

Modelling inorganic material in activated sludge systems

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Abstract

A simple predictive model for the activated sludge reactor inorganic suspended solids (ISS) concentration is presented. It is based on the accumulation of influent ISS in the reactor and an ordinary heterotrophic organism (OHO) ISS content (f_{iOHO}) of 0.15 mg ISS/mgOHOVSS and a variable phosphate accumulating organism (PAO) ISS content (f_{iPAO}) proportional to their P content (f_{XBGP}). The model is validated with data from 21 investigations conducted over the past 15 years on 30 aerobic and anoxic-aerobic nitrification denitrification (ND) systems and 18 anaerobic-anoxic-aerobic ND biological excess P removal (BEPR) 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, and to BEPR, which is high. For effective use of the model for design, two significant issues require attention: measurement of the influent ISS concentration, which is not commonly done in wastewater characterisation analyses; and estimating *a priori* the P content of PAOs (f_{XBGP}), which can vary considerably depending on the extent of anoxic P uptake BEPR that takes place in the system. Some guidance on selection of the mixed liquor VSS/TSS ratio for design is given.

Keywords: activated sludge, inorganic suspended solids, modelling, biological nutrient removal

Abbreviations

Aer	= Aerobic reactor	MP	= Mitchells Plain wastewater treatment plant
An	= Anaerobic reactor	MUCT	= Modified University of Cape Town NDBEPR system
ANO	= Autotrophic nitrifier organisms	ND	= Nitrification denitrification
Art	= Artificial wastewater	NDBEPR	= Nitrification denitrification biological excess phosphorus removal
AS	= Activated sludge	NOx	= Nitrate plus nitrite concentration
ASIM	= Activated sludge simulation programme - a platform for using AS models	OHO	= Ordinary heterotrophic organisms
ASM	= Activated sludge model	OHOVSS	= Volatile suspended solids of the ordinary heterotrophic organisms
Ax	= Anoxic reactor	OP	= Orthophosphate
BEPR	= Biological excess phosphorus removal	OUR	= Oxygen utilisation rate
BNR	= Biological nutrient removal	PAO	= Phosphate accumulating organisms
Cntl	= Control	PAOVSS	= Volatile suspended solids of the phosphate accumulating organisms
COD	= Chemical oxygen demand	RBCOD	= Readily biodegradable chemical oxygen demand concentration
conc.	= concentration	SB	= Sewage batch
degC	= degrees Centigrade	SCFA	= Short chain fatty acids
DSVI	= Diluted sludge volume index	SSP	= Steady state period (a number of consecutive sewage batch periods)
Exp	= Experimental	TDS	= Total dissolved solids
FA	= Fully aerobic	TIS	= Total inorganic solids
FSA	= free and saline ammonia	TKN	= Total Kjeldahl nitrogen
I#	= Investigation number	TP	= Total phosphorus
IAND	= Intermittently aerated nitrification denitrification system	TSS	= Total suspended solids
IDS	= Inorganic dissolved solids	UCT	= University of Cape Town NDBEPR system
ISS	= Inorganic suspended solids	USCOD	= Unbiodegradable soluble chemical oxygen demand
IWA	= International Water Association	UPCOD	= Unbiodegradable particulate chemical oxygen demand
MLE	= Modified Ludzack-Ettinger nitrification denitrification system	VDS	= Volatile dissolved solids
		VSS	= Volatile suspended solids
		WRC	= Water Research Commission
		WW	= Wastewater
		WWTP	= Wastewater treatment plant
		1Ax	= First anoxic reactor in the Modified UCT system
		2Ax	= Second anoxic reactor in the Modified UCT system

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Symbols

b_{HT}, b_{GT} = endogenous respiration rate for OHOs and PAOs at T°C
= 0.24/d and 0.04/d respectively at 20°C ($\theta_b = 1.029$ for both)

f_{avOHO}, f_{avPAO} = fraction of the VSS concentration which is OHOs and PAOs respectively

f_B = ISS/VSS ratio (mgISS/mgVSS) of OHOs and their endogenous residue estimated by Wentzel et al. (2002) = 0.17 mgISS/mgVSS

f_{cv} = COD/VSS ratio of organics = 1.48 mgCOD/mgVSS

f_{EH}, f_{EG} = endogenous residue fraction of the OHOs and PAOs = 0.20 and 0.25 respectively

f_i = VSS/TSS ratio of reactor sludge mass.

f_{iOHO} = inorganic content of OHO cell mass
= 0.15 mgISS/mgOHOVSS

f_{iPAO} = total inorganic solids content of PAOs
(= $f_{iPAOBM} + f_{iPAOPP}$)

f_{iPAOBM} = inorganic solids content of the PAO active biomass (without polyphosphate)(mgISS/mgVSS)
= 0.15 mgISS/mgPAOVSS

f_{iPAOPP} = inorganic material content of the PAO polyphosphate (mgISS/mgVSS)

$f_{S'up}$ = influent unbiodegradable particulate COD fraction

$f_{S'us}$ = influent unbiodegradable soluble COD fraction

$f_{Sb's}$ = influent readily biodegradable (RB) COD fraction with respect to biodegradable COD.

f_{xa} = Anaerobic mass fraction

f_{XBGMBM} = P content of PAO cell mass (without polyphosphate)

f_{XBGPM} = total P content of PAOs (= $f_{XBGMBM} + f_{XBGPP}$)

f_{XBGPP} = P content of the PAO cell mass
= 0.03 mgP/mgPAOVSS

f_{XBGPP} = polyphosphate content of PAOs (mgpolyphosphate/mgPAOVSS)

i_{TSSXBM} = TSS to COD ratio of active organisms in ASIM version of ASM#2
= 0.90 mgTSS/mgCOD (Gujer, 1993)

i_{TSSXI} = TSS to COD ratio of unbiodegradable particulate organics in ASIM version of ASM#2 = 0.75 mgTSS/mgCOD (Gujer, 1993)

i_{TSSXS} = TSS to COD ratio of biodegradable particulate substrate in ASIM version of ASM#2 = 0.75 mgTSS/mgCOD (Gujer, 1993)

MS_{fi} = COD mass load on reactor (kgCOD/d) = $Q_i S_{fi}$

MX_{Io} = mass of ISS in reactor (kgTSS)

MX_t = mass of TSS in reactor (kgTSS)

MX_v = VSS mass in reactor (kgVSS)

Q_i = average dry weather flow (ADWF, M ℓ /d)

R_{hn} = nominal hydraulic retention time (hours)

R_s = system sludge age (days)

S_{fi} = flow weighted average influent COD concentration entering biological reactor (mgCOD/ ℓ)

X_{Io} = ISS concentration in biological reactor (mgISS/ ℓ)

X_{Ioi} = influent ISS concentration entering biological reactor (mgISS/ ℓ)

X_v = measured or calculated VSS concentration in the reactor (mgVSS/ ℓ)

Y_H, Y_G = yield coefficient for OHOs and PAOs = 0.45 mgVSS/mgCOD

θ_b = temperature sensitivity coefficient for endogenous respiration = 1.029

3.286 = ISS/P ratio of polyphosphate

% = Percentage of influent readily biodegradable COD taken up by PAOs

Introduction

Reliable predictive models for the organic (volatile) suspended solids (VSS) concentration in activated sludge (AS) system reactors have been developed over the past two decades, e.g. the steady state design model (Ekama et al., 1993; WRC, 1984) and the IWA activated sludge simulation model (ASM)1 (Henze et al., 1987) for fully aerobic (FA) and anoxic-aerobic nitrification-denitrification (ND) systems, and the equivalent steady state design model (Wentzel et al., 1990) and IWA ASM2 (Henze et al., 1995) and 2d (Henze et al., 1999) for anaerobic-anoxic-aerobic ND biological excess phosphorus removal (BEPR) systems. The steady state models are largely stoichiometric materials mass balance based models, that serve as aids for the selection of optimum design parameters for activated sludge systems with measured (or assumed) influent wastewater flows and material concentrations as inputs. Additionally, the simulation models are based on biological transformation kinetic processes and also require, as input, the system design parameters (reactor volumes, recycle flows etc.). In contrast to the organic models above, predictive models for the reactor inorganic suspended solids (ISS), and hence the total suspended solids (TSS = VSS + ISS) concentrations have not received the same attention or general acceptance. Reasonably accurate estimates of the TSS concentration are important for the design and operation of the down-stream unit operations such as secondary settling tanks and sludge treatment systems.

In this paper, predictive models for the ISS concentration in the activated sludge reactor are reviewed and a new model is presented. This model is based on the ISS concentration measured in the influent wastewater and uptake of inorganic dissolved solids (IDS) by the biomass in the reactor. This model is evaluated against experimental data collected from 48 FA, ND and NDBEPR systems operated in the UCT Water Research Laboratory in 21 experimental investigations over 15 years.

Existing ISS and TSS models

Fully aerobic and anoxic aerobic systems

In the steady state design models and the original ASM1 for FA and ND systems, a fundamentally based predictive model for the accumulation of the inorganic suspended solids (ISS) in the reactor is not included. The total suspended solids (TSS), which is the sum of the VSS and ISS concentrations, is therefore calculated empirically from an assumed VSS/TSS ratio (f_i). This ratio is estimated from historical experience of its value for the particular kind of wastewater and activated sludge system under consideration, and can vary from 0.70 to 0.90. Once selected it has generally been assumed to remain constant with sludge age (WRC, 1984).

