Mass balance-based plant-wide wastewater treatment plant models – Part 2: Tracking the influent inorganic suspended solids

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Abstract

From an experimental and theoretical investigation of the continuity of influent inorganic suspended solids (ISS) along the links connecting the primary settling tank, fully aerobic or N removal activated sludge and anaerobic and aerobic digestion unit operations, it was found that the influent wastewater (fixed) ISS concentration is conserved through activated sludge and aerobic digestion unit operations. However, the measured ISS flux at different stages through a series of wastewater treatment plant unit operations is not equal to the influent ISS flux, because the ordinary heterotrophic organism (OHO) biomass contributes to the ISS flux by differing amounts depending on the active (OHO) fraction of the Volatile Suspended Solids (VSS) at that stage. Literature data indicated that conservation of influent ISS through primary sludge anaerobic digestion was within ±10%, which is too wide to be conclusive.

Keywords: wastewater treatment, influent inorganic suspended solids, anaerobic digestion, activated sludge, aerobic digestion, model validation

List of abbreviations

AD	anaerobic digestion
ADM1	Anaerobic Digestion Model No. 1
AerD	aerobic digestion
Alk	alkalinity with respect to the H_2CO_3* reference species
ADWF	average dry weather flow
AS	activated sludge
ASM1,2,3	Activated Sludge Models No. 1, 2 or 3
BEPR	biological excess phosphorus removal
BNR	biological nutrient removal
C	carbon
°C	degrees Centigrade
Ca	calcium
COD	chemical oxygen demand
d	day
Eq	equation
FSA	free and saline ammonia
H	hydrogen
ISS	inert suspended solids
K	potassium
ℓ	litres
Mg	magnesium
N	nitrogen
ND	nitrifying - denitrifying
NDBEPR	nitrifying - denitrifying biological excess phosphorus removal
O	oxygen
OHO	ordinary heterotrophic organism
OP	ortho-phosphorus
OrgN	organic nitrogen
OTR	oxygen transfer rate
OUR	oxygen utilisation rate, subscripts c, n and t denote carbonaceous, nitrification and total
P	phosphorus
PAO	phosphorus accumulating organism
pH	negative log of the hydrogen ion activity
PS	primary sludge
PST	primary settling tank
Q	flow
R	hydraulic retention time or sludge age for anaerobic digester
RBCOD	readily biodegradable COD
SBCOD	slowly biodegradable COD
SOUR	specific oxygen utilisation rate (mgO/(gVSS.d). Subscripts c, n and t denote carbonaceous, nitrification and total.
SS	settleable solids
TKN	total Kjeldahl nitrogen
TP	total phosphorus
TSS	total suspended solids
V	volume
VFA	volatile fatty acids
VSS	volatile suspended solids
VS	volatile solids
WAS	waste activated sludge
WW	wastewater
WWTP	wastewater treatment plant

List of symbols

b_H, b'_H	OHO endogenous respiration and death rates (/d). Additional subscripts T and 20 denote rates at T and 20°C
f_{av}, f_{at}	OHO fraction of AS with respect to VSS and TSS. Additional subscripts i or e denote aerobic digester influent or effluent.

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f_c	Carbon to VSS ratio of particulate organics
f_{cv}, f_{cvPS}	COD/VSS ratio of AS and PS
f_{EH}, f'_{EH}	unbiodegradable fraction of OHOs in endogenous respiration and death regeneration models
f_i, f_{ii}, f_{ie}	VSS/TSS ratio of AS. Subscripts i and e denote influent and effluent sludge. Subscript PS refers to primary sludge.
f_{iOHO}	Inorganic content of OHOs (mgISS/mgOHOVSS)
f_n, f_{nPS}	Nitrogen fraction of AS and PS (mgN/mgVSS)
f_{na}	Fraction of influent TKN that is FSA
f_{nu}	Fraction of influent TKN that is unbiodegradable soluble OrgN
f_{PSR}	Fraction of COD removed by primary sedimentation
f_p, f_{pPS}	Phosphorus fraction of AS (mgP/mgVSS). Additional subscript PS denotes primary sludge
$f_{AS'up}$, $f_{PS'up}$	Fraction of unbiodegradable COD in AS and PS
$f_{Sb's}$	Influent RBCOD fraction with respect to the biodegradable COD
$f_{S'up}$, $f_{S'us}$	Particulate and soluble unbiodegradable COD fraction of wastewater. Additional subscript R and S denote raw and settled wastewater.
f_{vsr}, f_{tsr}	Fraction of VSS and TSS removed in aerobic digestion.
f_{XBGP}	P content of PAOs (mgP/mgPAOVSS)
$f_{ZB,N}$, $f_{ZB,P}$	N and P content of OHOs (mgN or mgP per gOHOCOD)
N_{ai}	Influent ammonia (FSA) concentration (mgN/ℓ)
N_{obpi}, N_{obsi}	Influent biodegradable particulate and soluble OrgN concentration (mgN/ℓ)
N_{oupi}, N_{ousi}	Influent unbiodegradable particulate and soluble OrgN concentration (mgN/ℓ)
O	Oxygen utilisation rate [mgO/(ℓ·h)]. Subscripts c, n and t denote carbonaceous, nitrification and total
p_{CO2}	Partial pressure of CO_2
Q_i	Influent flow (ℓ/d)
R_h	Hydraulic retention time (d)
R_s	Sludge age (d)
R^2	Correlation coefficient
S_{bp}	Biodegradable particulate organics concentration (mgCOD/ℓ)
S_{bpi}, S_{bsi}	Influent biodegradable particulate and soluble COD concentrations (mgCOD/ℓ)
S_{ti}, S_{te}	Total influent and effluent COD concentration (mgCOD/ℓ)
S_{upi}, S_{usi}	Influent unbiodegradable particulate and soluble COD concentrations (mgCOD/ℓ)
V_d	Volume of digester
X_{BH}	OHO biomass concentration (mgVSS/ℓ)
X_{EH}	OHO endogenous residue concentration (mgVSS/ℓ)
X_I, X_{Ii}	Unbiodegradable organics concentration in reactor (mgVSS/ℓ). Additional subscript i denotes influent.
X_{Io}, X_{Ioi}	ISS (fixed and biomass) concentration in reactor (mgISS/ℓ). Additional subscript i denotes influent.
X_v, X_{vi}, X_{ve}	VSS concentration (mgVSS/ℓ). Additional subscript i and e denote influent and effluent.
X_t, X_{ti}, X_{te}	TSS concentration (mgTSS/ℓ). Additional subscript i and e denote influent and effluent.
Y_H	OHO yield coefficient (mgVSS/mgCOD)
α, β, γ, δ	substitution variables in VSS and TSS based steady state AerD model
4.57	mgO required per mgFSA-N nitrified to nitrate

