Tracking influent inorganic suspended solids through wastewater treatment plants

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Water Science & Technology **Vol 54 No 8 pp 101–109** © IWA Publishing 2006

Abstract From an experimental and theoretical investigation of the continuity of influent inorganic suspended solids (ISS) along the links connecting the primary settling tank (PST), fully aerobic or N removal activated sludge (AS) and anaerobic and aerobic sludge digestion unit operations, it was found that the influent wastewater (fixed) ISS concentration is conserved through primary sludge anaerobic digestion, activated sludge and aerobic digestion unit operations. However, the measured ISS flux at different stages through a series of wastewater treatment plant (WWTP) unit operations is not equal to the influent ISS flux, because the ordinary heterotrophic organisms (OHO) biomass contributes to the ISS flux by differing amounts depending on the active fraction of the VSS solids at that stage.

Keywords Activated sludge; aerobic digestion; anaerobic digestion; influent inorganic suspended solids; model validation; wastewater treatment

Introduction

The inorganic suspended solids (ISS) needs to be included in mass balance steady-state and dynamic simulation models for the whole wastewater treatment plant (WWTP) because it is included in the total (T)SS parameter which is commonly used for design and operation of WWTPs. If primary settling tanks (PSTs) are included in the WWTP configuration, then the influent ISS are 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. The waste activated sludge (WAS), containing the non-settleable ISS (if PSTs are included) or all the influent ISS (without PSTs), passes to sludge treatment facilities. The sludge treatment facilities of PS and/or WAS may be anaerobic (AD) or aerobic (AerD) digestion. Therefore, insofar as tracking the influent ISS is concerned, four main WWTP links need to be established: (1) the PST–AD link; (2) the AS–AerD link; (3) the AS–AD link; and (4) the PST–AerD link. In this paper, tracking the influent ISS along links 1 and 2 is 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.* (1992) 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 WAS. From the above data, it is reasonable

doi: 10.2166/wst.2006.777

to accept that in the absence of mineral precipitation, the influent PS ISS mass is conserved in AD.

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

This link is relatively simple to establish, because the same models are used to simulate the N removal activated sludge system and aerobic digester. Common compounds for the organic and N materials therefore already exist for this link in the steady state and dynamic simulation N removal activated sludge models. However, these models, of which aerobic digestion is a subset, usually do not include the reactor ISS concentration directly—this is usually calculated from an estimated VSS/TSS ratio for the activated sludge (WRC, 1984). If the ISS concentration calculated from such an estimated activated sludge VSS/TSS ratio is assumed to all have originated from the influent wastewater, significant errors will be made on the mass balance of this material around the WWTP. Ekama and Wentzel (2004) developed a predictive model for the ISS concentration in activated sludge systems. The applicability of this model to aerobic digestion of WAS is investigated below using the experimental data of van Haandel *et al.* (1998a, b).

The ISS model of Ekama and Wentzel (2004)

This model is based on the accumulation of influent ISS in the reactor and an ordinary heterotrophic organism (OHO) ISS content (f_{iOHO}) of 0.15 mgISS/mg OHO VSS. This OHO ISS (as distinct from the influent wastewater ISS) is not ‘real’ ISS; it arises principally from intracellular 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 3–20 days sludge age. The predicted reactor VSS/TSS ratio reflects the observed relative sensitivity to sludge age, which is low. This model can be readily integrated into the steady state and dynamic simulation activated sludge models. To use the model, measurement of the influent ISS concentration is required, which is not commonly done in wastewater characterization analyses, and a test procedure to do this accurately was developed. The model 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 this 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 wastewater treatment plant scheme at 25 °C in which 500 l/d raw municipal wastewater from the Campina Grande (Brazil) main sewer was fed to a 2 day retention time aerated lagoon (R0). All the daily 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. The experimental data measured on the effluent sludges from aerobic digesters R0 to R4 are listed in Table 1.

