= Saturation coefficient for growth on S_F	4.00	4.00	g COD m^{-3}
K_{fe}	= Saturation coefficient for fermentation of S_F	4.00	4.00	g COD m^{-3}
K_A	= Saturation coefficient for growth on acetate S_A	4.00	4.00	g COD m^{-3}
K_{NO3}	= Saturation / inhibition coefficient for nitrate	0.50	0.50	g N m^{-3}
K_{NH4}	= Saturation coefficient for ammonium (nutrient)	0.05	0.05	g N m^{-3}
K_P	= Saturation coefficient for phosphate (nutrient)	0.01	0.01	g P m^{-3}
K_{ALK}	= Saturation coefficient for alkalinity (HCO_3^-)	0.10	0.10	mole HCO_3^- m^{-3}
Phosphorus-accumulationg organisms: X_{PAO}				
q_{PHA}	= Rate constant for storage of X_{PHA} (base X_{PP})	3.00	2.00	g X_{PHA} g^{-1} X_{PAO} d^{-1}
q_{PP}	= Rate constant for storage of X_{PP}	1.50	1.00	g X_{PP} g^{-1} X_{PAO} d^{-1}
μ_{PAO}	= Maximum growth rate of PAO	1.00	0.67	d^{-1}
η_{NO3}	= Reduction factor for anoxic activity	0.60	0.60	-
b_{PAO}	= Rate for Lysis of X_{PAO}	0.20	0.10	d^{-1}
b_{PP}	= Rate for Lysis of X_{PP}	0.20	0.10	d^{-1}
b_{PHA}	= Rate for Lysis of X_{PHA}	0.20	0.10	d^{-1}
K_{O2}	= Saturation/inhibition coefficient for oxygen	0.20	0.20	g O_2 m^{-3}
K_{NO3}	= Saturation coefficient for nitrate, S_{NO3}	0.50	0.50	g N m^{-3}
K_A	= Saturation coefficient for acetate, S_A	4.00	4.00	g COD m^{-3}
K_{NH4}	= Saturation coefficient for ammonium (nutrient)	0.05	0.05	g N m^{-3}
K_{PS}	= Saturation coefficient for phosphorus in storage of PP	0.20	0.20	g P m^{-3}
K_P	= Saturation coefficient for phoshate (nutrient)	0.01	0.01	g P m^{-3}
K_{ALK}	= Saturation coefficient for alkalinity (HCO_3^-)	0.10	0.10	mole HCO_3^- m^{-3}
K_{PP}	= Saturation coefficient for poly-phosphate	0.01	0.01	g X_{PP} g^{-1} X_{PAO}
K_{MAX}	= Maximum ratio of X_{PP}/X_{PAO}	0.34	0.34	g X_{PP} g^{-1} X_{PAO}
K_{IPP}	= Inhibition coefficient for PP storage	0.02	0.02	g X_{PP} g^{-1} X_{PAO}
K_{PHA}	= Saturation coefficient for PHA	0.01	0.01	g X_{PHA} g^{-1} X_{PAO}
Nitrifying organisms (autotrophic organisms): X_{AUT}				
μ_{AUT}	= Maximum growth rate of X_{AUT}	1.00	0.35	d^{-1}
b_{AUT}	= Decay rate of X_{AUT}	0.15	0.05	d^{-1}
K_{O2}	= Saturation coefficient for oxygen	0.50	0.50	g O_2 m^{-3}
K_{NH4}	= Saturation coefficient for ammonium (substrate)	1.00	1.00	g N m^{-3}
K_{ALK}	= Saturation coefficient for alkalinity (HCO_3^-)	0.50	0.50	mole HCO_3^- m^{-3}
K_P	= Saturation coefficient for phosphorus (nutrient)	0.01	0.01	g P m^{-3}
Precipitation:				
k_{PRE}	= Rate constant for P precipitaion	1.00	1.00	m^3 g^{-1} $Fe(OH)_3$ d^{-1}
k_{RED}	= Rate constant for redissolution	0.60	0.60	d^{-1}
K_{ALK}	= Saturation coefficient for alkalinity	0.50	0.50	mole HCO_3^- m^{-3}

Table 11. An example of a stoichiometric matrix for ASM2d for soluble and particulate components and for precipitation processes. The absolute values of the stoichiometric coefficients are based on the typical stoichiometric parameters introduced in Table 9. *These values are not the ASM2d* but rather a typical application of the model