Introduction

The inorganic suspended solids (ISS) needs to be included in plant-wide wastewater treatment plant (WWTP) models because this parameter is commonly used for design and operation of WWTPs. If primary settling tanks (PSTs) are included in the WWTP configuration, then the influent ISS is separated into settleable and non-settleable fractions. The settleable ISS passes to the sludge treatment facilities with the primary sludge (PS), while the non-settleable ISS passes to the activated sludge (AS) system with the settled wastewater. In the AS system the influent ISS (non-settleable, and additionally settleable without PSTs) is entrapped to become all settleable and processes acting in the bioreactor will add or subtract from this ISS. The waste activated sludge (WAS) containing these ISS fractions passes to sludge treatment facilities. The sludge treatment facilities for PS and/or WAS may be anaerobic (AD) or aerobic (AerD) digestion. Therefore, insofar as tracking the influent ISS is concerned, all four WWTP links described by Wentzel et al. (2006, Part 1) need to be considered, i.e. the PST-AD link, the AS - AerD link, the AS - AD link and the PST - AerD link. In this paper, tracking of influent ISS along Links 1 and 2 are considered; in Parts 3 (Ekama et al., 2006) and 4 (Sötemann et al., 2006) tracking the influent ISS along Links 3 and 4 are considered.

The primary settling tank (PST) – anaerobic digester (AD) link

The results of Moen et al. (2001) show that for mesophilic and thermophilic anaerobic digestion of primary sludge, the effluent ISS mass is 108% and 110% of the influent ISS respectively. The results of Izzett et al. (1992) show that with mesophilic anaerobic digestion of a primary and humus sludge mixture, the effluent ISS mass is 89.3% of the influent ISS. Some decrease (removal) in ISS is expected for the Izzett et al. data because the sludge includes trickling filter biomass, which when digested results in a decrease in ISS. Biomass (live organisms) contains dissolved inorganic compounds which precipitate as ISS in the VSS-TSS test procedure. The lower the biomass concentration, the less ISS it contributes and the lower the ISS concentration. This is discussed in greater detail below with aerobic digestion of waste activated sludge (WAS). For the Moen et al. (2001) and Izzett et al. (1992) data the conservation of influent ISS through the primary sludge anaerobic digestion is within ±10%, which is too wide to be conclusive. However, until additional data are evaluated, it would be reasonable to accept that in the absence of mineral precipitation, the influent PS ISS mass is conserved through AD.

The activated sludge (AS) system – aerobic digester (AERD) link

This link is relatively easy to establish because the same models are used to simulate the N removal AS system and AerD. Common compounds for the organic and N materials therefore already exist for this link in the steady state and dynamic simulation N removal AS models. However, the steady state models (e.g. WRC, 1984) and ASM1 (Henze et al., 1987), of which aerobic digestion is a subset, do not include the reactor ISS concentration directly – this is calculated from an estimated VSS/TSS ratio for the AS (Ekama and Wentzel, 2004). If the ISS concentration calculated from such an estimated AS VSS/TSS ratio is assumed to have originated from the influent wastewater, significant errors will be

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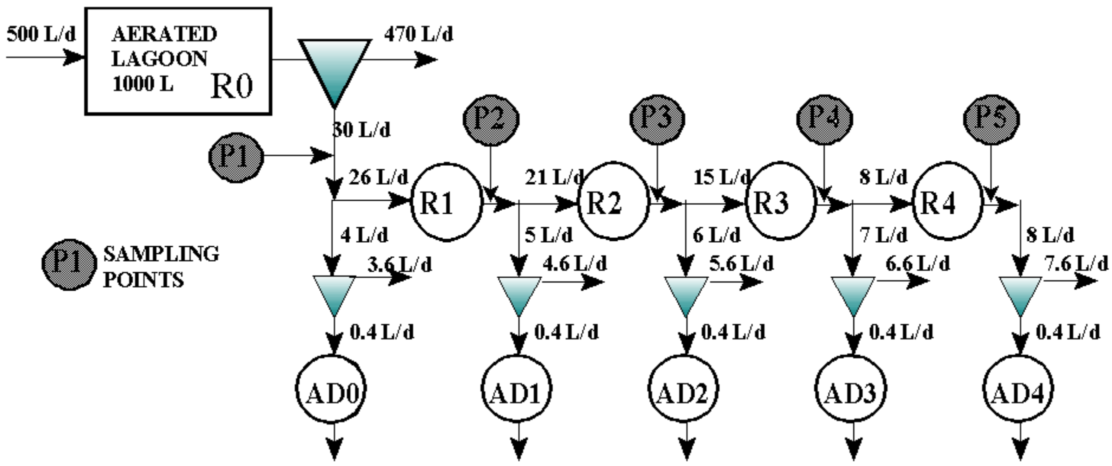

Figure 1 *Schematic diagram of the pilot plant aerated lagoon and four in series aerobic digesters (and anaerobic digesters) operated by Van Haandel et al. (1998a)*

made on the mass balance of this material around the WWTP. To extend ASM1 to include the reactor ISS concentration, *inter alia* Lesouef et al. (1992) included entrapment of influent ISS into the AS mixed liquor and the accumulation of ISS by active biomass, and Gujer (1993) and Gujer et al. (1999) additionally assigned an ISS content to non-active sludge mass fractions such as unbiodegradable particulate organics and endogenous residue. Following the approach of Lesouef et al. (1992), Ekama and Wentzel (2004) developed a predictive model for the ISS concentration in AS systems, which can be readily incorporated into steady state and dynamic simulation AS models. The applicability of this model to aerobic digestion of WAS is investigated in this paper below using the experimental data of Van Haandel et al. (1998a,b). These data are described in some detail because it also will be used to investigate the WAS - AD link (Ekama et al., 2006, Part 3).

