

CWM1 - A general model to describe biokinetic processes in subsurface flow constructed wetlands

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Abstract

This paper presents the Constructed Wetland Model N°1 (CWM1), a general model to describe biochemical transformation and degradation processes for organic matter and nitrogen in subsurface flow constructed wetlands. The main objective of CWM1 is to predict effluent concentrations from constructed wetlands and not to predict gaseous emissions. CWM1 describes aerobic, anoxic and anaerobic processes and is therefore applicable for both horizontal and vertical flow systems. 17 processes and 16 components (8 soluble and 8 particulate) are considered. CWM1 is based on the mathematical formulation as introduced by the IWA Activated Sludge Models (ASMs). It is important to notice that besides the biokinetic model a number of other processes have to be considered for the formulation of a full model for constructed wetlands such as water flow in the porous media, the influence of plants, the transport of particles/suspended matter to describe clogging processes, adsorption and desorption processes and the physical re-aeration.

Keywords

CWM1, constructed wetlands, mechanistic models, numerical simulation, subsurface flow.

INTRODUCTION

During the last few years, several models with different complexities have been developed to describe the great variety of degradation and removal processes in subsurface flow constructed wetlands (CWs) (Langergraber, 2008). These models couple flow models for either variably saturated or saturated flow in the subsurface with reaction models. Horizontal flow (HF) systems can be simulated when only saturated flow conditions are considered. The most advanced models using saturated flow models are the ones developed by Rousseau (2005) and Brovelli et al. (2007), both considering biokinetic models that are based on the IWA Activated Sludge Models (ASMs) (Henze et al., 2000). For modelling vertical flow (VF) CWs with intermittent loading, transient variably-saturated flow models are required. Due to the intermittent loading, these systems are highly dynamic, adding to the complexity of the overall system. The most advanced reaction models are implemented in CW2D (Langergraber, 2001; Langergraber and Šimůnek, 2005), in FITOVERT (Giraldi et al., 2008), both based on the mathematical formulation of the ASMs (Henze et al., 2000); and in the model developed by Ojeda et al. (2006), that considers processes

affecting solids, organic matter, nitrogen and sulphur. Ojeda's model was developed primarily for HF CWs but, because of the underlying flow model, it is also capable of simulating VF CWs.

The aim of the paper is to present a general biokinetic model to describe biochemical transformation and degradation processes for organic matter and nitrogen in subsurface flow CWs. The Constructed Wetland Model N°1 (CWM1) considers all relevant biokinetic processes occurring in HF and VF CWs with the main objective to predict effluent concentrations. In HF CWs, anaerobic processes play a major role. Therefore, the inclusion of anaerobic processes had to be considered. Langergraber et al. (2008) reviewed and discussed the pros and cons of different model formulations for the description of anaerobic processes. This work formed the basis for the formulation of CWM1.

In the following, CWM1 is presented in a similar way as the ASMs (Henze et al., 2000) in terms of notation and structure of the paper. Such as for the ASMs, the objective of CWM1 is to provide a widely accepted model formulation for biochemical transformation and degradation processes in constructed wetlands that can then be implemented in various simulation tools.

CWM1: DEFINITION OF COMPONENTS IN THE MODEL

As in the ASMs concentrations of soluble components are characterized by S_i and particulate components by X_i . All different microorganisms are considered particulate components and are referred to as bacteria only. Organic nitrogen is considered as a fraction of organic matter (COD). In CWM1 16 components (8 soluble and 8 particulate components) are considered:

Definition of soluble components, S_i

1. S_O [$M(O_2) L^{-3}$]: *Dissolved oxygen, O_2* . Dissolved oxygen can be directly measured and is subject to gas exchange.
2. S_F [$M(COD) L^{-3}$]: *Fermentable, readily biodegradable soluble COD*. This fraction of the COD is directly available for biodegradation by heterotrophic and fermenting bacteria and is produced from hydrolysis.
3. S_A [$M(COD) L^{-3}$]: *Fermentation products as acetate*. All fermentation products are assumed to be acetate only. Removal of S_A occurs by aerobic and anoxic growth of heterotrophic bacteria as well as anaerobic growths of acetotrophic bacteria.
4. S_I [$M(COD) L^{-3}$]: *Inert soluble COD*. S_I can not be further degraded in the treatment plant and is assumed to be part of the influent organic matter and can be produced from hydrolysis.
5. S_{NH} [$M(N) L^{-3}$]: *Ammonium and ammonia nitrogen (NH_4^+ -N and NH_3 -N)*. S_{NH} is assumed to be all NH_4^+ -N. As organic nitrogen is modelled as fraction of the COD, S_{NH} is produced by degradation of organic matter. S_{NH} is degraded by nitrification and by incorporation during biomass growth.
6. S_{NO} [$M(N) L^{-3}$]: *Nitrate and nitrite nitrogen (NO_3^- -N and NO_2^- -N)*. S_{NO} is assumed to include all nitrite and nitrate nitrogen since nitrite is not included as separate model component. For stoichiometric calculations, S_{NO} is considered to be NO_3^- -N only. S_{NO} is produced from nitrification and consumed by denitrification and anoxic sulphide oxidation.