When coding ASM1 into ASIM (Version 2.2), Gujer (1993) included TSS as a non-conservative compound (Gujer and Lawson, 1995), calculated from stoichiometric TSS/COD ratios for the individual mixed liquor organic components; for active biomass $i_{TSSXBM} = 0.9$ mgTSS/mgCOD, for unbiodegradable (inert) organic mass, either from the influent or generated through death-regeneration (endogenous residue), $i_{TSSXI} = 0.75$ mgTSS/mgCOD and for

TABLE 1
Activated sludge system design and operating parameters in the 21 investigations

No	Reference Date	Systems	Wastewater feed source, type and conc.	R_c (d) R_{th} (h)	VSS, TSS (mg/l) and VSS/TSS ratio	Objectives	Duration, No of SBs, SSPs and data
I1	Wentzel et al. (1989) 15/3/84-15/7/86	4 NDBEPR, 1xUCT and 3x 3 stage Bardenpho	Artificial, 100% acetate 450-550 mgCOD/l	7.5 - 20d 15.6 - 23.2h	VSS: 1036 - 2998 TSS: 2283 - 6181 f_i : 0.45 - 0.48	4 Enhanced PAO cultures, >90% aerobic P uptake, high PAO P content.	540 days, 4 systems 270 days each system Ave over last 6 R_c
I2	Clayton et al. (1989) 10/2/87-7/9/88	1x MUCT, An 0.16, 1Ax 0.13, 2Ax 0.22, Aer 0.49	MP Real Raw ~1000 mgCOD/l	18.5d 48h	VSS: 2370 TSS: 3000 f_i : 0.776	Plugflow 1st Anoxic, >90% aerobic P uptake, high PAO P content.	570 days, 1 system 38 SBs, 330 data
I3	Warburton et al. (1991) 11/2/88-11/12/89	2xSingle reactor LAND at 7 sludge ages	MP Real Raw ~500 mgCOD/l	5 - 20d 18 - 19h	VSS: 900 - 2980 TSS: 1020 - 3610 f_i : 0.826-0.882	Varied sludge age and aerobic mass fraction.	668 days 52 SBs, 1558 data. 7 ND systems
I4	Power et al. (1992) 24/1/89-30/1/89	2xMLE 70% anoxic	MP Real Raw ~500 mgCOD/l	20d 24h	VSS: 1830 TSS: 2120 f_i : 0.859	Effect of waste alum sludge addition on P removal. Used only Control system	311 days, 1 ND system 25 SBs, 15 SSPs, 228 data
I5	Ketley et al. (1991) 10/5/89-2/12/90	FA, IAND & MLE 0% & 100% Anoxic	Art and MP Real Raw 500-550 mgCOD/l	15d 18h	Art: 1800, 2000, 0.895 Real: 2270, 2500, 0.869	Effect of 100% Ax and Aer conditions and frequency of alternation between Ax and Aer	Art: 9 SSPs 183 data Real: 20 SSPs, 355 data; both on 2 systems
I6	Hulsman et al. (1992) 15/2/90-31/8/91	MLE & Wuhmann 50-70% Anoxic	Art & MP Real Raw 500-600 mgCOD/l	15d 15.6h	Art: 1910, 2140, 0.895 Real: 2000, 2450, 0.850	Effect of size, position and mixed liquor recycle on bulking	Art: 7 SSPs 185 data Real: 17 SSPs, 372 data on 2 systems
I7	De Villiers et al. (1994) 13/11/90-28/2/92	MLE & IAND 70% Anoxic	MP Real Raw ~500 mgCOD/l	15d 24h	VSS: 1350 TSS: 1580 f_i : 0.851	Difference between intermittent aeration in single reactor and separated Ax and Aer reactors	473 days, 34 SBs, 10 SSPs, 438 data, 2 systems
I8	Kaschula et al. (1993) 27/6/91-10/4/92	1x MUCT, An 0.15, 1Ax 0.20, 2Ax 0.32, Aer 0.33	MP Real Raw ~1000 mgCOD/l	20d 48h	VSS: 2720 TSS: 3250 f_i : 0.837	Effect of alternative detergent builders on BNR system. Used only Control system	21 SBs, 9 SSPs, 282 data 289 days
I9	Musvoto et al. (1992) 10/8/91-14/7/92	2x MUCT, An 0.15, 1Ax 0.20, 2Ax 0.45, Aer 0.20	MP Real Raw ~1000 mgCOD/l	20d 48h	VSS: 2940 TSS: 3600 f_i : 0.816-0.835	Effect of NO _x at anoxic-aerobic transition on bulking.	24 SBs, 13 SSPs, 366 data on 2 systems 340 days
I10	Pilson et al. (1995) 22/6/93-28/8/94	2x MUCT, An 0.15, 1Ax 0.20, 2Ax 0.32, Aer 0.33	MP Real Raw ~1000 mgCOD/l	20d, 12d 48h	Exp: 3690, 4340, 0.853. Cntl: 3390, 4050, 0.840	Effect of low temperature (12degC) on BNR	31 SBs, 21 SSPs, ~7 data per SB on 4 systems, 433 days
I11	Jadav (1994) 21/9/94-2/11/94	2x Single reactor Fully Aerobic	MP Real Raw ~1000 mgCOD/l	10d 24h	FA1: 2760, 3190, 0.866. FA2: 2850, 3310, 0.860	Accumulation of ISS in reactor. Measurement of influent ISS.	3 SBs, 42 days 38 data on FA1 15 data on FA2

I12	Ubisi et al. (1997) 30/3/95-26/6/96	2xMLE 25% anoxic	MP Real Raw ~500 mgCOD/l	12d & 20d 16h	Rs20: 2880, 3410, 0.844, Rs12: 2020, 2340, 0.863	Compared theoretical and measured active OHO concs and accumulation of ISS in reactor	28 SBs, 455 days Rs12 248 data Rs20 78 data
I13	Mellin et al. (1998) 1/5/95-2/12/96	MLE 50% Anoxic UCT An 0.15, Ax 0.35, Aer 0.50	MP Real Raw ~750 mgCOD/l	10d 24h	MLE: 1800, 2070, 0.871. UCT: 1880, 2290, 0.825	Effect of high temperature (30degC) on BNR	41 SBs, 582 days MLE 491 data UCT 496 data
I14	Sneyders et al. (1998) 18/3/96-25/7/97	2x UCT systems An 0.15, Ax 0.35, Aer 0.50	MP Real Raw ~750 mgCOD/l	10d 24h	Exp: 2000, 2650, 0.753, Cntl: 1700, 2140, 0.797	Effect of unstabilized landfill leachate dosing on BNR	31 SBs, 495 days 242 data on each system
I15	Tsai et al. (2002) 19/2/99-19/1/02	3x Single reactor LAND systems	MP Real Raw ~750 mgCOD/l	15d 24h	VSS: 1880-2010 TSS: 2200-2330 f _i : 0.855-0.865	Effect of NOx control with redox at anoxic-aerobic transition on bulking	69 SBs, 1066 days Exp 503, Cntl 240, War 152 data
I16	Cronje et al. (2000) 1/6/99-17/4/00	2xMLE systems 25% Anoxic	MP Real Raw ~500 & 1000 mgCOD/l	10d 12h & 24h	500: 2300, 26340, 0.875, 1000: 2720, 3120, 0.871	Compared theoretical and measured active OHO concs	500: 23 SBs, 162 data 1000: 5 SBs, 41 data
I17	Vermande et al. (2000) 6/7/99-18/6/00	UCT system An 0.15, Ax 0.35, Aer 0.50	MP Real Raw ~750 mgCOD/l	10d 24h	VSS: 1840 TSS: 2300 f _i : 0.847	Compared anoxic and aerobic P uptake BEPR and factors triggering these.	349 days 24 SBs, 177 data.
I18	Hercules et al. (2002) 1/1/99-1/6/01	2x ~2 Ml/d UCTs An 0.15, Ax 0.35, Aer 0.56.	Real MP well Settled 610 mgCOD/l. ModA 1.6Ml/d; ModB 2.2Ml/d	R _s (d), R _{an} (h) A:13.5, 21.5 B:15.0, 23.1	A: 2710, 3620, 0.750 B: 2790, 3660, 0.761	Loss of COD in anaerobic and effect of NOx at anoxic-aerobic transition on bulking.	7 SSPs, 589 days 156 data on each A&B
I19	Beecherry et al. (2001) 28/4/00-18/8/01	2xMLE 25% Anoxic	MP Real Raw Exp: 520 & 950mg/l Cntl: 500 & 750 mg/l	10d 12h, 18h, 14.4h	Exp: 2750, 3190, 0.862. Cntl: ~3200, 3640, 0.886.	Compared theoretical and measured active OHO concs and biodegradability of toilet paper	417 days. Exp: 26 SBs, 219data. Cntl: 18 SBs, 159 data.
I20	Lee et al. (2003) 7/7/01-28/4/02	2xMLE 33% Anoxic	MP Real Raw 10d: 750 mgCOD/l 20d: 750 mgCOD/l	10 & 20d 10:14-18.7h 20:14-31.7h	10: 3010, 3620, 0.834 20: 3390, 4200, 0.810	Compared theoretical and measured active OHO concs with microbiological parameters	17 SBs, 296 days 119 data on each.
I21	Muller et al. (2003) 16/8/02-18/12/02	1 FA, 1 MLE 0% and 25% anoxic	MP Real Raw FA: 500 mgCOD/l MLE: 500 mgCOD/l	3 (FA), 10d 8.9 & 12.5h	3d: 1081, 1260, 0.858 10d: 1854, 2175, 0.853	Measure aerobic and anoxic OHO yield.	125 days, 8 SBs 98data on each system
I22	This investigation		Measured every 2 hours flow and unfiltered and filtered (0.45µ) samples.		Measurement COD, TKN, TP, TSS, VSS and ISS.	Measurement of influent ISS/COD ratio for raw and settled WW at Mitchells Plain WWTP.	Did 24 hour tests twice 18/2/03 & 3/4/03