The ISS model of Ekama and Wentzel (2004)

This model is based on the accumulation and conservation of influent ISS in the reactor (i.e. negligible dissolution and/or precipitation of ISS in the reactor) and an ordinary heterotrophic organism (OHO) ISS content (f_{iOHO}) of 0.15 mg ISS/mgOHOVSS. This OHO ISS (as distinct from the influent wastewater ISS) is not 'real' ISS; it arises principally from intra-cellular *dissolved* inorganics which precipitate in the VSS-TSS test procedure. The model was validated with data from 21 investigations conducted over the past 15 years on 30 aerobic and anoxic-aerobic nitrification denitrification (ND) systems variously fed artificial and real wastewater and operated from 3 to 20 d sludge age. The predicted reactor VSS/TSS ratio reflects the observed relative sensitivity to sludge age, which is low. This model can be easily integrated into steady state and dynamic simulation AS models. To use the model, measurement of the influent ISS concentration is required. Ekama and Wentzel (2004) found that the usual test procedure for this overestimates the influent ISS by 12 to 25%. This could be the reason why some authors find discrepancies between the measured influent (fixed) ISS and the ISS mass recovered in the reactor. For example:

- Lesouef et al. (1992) had to include a fixed ISS dissolution rate in the reactor to predict the reactor ISS concentration correctly when including an OHO ISS content (f_{iOHO}) of 0.053 – clearly too much influent ISS was entering the reactor compared with the ISS mass measured in the reactor
- Gujer et al. (1999) in ASM3 assigned ISS contents to the active OHO, endogenous, influent particulate unbiodegradable and biodegradable organics of 0.075, 0.225, 0.225 and 0.225 mgISS/mgVSS respectively – these lead to significantly higher ISS concentrations in the reactor than would be predicted by the ISS model of Ekama and Wentzel (2004)
- Wentzel et al. (2002) assigned ISS contents to the active OHO and endogenous organics of 0.17 mgISS/mgVSS and included significant dissolution of influent ISS in order to account for the measured mass of ISS in the reactor from the measured mass of influent ISS determined by the conventional method.

The ISS model of Ekama and Wentzel (2004) was also validated for nitrification denitrification biological excess P removal (NDBEPR) systems with phosphorus accumulating organisms (PAOs), but this aspect of the ISS model is not relevant to this paper. If the ISS model can predict the changes in ISS concentration through a series of aerobic digesters, then it provides a framework for tracking the inorganic concentrations through the WWTP with ND activated sludge systems and aerobic digestion of WAS.

Experimental data

Van Haandel et al. (1998a,b) operated a pilot-scale WWTP scheme (Fig. 1) at 25°C in which 500 ℓ/d raw municipal wastewater was fed to a 2 d retention time aerated lagoon (R0). All the daily waste activated sludge (WAS) from the aerated lagoon was thickened into 30 ℓ which served as feed to a series of four aerobic digesters (R1 to R4) at retention times of 1.73 d, 2.14 d, 3.00 d and 5.63 d respectively. From the feed to each aerobic digester, 4, 5, 6, 7 and 8 ℓ/d of sludge volume was withdrawn, thickened to a volume of 0.40 ℓ/d and fed to five anaerobic digesters (AD0 to AD4) each at 20 d retention time. Each AD was therefore fed a WAS with different fraction of unbiodegradable organics depending on the extent of aerobic digestion before anaerobic digestion. The experimental data measured on the effluent sludges from R0 to R4 are listed in Table 1.

In addition, Van Haandel et al. (1998a) operated an AS system on the same raw wastewater feed at 13 different sludge ages between 3 and 10 d and at temperatures between 21 and 30°C. On sludge harvested from this system, they conducted six batch aerobic digestion tests at each sludge age and temperature. From the measured oxygen utilisation rate (OUR) and volatile suspended solids (VSS), nitrate and alkalinity concentrations with time, they determined the endogenous respiration rate of the OHOs at $b_{HT} = 0.24\ (1.040)^{(T-20)}$ /d for the OHO yield coefficient Y_H = 0.45 mgVSS/mgCOD, sludge COD/VSS ratio (f_{cv}) = 1.5 mgCOD/mgVSS and unbiodegradable endogenous residue

TABLE 1
Experimentally measured (Van Haandel et al., 1998a,b) and theoretically calculated characteristics of the activated sludge in the outflows from the 2d retention time aerated lagoon (R0) and the four in-series aerobic digesters (R1-R4) at 1.73d, 2.14d, 3.00d, 5.63d retention time at 25°C and fed to anaerobic digesters AD0 to AD4 respectively (Ekama et al., 2006, Part 3)