In addition, with the same raw wastewater feed, van Haandel *et al.* (1998a) operated an activated sludge system at 13 different sludge ages between 3 and 10 d and temperatures between 21 and 30 °C. On sludge harvested from this system, they conducted six

Table 1 Experimentally measured (van Haandel *et al.*, 1998a, b) and theoretically calculated characteristics of the activated sludge in the outflows from the aerated lagoon (R0) and the four in-series aerobic digesters (R1 to R4) at 25 °C [OUR in mgO/(l.h)]

Parameter	**R0** **Effl**	**R1** **Infl**	**R1** **Effl**	**R2** **Infl**	**R2** **Effl**	**R3** **Infl**	**R3** **Effl**	**R4** **Infl**	**R4** **Effl**	
Flow (l/d)	30	26	26	21	21	15	15	8	8	
Ret. time (d)	2.00	1.73	1.73	2.14	2.14	3.00	3.00	5.63	5.63	
	Exper	Theory	Exper	Theory	Exper	Theory	Exper	Theory	Exper	Theory
TSS – X_t g/l	4.20	4.24	3.71	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_c	–	33.39	–	22.18	–	13.64	–	7.27	–	2.75
OUR_n	–	10.17	–	6.76	–	4.16	–	2.22	–	0.84
OUR_t	44	43.57	29	28.94	16	17.80	8	9.49	4	3.59
f_{av} – (Eq 24)	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	–	
f_{at} – (Eq 21)	0.54	0.540	0.40	0.433	0.29	0.317	0.17	0.196	0.10	0.084
δ – (Eq 11)	–	0.702	–	1.158	–	2.008	–	3.941	–	
γ – (Eq 14)	–	1.158	–	2.008	–	3.941	–	10.743	–	
OHOVSS g/l	2.29	2.29	1.51	1.52	0.83	0.93	0.42	0.50	0.21	0.19
ISS_{infl} - g/l	–	0.88	–	0.88	–	0.88	–	0.88	–	0.88
ISS_{bio} – g/l	–	0.34	–	0.23	–	0.14	–	0.07	–	0.03
ISS_{tot} – g/l	1.19	1.23	1.02	1.11	1.02	1.02	0.94	0.96	0.85	0.91
VSS rem f_{vsr}		0.204	0.163	0.95	0.250	0.181	0.169	0.157	0.197	
TSS rem f_{tsr}		0.172	0.110	0.158	0.222	0.140	0.137	0.116	0.159	

Note: Effi = effluent, Infl = influent, other parameters are defined in the text batch aerobic digestion tests at each sludge age and temperature. From the measured oxygen utilization rate (OUR) and volatile suspended solids (VSS), nitrate and alkalinity concentrations with time, they determined the specific endogenous respiration rate of the OHOs, $b_{HT} = 0.24\ (1.040)^{(T\text{-}20)}$/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 fraction $(f_{EH}) = 0.20$. This is very close to the b_{HT} rate determined by Marais and Ekama (1976) of $0.24\ (1.029)^{(T\text{-}20)}$ 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. 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 model yield near identical results 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 (Henze *et al.*, 1987). Endogenous respiration models the net effect of the death-regeneration and the former is used in steady-state models because it leads to much simpler equations with negligible loss of accuracy.

Theoretical modeling: steady state aerobic digestion model with ISS

In the steady state aerobic digestion 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), the following is accepted.

(1) The unbiodegradable organics in the influent to the digester, which comprises both (i) the wastewater unbiodegradable particulate organics (S_{upi}) that accumulate in the activated sludge reactor as VSS (X_I); and (ii) the OHO unbiodegradable particulate organics (endogenous residue, X_{EH}) generated in the activated sludge reactor, remain unaffected with the result that their concentrations do not change in the digester. These two concentrations are lumped together and denoted X_{Ii}, i.e. the influent unbiodegradable VSS to the digester.

(2) The inorganic suspended solids (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.

(3) The OHOs (X_{BH}) decrease in the digester *via* endogenous respiration. This decrease in OHO concentration in (3) above gives rise to five ancillary effects:

(4) 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;

(5) a decrease in the ISS concentration proportional with the OHO decrease;

(6) the utilization of oxygen for endogenous respiration;

(7) the release of ammonia and ortho-phosphate (OP) to the bulk liquid, the former of which may be nitrified;

(8) the utilization of oxygen for nitrification.

The equations for the steady state single reactor completely mixed aerobic digester 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 (Equations 1 to 23), where $f_{avi}, f_{ati}, f_{ave}\, f_{ate} =$ active fraction with respect to VSS (subscript v) and TSS (subscript t) for the influent (subscript i) and effluent (subscript e) sludges, $f_{vsr}, f_{tsr} =$ fraction of VSS (subscript v) and TSS (subscript t) solids removed; $f_{ii}, f_{ie} =$ VSS/TSS ratio of the influent (subscript i) and effluent (subscript e) solids; $V_d =$ digester volume; $Q_i =$ influent flow; O_c, O_n, $O_t =$ organic, nitrification and total oxygen utilization rates [mgO/(l.d)]; f_{EH} and $b_{HT} =$ OHO unbiodegradable fraction and endogenous respiration rate in the endogenous