7. S_{SO_4} [M(S) L⁻³]: *Sulphate sulphur*. S_{SO_4} is expressed as sulphur. Sulphate reducing bacteria use S_{SO_4} as an electron acceptor for oxidation of S_A . S_{SO_4} is produced from aerobic and anoxic sulphide oxidation.

8. S_{H_2S} [M(S) L⁻³]: *Dihydrogensulphide sulphur*. S_{H_2S} is produced by reduction of S_{SO_4} whereas S_{H_2S} is converted to S_{SO_4} by sulphide oxidisers such as *Thiobacillus*.

Definition of particulate components, X_i

9. X_S [M(COD) L⁻³]: *Slowly biodegradable particulate COD*. X_S represents organic substances which have to undergo cell external hydrolysis before they are available for degradation. When bacteria die, the biodegradable parts of their cells are added to the amount of X_S . X_S losses occur through hydrolysis by heterotrophic bacteria.

10. X_I [M(COD) L⁻³]: *Inert particulate COD*. This part of the particulate organic material is not degraded in the system of interest. X_I is assumed to remain in the pore space unless higher flow rates exert enough shear stress to drag along solids.

11. X_H [M(COD) L⁻³]: *Heterotrophic bacteria*. These organisms are assumed to be the 'allrounder' heterotrophic being responsible for hydrolysis, mineralization of organic matter (aerobic growth) and denitrification (anoxic growth).

12. X_A [M(COD) L⁻³]: *Autotrophic nitrifying bacteria*. Nitrifying organisms are responsible for nitrification. It is assumed that S_{NH} is directly nitrified to S_{NO} . Nitrite, as an intermediate product of nitrification, is not considered.

13. X_{FB} [M(COD) L⁻³]: *Fermenting bacteria*. Under anaerobic conditions fermenting bacteria consume fermentable, readily biodegradable soluble COD S_F and produce acetate S_A .

14. X_{AMB} [M(COD) L⁻³]: *Acetotrophic methanogenic bacteria*. Anaerobically growing acetotrophic methanogenic bacteria consume acetate S_A and produce methane (which is not considered as a model component).

15. X_{ASRB} [M(COD) L⁻³]: *Acetotrophic sulphate reducing bacteria*. Sulphate reducing bacteria use S_{SO_4} as an electron acceptor for oxidation of acetate S_A and produce S_{H_2S} .

16. X_{SOB} [M(COD) L⁻³]: *Sulphide oxidising bacteria*. Sulphur oxidising bacteria are chemoautotrophic organisms that use oxygen S_O or nitrate S_{NO} to oxidise sulphide S_{H_2S} to sulphate S_{SO_4} .

CWM1: DEFINITION OF PROCESSES IN THE MODEL

CWM1 considers the following 17 biochemical transformation and degradation processes:

1. *Hydrolysis*: Hydrolysis describes the conversion of slowly biodegradable organic matter X_S into readily biodegradable organic matter S_F , with a small fraction being converted into inert organic matter S_I . Ammonium S_{NH_4} is released during this transformation process. We further assume that hydrolysis does not take place under direct dependence of the oxygen conditions. Hydrolysis is performed by heterotrophic and fermenting bacteria and both of their growths are directly

influenced by oxygen concentration S_O . Hydrolysis by fermenting bacteria is supposed to be lower and is corrected with a factor (η_H).

2. *Aerobic growth of X_H on S_F* : Heterotrophic growth rates are dependent on substrate and ammonium availability as well as on electron acceptor concentrations (either oxygen or nitrate). Aerobic growth of heterotrophic bacteria on S_F (mineralization of organic matter) consumes oxygen S_O and readily biodegradable organic matter S_F , while ammonium S_{NH_4} is incorporated in the biomass.