Parameter	R0	R1	R1	R2	R2	R3	R3	R4	R4	
Sample point	P1	P1	P2	P2	P3	P3	P4	P4	P5	P5
	Effl	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl	
Flow ℓ/d	30	26	26	21	21	15	15	8	8	
	Exper	Theory	Exper	Theory	Exper	Theory	Exper	Theory	Exper	Theory
TSS - X_t (g/ℓ)	4.20	4.24	3.74	3.51	2.91	2.95	2.51	2.54	2.11	2.24
VSS - X_v (g/ℓ)	3.01	3.01	2.52	2.40	1.89	1.93	1.57	1.58	1.26	1.33
VSS/TSS - f_i	0.720	0.711	0.674	0.683	0.651	0.654	0.625	0.623	0.598	0.594
OUR_t - mgO/(ℓ.h)	44	43.57	29	28.94	16	17.80	8	9.49	4	3.59
f_{av} - Eq. 19	0.76	0.760	0.60	0.634	0.44	0.485	0.27	0.315	0.17	0.142
β - Eq. 1	-	0.516	-	0.777	-	1.264	-	2.371	-	
α - Eq. 4	-	0.777	-	1.264	-	2.371	-	6.265	-	
δ - Eq. 9	-	0.702	-	1.158	-	2.008	-	3.941	-	
γ - Eq. 12	-	1.158	-	2.008	-	3.941	-	10.743	-	
f_{at} - Eq. 18	0.54	0.540	0.40	0.433	0.29	0.317	0.17	0.196	0.10	0.084
OHOVSS - g/ℓ	2.29	2.29	1.51	1.52	0.83	0.93	0.42	0.50	0.21	0.19
ISSinfl - g/ℓ	-	0.88	-	0.88	-	0.88	-	0.88	-	0.88
ISSbio - g/ℓ	-	0.34	-	0.23	-	0.14	-	0.07	-	0.03
ISStot - g/ℓ	1.19	1.23	1.02	1.11	1.02	1.02	0.94	0.96	0.85	0.91
OURc - mgO/(ℓ.h)	-	33.39	-	22.18	-	13.64	-	7.27	-	2.75
OURn - mgO/(ℓ.h)	-	10.17	-	6.76	-	4.16	-	2.22	-	0.84
OURt - mgO/(ℓ.h)	44	43.57	29	28.94	16	17.8	8	9.49	4	3.59
VSS removed f_{vsr}		0.204	0.163	0.195	0.250	0.181	0.169	0.157	0.197	
TSS removed f_{tsr}		0.172	0.110	0.158	0.222	0.140	0.137	0.116	0.159	
Sludge fed to	AD0 at 4ℓ/d		AD1 at 5 ℓ/d		AD2 at 6 ℓ/d		AD3 at 7ℓ/d		AD4 at 8ℓ/d	
Thickening	10.0x		12.5x		15.0x		17.5x		20.0x	
Influent COD (g/ℓ)	45.37	45.16	47.25	44.94	42.75	43.40	41.25	41.46	37.87	39.96
Infl BioCOD (g/ℓ)*	31.76	31.56	26.05	26.21	17.27	19.35	10.15	12.03	5.81	5.20
Unbio frac ($f_{AS'up}$)*	0.300	0.301	0.449	0.417	0.596	0.554	0.754	0.710	0.847	0.870

Note: The effluent from R0 and the influent to R1 are the same sludge - hence the experimental measured and theoretical calculated results are listed side by side. Likewise, the effluent from R1 and the influent to R2 is the same sludge, and so on.
*Unbiodegradable fraction of the AS ($f_{AS'up}$) based on OHO unbiodegradable fraction (f'_{EH}) = 0.08 of death-regeneration model.

fraction (f_{EH}) = 0.20. This is very close to the b_{HT} rate determined by Marais and Ekama (1976) of 0.24 $(1.029)^{(T-20)}$ between 8 and 20°C for the same Y_H and f_{EH} and f_{cv} = 1.48. The b_{HT} value of the WAS from the aerated lagoon (R0) and in the subsequent aerobic digesters (R1 to R4) therefore could be determined with confidence to be $0.24(1.04)^{(25-20)}$ = 0.292 /d at 25°C.

To readers not familiar with the steady state activated sludge model of Marais and Ekama (1976) (or WRC, 1984), the b_{H20} = 0.24 /d and f_{EH} = 0.20 may seem incorrect compared with the ASM1 values of b'_{H20} = 0.62 and f'_{EH} = 0.08. Dold et al. (1980) and Warner et al. (1986) showed that the b_{H20} = 0.24 /d and f_{EH} = 0.20 of the endogenous respiration or aerobic digestion model, which is included in and is a subset of the steady state model of Marais and Ekama (1976), yield identical results under aerobic conditions to the b'_{H20} = 0.62 /d and f'_{EH} = 0.08 of the death-regeneration model included in the kinetic simulation models like ASM1. The endogenous respiration approach models the net effect of the death-regeneration. The former is used in steady state AS and AerD models because it leads to much simpler equations with negligible loss of accuracy. If it is accepted that the death-regeneration approach is a more realistic model of what happens in AS, then it follows that the f_{EH} = 0.20 of the endogenous respiration model is not a good estimate of the 'real' unbiodegradable fraction of the OHO biomass. The f'_{EH} = 0.08 of the death-regeneration model would be a much closer estimate of the 'real' unbiodegradable fraction of the OHO biomass. This is important when calculating the unbiodegradable fraction of WAS for AD (Ekama et al., 2006, Part 3).

Theoretical modelling – steady state AerD model

In the steady state AerD model of Marais and Ekama (1976, see also Van Haandel et al., 1998a), extended here to include the ISS model of Ekama and Wentzel (2004), it is assumed that:

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- The unbiodegradable organics in the influent to the digester, which comprise both:
  - the wastewater unbiodegradable particulate organics (S_{upi}) that accumulate in the activated sludge reactor as VSS (X_I) and
  - the OHO unbiodegradable particulate organics (endogenous residue, X_{EH}) generated in the AS reactor,

  remain unaffected with the result that their concentrations do not change in the digester. These two concentrations are therefore lumped together [which assumes their CHON composition is the same, which appears not to be the case (Wentzel at al., 2006, Part 1), but is acceptable for this steady state model] and denoted X_{Ii}, viz. the influent unbiodegradable VSS to the digester.
- The 'fixed' ISS concentration from the (original) influent wastewater also does not change during digestion, i.e. no precipitation or dissolution of inorganics takes place in the digester.
- The OHOs (X_{BH}) decrease in the digester via endogenous respiration. This decrease in OHO concentration gives rise to five ancillary effects, i.e.
  - a generation of unbiodegradable VSS in the form of 'new' endogenous residue (X_{EH}) which is 20% (f_{EH}) of the OHOs that are 'lost' in endogenous respiration,
  - a decrease in the ISS concentration proportional with the OHO decrease,
  - the utilisation of oxygen for endogenous respiration,
  - the release of ammonia and ortho-phosphate (OP) to the bulk liquid, the former of which may be nitrified and
  - the utilisation of oxygen for nitrification.

The equations for the steady state single reactor completely mixed AerD model were derived from the above assumptions. In the interests of brevity, their derivation is not given, but the equations of the model in terms of the VSS and TSS concentration measures are listed in Table 2 (Eqs. (1) to (23)). Also, from the VSS based model, it can be shown that with b_{HT}, Y_H, f_{EH} and f_{cv} known, the active OHO fraction of the VSS (f_{av}) is given by:

$$f_{av} = \frac{OUR_t}{(f_{cv} + 4.57 f_n)(1 - f_{EH}) b_{HT} X_v} \tag{24}$$

where:

OUR_t	=	total endogenous oxygen utilisation rate including complete nitrification of VSS released ammonia – mgO/(ℓ·d) – i.e. at zero residual influent biodegradable COD and ammonia concentrations.
f_n	=	TKN/VSS ratio of activated sludge
	=	0.10 mgN/mgVSS = 67.6 mgN/gCOD
X_v	=	volatile suspended solids (VSS) concentration.