Table 2 Steady-state aerobic digestion model based on the steady-state activated sludge and ISS models of Marais and Ekama (1976) and 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)	$V_d O_n = 0\,(\text{No Nitrification})$	(7a)	$V_d O_n = 0\,(\text{No Nitrification})$	(17a)
	$V_d O_n = 4.57 f_n f_{vsr} Q_i X_{vi}$	(7b)	$V_d O_n = 4.57\, f_n Q_i X_{ti} f_{tsr}(1 - f_{EH})/(1 + f_{iOHO} - f_{EH})$	(17b)
Total oxygen demand (kgO/d)	$V_d O_t = V_d O_c + V_d O_n$	(8)	$V_d O_t = V_d O_c + V_d O_n$	(18)
Effluent FSA conc (mgN/l)	$N_{ae} = f_n X_{vi} f_{vsr}\,(\text{No nitrification})$	(9a)	$N_{ae} = f_n X_{ti} f_{tsr}(1 - f_{EH})/(1 + f_{iOHO} - f_{EH})\,(\text{No nitrification})$	(19a)
	$N_{ne} = f_n X_{vi} f_{vsr}\,(\text{Full nitrification})$	(9b)	$N_{ne} = f_n X_{ti} f_{tsr}(1 - f_{EH})/(1 + f_{iOHO} - f_{EH})\,(\text{Full nitrification})$	(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)

respiration model (i.e. 0.20 and 0.24/d at 20 °C); f_{iOHO} = ISS content of OHOs = 0.15 mgISS/mgOHOVSS (Ekama and Wentzel, 2004). N_{ae}, N_{ne} and P_{se} are the effluent ammonia (no nitrification, $N_{ne} = 0$), nitrate (complete nitrification, $N_{ae} = 0$) and phosphorus concentrations. With Equations 1–23, for known influent active fraction (f_{avi} or f_{ati}) if (1) effluent active fraction (f_{ave} or f_{ate}) is specified (i.e. a level of sludge stability), then use Equations 2 or 12 to calculate α or γ and Equations 3 or 13 to calculate the required R_h or (2) if R_h is known, then use Equations 4 or 14 to calculate α or γ and Equations 2 or 12 to calculate f_{ave} or f_{ate}.

Also, from the VSS based model, with b_{HT}, Y_H, f_{EH} and f_{cv} known, it can be shown that the active fraction (f_{av}) is given by:

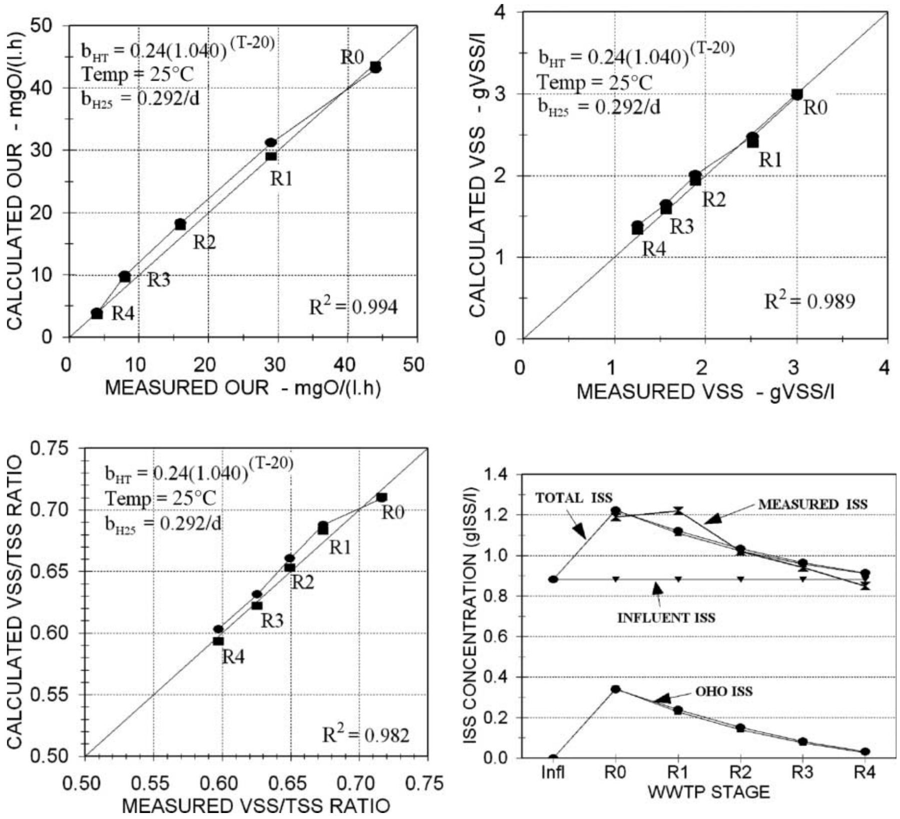
$$f_{av} = \mathrm{OUR_t}/[(f_{cv} + 4.57 f_n)(1 - f_{EH}) b_{HT} X_v] \qquad (24)$$

