Integrated biological, chemical and physical processes kinetic modelling Part 1 – Anoxic-aerobic C and N removal in the activated sludge system

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Abstract

The biological kinetic Activated Sludge Model No. 1 (ASM1, Henze et al., 1987; Dold et al., 1991) for carbon (C) and nitrogen (N) removal is integrated with the mixed weak acid/base model of Musvoto et al. (1997, 2000a,b,c) to extend application of ASM1 to situations where an estimate for pH is important. Because chemical precipitation is generally not significant when treating municipal wastewaters for C and N removal, only gas and liquid phase processes were considered for this integrated model. The biological processes in ASM1 were modified to take into account the effect of the interaction of the weak acid/base species of the ammonia, carbonate and phosphate systems and pH on heterotrophic and autotrophic organism behaviour, which includes generation and utilisation CO_2 in metabolism, use of specific weak acid/base species for organism growth and generation and utilisation of H^+. With these modifications, simulations with the model were compared with those of ASM1 and experimental data in the literature; a good correlation was obtained. However, these comparisons are only a preliminary validation, because, despite their inclusion, the weak acid/bases and pH do not have a significant effect on the biological processes in the cases considered (i.e. well buffered wastewater). A difficulty in calibrating this model is selection of the k_{LA} value for the aeration system, which affects the pH in the anoxic and aerobic reactors through CO_2 gas exchange. Aerobic reactor outflows from two full-scale wastewater treatment plants with fine bubble aeration systems were found to be around 20% supersaturated with CO_2. The performance of a ND activated sludge system with low influent alkalinity is evaluated.

Keywords: Activated sludge, weak acid/base chemistry, integrated modelling, N removal

Abbreviations

ACP	Amorphous calcium phosphate
ADL	Anaerobic digester liquor
Alk	Alkalinity
ANO	Autotrophic nitrifier organism
AS	Activated sludge
ASim	A computer simulation programme for NDBEPR systems (Gujer, 1998)
ASM1 &2d	Activated Sludge Models No. 1 and 2d
ATP	Adenosine triphosphate
BA	Biological activated sludge processes name prefix
BEPR	Biological excess phosphorus removal
C	Carbon
CED	Chemical equilibrium dissociation
CIP	Chemical ion pairing
COD	Chemical oxygen demand
CP	Chemical/physical
CPB	Chemical/physical/biological
DO	Dissolved oxygen
IWA	International Water Association
IAWPRC	International Association for Water Pollution Research and Control (former IWA)
N	Nitrogen
ND	Nitrification/Denitrification
OHO	Ordinary heterotrophic organism
OUR	Oxygen utilisation rate
P	Phosphorus
pH	-ve log of the hydrogen ion (H^+) activity
PGE	Physical gas exchange
PMP	Physical mineral precipitation
RBCOD	Readily biodegradable COD
SBCOD	Slowly biodegradable COD
SBR	Sequencing batch reactor
SCFA	Short chain fatty acid
T	Temperature
TDS	Total dissolved solids
TKN	Total Kjeldahl nitrogen
TN	Total inorganic nitrogen (FSA+nitrate+nitrite)
TOC	Total organic carbon
UCTOLD	A computer simulation programme for ND AS systems (see Dold et al., 1991)
UCTPHO	A computer simulation programme for NDBEPR AS systems (see Wentzel et al., 1992 and Dold et al., 1991)
VSS	Volatile suspended solids
W	Watts

Symbols

b	Endogenous respiration/death rate of organisms. Subscripts A and H denote rates for ANOs and OHOs respectively
C_T	Total inorganic carbon
D_{LCO2}, D_{LO2}	Liquid phase molecular diffusion coefficient for CO_2 and O_2
f_E	Endogenous residue fraction of biomass
$f_{ZE,P}$	P content of endogenous residue fraction of OHOs
$f_{ZB,N}$	N content of the OHOs

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Received 11 January 2005; accepted in revised form 25 April 2005.