Equation (24) applies provided nitrification is complete (i.e. low effluent free and saline ammonia, FSA concentration), which was the case for the activated sludges from the aerated lagoon and the four in-series aerobic digesters of Van Haandel et al. (1998a). Thus with known values for f_{cv}, f_n, f_{EH}, and b_{HT}, i.e. 1.5mgCOD/mgVSS, 0.10 mgN/mgVSS, 0.20 and 0.292/d at 25°C, the active fraction of the VSS (f_{av}) can be calculated with Eq. (24) from measured values of OUR_t and X_v at the 5 sampling points (P) in Fig. 1. From the measured values of OUR_t and X_v in Table 1, the experimentally measured characteristics of the WAS in the outflow of the aerated lagoon (R0) and the four in-series aerobic digesters (R1 to R4) and fed to the five anaerobic digesters (AD0 to AD4) were calculated and are also given in Table 1, viz.:

- The active OHO fraction of the VSS (f_{av}) calculated from Eq. (24)
- The total COD concentration calculated from the measured VSS concentration and COD/VSS ratio of the sludge (f_{cv} = 1.5 mgCOD/mgVSS)
- The biodegradable COD concentration calculated from the biodegradable fraction of the OHOs, i.e. $(1-f'_{EH}) f_{av} f_{cv} X_v$,
- The unbiodegradable COD fraction of the digester feed sludge ($f_{AS'up}$) calculated from the active fraction of the VSS mass, i.e. $f_{AS'up} = 1 - (1-f'_{EH}) f_{av}$, where f'_{EH} = 0.08.

The use of f'_{EH} = 0.08 here, instead of f_{EH} = 0.20, to calculate the biodegradable COD concentration and unbiodegradable COD fraction of the WAS fed to the anaerobic digesters was discussed above. When WAS is fed to an *aerobic* digester, it is acceptable to use the net effect endogenous respiration approach to model the digester because the conditions remain aerobic. However, when the WAS is fed to an *anaerobic* digester, it is no longer valid to use the net effect endogenous respiration model constants because the biodegradable organics of the WAS are now utilised anaerobically by a different organism group with different stoichiometric constants and so the 'real' biodegradable organic content of OHOs as included in the death-regeneration model ($1-f'_{EH}$ = 0.92) has to be used.

Aerobic digestion model validation

From the steady state activated sludge model of Marais and Ekama (1976, see also WRC, 1984), extended by Ekama and Wentzel (2004) to include the ISS concentration, the mass of VSS, ISS and TSS in the reactor is related to the organic (COD) and inorganic (ISS) loads on the reactor, the OHO kinetic and stoichiometric constants (b_{HT}, Y_H, f_{cv}, f_{EH} and f_{iOHO}), the wastewater unbiodegradable soluble and particulate COD fractions ($f_{S'us}$, $f_{S'up}$) and the sludge age (R_s). With the ISS content of the OHOs (f_{iOHO}) at 0.15 mgISS/mgOHOVSS as determined by Ekama and Wentzel (2004) and assuming $f_{S'us}$ = 0.07, the calculated raw wastewater characteristics fed to the 1 000 ℓ volume 2 d retention time aerated lagoon (R0) of Van Haandel et al. (1998a) at 500 ℓ/d and 25°C to match the measured data at P1 (Fig. 1, i.e. VSS/TSS ratio, f_i = 0.71 and OHO active fraction, f_{av} = 0.76, Table 1) are total influent COD concentration (S_{ti}) = 563 mgCOD/ℓ, $f_{S'up}$ = 0.072 and the influent inorganic suspended solids concentration (X_{Ioi}) = 52.9 mg ISS/ℓ. These raw wastewater characteristics were used for the theoretical calculations through the aerated lagoon (R0) and aerobic digester sequence (R1 to R4) with the theoretically calculated effluent concentrations of the upstream AerD becoming the influent concentrations to the downstream one. For example, the effluent active fraction of the VSS from the aerated lagoon (R0, $f_{ave,R0}$) is 0.76 and is the influent active fraction to the first AerD (R1, $f_{avi,R1}$). From Eq. (1), with f_{EH} = 0.20, β = 0.516. With b_{H25}= 0.292/d and the retention time (R_h) in digester R1 = 1.73 d, α = 0.777 (Eq. 4). Hence, from Eq. (2), the effluent active fraction from R1 ($f_{ave,R1}$) = 0.634. Similarly, the effluent active fraction of the TSS from the aerated lagoon (R0, $f_{ate,R0}$) is 0.54. From Eq. (11), with f_{iOHO} = 0.15, δ = 0.702. With b_{H25}= 0.292/d and the retention time (R_h) in digester R1 = 1.73 d, γ = 1.158 (Eq. 14). Hence from Eq. 12, the effluent active fraction from R1 ($f_{ate,R1}$) = 0.433. The VSS/TSS ratio (f_{ii}) of the sludge from the aerated lagoon (R0) is 0.711 (Eq. 21) and with f_{ave} = 0.634 and f_{ate} = 0.433, the effluent VSS/TSS ratio (f_{ie}) from digester R1 is 0.683 (Eq. 22). With the β and α values known from the influent and effluent active fractions, the

TABLE 2
Equations of the steady state aerobic digestion model based on the steady state activated sludge model of Marais and Ekama (1976) and the ISS model of Ekama and Wentzel (2004).