Notes: Total number of systems = 48. MP=Mitchells Plain WWTP. WW = Wastewater. MLE = Modified Ludzack-Ettinger. An=Anaerobic. Ax = Anoxic. Aer= Aerobic. LAND= intermittently aerated nitrification denitrification. FA = fully aerobic. Ml= Megalitres. Exp= Experimental. Cntl= Control. War=LAND system. Art=Artificial. SSPs = steady state periods. SB =Sewage batch. R_s=sludge age. R_{an} = nominal hydraulic retention time. PAO = Phosphate accumulating organisms. OHO=ordinary heterotrophic organisms. d=day. h=hour. f_i = VSS/TSS ratio. NDBEPR=nitrification denitrification biological nutrient removal. M/UCT=Modified/University of Cape Town system.

slowly biodegradable particulate substrate, $i_{TSSXS} = 0.75 \text{ mgTSS/mgCOD}$. These ratios are equivalent to 0.332 and 0.11 mgISS/mgVSS respectively for a COD/VSS ratio of 1.48 mgCOD/mgVSS. Additionally in the coded model, inorganics (ISS) present in the influent add directly to the reactor TSS. With the ASIM default inorganics present in the influent (0.117 mgISS/mgCOD, Gujer, 1993), the predicted VSS/TSS ratios of the mixed liquor are around 0.60 and 0.55 mgVSS/mgTSS for sludge ages of 4 and 30 d respectively; with zero influent inorganics, the VSS/TSS ratios are 0.80 and 0.85 respectively. Clearly in this model, the predicted mixed liquor inorganics (ISS) concentration is very sensitive to the influent inorganics concentration, but this sensitivity may be artificial because the influent ISS/COD ratio (X_{ioi}/S_{ii}) of 0.117 is very high compared with the raw wastewater values measured on the source wastewater (Mitchells Plain wastewater treatment plant (WWTP) for the 48 experimental systems discussed in this paper, i.e. 0.041-0.050 mgISS/mgCOD).

In modelling experimentally determined ISS concentrations in activated sludge mixed liquor (Investigation I12 - see Table 1), Wentzel et al. (2002) evaluated a number of approaches based on either direct incorporation of influent inorganics (particulate only or total including dissolved solids) or stoichiometric incorporation of inorganics into the organic mixed liquor fractions in addition to direct incorporation of influent inorganics (particulate only or total including dissolved solids). They concluded that the latter approach, which is similar to that of Gujer (1993), provided predictions that best correlated with the experimental observations. With this approach, active biomass and endogenous residue were estimated to contain (f_b) 0.17 mgISS/mgVSS, while the influent unbiodegradable organics were estimated to contain no inorganics (in contrast to Gujer, 1993); additionally, either 20% of the influent inorganic particulate (IPS = ISS) or 1.7% of the total inorganic solids (TIS = ISS + TDS) respectively were entrapped in the mixed liquor. A reasonably close correlation between predicted and measured reactor ISS concentrations was obtained for the ND systems at 12 and 20 ds sludge age. The influent ISS/COD ratio measured by Ubisi et al. (1997) (I12) was 0.093 mgISS/mgCOD, more than twice the ratio measured on the source wastewater at the WWTP by a different method (see below).

Nitrification denitrification biological excess P removal (NDBEPR) systems

When modelling ISS and TSS concentrations in NDBEPR systems, due cognizance must be given to the increased intracellular accumulation of inorganic dissolved solids into the phosphate accumulating organisms (PAOs) as polyphosphate and associated counter ions. In the steady state design model for NDBEPR (Wentzel et al., 1990), this increased ISS accumulation is recognised; the reactor TSS concentration is calculated from a constant VSS/TSS ratio of 0.46 mgVSS/mgTSS for active PAOs and their associated endogenous residue, whereas the rest of the sludge is based on the empirical ratio between 0.75-0.85 mgVSS/mgTSS derived for ND activated sludge, which includes accumulated influent ISS and remains constant with sludge age. Again, the 0.46 ratio for the PAOs and the selected ratio for the rest of the sludge are assumed to remain constant with sludge age (Wentzel et al. 1990).

In ASM2 and 2d, the principles developed by Gujer above are applied, but additionally the accumulation of inorganics due to polyphosphate and counter ion accumulation in PAOs is included at 3.23 mgISS/mgP.

Model development

The concept of mixed liquor organic material (VSS) containing inorganic suspended solids (ISS) as implied above by the mgTSS/mgCOD ratios, may be difficult to grasp. It's not clear how Gujer (1993) visualised this, but in this paper the ISS content of the organics is not visualised as actual inorganics in the VSS itself as it exists in the reactor, but rather as inorganics that are formed in the test procedure. When the mixed liquor organics are in the activated sludge reactor, in particular the active biomass, they include intracellular and/or bound water, which contains dissolved solids. When the organics are dried in the TSS test procedure, these dissolved solids precipitate to form ISS. It is mainly for this conceptual reason that in this paper, only active biomass is accepted to have an ISS/VSS ratio; the unbiodegradable organic components of the mixed liquor clearly cannot contain intracellular water and the bound water is accepted to be negligible.

Experimental data measured in the Water Research Laboratory at the University of Cape Town (UCT) over the past 15 years form the basis for the model development. Altogether 21 investigations were considered, some of which ran concurrently (Table 1). In these investigations, artificial or real wastewater was fed to 30 FA or ND and 18 NDBEPR systems operated over a range of sludge ages (3 to 20d) and nominal hydraulic retention times 8.9 to 48 h (Table 1).

Conceptual model

Conceptually the reactor ISS concentration predictive model is based on the following principles:

- ISS in the influent (X_{ioi} , mgISS/l) accumulates in the reactor (X_{io}). From a mass balance, this accumulation is proportional to the sludge age (R_s) and inversely proportional to the nominal hydraulic retention time (R_{in}), i.e.

$$X_{io} = X_{ioi} R_s / R_{in} \text{ mgISS/l} \quad (1)$$

This is in agreement with proposals of Gujer (1993) reviewed above.

- Precipitation of minerals in the biological reactor, unless stimulated by chemical dosing, and dissolution of influent ISS, are considered negligible.
- In contrast to the inorganic models of ASM2, 2d and Gujer (1993), but in agreement with Wentzel et al. (2002), slowly biodegradable particulate substrate does not contain an inorganic component.
- The ordinary heterotrophic organisms (HOs) and the phosphate accumulating organisms (PAOs) take up intra-cellular inorganic dissolved solids (IDS) as part of the biomass which, when sludge samples are dried and incinerated in the TSS-VSS test procedure, precipitate as inorganic solids. In so far as solids (organic and inorganic) accumulation in the reactor is concerned, the autotrophic nitrifying organisms (ANOs) are ignored because their relative contribution is very small (<2%).
- Additionally, the PAOs take up inorganic dissolved solids (IDS) and store it as polyphosphate with associated counter ions, in conformity with ASM2 and 2d.
- Although in ASM2, 2d, Gujer (1993) and Wentzel et al. (2002), inorganics are included in the endogenous residue fraction, Wentzel et al. (2002) noted that there is no information in the literature on the validity of this assumption. In the model developed here, it is assumed that there are no inorganics

associated with unbiodegradable particulate organics, which includes endogenous residue. This assumption will be evaluated in the model application.

Following the above, the combined measured ISS in the reactor is given by:

$$X_{Io} = X_{Ioi} R_s R_{hn} + X_v (f_{iOHO} f_{avOHO} + f_{iPAO} f_{avPAO}) \text{ mgISS}/\ell \quad (2)$$

where:

X_v = measured or calculated VSS concentration in the reactor (mgVSS/ ℓ)

f_{iOHO}, f_{iPAO} = inorganic material content of the OHOs and PAOs respectively (mgISS/mgVSS)

f_{avOHO}, f_{avPAO} = fraction of the VSS concentration which is OHOs and PAOs respectively, and

$f_{iPAO} = f_{iPAOBM} + f_{iPAOPP}$

where:

f_{iPAOBM} = inorganic material content of the PAO active biomass (mgISS/mgVSS)

f_{iPAOPP} = inorganic material content of the PAO polyphosphate (mgISS/mgVSS)

The OHO and PAO fractions of the VSS (f_{avOHO}, f_{avPAO}) are defined by, and can be calculated with the existing AS models. The one used in this ISS model development is the steady state BEPR model of Wentzel et al. (1990), which for zero anaerobic mass fraction and influent SCFA COD (i.e. no BEPR) is identical to the steady state ND AS model of Ekama et al. (1983) and WRC (1984). Although developed earlier, these steady state models are essentially a subset of the dynamic simulation models which can be calibrated to give similar results for the same input conditions. The ISS model developed here therefore can be included relatively simply in these dynamic simulation models and the numerical values determined for f_{iOHO} and f_{iPAO} are consistent for these models.