where $\mathrm{OUR_t}$ is the total endogenous oxygen utilization rate including complete nitrification of VSS released ammonia [mgO/(l.d)], i.e. at zero residual influent biodegradable COD and ammonia concentrations; f_n is the TKN/VSS ratio of activated sludge (0.10 mgN/mgVSS = 67.6 mgN/gCOD); and X_v is the volatile settleable 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. 1.5 mgCOD/mgVSS, 0.10 mgN/mgVSS, 0.20 and 0.292/d at 25 °C respectively, the active fraction of the VSS (f_{av}) can be calculated using Equation 24 from measured values of $\mathrm{OUR_t}$ and X_v. From the measured values of $\mathrm{OUR_t}$ 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) were calculated and are also given in Table 1.

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 biological 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 (i.e. VSS/TSS ratio, $f_i = 0.71$ and OHO active fraction, $f_{av} = 0.76$, Table 1) are (i) 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 system becoming the influent concentrations of the downstream one.

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 are compared with the measured values in Figures 1–3. It can be seen that the correspondences are very good (correlation coefficients $R^2 > 0.98$). With regard to the ISS concentration (thickened down to 30 l), Figure 4 shows the component concentrations of the total ISS though the aerated lagoon and four in-series digesters. The ‘fixed’ ISS originating from the influent wastewater



Figures 1 to 4 Steady state model (■) and ASM1 (●) predicted *versus* measured oxygen utilization rate (OUR, Figure 1, top left), VSS (Figure 2, top right) and VSS/TSS ratio (Figure 3, bottom left), and steady-state model influent (▼), OHO biomass (■), total (▲), ASM1 model predicted (●) and experimentally measured ISS concentration (Figure 4, bottom right) in the outflow sludges from the aerated lagoon (R0) and the four in-series aerobic digesters (R1 to R4) of van Haandel *et al.* (1998a)

remains constant at 0.882 gTSS/l [from 52.9(mgISS/l) × 500(l/d)/30(l/d)] 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 from R0 to R4. The experimentally measured ISS concentrations also are plotted in Figure 4 and it can be seen that the theoretically predicted ISS concentrations correspond closely with these. The calculated and measured VSS/TSS ratios through the R0 to R4 series also correspond very well (Figure 3). From Figures 3 and 4, 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 applies to the van Haandel *et al.* (1998a) data. 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 digester series

The aerated lagoon and four in-series aerobic digester WWTP sequence was simulated in Aquasim (Reichert, 1998) with ASM1 (Henze *et al.*, 1987), 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 Figures 1 to 4 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 aerobic digester model in terms of VSS or TSS is sufficiently accurate to include in a steady-state WWTP model. Since this model is expressed in terms of the same compounds as the activated sludge models, this establishes the activated sludge–aerobic digester link.

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 and aerobic digestion unit operations, the following can be concluded.

(1) From the experimental data in several literature sources, it is reasonable to accept that the influent wastewater (fixed) ISS concentration is conserved through primary sludge anaerobic digestion, activated sludge and waste activated sludge aerobic digestion systems.

(2) The measured ISS flux at different stages through a series of WWTP unit operations is not equal to the influent ISS flux. The OHO biomass contributes to the fixed ISS flux by differing amounts depending on the active fraction of the VSS solids.

(3) 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. This not only provides additional validation for the ISS model, but also shows that it can be used for tracking the ISS through activated sludge and aerobic digester systems down to very low active fractions.

(4) The steady-state aerobic digester model developed for stabilization of WAS was found to correlate very well with literature data. This model also can be applied to model aerobic digestion of PS and PS-WAS blends (Sötemann *et al.*, 2006). 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 the PST (Wentzel *et al.*, 2006).

This research has indicated that the mass balances based steady-state 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.

Acknowledgements

This research was supported by the Water Research Commission, the National Research Foundation and the University of Cape Town and is published with their permission.

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