$f_{ZB,P}$	P content of the OHOs
$f_{ZE,P}$	P content of endogenous residue fraction of OHOs
f_{xm}	Maximum unaerated sludge mass fraction for nitrification
$^{(1)}H_c$	Dimensionless Henry's law constant.
k_G	Gas phase individual mass transfer coefficient
K	Half saturation coefficient in process switching functions
$^{(1)}K_H$, $^{(1)}K'_H$	Henry's law constant. Prime (') denotes value corrected for ionic strength effects.
K_I , K_{II}	Inhibition constants for pH effect on growth of ANOs
k_L	Liquid phase individual mass transfer coefficient
$^{(1)}K_{La}$	Overall liquid phase mass transfer rate coefficient.
K_{max}	Inhibition constant for pH effect on growth of ANOs
$^{(2)}K_n$	ANO half saturation coefficient.
$^{(1)}K_f$, $^{(1)}K_r$	Weak acid/base forward (f) and reverse (r) dissociation rate constants. Prime (') denotes value corrected for ionic strength effects.
n	Diffusivity coefficient
N_{obs} , N_{obsi}	Biodegradable soluble organic N, and in influent
p_{CO2}, p_{N2}, p_{O2}	Partial pressure of CO_2, N_2 and O_2 gases
R	Universal gas constant
R_{sm}	Minimum sludge age for nitrification
S_{bLost}	Biodegradable COD lost when nitrate is N source for growth
Y_{ZA}	ANO yield coefficient
Y_{ZH} , Y'_{ZH}	OHO yield coefficient under aerobic and anoxic conditions respectively
$^{(2)}\mu_A$	ANO maximum specific growth rate
θ_{ns}	pH sensitivity coefficient for ANOs for pH<7.2
[ ]	denotes compound concentration in mol/ℓ
$^{(1)}$	Additional subscripts O_2, CO_2, NH_3 and N_2 are the coefficients for O_2, CO_2, NH_3 and N_2 respectively.
$^{(2)}$	Additional subscripts pH, 7.2, T and 20 are the values at pH, pH=7.2, T and T=20°C respectively.

Introduction

A number of mathematical models describing the kinetics of the biological processes for carbon (C), nitrogen (N) and phosphorus (P) removal by the activated sludge system have been developed, e.g. the C and N removal models of van Haandel et al. (1981) and Activated Sludge Model No. 1 (ASM1, Henze et al., 1987), and the C, N and P removal models UCTPHO (Wentzel et al., 1992) and ASM2 and 2d (Henze et al., 1995, 1999). These models are commonly used in research, design, operation and system development and can be coded into computer shell packages such as ASim (Gujer, 1993) and Aquasim (Reichert, 1998) and various versions of them are commercially available.

In all these models, it is assumed that the biological processes operate in an aqueous phase of constant pH, i.e. that there is sufficient buffer capacity in the aqueous phase to absorb or supply the protons (H^+) required or generated directly or indirectly (via e.g. the weak acid base species) by the biological processes without a change in pH. For most applications with municipal wastewater, where the concentrations of C, N and P are low, this is a reasonable assumption. In fact, in some models, the parameter Alkalinity is included to check that this condition remains true (e.g. ASM1, Henze et al., 1987; UCTOLD and IAWPRC, Dold et al., 1991). However, in the treatment of a number of wastewaters this assumption is not valid, e.g. in the nitrification of wastewaters with low buffer capacity and/or high nitrogen (N) concentrations, or in the treatment of wastewaters where the generation or utilisation of short-chain fatty acids (SCFA) is significant.

In this paper, the biological processes of C and N removal in activated sludge systems are integrated into the three phase mixed weak acid/base chemical-physical kinetic model developed by Musvoto et al. (1997, 2000a,b,c). This chemical-physical model includes kinetic descriptions for:

(i) the ionic equilibrium reactions of the important weak acid/base systems that govern pH in wastewater treatment systems, i.e. the ammonia, carbonate (inorganic carbon), short chain fatty acid (SCFA), phosphate and water systems,
(ii) CO_2 and NH_3 gas exchange between aqueous and gas phases,
(iii) ion pairing and
(iv) precipitation of common minerals associated with Calcium (Ca), Magnesium (Mg), carbonate and phosphate system species.