In the ISS model developed here (Eq 2), there are three unknown parameters which need to be determined, i.e. the influent ISS concentration (X_{Ioi}), which may be directly measured, and the inorganic contents of the OHOs and PAOs (f_{iOHO} and f_{iPAO}), which cannot be measured directly, only calculated indirectly by matching measured and model predicted reactor ISS and VSS concentrations. Because in the 21 investigations (I1 to I21), the influent ISS concentration generally was not measured, except in I11, I12, I18 and in two 24 h tests at the WWTP (I22, see Table 1), the values of all three parameters were determined from the results of the 48 experimental systems.

Experimental investigation

Details of the 21 experimental investigations are listed in Table 1. For the 42 systems fed real wastewater, Mitchells Plain unsettled (raw) wastewater was collected at the treatment plant in 2 m³ batches, trucked to the laboratory, macerated and stored in 400 ℓ stainless steel tanks in a 4°C cold room. Daily, the wastewater volume required for the activated sludge systems was, after thorough mixing, drawn from the 400 ℓ tanks, strained through 1mm mesh to avoid pipe blockages, diluted with tap water to the target influent COD concentration for the AS system, and poured into the system's feed drum. The collected sewage batches were used over a period of 2 to 3 weeks. During this time, the systems were tested at least every second day, but usually more frequently, for influent, reactor(s) and effluent unfiltered and filtered chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), free and saline

ammonia (FSA), nitrate, nitrite, total phosphorus (TP), orthophosphate (OP), VSS and TSS concentrations, and oxygen utilisation rate (OUR) and diluted sludge volume index (DSVI) in the aerobic reactor. These measurements, which are listed in the reports of the investigations (Table 1), were averaged over the sewage batches (SB) or longer steady state periods (SSPs) when the influent concentrations over several consecutive sewage batches did not change significantly and system operating conditions were not changed.

Model application

In application of the model (Eq. 2) to the various systems, the following were accepted:

- Systems fed artificial wastewater received zero or very low influent ISS ($X_{Ioi} = 0$). The ISS measured in the reactor is therefore predominantly the ISS content of the OHOs and/or PAOs. The 6 systems (2 ND and 4 NDBEPR) fed artificial wastewater formed the starting point for determining the initial estimates for the OHO and PAO ISS contents (f_{iOHO} and f_{iPAO}).
- Because the influent ISS concentrations (X_{Ioi}) were not measured, except in I11, I12 and I18, this concentration was calculated with Eq. (2) from the measured reactor ISS concentration (X_{Io}) and the initial estimates of f_{iOHO} and f_{iPAO} for each SB or SSP and each system in each investigation. Because different influent COD concentrations were fed to the different systems by diluting the collected wastewater with tap water to a target feed COD concentration, this calculated influent ISS concentration was expressed as a ratio of the feed COD concentration (S_i) i.e. X_{Ioi}/S_i mgISS/mgCOD, to make the influent ISS comparable between systems and investigations. Consistency of the influent X_{Ioi}/S_i ratio over a range of sludge ages and retention times in the same investigation and between investigations allowed refinement of the initial f_{iOHO} estimate from the artificial wastewater systems.

Calculation method

In more detail, for each SB or SSP of a system in an investigation, the OHO and/or PAO active fractions (f_{avOHO}, f_{avPAO}) for FA, ND or NDBEPR systems were calculated iteratively with the aid of the steady state BEPR model of Wentzel et al. (1990). The measured values for the influent COD, RBCOD fraction and unbiodegradable soluble COD fraction ($f_{S_{us}} = \text{filtered effluent COD}/S_i$) were input to the model together with the system constraints, and the particulate unbiodegradable COD fraction ($f_{S_{up}}$) was varied until the calculated system VSS mass, comprising active and endogenous PAO and OHO components and unbiodegradable particulate VSS from the influent, matched the measured values. For the NDBEPR systems, when the correct $f_{S_{up}}$ had been found, the calculated P removal was matched to that measured by decreasing the PAO P content (f_{xBGP}) from the standard value of 0.38 mgP/mgPAOVSS to a lower value (Ekama and Wentzel, 1999). Generally, when the P uptake was predominantly aerobic (>90% of total P uptake), the calculated f_{xBGP} was close to the 0.38 mgP/mgPAOVSS value for the enhanced PAO cultures of Wentzel et al. (1989a) (e.g. I1, I2 and I14). However, when significant anoxic P uptake took place (>20%), the calculated f_{xBGP} was lower than 0.38 mgP/mgPAOVSS (i.e. I8, I9, I10, I13, I17 and I18). For the FA and ND systems, the anaerobic mass fraction (f_{xa}) and influent RBCOD fraction ($f_{Sb's}$) were set to zero, which in the model stops PAOs, and their associated endogenous VSS from forming in the system, with the

result that $f_{avPAO} = 0$. For the enhanced PAO cultures of Wentzel et al. (1989a) (I1), $f_{sb's}$ was set to 1.0 because all the influent COD was in SCFA form, which in the model, stops OHOs and their associated endogenous VSS, from forming in the system, with the result that $f_{avOHO} = 0$.

With the f_{avOHO} and f_{avPAO} known for each SB or SSP of a system in an investigation, Eq. (2) was used with the measured reactor ISS concentration (X_{loi}) and initial estimates for the ISS contents of the OHOs and PAOs (f_{iOHO} and f_{iPAO}) to calculate the influent ISS concentration (X_{loi}) for each SB or SSP of a system in an investigation. For each system in an investigation, the weighted mean X_{loi} values were determined by multiplying the SB or SSP average X_{loi} values by the number of tests in the SB or SSP, adding these over the whole investigation and dividing by the total number of tests on the system in the investigation. For investigations with more than one system, a weighted investigation mean X_{loi} mean was calculated from the weighted system X_{loi} means. The investigation weighted mean X_{loi} and selected f_{iOHO} and f_{iPAO} were then applied in Eq. 2 to the SB or SSP average data to determine the calculated reactor ISS concentrations (X_{loi}) for each SB or SSP, which were then compared with measured SB or SSP ISS concentrations on each system. For those investigations where the influent ISS was not measured, the final f_{iOHO} and f_{iPAO} values accepted were those that gave the most consistent comparison between calculated and measured reactor ISS concentrations over all the SBs or SSPs of the different systems of an investigation and between investigations. For those investigations where the influent ISS (X_{loi}) was measured (i.e. I11, I12 and I18), the f_{iOHO} and f_{iPAO} values were varied until the calculated weighted mean influent ISS matched that measured for the investigation.

Determination of the ISS content of PAOs - f_{iPAO}

The four 100% acetate feed enhanced PAO culture systems of Wentzel et al. (1989a) at 7.5, 10, 10 and 20 d sludge age, yielded VSS/TSS ratios of 0.45, 0.46, 0.46 and 0.48 mgVSS/TSS respectively. The values seem extra-ordinarily low and indicate very high ISS concentrations in the systems, higher than the VSS concentrations. Wentzel et al. (1989b) state that the reason for these high ISS concentrations is the very high phosphate content of the PAOs ($f_{XBGP} = 0.38$ mgP/mgPAOVSS). Accepting a biomass structural P content (f_{XBGPBM}) of 0.03 mgP/mgVSS gives an intracellular polyphosphate content (f_{XBGPP}) of 0.35 mgP/mgPAOVSS (i.e. $f_{XBGPP} = f_{XBGP} - f_{XBGPBM}$). This polyphosphate is charge balanced by cations Mg, Ca and K but mainly Mg, all of which were measured as ISS in the test procedure.

Applying Eq. (2) with both X_{loi} and $f_{avOHO} = 0$ to the enhanced PAO cultures yields a total ISS content of PAOs (f_{iPAO}) of 1.30 mgISS/mgPAOVSS. This constant f_{iPAO} value in the PAO steady-state BEPR model of Wentzel et al. (1990) predicted the observed increasing VSS/TSS ratio with sludge age very accurately (Fig. 1). The predicted and measured reactor ISS and VSS concentrations and masses are compared in Figs. 1 and 2 respectively. These correlations also are very good. The consistency with which a constant f_{iPAO} predicts the observed changes in VSS/TSS ratio with sludge age gives credibility to the approach of Eq. (2) (with both f_{iOHO} and $X_{loi} = 0$). This $f_{iPAO} = 1.30$ did not require to be revised in the subsequent ISS model development for real wastewater, but did require modification to take into account reduced polyphosphate storage with anoxic P uptake BEPR (see below).