3. *Aerobic growth of X_H on S_A* . This process is similar to the previous one and consumes oxygen S_O and acetate S_A , while ammonium S_{NH_4} is incorporated in the biomass.

4. *Anoxic growth of X_H on S_F* : Anoxic growth of heterotrophs (denitrification) consumes nitrate S_{NO} and readily biodegradable organic matter S_F . Again, ammonium S_{NH_4} is incorporated in the biomass.

5. *Anoxic growth of X_H on S_A* : As for aerobic growth, denitrifiers can also use acetate as substrate. This process consumes nitrate S_{NO} and acetate S_A . Ammonium S_{NH_4} is incorporated in the biomass.

6. *Lysis of X_H* : Lysis is assumed to represent the sum of all decay and sink processes for bacteria and is described similar for all types of bacteria. Lysis of heterotrophic bacteria produces organic matter (mainly X_S , and small fractions of X_I and S_F) and ammonium S_{NH_4} .

7. *Aerobic growth of X_A on S_{NH}* : Aerobic growth of nitrifying bacteria (nitrification) consumes ammonia S_{NH_4} and oxygen S_O , and produces nitrate S_{NO} . Additionally, a small portion of S_{NH_4} is incorporated in the biomass.

8. *Lysis of X_A* : Lysis of X_A is described in the same way as process 6 (Lysis of heterotrophic X_H).

9. *Growth of X_{FB}* : Growth of fermenting bacteria under anaerobic conditions consumes readily biodegradable organic matter S_F and results in the production of acetate S_A . Again, ammonium S_{NH_4} is incorporated in the biomass.

10. *Lysis of X_{FB}* : Lysis of X_{FB} is described in the same way as process 6.

11. *Growth of X_{AMB}* : Anaerobically growing acetotrophic, methanogenic bacteria consume acetate S_A and incorporate S_{NH_4} in the biomass.

12. *Lysis of X_{AMB}* : Lysis of X_{AMB} is described in the same way as process 6.

13. *Growth of X_{ASRB}* : Anaerobic growth of acetotrophic, sulphate uses sulphate S_{SO_4} as an electron acceptor for oxidation of acetate S_A . This process produces sulphide S_{H_2S} and, again, ammonia S_{NH_4} is incorporated in the biomass.

14. *Lysis of X_{ASRB}* : Lysis of X_{ASRB} is described in the same way as process 6.

15. *Aerobic growth of X_{SOB} on S_{H_2S}* : The opposite process to process 13, the oxidation of S_{H_2S} to S_{SO_4} , was also included in the model. This can occur either under aerobic or anoxic conditions. Aerobic growth of sulphide oxidizing bacteria consumes oxygen S_O and sulphide S_{H_2S} and produces sulphate S_{SO_4} , whereas ammonia S_{NH_4} is incorporated in the biomass.

16. *Anoxic growth of X_{SOB} on S_{H2S}* : Similar to the previous process anoxic growth of sulphide oxidizing bacteria consumes nitrate S_{NO} and sulphide S_{H2S} , produces sulphate S_{SO4} , and ammonia S_{NH4} is incorporated in the biomass.

17. *Lysis of X_{SOB}* : Lysis of X_{SOB} is described in the same way as process 6.

CWM1: STOICHIOMETRY AND KINETICS

The CWM1 stoichiometric matrix is presented in Table 1. The presentation is based on the IWA ASM mathematical formulation. Blank fields in the stoichiometric matrix indicate that a process does not influence the concentration of a respective component. The stoichiometric factors $v_{5,j}$ for ammonia S_{NH4} calculated from a mass balance are as follows:

$$\begin{aligned}
 v_{5,1} &= i_{N,XS} - (1 - f_{HYD,SI}) * i_{N,SF} - f_{HYD,SI} * i_{N,SI} \\
 v_{5,2} = v_{5,3} &= i_{N,SF}/Y_H - i_{N,BM} \\
 v_{5,4} = v_{5,5} = v_{5,11} = v_{5,13} = v_{5,15} = v_{5,16} &= -i_{N,BM} \\
 v_{5,6} = v_{5,8} = v_{5,10} = v_{5,12} = v_{5,14} = v_{5,17} &= i_{N,BM} - f_{BM,SF} * i_{N,SF} - (1 - f_{BM,SF} - f_{BM,XI}) * i_{N,XS} - f_{BM,XI} * i_{N,XI} \quad (1) \\
 v_{5,7} &= -i_{N,BM} - \frac{1}{Y_A} \\
 v_{5,9} &= i_{N,SF}/Y_{FB} - i_{N,BM}
 \end{aligned}$$

Such in the IWA ASMs, the kinetic expressions of CWM1 are based in switching functions (hyperbolic of saturation terms and Monod equations, Henze et al., 2000). In Table 2, the CWM1 kinetic expressions for the 17 processes considered are presented. Lysis processes are modelled using first-order decay rates.