Because in the activated sludge system, mineral precipitation usually is not significant, only parts (i) and (ii) of the model, i.e. the aqueous and gas phase processes, are considered. Furthermore, because of the complex interaction between pH and biological excess P removal (BEPR), only the biological processes of C and N removal are included into the integrated model at this stage. In Part 2, the biological processes of anaerobic digestion are incorporated into the model, but initially also only in two (aqueous-gas) phases (Sötemann et al., 2005). In subsequent model extensions, BEPR and the third (solid) phase of mineral precipitation will be incorporated into the models to develop the components required for an integrated chemical, physical and biological process kinetic model for the whole wastewater treatment plant.

Model development

Central to the mixed weak acid base chemical-physical model of Musvoto et al. (1997, 2000a,b,c) is that the hydrogen ion (H^+) is included explicitly as a compound. Integrating the biological processes of C and N removal of ASM1 into this chemical-physical model requires a number of interactions between the chemical and biological processes to be defined, such as:

- the influence of the biological processes on the weak acid/base systems species and H^+ concentrations, i.e. production and/or utilisation of H^+, CO_2, ammonia and phosphate in the growth and death (endogenous respiration) processes, and
- the effect of pH on the biological process rates where these are expected to be significant, e.g. on the autotrophic nitrifier organism (ANO) maximum specific growth rate.

Additionally, interactions with the physical processes require consideration, such as:

- production of N_2 and loss of this species via gas exchange and
- input of O_2 via aeration and use of this in biological processes.

The mixed weak acid base kinetic model of Musvoto et al. (1997) comprises (see their Table 1):

(1) The aqueous phase forward and reverse dissociation chemical processes of the ammonia, carbonate, phosphate, SCFA and water weak acid/base system species, i.e. processes 1-6 and 9-18 involving compounds 1-5 and 7-14.

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ISSN 0378-4738 = Water SA Vol. 31 No. 4 October 2005
ISSN 1816-7950 = Water SA (on-line)

TABLE 1
Petersen matrix overview of the integrated chemical-physical-biological processes model for simulating wastewater treatment plant unit operations

Integrated CPB model matrix structure			Compounds				
			Chemical (C)		Physical (P)	Biological (B)	
			Equilibrium dissociation (CED)	Ion pairing (CIP)	Gas exchange (PGE)	Activated sludge (BA)	Anaerobic digest (BD)
PROCESSES	CHEMICAL	Equilibrium Dissociaton	15 compounds of the 6 weak acid base systems: C1-C5[a], C7-C14[a], C28-C29[d] 18 chemical equilibrium dissociation processes of the 6 weak acid base systems: C1-C6[a], C9-C18[a], C47-C48[d]	13 compounds associated with 22 ion pairing processes including Ca and Mg: C15-C27[b]	3 compounds CO_2 gas P1 (C6)[a] O_2 and N_2 gases P2-P3[c]	13 compounds for activated sludge (A) : A1 - A14; 13 from ASM1 minus A10 (FSA = C1+C2) plus A14 (dissolved N_2 gas) and replacing in A13 S_{lost} for A1k now obsolete	8 compounds for anaerobic digestion (D): D1-D7 and P4. CH_4 (P4) is produced directly as a gas due to its insolubility and H_2 (D3) is completely utilised as a dissolved gas
		Ion Pairing	22 chemical ion pairing processes (CIP) of 11 ion pairs: C20-C41[b]				
		Minl Pptn	5 physical mineral precipitation processes (PMP): P1 (C19)[a], P2-P5 (C42-C45)[b] No additional compounds - all included with CIP				
	PHYSICAL	Gas Exchange	4 physical gas exchange (PGE) dissolution and expulsion processes; 2 for CO_2 and 2 for N_2, P6-P7[c] (C7-C8)[a] and P9-P10[c]. 1 physical gas exchange (PGE) expulsion process for NH_3; P8[c] (C46)[a] 1 physical gas exchange (PGE) dissolution process for O_2; P11[c] CH_4 in BD produced directly as a gas (insoluble). H_2 in BD considered soluble and negligible with respect to CO_2 and CH_4 K_{La} rates different with aeration (active) or not (passive).				
	BIOLOGICAL	Actvd Sludge	12 biological (B) activated sludge (BA) processes, i.e. all 8 of ASM1 plus aerobic and anoxic heterotrophic growth with nitrate (A1b and A2b)[c] and anoxic hydrolysis of slowly biodegradable organics (COD, S_{bp}) (A9)[c] and organic N (N_{obp}, A10)[c].				
		Anaer Digst	10 biological (B) anaerobic digestion (BD) processes. [d]				