Stoichiometric matrix for soluble components

Process	component	S_{O2}	S_F	S_A	S_I	S_{NH4}	S_{N2}	S_{NO3}	S_{PO4}	S_{ALK}
	expressed as >	O_2	COD	COD	COD	N	N	N	P	Mole
1	Aerobic Hydrolysis		1.00			0.01				0.001
2	Anoxic Hydrolysis		1.00			0.01				0.001
3	Anaerobic Hydrolysis		1.00			0.01				0.001
Heterotrophic organisms: X_H										
4	Growth on S_F	-0.60	-1.60			-0.022			-0.004	-0.001
5	Growth on S_A	-0.60		-1.60		-0.07			-0.02	0.021
6	Denitrification with S_F		-1.60			-0.022	0.21	-0.21	-0.004	0.014
7	Denitrification with S_A			-1.60		-0.07	0.21	-0.21	-0.02	0.036
8	Fermentation of S_F		-1	1		0.03			0.01	-0.014
9	Lysis					0.031			0.01	0.002
Phosphorus accumulating organisms (PAO): X_{PAO}										
10	Storage of PHA			-1					0.40	0.009
11	Aerobic storage of PP	-0.20							-1	0.016
12	Anoxic storage of PP						0.07	-0.07	-1	0.021
13	Aerobic growth	-0.60				-0.07			-0.02	-0.004
14	Anoxic growth					-0.07	0.21	-0.21	-0.02	0.011
15	Lysis of PAO					0.031			0.01	0.002
16	Lysis of PP								1	-0.016
17	Lysis of PHA			1						-0.016
Nitrifying organisms (autotrophic organisms): X_{AUT}										
18	Aerobic Growth	-18.0				-4.24		4.17	-0.02	-0.60
19	Lysis					0.031			0.01	0.002
Simultaneous precipitation of phosphorus with ferric hydroxide ($Fe(OH_3)$):										
20	Precipitation								-1	0.048
21	Redissolution								1	-0.048

Stoichiometric matrix for particulate components

Process	component	X_I	X_S	X_H	X_{PAO}	X_{PP}	X_{PHA}	X_A	X_{TSS}	X_{MeOH}	X_{MeP}
	expressed as >	COD	COD	COD	COD	P	COD	COD	TSS	TSS	TSS
1	Aerobic Hydrolysis		-1						-0.75		
2	Anoxic Hydrolysis		-1						-0.75		
3	Anaerobic Hydrolysis		-1						-0.75		
Heterotrophic organisms: X_H											
4	Growth on S_S			1					0.90		
5	Growth on S_A			1					0.90		
6	Denitrification with S_S			1					0.90		
7	Denitrification with S_A			1					0.90		
8	Fermentation										
9	Lysis	0.10	0.9	-1					-0.15		
Phosphorus accumulating organisms (PAO): X_{PAO}											
10	Storage of PHA					-0.40	1		-0.69		
11	Aerobic storage of PP					1	-0.20		3.11		
12	Anoxic storage of PP					1	-0.20		3.11		
13	Aerobic growth				1		-1.60		-0.06		
14	Anoxic growth				1		-1.60		-0.06		
15	Lysis of PAO	0.10	0.90		-1				-0.15		
16	Lysis of PP					-1			-3.23		
17	Lysis of PHA						-1		-0.60		
Nitrifying organisms (autotrophic organisms): X_{AUT}											
18	Aerobic Growth							1	0.90		
19	Lysis	0.10	0.90					-1	-0.15		
Simultaneous precipitation of phosphorus with ferric hydroxide ($Fe(OH_3)$):											
20	Precipitation								1.42	-3.45	4.87
21	Redissolution								-1.42	3.45	-4.87

Table 9 is a list of typical stoichiometric coefficients of ASM2 and ASM2d and includes the factors which are required for the use of the conservation equations (see also Table 1). Many of the conversion factors have been estimated without performing specific experiments for their determination. These values indicate an order of magnitude. The stoichiometric coefficients are either based on previous experience with ASM1 or they are derived from verification trials of ASM2 relative to full-scale experience. Experience with the three yield coefficients, Y_{PAO}, Y_{PO4} and Y_{PHA} of the PAO is still scarce.

Table 10 is a summary of the definitions and typical values of all kinetic parameters of the models ASM2 and ASM2d. Again, some kinetic parameters were estimated based on the experience with ASM1, those relating to biological phosphorus removal being estimated based on laboratory experience and full-scale verification trials of ASM2. Note that saturation coefficients K_i for any specific compound may be different for different organisms (e.g. K_{O2} may have four different values, depending on the process and organism to which it relates).

Future experience may well lead to different 'good estimates' of the parameters of the model. Since experimental results of many pilot studies have been performed without considering the requirements of model calibration, we do not currently have a sufficient basis to calibrate ASM2 or ASM2d to a 'typical wastewater'.

Finally a full stoichiometric matrix for ASM2d, based on the proposed stoichiometric parameters in Table 9 is presented in Table 11.

Table 11 is not meant to be a part of ASM2d but rather it should indicate approximate values of stoichiometric coefficients ν_{ji}.

Table 11 may be used to test computer code, which might be developed to predict stoichiometric coefficients ν_{ji} based on conversion factors and stoichiometric constants as introduced in Table 9.

LIMITATIONS

All models have limitations. For ASM2d among the more important ones are:

- the model is valid for municipal wastewater only
- processes with overflow of S_A to the aeration tank cannot be modeled
- the wastewater must contain sufficient Mg^{++} and K^+
- pH should be near neutral
- temperature is expected to be in the range of 10-25 °C

Use of the model outside of these limitations is not recommended.

CONCLUSION

ASM2d should be used as a basis for modeling of simultaneous biological phosphorus uptake and nitrification-denitrification. As compared with ASM2 it will improve the accuracy when modeling nitrate and phosphate dynamics. ASM2d is considered to be a platform and a reference for further research and development of kinetic models for biological nutrient removal in activated sludge systems.

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