Using Table 1 and Table 2, the reaction rate r_i for component i can be calculated as:

$$r_i = \sum_{j=1}^R v_{j,i} * \rho_j \quad (2)$$

where $i = 1, \dots, N$, N = number of components (16), $j = 1, \dots, R$, R = number of processes (17), $v_{j,i}$ is the stoichiometric factor for component i and process j (Table 1), and ρ_j is the reaction rate for process j as defined in Table 2.

CWM1: TYPICAL WASTEWATER CHARACTERISTICS, KINETIC AND STOICHIOMETRIC PARAMETERS

It is the responsibility of the user of CWM1 to determine the concentrations of the relevant components in the wastewater. In Table 3 and Table 4, the kinetic and stoichiometric parameters, respectively, are listed and values for these parameters are given.

Kinetic parameters in Table 3 are given for 20°C and if relevant for 10°C. It is assumed that temperature dependencies occur for rate constants only with the exception of the saturation coefficient for hydrolysis K_X and the saturation/inhibition coefficient for S_{NH} for nitrification K_{NHA} such as reported by Langergraber (2007). Temperature dependencies should be modelled as described by Henze et al. (2000).

Table 1: CWM1 stoichiometric matrix

j ↓	Process Component expressed as →	i →															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		S _O	S _F	S _A	S _I	S _{NH}	S _{NO}	S _{SO4}	S _{H2S}	X _S	X _I	X _H	X _A	X _{FB}	X _{AMB}	X _{ASRB}	X _{SOB}
	O ₂	COD	COD	COD	N	N	S	S	COD	COD	COD	COD	COD	COD	COD	COD	
1	Hydrolysis		1-f _{Hyd,SI}		f _{Hyd,SI}	v _{5,1}				-1							
2	Aerobic growth of X _H on S _F	1 - $\frac{1}{Y_H}$	-1/Y _H			v _{5,2}					1						
3	Anoxic growth of X _H on S _F		-1/Y _H			v _{5,3}	$-\frac{1-Y_H}{2.86 \cdot Y_H}$				1						
4	Aerobic growth of X _H on S _A	1 - $\frac{1}{Y_H}$		-1/Y _H		v _{5,4}					1						
5	Anoxic growth of X _H on S _A			-1/Y _H		v _{5,5}	$-\frac{1-Y_H}{2.86 \cdot Y_H}$				1						
6	Lysis of X _H		f _{BM,SF}			v _{5,6}				v _{9,Lysis}	f _{BM,XI}	-1					
7	Aerobic growth of X _A on S _{NH}	$-\frac{4.57 - Y_A}{Y_A}$				$-i_{N,BM} - \frac{1}{Y_A}$	1/Y _A					1					
8	Lysis of X _A		f _{BM,SF}			v _{5,8}				v _{9,Lysis}	f _{BM,XI}		-1				
9	Growth of X _{FB}		-1/Y _{FB}	$\frac{1 - Y_{FB}}{Y_{FB}}$		v _{5,9}							1				
10	Lysis of X _{FB}		f _{BM,SF}			v _{5,10}				v _{9,Lysis}	f _{BM,XI}			-1			
11	Growth of X _{AMB}			-1/Y _{AMB}		v _{5,11}								1			
12	Lysis of X _{AMB}		f _{BM,SF}			v _{5,12}				v _{9,Lysis}	f _{BM,XI}				-1		
13	Growth of X _{ASRB}			-1/Y _{ASRB}		v _{5,13}	$-\frac{1 - Y_{ASRB}}{2 \cdot Y_{ASRB}}$	$\frac{1 - Y_{ASRB}}{2 \cdot Y_{ASRB}}$							1		
14	Lysis of X _{ASRB}		f _{BM,SF}			v _{5,14}				v _{9,Lysis}	f _{BM,XI}					-1	
15	Aerobic growth of X _{SOB} on S _{H2S}	$-\frac{2 - Y_{SOB}}{Y_{SOB}}$				v _{5,15}		1/Y _{SOB}	-1/Y _{SOB}							1	
16	Anoxic growth of X _{SOB} on S _{H2S}					v _{5,16}	$-\frac{1 - Y_{SOB}}{0.875 \cdot Y_{SOB}}$	1/Y _{SOB}	-1/Y _{SOB}							1	
17	Lysis of X _{SOB}		f _{BM,SF}			v _{5,17}				v _{9,Lysis}	f _{BM,XI}					-1	