Notes: 1 [a] see Table 1 of Musvoto et al. (1997); [b] see Tables 1b, 1c and 3 of Musvoto et al. (2000a); [c] see Tables 2 and 3 in this paper; [d] see Table 2 in Sötemann et al. (2005);.
2 Only reactant compounds are specified. Product and inert (unbiodegradable) are omitted but implicit, e.g. mineral precipitates, water, non-reactive sink gases and unbiodegradable COD and OrgN.

(2) The gas and solid phase physical processes of the carbonate system, i.e. CO_2 gas exchange (dissolution and expulsion) and $CaCO_3$ precipitation, i.e. processes 7, 8 and 19 respectively involving compounds 3, 6 and 15.

Keeping the same numbering of processes and compounds, Musvoto et al. (2000a) extended this model to include (see their Tables 1b and 3):

(3) Ion pairing of Ca and Mg with hydroxide and the various species of the carbonate and phosphate systems; this added 22 processes, i.e. the aqueous phase forward and reverse dissociation chemical processes of the 11 ion pairs (processes 20-41) and 12 compounds, i.e. Mg and 11 ion pair species (compounds 16-27) respectively (see their Table 1b).

(4) The gas and solid phase physical processes of the ammonia, carbonate and phosphate systems, i.e. ammonia gas stripping and mineral precipitation of four additional minerals associated with Ca and Mg and species of the ammonia, carbonate and phosphate systems, i.e. struvite ($MgNH_4PO_4$), newberyite ($MgHPO_4$), amorphous calcium phosphate [ACP, $Ca_3(PO_4)_2$] and $MgCO_3$; this added 5 additional processes i.e. 42 to 46 but no new compounds as the precipitated minerals were not included explicitly (see their Table 3).

Before incorporating the biological processes of ASM1 into the mixed weak acid/base chemical physical (CP) model of Musvoto et al. (1997, 2000a), all the processes and compounds were categorised into chemical (C), physical (P) and biological (B) groups and subgroups (Table 1). This was done for ease of discussion of the assembly of a particular integrated chemical-physical-biological (CPB) processes model, be it aerobic or anaerobic. For easy cross reference to the source chemical physical (CP) and biological (B) models, the numbers of the processes and compounds were not changed from those in the source models. The

following general groups and subgroups of processes and compounds were adopted, which are summarised in Table 1:

(1) The chemical (C) processes, which comprise those of equilibrium dissociation (CED - forward and reverse weak acid base dissociation) and ion pairing (CIP). These are processes 1-41 in the Musvoto et al. (2000a) CP source model, but the physical (P) processes 7, 8 and 19 are excluded. These processes have the same numbers as in the source model, but the prefix C is added, i.e. C1-C41. The 27 compounds associated with these chemical processes are also numbered identically to the source model, but have the prefix C added, i.e. compounds C1-C5 and C7-C14 involved in the equilibrium dissociation (CED) processes and compounds C4, C5, C8, C10-C12 and C15-C27 involved in the ion pairing (CIP) processes. The only compound that does not belong to this group is the CO_2 gas (C6). CO_2 is included with the compounds associated with the physical (P) processes and so is labelled P1.