The P uptake in the enhanced PAO cultures was predominantly aerobic (>90%) and the P content of the PAOs (f_{XBGP}) was 0.38 mgP/mgPAOVSS. Accepting a PAO cell structural P content

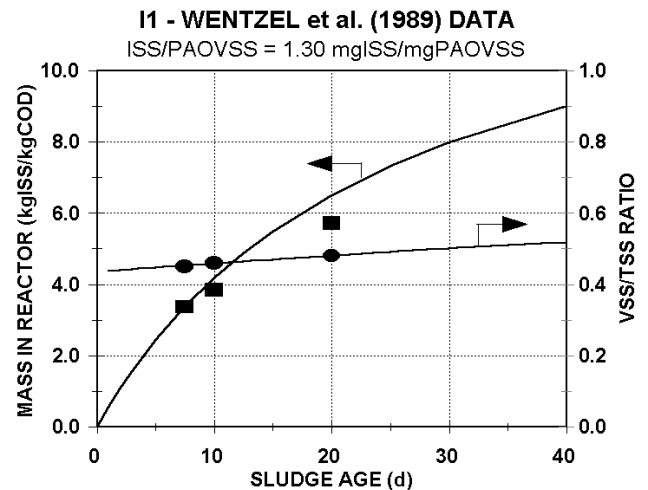


Figure 1
Measured reactor ISS mass in kgISS/kgCOD load (■) and VSS/TSS ratio (●) and predicted (lines) vs. sludge age for the four acetate fed enhanced PAO culture systems of Wentzel et al. (1989) (I1) accepting PAO ISS content $f_{iPAO} = 1.30$ mgISS/mgVSS (>90% aerobic P uptake BEPR)

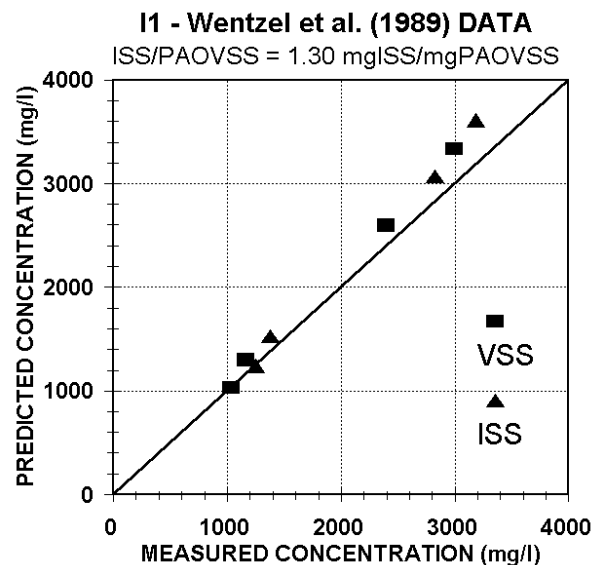


Figure 2
Predicted vs. measured VSS (■) and ISS (▲) concentrations for the four enhanced PAO culture systems of Wentzel et al. (1989) (I1) at sludge ages 7.5, 10, 10 and 20 d for ISS content of PAOs ($f_{iPAO} = 1.3$ mgISS/mgPAOVSS)

(f_{XBGPBM}) of 0.03 mgP/mgVSS and a polyphosphate content (f_{XBGPP}) of 0.35 mgP/mgVSS, theoretical ISS values for the polyphosphate (f_{iPAOPP}) and PAO active biomass (f_{iPAOBM}) can be calculated. With the average molar ratio of polyphosphate cations from Fukase et al. (1982), Arvin and Kristensen (1985), Comeau et al. (1985) and Wentzel et al. (1989b) of Mg:K:Ca:P = 0.275:0.295:0.05:1, and recognising that P in polyphosphate exists as PO_3 , then the molecular mass of polyphosphate is 98.8 mg/mmol. With polyphosphate entirely inorganic, the theoretical ISS/P ratio for polyphosphate is 3.19 mgISS/mgP, closely equal to the value of 3.23 mgISS/mgP adopted in ASM2 and 2d. A $f_{XBGPP} = 0.35$ mgpolyP/mgPAOVSS gives $f_{iPAOPP} = 1.12$ mgISS/mgPAOVSS for the polyphosphate.

Accepting that the PAO cell non-polyphosphate inorganic content f_{iPAOBM} is equal to the OHO inorganic content (f_{iOHO}) of 0.15 mgISS/mgVSS (see later), then the total PAO inorganic content (f_{iPAO}) = $1.12 + 0.15 = 1.27$ mgISS/mgPAOVSS. This very closely matches the value of 1.30 determined above in application of the model to the enhanced PAO culture data, and lends further support to this value.

Determination of the ISS content of OHOs - f_{iOHO}

The OHO active biomass in AS systems contains ISS as indicated by work on pure OHO cultures (e.g. Gaudy and Gaudy, 1980). A range of OHO ISS content (f_{iOHO}) values are reported in the literature, from 0.05 to 0.25 mgISS/mgOHOVSS. Five investigations with 15 fully aerobic (FA) and nitrification-denitrification (ND) systems (i.e. no PAOs) listed in Table 1 were selected as the basis for determining the f_{iOHO} , viz. I3, I5, I6, I11 and I12. These systems were selected because they were operated over a range of sludge ages (I3; 5 to 20d); were fed artificial wastewater, i.e. zero or low X_{iOI} ; or included measurement of influent total dissolved (TDS) and suspended (TSS) solids, each separated into organics (VDS, VSS) and inorganics (IDS, ISS), i.e. I11 and I12.

For the 2 artificial wastewater fed ND systems of I5 and I6, it was expected that the influent ISS would be zero or at least very low. With $X_{iOI} = 0$, f_{iOHO} needed to be 0.276 and 0.265 mgISS/mgOHOVSS respectively to account for the measured ISS in the reactor. This was outside the literature range and considered too high, which was confirmed with the data from the real wastewater investigations I3, I5, I6 and I11, where such high f_{iOHO} values led to negative influent ISS concentrations, especially for the I3 short sludge age systems.

The SB or SSP calculated vs. measured reactor ISS concentrations (X_{iOI}) and VSS/TSS ratios for the 7 real wastewater systems of I3 for $f_{iOHO} = 0.276$ and the corresponding investigation weighted mean influent ISS/COD ratio = 0.0170 are shown in Figs. 3 and 4 respectively. The reactor ISS (Fig. 3) data correlate poorly and the system mean reactor ISS concentrations at the different sludge ages lie at a much flatter slope than the 1:1 correlation line. The VSS/TSS ratio data (Fig. 4) also correlate poorly and the system mean ratios at the different sludge ages lie almost perpendicular to the 1:1 correlation line. The calculated system mean influent ISS (X_{iOI}) for $f_{iOHO} = 0.276$ to account for the measured reactor TSS (X_{iOI}) is plotted vs. sludge age in Fig 5. Not only does the calculated X_{iOI} decrease with sludge age, but also -ve values are obtained at the low sludge ages of 5 and 6 d. Moreover, the estimated influent ISS/COD ratio is too low (0.017 mgISS/mgCOD) compared with that measured on the wastewater in the laboratory (i.e. 0.031 in I11) and at the treatment plant (0.041-0.050 in I22, see Table 2). This means that $f_{iOHO} = 0.276$ is too high and does not correctly account for the changes in measured reactor ISS with sludge age. Curiously, the best correlation between calculated and measured reactor ISS for the 7 systems of I3 is obtained when $f_{iOHO} = 0.0$ (Figs. 6 to 8), which gives the least variation in influent ISS concentration (X_{iOI}) with sludge age (Fig. 8); and an investigation weighted mean influent ISS/COD ratio of 0.045, which is midway between the ratios measured in the two 24 h tests at the source WWTP (0.04 to 0.05, Table 2).

In the I11 and I12 investigations with FA and ND systems, influent and effluent TDS and IDS, and TSS and ISS were measured. In I11, the average measured influent ISS/COD ratio (X_{iOI}/S_i) was 0.031 mgISS/mgCOD. At this value, for I11 the f_{iOHO} has to be 0.11 mgISS/mgOHOVSS to account for the measured reactor ISS. Interestingly, in this investigation, a 46.1 mg/l decrease in inor-

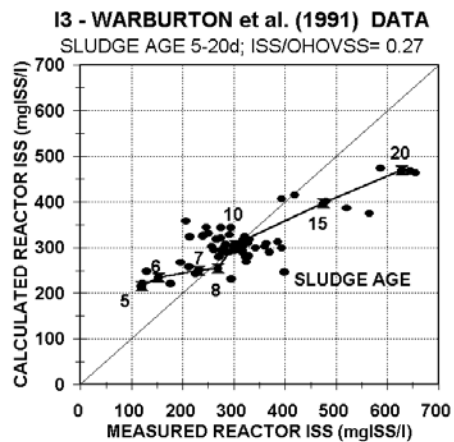


Figure 3

Calculated with OHO ISS content $f_{iOHO} = 0.27$ mgISS/mgOHOVSS vs. measured sewage batch average (●) and system average (●) reactor ISS concentration for the seven real WW ND systems of Warburton et al. (1991) (I3) at sludge ages 5, 6, 7, 8, 10, 15 and 20 d

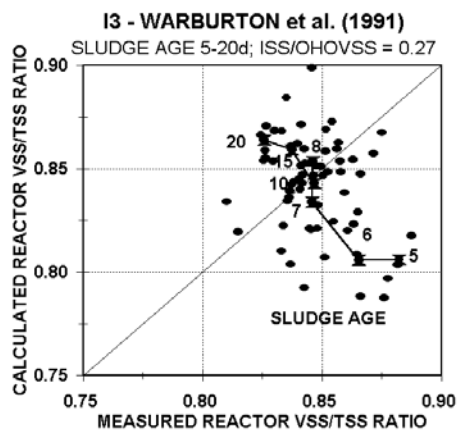


Figure 4

Calculated with OHO ISS content $f_{iOHO} = 0.27$ mgISS/mgOHOVSS vs. measured sewage batch average (●) and system average (●) reactor VSS/TSS ratio for the seven real WW ND systems of Warburton et al. (1991) (I3) at sludge ages 5, 6, 7, 8, 10, 15 and 20 d.