$$v_{9,Lysis} = 1 - f_{BM,SF} - f_{BM,XI}$$

Table 2: CWM1 process rates

j	Process	Process rate ρ_j
1	Hydrolysis	$k_h * \left[\frac{X_s / (X_H + X_{FB})}{K_x + (X_s / (X_H + X_{FB}))} \right] * (X_H + \eta_n * X_{FB})$
2	Aerobic growth of X_H on S_F	$\mu_H * \left(\frac{S_F}{K_{SF} + S_F} \right) * \left(\frac{S_F}{S_F + S_A} \right) * \left(\frac{S_O}{K_{OH} + S_O} \right) * \left(\frac{S_{NH}}{K_{NH} + S_{NH}} \right) * \left(\frac{K_{H2SH}}{K_{H2SH} + S_{H2S^*}} \right) * X_H$
3	Anoxic growth of X_H on S_F	$n_g * \mu_H * \left(\frac{S_F}{K_{SF} + S_F} \right) * \left(\frac{S_F}{S_F + S_A} \right) * \left(\frac{K_{OH}}{K_{OH} + S_O} \right) * \left(\frac{S_{NO}}{K_{NO} + S_{NO}} \right) * \left(\frac{S_{NH}}{K_{NH} + S_{NH}} \right) * \left(\frac{K_{H2SH}}{K_{H2SH} + S_{H2S^*}} \right) * X_H$
4	Aerobic growth of X_H on S_A	$\mu_H * \left(\frac{S_A}{K_{SA} + S_A} \right) * \left(\frac{S_A}{S_F + S_A} \right) * \left(\frac{S_O}{K_{OH} + S_O} \right) * \left(\frac{S_{NH}}{K_{NH} + S_{NH}} \right) * \left(\frac{K_{H2SH}}{K_{H2SH} + S_{H2S^*}} \right) * X_H$
5	Anoxic growth of X_H on S_A	$n_g * \mu_H * \left(\frac{S_A}{K_{SA} + S_A} \right) * \left(\frac{S_A}{S_F + S_A} \right) * \left(\frac{K_{OH}}{K_{OH} + S_O} \right) * \left(\frac{S_{NO}}{K_{NO} + S_{NO}} \right) * \left(\frac{S_{NH}}{K_{NH} + S_{NH}} \right) * \left(\frac{K_{H2SH}}{K_{H2SH} + S_{H2S^*}} \right) * X_H$
6	Lysis of X_H	$b_H * X_H$
7	Aerobic growth of X_A on S_{NH}	$\mu_A * \left(\frac{S_{NH}}{K_{NHA} + S_{NH}} \right) * \left(\frac{S_O}{K_{OA} + S_O} \right) * \left(\frac{K_{H2SA}}{K_{H2SA} + S_{H2S^*}} \right) * X_A$
8	Lysis of X_A	$b_A * X_A$
9	Growth of X_{FB}	$\mu_{FB} * \left(\frac{S_F}{K_{SFB} + S_F} \right) * \left(\frac{K_{H2SFB}}{K_{H2SFB} + S_{H2S^*}} \right) * \left(\frac{K_{OFB}}{K_{OFB} + S_O} \right) * \left(\frac{K_{NOFB}}{K_{NOFB} + S_{NO}} \right) * \left(\frac{S_{NH}}{K_{NHFB} + S_{NH}} \right) * X_{FB}$
10	Lysis of X_{FB}	$b_{FB} * X_{FB}$
11	Growth of X_{AMB}	$\mu_{AMB} * \left(\frac{S_A}{K_{SAMB} + S_A} \right) * \left(\frac{K_{H2SAMB}}{K_{H2SAMB} + S_{H2S^*}} \right) * \left(\frac{K_{OAMB}}{K_{OAMB} + S_O} \right) * \left(\frac{K_{NOAMB}}{K_{NOAMB} + S_{NO}} \right) * \left(\frac{S_{NH}}{K_{NHAMB} + S_{NH}} \right) * X_{AMB}$
12	Lysis of X_{AMB}	$b_{AMB} * X_{AMB}$
13	Growth of X_{ASRB}	$\mu_{ASRB} * \left(\frac{S_A}{K_{SASRB} + S_A} \right) * \left(\frac{S_{SO4}}{K_{SOASRB} + S_{SO4}} \right) * \left(\frac{K_{H2SASRB}}{K_{H2SASRB} + S_{H2S^*}} \right) * \left(\frac{K_{OASRB}}{K_{OASRB} + S_O} \right) * \left(\frac{K_{NOASRB}}{K_{NOASRB} + S_{NO}} \right) * \left(\frac{S_{NH}}{K_{NHASRB} + S_{NH}} \right) * X_{ASRB}$
14	Lysis of X_{ASRB}	$b_{ASRB} * X_{ASRB}$
15	Aerobic growth of X_{SOB} on S_{H2S}	$\mu_{SOB} * \left(\frac{S_{H2S}}{K_{SSOB} + S_{H2S}} \right) * \left(\frac{S_O}{K_{OSOB} + S_O} \right) * \left(\frac{S_{NH}}{K_{NHSOB} + S_{NH}} \right) * X_{SOB}$
16	Anoxic growth of X_{SOB} on S_{H2S}	$\mu_{SOB} * \eta_{SOB} * \left(\frac{S_{H2S}}{K_{SSOB} + S_{H2S}} \right) * \left(\frac{S_{NO}}{K_{NOSOB} + S_{NO}} \right) * \left(\frac{K_{OSOB}}{K_{OSOB} + S_O} \right) * \left(\frac{S_{NH}}{K_{NHSOB} + S_{NH}} \right) * X_{SOB}$
17	Lysis of X_{SOB}	$b_{SOB} * X_{SOB}$