(2) The physical (P) processes, which comprise those of mineral precipitation (PMP) and gas exchange (PGE). The five mineral precipitation processes 19 and 42 to 45 in the Musvoto et al. (2000a) CP source model are renumbered P1 to P5. Since the precipitants are not explicitly included, these processes involve only existing compounds in the model (viz. C1, C5, C11, C12, C15 and C16) and so add no new compounds. Physical gas exchange (PGE) combines gas dissolution (forward) and expulsion (reverse) processes. The two physical gas exchange processes for CO_2 (dissolution, 7 and expulsion, 8) of Musvoto et al. (1997), are numbered P6 and P7, but from the link with the inter-phase mass transfer developed by Musvoto et al. (1997), the rate formulations are expressed directly in terms of the more conventional mass transfer rate coefficient and the CO_2 partial pressure (p_{CO2}) (Table 3). Summing these two processes (P6 and P7) is directly equivalent to the conventional inter-phase mass transfer gas exchange. For ammonia, the expulsion ("stripping") process (46) of Musvoto et al. (2000a) is numbered P8 (Table 3). For this gas, the gas phase is accepted to contain zero ammonia (infinite sink) and hence a gaseous ammonia compound is omitted and so also a dissolution process. Added to the PGE processes of the source model to form the integrated CPB activated sludge model are the gas exchange processes for N_2 (dissolution P9 and expulsion P10) formulated in the same manner as for CO_2. Also added is the process for O_2 dissolution by aeration, P11 (Table 3). The new compounds associated with these additional PGE processes are the dissolved and gaseous compounds of oxygen and nitrogen. Dissolved oxygen (A8) and nitrogen (A14) are compounds of the biological processes part of the model (see below) so only 2 physical compounds need to be added for the CPB activated sludge model, i.e. gaseous oxygen (P2) and gaseous nitrogen (P3).

No additional physical gas exchange processes would need to be added to incorporate the biological processes of anaerobic digestion, only one gaseous compound methane (CH_4) - it can be assumed that because CH_4 is very insoluble, CH_4 gas is formed directly by the biological processes. Also in anaerobic digestion, dissolved hydrogen is produced and utilised but hydrogen gas production is negligible compared with CO_2 and CH_4 and hence hydrogen need be included only as a dissolved species (Table 1).

In model application, the gas exchange processes can be passive (no gas bubbling) or active (with gas bubbling, e.g. aeration). For both cases, the gas exchange formulations apply, including that of O_2 dissolution (P11), which specifically requires aeration. However, the values of the gas exchange constants (K_{La}) differ significantly for the two situations.

(3) The biological (B) processes comprise the biological C and N removal process of activated sludge (ASM1) with prefix A and in Sötemann et al. (2005) of anaerobic digestion with prefix D (Table 1). Also for the biological processes and compounds of the activated sludge model, the same numbers of ASM1 were retained, except the prefix A was added to each, i.e. processes A1 to A8 and compounds A1 to A13. However, two biological processes are added, viz. aerobic and anoxic growth of heterotrophs (OHOs) with nitrate as N source (Dold and Marais, 1985), because these two processes affect reactor pH and these were numbered A1b and A2b. Of the 13 compounds in ASM1, two become redundant in the integrated CPB model – the free and saline ammonia (FSA, A10) because NH_3 and $NH_4^+$are in the chemical compounds group and the Alkalinity (A13), which is now obsolete. Apart from the ammonium (NH_4^+, C1), three other compounds in the source CP model are also involved with the biological processes, i.e. H_2CO_3* (C3) through CO_2 generation or uptake, H^+ (i.e. pH, C7) through ammonification, nitrification, denitrification and OHO growth/death and HPO_4^{2-} through uptake for OHO growth and release from OHO death. Details of the biological processes of anaerobic digestion are given by Sötemann et al. (2005).

Following the grouping and numbering system above (Table 1), the integrated two phase (aqueous-gas) chemical physical biological (CPB) activated sludge model for C and N removal was assembled by including:

(1) The chemical equilibrium dissociation (CED) processes for the weak acid/bases (C1-C6 and C9-C18) with associated compounds C1-C5 and C7-C14 (Table 1 of Musvoto et al., 1997, not repeated here). Although the SCFA weak acid/base system is included, in the application here the SCFA are set to zero (see below).
(2) The biological activated sludge processes (BA) of C and N removal from ASM1 (A1 to A8), including aerobic and anoxic OHO growth on ammonium (processes A1a and A2a) and nitrate (processes A1b and A2b), with their associated new compounds NH_4^+ (C1), H_2CO_3* (C3), H^+ (C7), HPO_4^{2-} (C11) and the remaining original 11 activated sludge system compounds (A1-A9, A11-A12) (see Table 2).
(3) The physical gas exchange (PGE) processes of ammonia (C46/P8), carbon dioxide (P6 and P7) and nitrogen (P9 and P10) gases and aeration dissolution of oxygen (P11) with their associated compounds dissolved ammonia (C2) and dissolved and gaseous carbon dioxide (C3 and C6), oxygen (A8 and P2) and nitrogen (A14 and P3). A gaseous ammonia compound is not included, because the gas stream is accepted to contain zero ammonia (Table 3).

Not included in the integrated CPB activated sludge model are the chemical ion pairing (CIP) processes (C20-C41), because this was not considered important for activated sludge systems treating municipal wastewater (TDS < 1 000 mg/ℓ); and the physical mineral precipitation (PMP) processes (C19, C42-C45 or P1-P5), because only the gas and aqueous phases are considered in this first integrated AS model.

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ISSN 0378-4738 = Water SA Vol. 31 No. 4 October 2005
ISSN 1816-7950 = Water SA (on-line)

Available on website http://www.wrc.org.za
ISSN 0378-4738 = Water SA Vol. 31 No. 4 October 2005
ISSN 1816-7950 = Water SA (on-line)

TABLE 2
Matrix representation of the biological processes of ASM1, including anoxic and aerobic growth of OHOs on nitrate (processes A1b and A2b), combined with parts of the mixed weak acid base chemical-physical model of Musvoto et al. (2000a) to yield the two phase (aqueous-gas) integrated chemical-physical-biological (CPB) processes activated sludge system model for C and N removal (see Table 3 for physical processes).

	No, i	C3	C7	C11	A1	A2	A3	A4	A5	A6	A7	A8	A9	C1/A10	A11	A12	A13	A14	
No j	Compounds Processes	$H_2CO_3^*$	H^+	HPO_4^{2-}	S_I	S_{bs}	X_I	S_{enm}	Z_{BH}	Z_{BA}	Z_E	O_2 dissolved	NO_3^-	NH_4^+	N_{obs}	N_{obp}	S_{Lost}	N_2 dslvd	Process rate , ρ_j
A1a	Aerobic growth of Z_{BH} with NH_4^+	$(1-Y_{ZH})/(3Y_{ZH})$	$f_{ZB,N}/14-2f_{ZB,P}/31$	$-f_{ZB,P}$		$-1/Y_{ZH}$			1			$-(1-Y_{ZH})/Y_{ZH}$		$-f_{ZB,N}$					$\mu_H \left[\frac{S_{bs}}{K_{SH}+S_{bs}}\right]\left[\begin{matrix}HAir\\On\end{matrix}\right]\left[\frac{NH_4^+}{limit}\right] Z_{BH}$
A1b	Aerobic growth of Z_{BH} with NO_3^-	F*	$-f_{ZB,N}/14-2f_{ZB,P}/31$	$-f_{ZB,P}$		$-1/Y_{ZH}$			1			$-(1-Y_{ZH})/Y_{ZH}$	$-f_{ZB,N}$					-64/14 $f_{ZB,N}$		$\mu_H \left[\frac{S_{bs}}{K_{SH}+S_{bs}}\right]\left[\begin{matrix}HAir\\On\end{matrix}\right]\left[\frac{1-NH_4^+}{limit}\right]\left[\frac{NO_3}{limit}\right] Z_{BH}$
A2a	Anoxic growth of Z_{BH} with NH_4^+	$(1-Y'_{ZH})/(3Y'_{ZH})$	A*	$-f_{ZB,P}$		$-1/Y'_{ZH}$			1				$-(1-Y'_{ZH})/(2.86Y'_{ZH})$	$-f_{ZB,N}$				D*	$\mu_H \left[\frac{S_{bs}}{K_{SH}+S_{bs}}\right]\left[\begin{matrix}HAir\\Off\end{matrix}\right]\left[\frac{NH_4^+}{limit}\right]\left[\frac{NO_3}{limit}\right] Z_{BH}\,\eta_G$
A2b	Anoxic growth of Z_{BH} with NO_3^-	F*	C*	$-f_{ZB,P}$		$-1/Y'_{ZH}$			1				B*				-64/14 $f_{ZB,N}$	D*	$\mu_H \left[\frac{S_{bs}}{K_{SH}+S_{bs}}\right]\left[\begin{matrix}HAir\\Off\end{matrix}\right]\left[\frac{1-NH_4^+}{limit}\right]\left[\frac{NO_3}{limit}\right] Z_{BH}\,\eta_G$
A3	Aerobic growth of Z_{BA}	-3/8	$f_{ZB,N}/14+1/(7Y_{ZA})$							1		$-(4.57-Y_{ZA})/Y_{ZA}$	$1/Y_{ZA}$	$-(1/Y_{ZA})-f_{ZB,N}$					$\mu_A \left[\frac{NH_4^+}{K_{SA}+NH_4^+}\right]\left[\begin{matrix}A\ Air\\On\end{matrix}\right] Z_{BA}$
A4	Death of Z_{BH}		$2(f_{ZB,P}-f_E f_{ZE,P})/31$	$f_{ZB,P}-f_E f_{ZE,P}$				$1-f_E$	-1		f_E					$f_{ZB,N}-f_E f_{ZE,N}$			$b_H\, Z_{BH}$
A5	Death of Z_{BA}							$1-f_E$		-1	f_E					$f_{ZB,N}-f_E f_{ZE,N}$			$b_A\, Z_{BA}$
A6	Ammonification of N_{obs}		-1/14											1	-1				$K_R\, N_{obs}\, Z_{BH}$
A7	Hydrolysis of S_{enm}					1		-1											E^* ;
A8	Hydrolysis of N_{obp}														1	-1			$E^*.(N_{obp}/S_{enm})$
	Units	gC/m^3	gH/m^3	gP/m^3	$gCOD/m^3$	$gCOD/m^3$	$gCOD/m^3$	$gCOD/m^3$	$gCOD/m^3$	$gCOD/m^3$	$gCOD/m^3$	$-gCOD/m^3$	gN/m^3	gN/m^3	gN/m^3	gN/m^3	$+gCOD/m^3$	gN/m^3	