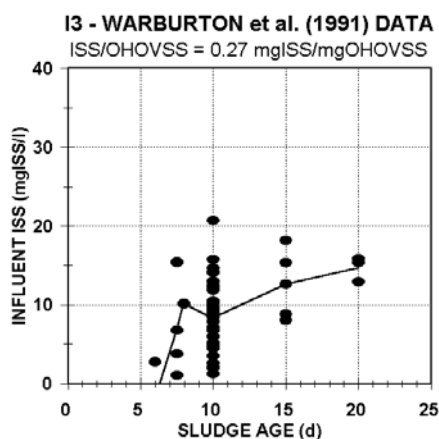


Figure 5

Calculated sewage batch average (●) and system average (●) influent ISS concentration vs. sludge age for the seven real WW ND systems of Warburton et al. (1991) (I3) for OHO ISS content $f_{iOHO} = 0.27$ gISS/mgOHOVSS.

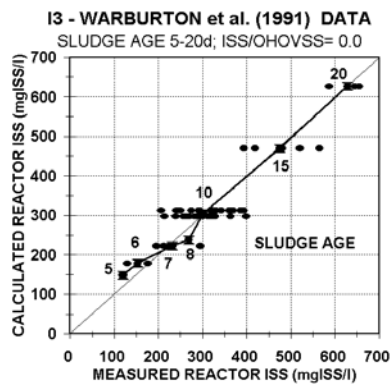


Figure 6

Calculated with OHO ISS content $f_{iOHO} = 0.0$ mgISS/mgOHOVSS vs. measured sewage batch average (●) and system average (●) reactor ISS concentration for the seven real WW ND systems of Warburton et al. (1991) (I3) at sludge ages 5, 6, 7, 8, 10, 15 and 20 d

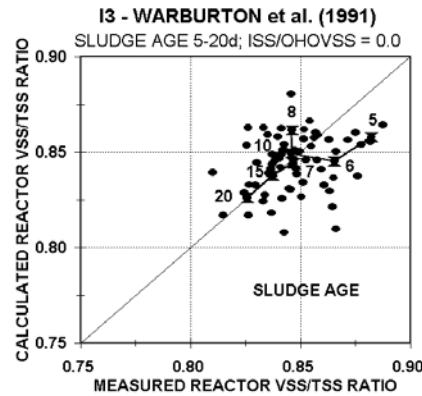


Figure 7

Calculated with OHO ISS content $f_{iOHO} = 0.0$ mgISS/mgOHOVSS vs. measured sewage batch average (●) and system average (●) reactor VSS/TSS ratio for the seven real WW ND systems of Warburton et al. (1991) (I3) at sludge ages 5, 6, 7, 8, 10, 15 and 20 d

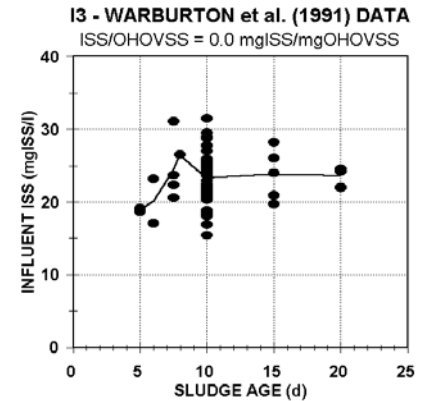


Figure 8

Calculated sewage batch average (●) and system average (●) influent ISS concentration vs. sludge age for the seven real WW ND systems of Warburton et al. (1991) (I3) for OHO ISS content $f_{iOHO} = 0.0$ mgISS/mgOHOVSS

At the Mitchells Plain wastewater treatment plant			In the laboratory	
Investigation	Raw	Settled	Investigation	Raw
I18 ^a	-	0.041	I11 ^a	0.031
I22: Test 1 ^b	0.041	0.039	I12 ^a	0.087-0.096
I22: Test 2 ^b	0.050	0.043		

^a Determined by filtration through Whatman's No 1 ashless filter papers of known dry mass, drying at 105°C for 24 h and incineration in a crucible of known dry mass at 600°C for 20 min

^b Determined by filtration through pretreated glass fibre membranes of known dry mass, drying at 105°C for 24 h and incineration at 600°C for 20 min. Filter pretreatment comprises incineration at 600°C for 6 h to stabilise its mass before subsequent heating.

ganic dissolved solids (IDS) between influent and effluent was measured. If this IDS was all taken up by OHOs (and did not form precipitates in the reactor), then the f_{iOHO} would have to be 0.45, which is much too high. In I12 (see also Wentzel et al., 2002), the measured influent ISS/COD (X_{iOHO}/S_{ii}) ratio was 0.093 mgISS/mgCOD, 3 times higher than the I11 influent ISS/COD ratio. This high influent ISS/COD ratio cannot be accounted for by the measured reactor ISS, even with $f_{iOHO} = 0.0$. The highest value that the influent ISS/COD ratio can take into account for the measured reactor ISS is 0.036 mgISS/mgCOD, which is close to the measured influent ISS/COD ratio for I11. This means that in this investigation either dissolution of influent ISS took place in the reactor or the measured influent ISS was too high. When modelling this data, Wentzel et al. (2002) found that only 20% of the measured influent ISS became enmeshed in the mixed liquor if $f_{iOHO} = 0.17$

mgISS/mgOHOVSS and endogenous residue also included inorganics. Compared with the influent ISS concentration measured by a different method at the source WWTP (I22 - see Table 1), i.e. 0.041 mgISS/mgCOD (Table 2), it does seem that the influent ISS was measured too high in I12. Measurement of influent ISS is discussed further below.

By trial and error comparison of the calculated and measured reactor ISS concentrations within the systems of an investigation and between investigations and taking cognizance of the measured influent ISS/COD ratio at the source WWTP (I22), it was concluded that $f_{iOHO} = 0.15$ mgISS/mgOHOVSS is the best compromise value for the 2 artificial (I5, I6) and 13 real (I3, I5, I6, I11, I12) WW systems of the 5 investigations discussed above. For the 7 systems and 52 SBs of I3, with $f_{iOHO} = 0.15$ the investigation weighted mean influent ISS/COD ratio of all 7 systems is 0.030. With these values, the calculated vs. measured reactor ISS and VSS/TSS ratio are shown in Figs. 9 and 10 respectively, and the influent ISS (X_{iOHO}) and reactor VSS/TSS ratio vs. sludge age in Figs. 11 and 12 respectively. The calculated influent ISS concentration vs. sludge age is reasonably consistent between 16 and 19 mgISS/l ($X_{iOHO}/S_{ii} = 0.030$ to 0.036) except for the 5 and 6 d sludge age, where it is lower. At these short sludge ages, the systems were not

operated for a long time; so relative to the other sludge ages, the data are few and therefore may not be as reliable as for the longer sludge ages (Table 1). For the 3 SBs of I11, in which the influent ISS was measured (investigation weighted average influent ISS/COD ratio = 0.031), the f_{iOHO} is 0.11. This is quite close to the $f_{iOHO} = 0.15$ estimated for I3, I5 and I6. The calculated vs. measured reactor and influent ISS concentrations for I11 with $f_{iOHO} = 0.11$ are shown in Figs. 13 and 14. The correlations are quite good. For I11, the calculated and measured influent and reactor ISS concentrations also correlate reasonably well for $f_{iOHO} = 0.15$ (not shown). For I5 and I6 with $f_{iOHO} = 0.15$, the calculated vs. measured SB average reactor ISS concentrations are shown in Figs. 15 to 18, for which the investigation weighted mean influent ISS/COD ratio = 0.0074 and 0.0077 respectively for artificial wastewater and 0.023 and 0.020 mgISS/mgCOD for real WW. It can be seen that a good

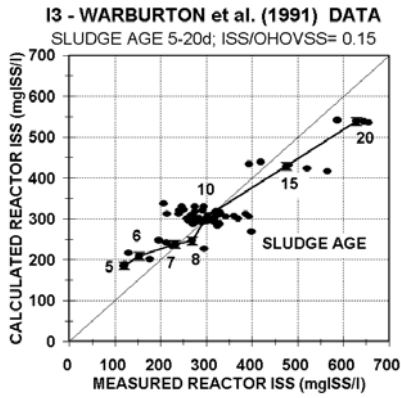


Figure 9

Calculated with OHO ISS content $f_{iOHO} = 0.15 \text{ mgISS/mgOHOVSS}$ vs. measured sewage batch average (●) and system average (♣) reactor ISS concentration for the seven real WW ND systems of Warburton et al. (1991) (I3) at sludge ages 5, 6, 7, 8, 10, 15 and 20 d.