DISCUSSION

The main objective of CWM1 is to predict effluent concentrations without any prediction of gaseous emissions. Therefore methane is not considered as a model component. The model formulation aimed to use a minimum number of processes to predict the effluent concentrations based on the aerobic, anoxic and anaerobic processes occurring in subsurface flow systems.

For implementing anaerobic processes, the model descriptions in the models of Maurer and Rittmann (2004), Rousseau (2005), Ojeda et al. (2006) and Mena (2008) have been compared and pros and cons have been discussed (Langergraber et al., 2008). Based on these observations and the aim to describe only the minimum number of processes required it was found that the following processes can be neglected:

1. *Processes with iron as electron acceptor*: In subsurface flow wetland microcosms, Burgoon (1993) demonstrated that iron reduction can reach a maximum of 0.1, in nitrate rich environment, and of 0.2, in sulphate rich environment, percentage of the total removed acetate by different pathways. Therefore, it is supposed that these processes play a minor role when treating domestic wastewater. However, they can be easily added if necessary e.g. for modeling the treatment of industrial and mining wastewaters.
2. *Processes with hydrogen as electron donor*: It is assumed the hydrogen occurs only as intermediate product and is consumed rather quickly. Therefore, it is further assumed that processes with hydrogen as electron donor (SO_4 reduction with H_2 , etc.) and H_2 volatilisation can be neglected. Neglecting these processes has the following consequences when methane as compound is considered or not:
 - If methane is considered as a model compound (i.e. one is interested in modelling gaseous emissions), then methanogenesis has to be considered to occur via just one pathway, resulting in that the stoichiometry has to be changed (100% of S_F converted to 100% S_A to 100% CH_4). Further on if methane is considered, methane oxidation could be an issue as methane produced at the bottom of the CW is oxidized when transported upwards to the surface.
 - If one does not consider methane as a model compound, then the transformation H_2 to methane is not important as it is just a sink and not affecting other components. In CWM1 methanogenesis and sulphur reduction are lumped together for H_2 and S_A . It is assumed that there is only one methanogenic precursor (H_2 and S_A lumped together) which is in the model, however, referred to as acetate S_A .

Both model descriptions (with or without methane) result in that one process is ignored: in the first case H_2 volatilisation, in the second case SO_4 reduction with H_2 , respectively.

Biological sulphide oxidation (that occurs under aerobic and anoxic conditions) has been reported to play a role in some CW systems (Gonzalías, 2008) and is therefore included in the CWM1 model formulation.

As CWM1 describes the biochemical transformation processes caused by microorganisms only the authors want to point out that there are a number of other processes that have to be considered for the formulation of a full model for constructed wetlands:

- the flow model describing water flow in the porous media is of utmost importance (see e.g. Langergraber, 2008); finite element or finite difference models shall be used for describing water flow,

- the influence of plants (growth, decay, decomposition, nutrient uptake, root oxygen release, etc.),
- transport of particles/suspended matter and the description of clogging processes,
- adsorption and desorption processes, and
- physical re-aeration.