Parameter	Model in terms of VSS	Model in terms of TSS
Influent active fraction (f_{avi}, f_{ati})	$\beta = 1/f_{avi} - (1-f_{EH})$ ...(1)	$\delta = 1/f_{ati} - (1+f_{iOHO})$ ...(11)
Effluent active fraction (f_{ave}, f_{ate})	$\alpha = 1/f_{ave} - (1-f_{EH})$ ...(2)	$\gamma = 1/f_{ate} - (1+f_{iOHO})$ ...(12)
Retention time (R_h, d)	$R_h = \frac{1}{b_{HT}}\left[\frac{\alpha}{\beta} - 1\right]$ ...(3)	$R_h = \frac{\gamma - \delta}{b_{HT}(\delta + f_{EH})}$ ....(13)
Effluent active fraction (f_{ave}, f_{ate})	$\alpha = \beta(1 + b_{HT} R_h)$ ....(4)	$\gamma = \delta + b_{HT} R_h (\delta + f_{EH})$ ...(14)
Fraction solids removal (f_{vsr}, f_{tsr})	$f_{vsr} = f_{avi}(1-f_{EH})\ (1-\beta/\alpha)$ ...(5)	$f_{tsr} = 1 - \frac{f_{ati}}{f_{ate}(1+b_{HT}R_h)}$ ...(15)
Organic Oxygen Demand (kgO/d)	$V_d O_c = f_{cv} f_{vsr} Q_i X_{vi}$ ...(6)	$V_d O_c = f_{cv} Q_i X_{ti} f_{tsr}(1-f_{EH})/(1+f_{iOHO} - f_{EH})$ ....(16)
Nitrif. Oxygen Demand (kgO/d	$V_d O_n = 4.57 f_n f_{vsr} Q_i X_{vi}$ ....(7)	$V_d O_n = 4.57 f_n Q_i X_{ti} f_{tsr}(1-f_{EH})/(1+f_{iOHO} - f_{EH})$ ....(17)
Total Oxygen Demand (kgO/d)	$V_d O_t = (f_{cv} + 4.57 f_n) f_{vsr} Q_i X_{vi}$ ...(8)	$V_d O_t = (f_{cv} + 4.57 f_n) Q_i X_{ti} f_{tsr}(1-f_{EH})/(1+f_{iOHO} - f_{EH})$ ....(18)
Effluent Ammonia Conc (mgN/ℓ)	$N_{ae} = N_{ne} = f_n X_{vi} f_{vsr}$ .....(9a & 9b)	$N_{ae} = N_{ne} = f_n X_{ti} f_{tsr}(1-f_{EH})/(1+f_{iOHO} - f_{EH})$ ......(19a & 19b)
Effluent Ortho-P Conc (mgP/ℓ)	$P_{se} = f_p X_{vi} f_{vsr}$ ....(10)	$P_{se} = f_p X_{ti} f_{tsr}(1-f_{EH})/(1+f_{iOHO} - f_{EH})$ ....(20)
VSS/TSS ratio	$f_{ii} = \frac{f_{ati}}{f_{avi}}$ ..(21); $f_{ie} = \frac{f_{ate}}{f_{ave}}$ ..(22); $f_{ie} = \frac{(1-f_{vsr})}{(1-f_{tsr})} f_{ii}$ ..(23a); $f_{ie} = \frac{f_{ii}[1/(b_H R_h) + 1] - f_{ati}(1-f_{EH})}{[(1/(b_H R_h)) + 1] - f_{ati}(1 + f_{iOHO} - f_{EH})}$ ..(23b)	

Notes: (1) For known influent active fraction (favi, fati) if (i) effluent active fraction is specified (i.e. a level of sludge stability), then use Eqs. 2 or 12 to calculate α or γ and Eqs. 3 or 13 to calculate the required retention time (Rh) or (ii) if Rh is known, then use Eqs. 4 or 14 to calculate α or γ and Eqs. 2 or 12 to calculate the resulting effluent active fraction.

(2) Symbols: favi, fati, fave fate = active fraction with respect to VSS (subscript v) and TSS (subscript t) for the influent (subscript i) and effluent (subscript e) sludges, fvsr, ftsr = fraction of VSS (subscript v) and TSS (subscript t) solids removed; fii, fie = VSS/TSS ratio of the influent (subscript i) and effluent (subscript e) solids; Vd= digester volume; Qi = influent flow; Oc, On, Ot = organic, nitrification and total oxygen utilisation rates - mgO/(ℓ.d); fEH and bHT = unbiodegradable fraction and endogenous respiration rate of the OHOs in the endogenous respiration model (i.e. 0.20 and 0.24/d at 20°C); fiOHO = ISS content of OHOs = 0.15 mgISS/mgOHOVSS. Nae, Nne and Pse are the effluent ammonia (no nitrification, Nne=0), nitrate (complete nitrification, Nae=0) and phosphorus concentrations.

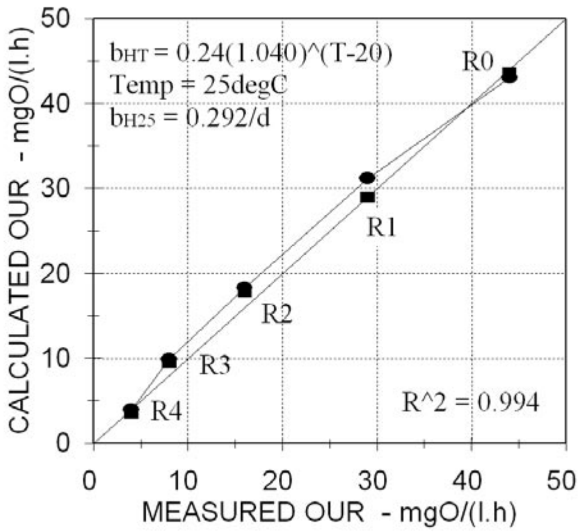


Figure 2
Steady state model (■) and ASM1 (●) predicted versus measured oxygen utilisation rate (OUR) in the outflow sludges from the aerated lagoon (R0) and the 4 in-series aerobic digesters (R1 to R4) of Van Haandel et al. (1998a).