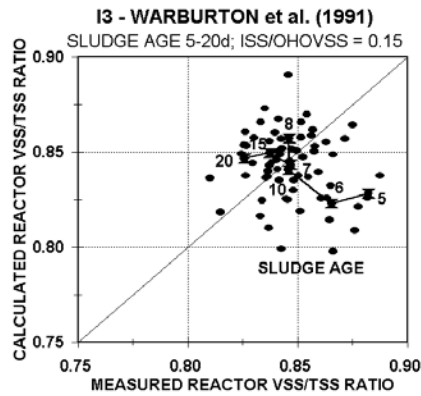


Figure 10

Calculated with OHO ISS content $f_{iOHO} = 0.15 \text{ mgISS/mgOHOVSS}$ vs. measured sewage batch average (●) and system average (♣) reactor ISS concentration for the seven real WW ND systems of Warburton et al. (1991) (I3) at sludge ages 5, 6, 7, 8, 10, 15 and 20 d.

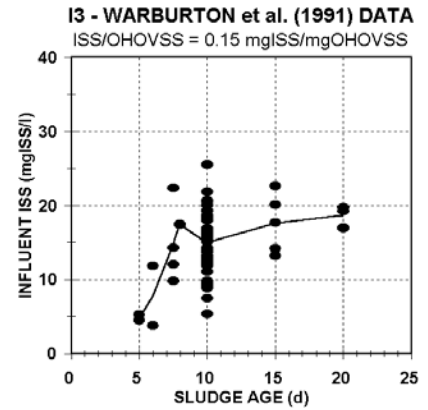


Figure 11

Calculated sewage batch average (●) and system average (♣) influent ISS concentration vs. sludge age for the seven real WW ND systems of Warburton et al. (1991) (I3) for OHO ISS content $f_{iOHO} = 0.15 \text{ mgISS/mgOHOVSS}$

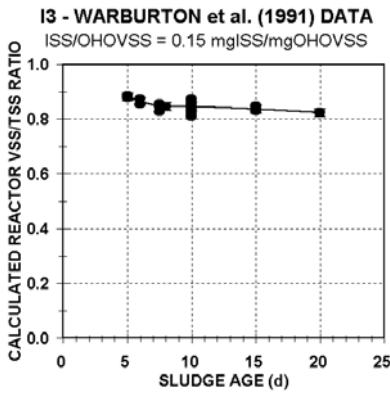


Figure 12

Calculated sewage batch average (●) and system average (♣) reactor VSS/TSS ratio vs. sludge age for the seven real WW ND systems of Warburton et al. (1991) (I3) for OHO ISS content $f_{iOHO} = 0.15 \text{ mgISS/mgOHOVSS}$

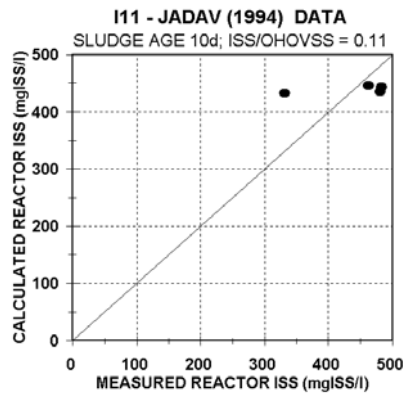


Figure 13

Calculated with OHO ISS content $f_{iOHO} = 0.11 \text{ mgISS/mgOHOVSS}$ vs. measured sewage batch average (●) reactor ISS concentration for the two real WW ND systems of Jadav (1994) (I11) at 10 d sludge age

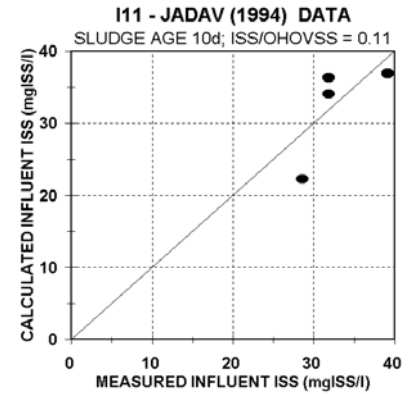


Figure 14

Calculated with OHO ISS content $f_{iOHO} = 0.11 \text{ mgISS/mgOHOVSS}$ vs. measured sewage batch average (●) reactor ISS concentration for the two real WW ND systems of Jadav (1994) (I11) at 10 d sludge age

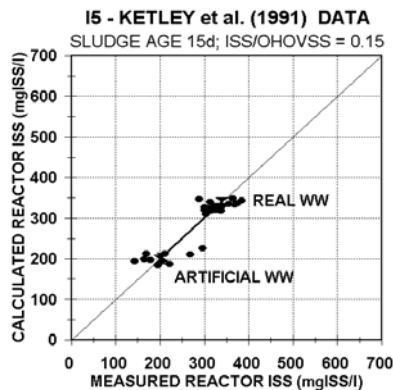


Figure 15

Calculated with OHO ISS content $f_{iOHO} = 0.15 \text{ mgISS/mgOHOVSS}$ vs. measured sewage batch average (●) and system average (♣) reactor ISS concentration for the artificial and real WW ND systems of Ketley et al. (1991) (I5) at 15 d sludge age

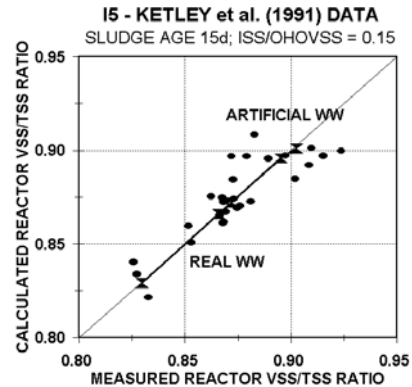


Figure 16

Calculated with OHO ISS content $f_{iOHO} = 0.15 \text{ mgISS/mgOHOVSS}$ vs. measured sewage batch average (●) and system average (♣) reactor VSS/TSS ratio for the artificial and real WW ND systems of Ketley et al. (1991) (I5) at 15 d sludge age

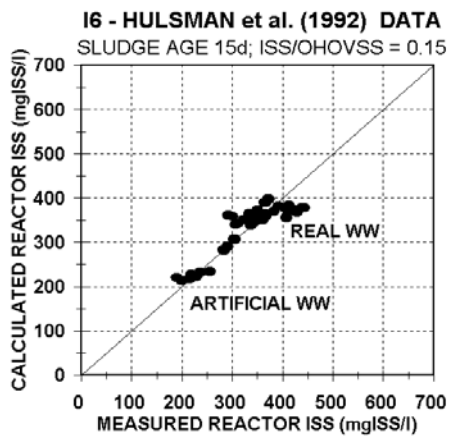


Figure 17

Calculated with OHO ISS content $f_{iOHO} = 0.15 \text{ mgISS/mgOHOVSS}$ vs. measured sewage batch average (●) and system average (▲) reactor ISS concentration for the artificial and real WW ND systems of Hulsman et al. (1992) (I6) at 15 d sludge age

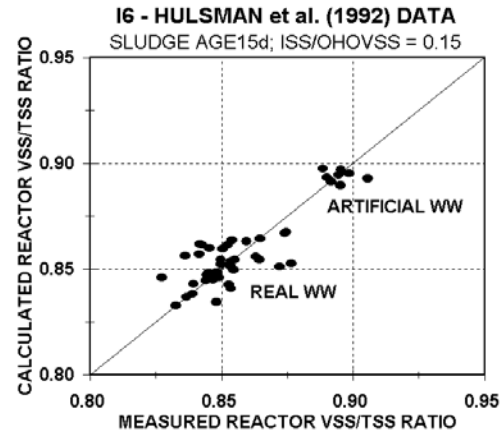


Figure 18

Calculated with OHO ISS content $f_{iOHO} = 0.15 \text{ mgISS/mgOHOVSS}$ vs. measured sewage batch average (●) and system average (▲) reactor VSS/TSS ratio for the artificial and real WW ND systems of Hulsman et al. (1992) (I6) at 15 d sludge age

correlation is obtained for these investigations also and the calculated influent ISS concentration for the artificial wastewater is very low, as expected, and for the real wastewater much higher and close to the values measured (I22 - Table 2).

With f_{iOHO} fixed at $0.15 \text{ mgISS/mgOHOVSS}$, the influent ISS/COD ratio to account for the measured reactor ISS was determined for the 15 systems of the remaining 8 investigations on FA and ND systems, viz. I4, I7, I13, I15, I16, I19, I20 and I21 (Table 1). These systems represent sludge ages from 3 to 20 d, nominal hydraulic retention times from 7 to 24 h and feed COD concentrations from 500 to 1 000 mgCOD/l (Table 1). The system weighted average influent ISS/COD ratio vs. sludge age results for all 30 FA and ND systems are shown plotted in Fig. 19. As expected for the artificial wastewater systems (I5 and I6), very low influent ISS/COD ratios are obtained to correctly predict reactor ISS concentration and the real wastewater ratios are 3 to 5 times higher. However, for the real wastewater systems, the system average influent ISS/COD ratios vary over a fairly wide range from 0.016 (I15) to 0.040 (I20) even though the systems were fed wastewater from the same source. This variability appears independent of sludge age. The measured influent ISS/COD ratios from Table 2 are also plotted in Fig. 19. The calculated influent ISS/COD ratios compare reasonably well with the measured ratios, except the I12 measured value, which is three times higher at 0.09 mgISS/mgCOD (not shown). This value is clearly an outlier from all the other FA and ND systems and measured influent ISS/COD ratios in the database. Because a large set of reliable measurements of influent ISS are not available in the database, it could not be established whether the variability in the calculated influent ISS/COD ratio is real and due to the nature of the wastewater batches collected from the wastewater treatment plant, or inadequacy in the model structure. Clearly, investigations into the measurement of the ISS content of wastewater (raw and settled) are required to develop both suitable analytical methods and a larger database on wastewater ISS concentrations (see below).