SUMMARY

This paper introduces the Constructed Wetland Model N°1 (CWM1) that describes all relevant aerobic, anoxic and anaerobic biokinetic processes occurring in HF and VF CWs required to predict effluent concentrations. 17 processes and 16 components (8 solute and 8 particulate) are considered. The authors hope that CWM1, such as for the IWA ASMs, will become a widely accepted model formulation for biochemical transformation and degradation processes in constructed wetlands and will be implemented in many simulation platforms.

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APPENDIX: CWM1 PARAMETERS

Table 3: Kinetic parameters (at 20°C, values in brackets at 10°C)

Parameter	Description [unit]	Value	Reference
Hydrolysis			
K_h	hydrolysis rate constant [1/d]	3 (2)	H(2000)
K_X	saturation/inhibition coefficient for hydrolysis [g COD _{SF} /g COD _{BM}]	0.1 (0.22)	L(2007)
η_H	Correction factor for hydrolysis by fermenting bacteria [-]	0.1	H(2000)
Heterotrophic bacteria (aerobic growth and denitrification)			
μ_H	maximum aerobic growth rate on CR [1/d]	6 (3)	L&S(2005)
η_H	Correction factor for denitrification by heterotrophs [-]	0.8	H(2000)
b_H	rate constant for lysis [1/d]	0.4 (0.2)	L&S(2005)
K_{OH}	saturation/inhibition coefficient for S _O [mg O ₂ /L]	0.2	L&S(2005)
K_{SF}	saturation/inhibition coefficient for S _F [mg COD _{SF} /L]	2	L&S(2005)
K_{SA}	saturation/inhibition coefficient for S _A [mg COD _{SA} /L]	4	H(2000)
K_{NOH}	saturation/inhibition coefficient for S _{NO} [mg N/L]	0.5	H(2000)
K_{NHH}	saturation/inhibition coefficient for S _{NH} (nutrient) [mg N/L]	0.05	L&S(2005)
K_{H2SH}	saturation/inhibition coefficient for S _{H2S} [mg S/L]	140	R(2005)
Autotrophic bacteria			
μ_A	maximum aerobic growth rate on S _{NH} [1/d]	1 (0.35)	H(2000)
b_A	rate constant for lysis [1/d]	0.15 (0.05)	H(2000)
K_{OA}	saturation/inhibition coefficient for S _O [mg O ₂ /L]	1	L&S(2005)
K_{NHA}	saturation/inhibition coefficient for S _{NH} [mg N/L]	0.5 (5)	L(2007)
K_{H2SA}	saturation/inhibition coefficient for S _{H2S} [mg S/L]	140	R(2005)
Fermenting bacteria			
μ_{AMB}	maximum aerobic growth rate for X _{FB} [1/d]	3 (1.5)	H(2000)
b_{AMB}	rate constant for lysis [1/d]	0.02	K&F(1998)
K_{OFB}	saturation/inhibition coefficient for S _O [mg O ₂ /L]	0.2	H(2000)
K_{SFB}	saturation/inhibition coefficient for S _F [mg COD _{SF} /L]	28	K&F(1998)
K_{NOFB}	saturation/inhibition coefficient for S _{NO} [mg N/L]	0.5	H(2000)
K_{NHFB}	saturation/inhibition coefficient for S _{NH} (nutrient) [mg N/L]	0.01	R(2005)
K_{H2SFB}	saturation/inhibition coefficient for S _{H2S} [mg S/L]	140	K&F(1998)
Acetotrophic methanogenic bacteria			
μ_{AMB}	maximum aerobic growth rate on for X _{AMB} [1/d]	0.085	K&F(1998)
b_{AMB}	rate constant for lysis [1/d]	0.008	K&F(1998)
K_{OAMB}	saturation/inhibition coefficient for S _O [mg O ₂ /L]	0.0002	R(2005)
K_{SAMB}	saturation/inhibition coefficient for S _F [mg COD _{SA} /L]	56	K&F(1998)
K_{NOAMB}	saturation/inhibition coefficient for S _{NO} [mg N/L]	0.0005	R(2005)
K_{NHAMB}	saturation/inhibition coefficient for S _{NH} (nutrient) [mg N/L]	0.01	R(2005)
K_{H2SAMB}	saturation/inhibition coefficient for S _{H2S} [mg S/L]	140	K&F(1998)

References: H(2000) = Henze et al. (2000) ; K&F(1998) = Kalyuzhnyi and Fedorovich (1998); L(2007) = Langergraber (2007); L&S (2005) = Langergraber and Šimůnek (2005); R(2005) = Rousseau (2005).