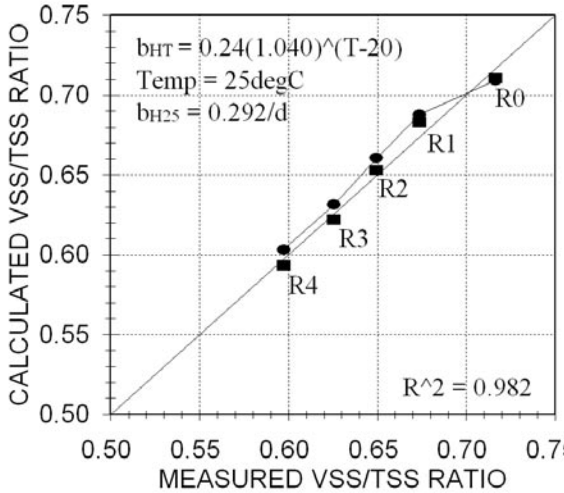


Figure 4
Steady state model (■) and ASM1 (●) predicted versus measured VSS/TSS ratio in the outflow sludges from the aerated lagoon (R0) and the 4 in-series aerobic digesters (R1 to R4) of Van Haandel et al. (1998a).

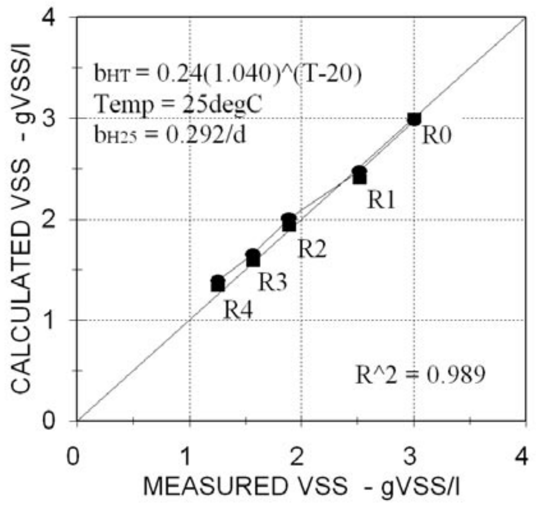


Figure 3
Steady state model (■) and ASM1 (●) predicted versus measured VSS concentration in the outflow sludges from the aerated lagoon (R0) and the 4 in-series aerobic digesters (R1 to R4) of Van Haandel et al. (1998a).

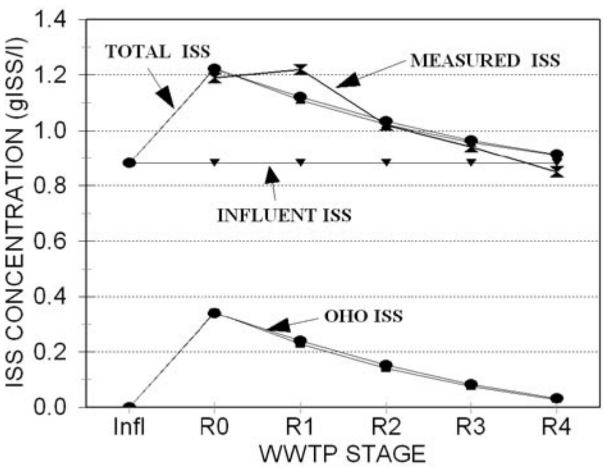
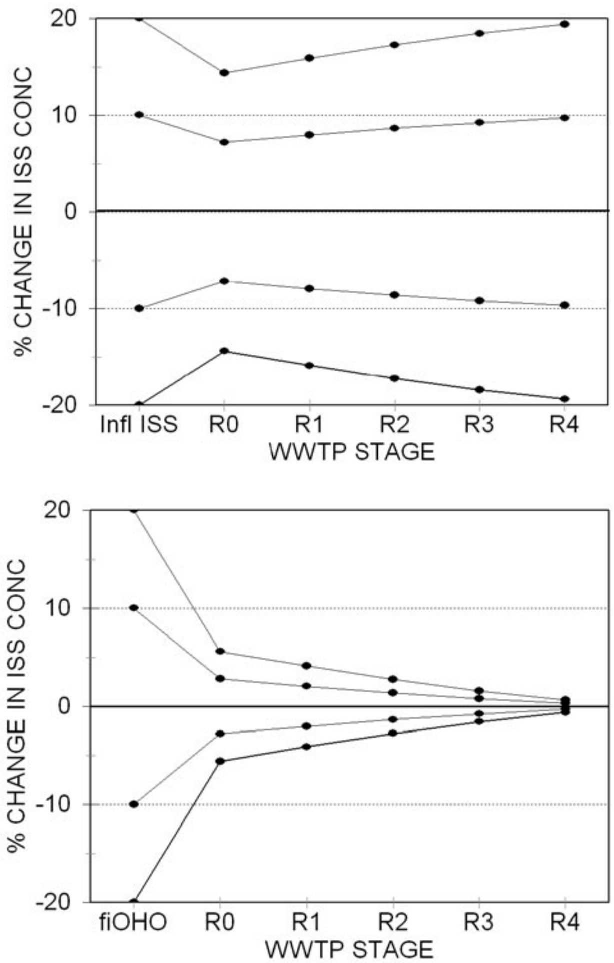


Figure 5
Steady state model influent (▼), OHO biomass (■) and total (▲), ASM model predicted (⧖) and experimentally measured (●) ISS concentration in the outflow sludges from the aerated lagoon (R0) and the 4 in-series aerobic digesters (R1 to R4) of Van Haandel et al. (1998a)

fraction of VSS removed (f_{vsr}) in the 1st digester (R1) = 0.204 (Eq. 5). Then from Eqs. (6) to (8), the organic, nitrification and total oxygen utilisation rate (OUR) can be calculated from the known load of VSS on the digester, i.e. 22.18, 6.76 and 28.94 mgO/(ℓ·h) respectively. This calculation is then followed through the remaining series of three digesters (R2 to R4) with the effluent active fractions of R1 ($f_{ave,R1}$) becoming the influent active fractions of R2 ($f_{avi,R2}$) and so on. The theoretically calculated and experimentally measured results are compared in Table 1.