$$A^* = -\frac{1-Y'_{ZH}}{14*2.86Y'_{ZH}} + \frac{f_{ZB,N}}{14} - 2*\frac{f_{ZB,P}}{31} \qquad B^* = -\frac{1-Y'_{ZH}}{2.86Y'_{ZH}} + f_{ZB,N} \qquad C^* = -\frac{1-Y'_{ZH}}{14*2.86Y'_{ZH}} - \frac{f_{ZB,N}}{14} - 2*\frac{f_{ZB,P}}{31} \qquad D^* = \frac{1-Y'_{ZH}}{2.86Y'_{ZH}}$$

$$E^* = K_H \left[\frac{(S_{enm}/Z_{BH})}{K_X+(S_{enm}/Z_{BH})}\right]\left(\left[\begin{matrix}HAir\\On\end{matrix}\right] + \eta_S \left[\begin{matrix}H\ Air\\Off\end{matrix}\right]\left[\frac{NO_3}{limit}\right]\right) Z_{BH} \qquad F^* = \frac{1-Y^\circ_{ZH}}{3Y^\circ_{ZH}} + \frac{64}{14x3} f_{ZB,N}$$

Notes: (1) Compound A1-A13 numbered identically to ASM1, except NH_4^+, which is C1 in Musvoto et al. (1997) and 10 in ASM1. NH_4^+ in ASM1 is actually the free (NH_3) and saline (NH_4^+) ammonia (FSA), where here it is only the saline. $H_2CO_3^*$ alkalinity (compound 13) is no longer required. Ammonium (C1), dissolved CO_2 (C3) and dinitrogen (A14), H^+ (C7) and mono-hydrogen phosphate (C11) are included here because they are involved with the biological activated sludge processes. $Y^\circ_{ZH} = Y_{ZH}$ for aerobic, $Y^\circ_{ZH} = Y'_{ZH}$ for anoxic.