Table 3 (cont'd): Kinetic parameters (at 20°C, values in brackets at 10°C)

Parameter	Description [unit]	Value	Reference
Acetotrophic sulphate reducing bacteria			
μ_{ASRB}	maximum aerobic growth rate for X_{ASRB} [1/d]	0.18	K&F(1998)
b_{ASRB}	rate constant for lysis [1/d]	0.012	K&F(1998)
K_{OASRB}	saturation/inhibition coefficient for S_O [mg O ₂ /L]	0.0002	R(2005)
K_{SASRB}	saturation/inhibition coefficient for S_F [mg COD _{SA} /L]	24	K&F(1998)
K_{NOASRB}	saturation/inhibition coefficient for S_{NO} [mg N/L]	0.0005	R(2005)
K_{NHASRB}	saturation/inhibition coefficient for S_{NH} (nutrient) [mg N/L]	0.01	R(2005)
K_{SOASRB}	saturation/inhibition coefficient for S_{SO4} [mg S/L]	19	K&F(1998)
$K_{H2SASRB}$	saturation/inhibition coefficient for S_{H2S} [mg S/L]	140	K&F(1998)
Sulphide oxidising bacteria			
μ_{SOB}	maximum aerobic growth rate for X_{SOB} [1/d]	5.28	dW(1995)
b_{SOB}	rate constant for lysis [1/d]	0.15	R(2005)
K_{OSOB}	saturation/inhibition coefficient for S_O [mg O ₂ /L]	0.2	R(2005)
K_{NOSOB}	saturation/inhibition coefficient for S_{NO} [mg N/L]	0.5	R(2005)
$K_{NH SOB}$	saturation/inhibition coefficient for S_{NH} (nutrient) [mg N/L]	0.05	R(2005)
K_{SSOB}	saturation/inhibition coefficient for S_{HS} [mg S/L]	0.24	dW(1995)

References: dW(1995) = de Wit et al. (1995); K&F(1998) = Kalyuzhnyi and Fedorovich (1998); R(2005) = Rousseau (2005).

Table 4: Stoichiometric parameters for organic matter and bacteria and composition parameters

Stoichiometric parameters			
$f_{Hyd,SI}$	Production of S_I in hydrolysis [g COD _{SI} /g COD _{XS}]	0.0	L&S(2005)
$f_{BM,SF}$	Fraction of S_F generated in biomass lysis [g COD _{SF} /g COD _{BM}]	0.05	L&S(2005)
$f_{BM,XI}$	Fraction of X_I generated in biomass lysis [g COD _{XI} /g COD _{BM}]	0.1	L&S(2005)
Y_H	Yield coefficient for heterotrophic bacteria [g COD _{BM} /g COD _{SF}]	0.63	H(2000)
Y_A	Yield coefficient for autotrophic bacteria [g COD _{BM} /g N]	0.24	H(2000)
Y_{FB}	Yield coefficient for fermenting bacteria [g COD _{BM} /g COD _{SF}]	0.053	K&F(1998)
Y_{AMB}	Yield coefficient for acetotrophic methanogenic bacteria [g COD _{BM} /g COD _{SA}]	0.032	K&F(1998)
Y_{ASRB}	Yield coefficient for acetotrophic sulphur reducing bacteria [g COD _{BM} /g COD _{SA}]	0.05	K&F(1998)
Y_{SOB}	Yield coefficient for sulphide oxidizing bacteria [g COD _{BM} /g S]	0.12	dW(1995)
Composition parameters			
$i_{N,SF}$	N content of S_F [g N/g COD _{SF}]	0.03	L&S(2005)
$i_{N,SI}$	N content of S_I [g N/g COD _{SI}]	0.01	L&S(2005)
$i_{N,XS}$	N content of X_S [g N/g COD _{XS}]	0.04	L&S(2005)
$i_{N,XI}$	N content of X_I [g N/g COD _{XI}]	0.03	H(2000)
$i_{N,BM}$	N content of biomass [g N/g COD _{BM}]	0.07	L&S(2005)

References: dW(1995) = de Wit et al. (1995); H(2000) = Henze et al. (2000) ; K&F(1998) = Kalyuzhnyi and Fedorovich (1998); L&S (2005) = Langergraber and Šimůnek (2005).