From Table 1, the calculated total OUR, VSS concentration and VSS/TSS ratio of the sludge in the outflow from R0 to R4 at sampling points P1 to P5 are compared with the measured values in Figs. 2 to 4. It can be seen that the correspondences are very good (correlation coefficients $R^2 > 0.98$). With regard to the ISS concentration (in the 30 ℓ sludge volume fed to the AerDs), Fig. 5 shows the component concentrations of the total ISS though the aerated lagoon and four digesters in series. The "fixed" ISS originating from the influent wastewater remains constant at 0.882 gTSS/ℓ as expected. The biomass ISS concentration decreases through the R0 to R4 series as the OHO biomass concentration decreases which results in a decreasing total ISS concentration through R0 to R4. The experimentally measured ISS concentrations also are plotted in Fig. 5 and it can be seen that the theoretically predicted ISS concentrations correspond closely with these (R^2=0.830). The calculated and measured VSS/TSS ratios through the R0 to R4 series also correspond very well (R^2=0.982, Fig. 4). From Figs. 4 and 5, the close correspondence between calculated and measured ISS concentrations is not possible without including an OHO ISS content (f_{iOHO}), and the value of 0.15 mgISS/mgOHOVSS estimated by Ekama and Wentzel (2004) clearly also closely applies to the Van Haandel et al. (1998a) data. The 'fixed' (originating from the raw waste-



Figures 6a and 6b
Sensitivity analysis with ISS model showing % change in ISS concentration at the differnt WWTP stages (Fig. 1) for ±10% and ±20% changes in OHO ISS content (f_{iOHO}, Fig. 6a, top) and influent ISS concentration (Infl ISS, Fig. 6b, bottom)

water) ISS concentration and OHO ISS content (f_{iOHO}) values that minimise the variance (error) between the measured and predicted ISS concentrations at points P1 to P5 in Fig. 1 are 51.2 mgISS/ℓ and 0.171 mgISS/mgOHOVSS ($R^2 = 0.847$). These values are very close to the 52.9 mgISS/ℓ and 0.150 mgISS/mgOHOVSS determined from the Ekama and Wentzel (2004) model ($R^2 = 0.830$). This not only provides additional validation for the ISS model, but also shows that it can be used for tracking the ISS concentration through aerobic digestion down to very low active fractions – the f_{ave} from R4 is 0.142, which is equivalent to an extended aeration activated sludge system at around 60 d sludge age.

Simulation of aerated lagoon and aerobic digesters series

The aerated lagoon and four in-series AerD WWTP sequence was simulated in Aquasim (Reichart, 1998) with ASM1, modified to include the ISS model of Ekama and Wentzel (2004). The theoretically predicted OUR, VSS concentration, VSS/TSS ratio, and ISS concentration are shown plotted in Figs. 2 to 5 together with the steady state model calculated results and experimental data. It can be seen that the ASM1 and steady state model results match very closely and both correlate very well with the experimental data. This shows that the steady state AerD model in terms of VSS or TSS is sufficiently accurate to include in a steady state plant-wide WWTP model. Since this model is expressed in terms of the same compounds as the AS models, this establishes the AS - AerD link.

Sensitivity analysis

The sensitivity of the ISS model to its primary variables OHO ISS content (f_{iOHO}) and influent ISS concentration was assessed by changing each by plus and minus 10% and 20% from the model values determined for the Van Haandel et al. (1998a) data, i.e. $f_{iOHO} = 0.15$ and influent ISS = 52.9 mgISS/ℓ, and calculating the percentage change in the total ISS concentrations in R0 to R4 at sampling points P1 to P5 (Fig. 1). The results are shown in Fig. 6. It can be seen that the ISS concentrations are relatively insensitive to the changes in the OHO ISS content (Fig. 6a) – they change from 28% to 3% of the change in OHO ISS content down the WWTP stage, or equivalently as endogenous respiration progresses (sludge age increases). The ISS concentrations are much more sensitive to changes in the influent wastewater ISS concentration (Fig. 6b) - they change from 72% to 97% of the change in influent ISS as endogenous respiration progresses. From this it is clear that for the Van Haandel et al. (1998a) data, the OHO ISS contributes 28% and the influent ISS contributes 72% of the total ISS at short sludge ages (R0 at 2 d) when the OHO active fraction is high (0.76). At very long sludge ages (R4, equivalent to about 60 d) the OHO active fraction is very low (0.14) so the OHO ISS contributes only 3% and the influent ISS 97% to the total ISS. This greater sensitivity of the model to the influent ISS emphasises the importance of measuring the influent ISS concentration accurately. A test procedure which improves influent ISS determination is described by Ekama and Wentzel (2004).

Conclusions

From this investigation of the continuity of wastewater organic, inorganic and N compounds across the links between the primary settling tank (PST), fully aerobic or N removal activated sludge (AS) and anaerobic (AD) and aerobic (AerD) digestion unit operations, the following can be concluded:

- From the experimental data of Van Haandel et al. (1998a), the influent wastewater (fixed) ISS concentration is conserved through AS and waste activated sludge (WAS) aerobic digestion (AerD) systems.
- From the experimental data of Izzett et al. (1992) and Moen et al. (2001), the evidence is inconclusive whether the influent wastewater (fixed) settleable ISS concentration is conserved through primary sludge (PS) AD. The ISS mass balance over the ADs was narrowly within ±10%. More data on this aspect need to be evaluated.
- The measured ISS flux at different stages through a series of WWTP unit operations is not equal to the influent ISS flux. The ordinary heterotrophic organism (OHO) biomass contributes to the fixed ISS flux by differing amounts depending on the active (OHO) fraction of the VSS.
- The ISS model of Ekama and Wentzel (2004), which assigns an ISS content to OHOs of 0.15 mgISS/mgOHOVSS, correlates very well with experimental data from a WWTP comprising an aerated lagoon and four in-series aerobic digesters, covering an effective sludge age range from 2 to 60 d. This not only provides additional validation for the ISS model, but also shows that it can be used for tracking the ISS through AerD systems down to very low active fractions.

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- The steady state AerD model developed for stabilisation of WAS in terms of VSS and TSS was found to correlate very well with literature data. This model also can be applied to model AerD of PS and PS-WAS blends (Sötemann et al., 2006, Part 4). To use the model requires the equivalent influent active fraction of the PS to be calculated. This influent active fraction can be calculated from the biodegradable COD fraction of the PS determined from a mass balance around PST (Wentzel et al., 2006, Part 1).

This research has indicated that the mass balance-based steady state and dynamic simulation activated sludge and aerobic digestion models, modified to include the ISS compound, provide internally consistent and externally compatible elements that can be coupled to produce an integrated steady state model for the whole WWTP.

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