Figure 20 shows, vs. sludge age, the relative proportion of the influent and OHO ISS in the reactor and the VSS/TSS ratio for the measured Mitchells Plain influent ISS/COD of 0.031 and an OHO ISS content (f_{iOHO}) of $0.15 \text{ mgISS/mgOHOVSS}$. It can be seen that while the mixed liquor VSS/TSS ratio remains approximately constant, which is in conformity with observation, the percentage

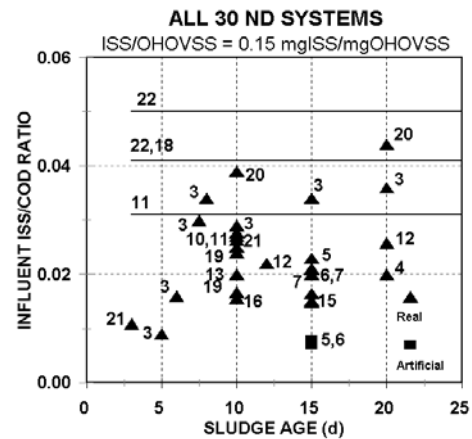


Figure 19

Calculated system average influent ISS concentration (as a ratio of the influent COD concentration) vs. sludge age for the 30 ND systems fed artificial (■) and real (▲) WW with ratios measured in the laboratory (line, I11) and at the source WWTP (lines, I18, I22)

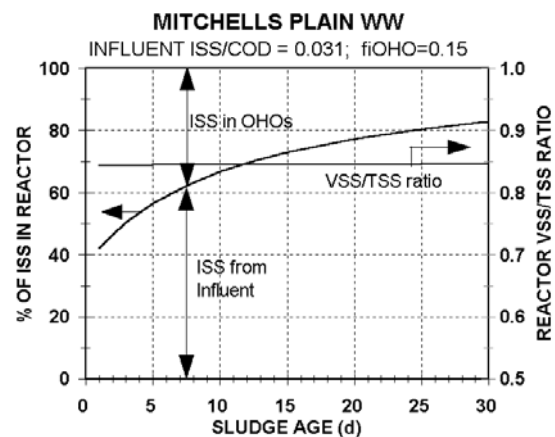


Figure 20

% of reactor ISS from the influent and in OHOs and reactor VSS/TSS ratio vs. sludge age for the Mitchells Plain WWTP measured influent ISS/COD ratio of $0.031 \text{ mgISS/mgCOD}$ and OHO ISS content of $0.15 \text{ mgISS/mgOHOVSS}$

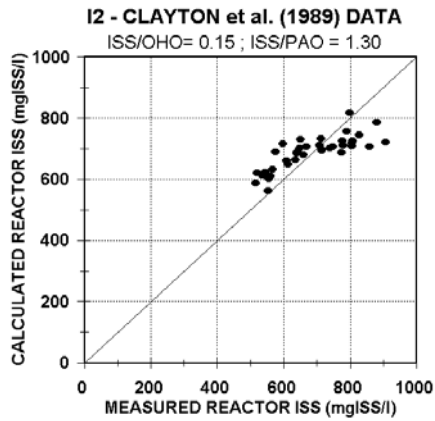


Figure 21

Calculated vs. measured sewage batch average reactor ISS concentration (●) for OHO and PAO ISS content (f_{iOHO} and f_{iPAO}) of 0.15 and 1.30 mgISS/mgVSS for the >90% aerobic P uptake BEPR MUCT system of Clayton et al. (1989) at 18 d sludge age

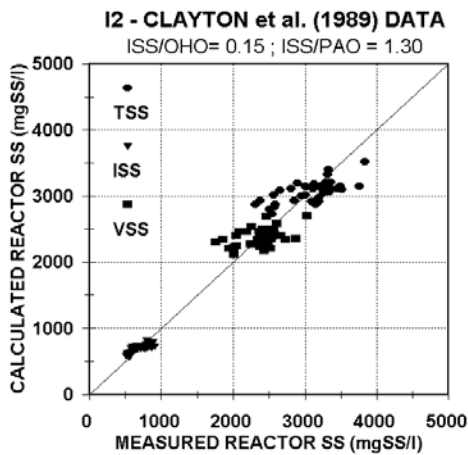


Figure 22

Calculated vs. measured sewage batch average reactor ISS (▼), VSS (■) and TSS (●) concentrations for OHO and PAO ISS content (f_{iOHO} and f_{iPAO}) of 0.15 and 1.30 mgISS/mgVSS for the >90% aerobic P uptake BEPR MUCT system of Clayton et al. (1989) at 18 d sludge age

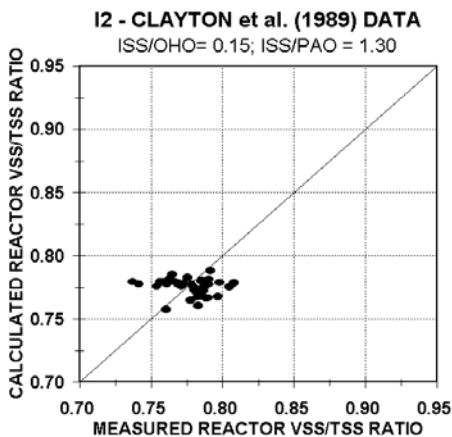


Figure 23

Calculated vs. measured sewage batch average reactor VSS/TSS ratio (●) for OHO and PAO ISS content (f_{iOHO} and f_{iPAO}) of 0.15 and 1.30 mgISS/mgVSS for the >90% aerobic P uptake BEPR MUCT system of Clayton et al. (1989) at 18 d sludge age

of the ISS in the reactor originating from the influent increases from about 60% at 5 d sludge age to 92% at 30 d. This increase arises because influent ISS mass accumulates in proportion to sludge age (Eq. 1); and the OHO active fraction (f_{avOHO}) decreases with sludge age. This demonstrates that modelling the observed relative insensitivity of the VSS/TSS ratio in the reactor to sludge age by recognising only influent ISS accumulation is not possible - an ISS contribution by the OHOs is required to do this. Including an ISS content in the OHO endogenous residue did not improve the correlation and because this does not conform to the conceptual basis of this ISS model, i.e. the organism ISS is principally formed from intra-cellular inorganic dissolved solids (IDS) in the test procedure, including ISS in the unbiodegradable organics was not considered further.

Combining the OHO and PAO ISS contents for NDBEPR systems fed real wastewater

The f_{iPAO} fixed at 1.30 from the enhanced PAO cultures and f_{iOHO} fixed at 0.15 from the FA and ND systems fed artificial and real wastewater, were applied to two NDBEPR systems fed real wastewater, i.e. the I2 system and the Experimental system of I14. In these two systems, the P uptake was predominantly aerobic (> 90%). The calculated vs. measured reactor ISS, VSS and TSS concentrations and the VSS/TSS ratio are shown in Figs. 21 to 23. A good correlation was obtained indicating that no refinement of the f_{iPAO} and f_{iOHO} values was necessary. Even though the investigations were conducted a decade apart, of concern was that influent ISS/COD ratio required to obtain a good match between the predicted and measured data was significantly different; 0.022 mgISS/mgCOD for I2 and 0.004 for I14. Although a lower value was expected for I14 because landfill leachate (with no ISS) equivalent to about 200 mgCOD/l was dosed to the system, the 0.004 mgISS/mgCOD value is very low and below the artificial WW values found for I5 and I6. This indicates that some inconsistencies may be present in the ISS model (Eq 2).

When $f_{iPAO} = 1.30$ mg ISS/mgPAOVSS for a PAO P content ($f_{XBGP} = 0.38$ mgP/mgPAOVSS) was applied to the systems with significant anoxic P uptake (>20%), poor calculated vs. measured reactor ISS correlations and inconsistent influent ISS/COD ratios were obtained. For significant anoxic P uptake (>20%), the calculated P content of the PAOs (f_{XBGP}) was lower than 0.38 and ranged between 0.10 (Exp of I10 and M2 of I9) and 0.30 mgP/mgPAOVSS (I17 and Cntl of I14). The lower the P content of the PAOs (f_{XBGP}) below 0.38, the lower the ISS content below 1.30. Accordingly a linear relationship was established between the polyphosphate and ISS contents of the PAOs. Following the ASM models, the P content of the PAO biomass and polyphosphate are considered separately. Accepting that without polyphosphate, the P and ISS content of PAOs is the same as OHOs, i.e. $f_{XBGPBM} = 0.03$ mgP/mgPAOVSS and $f_{iPAOBM} = 0.15$ mgISS/mgPAOVSS, and that ISS content of the polyphosphate adds to this, then the combined ISS content of PAOs (f_{iPAO}) is given by:

$$f_{iPAO} = 3.286 f_{XBGP} + f_{iPAOBM} \text{ mg ISS/mgPAOVSS} \quad (3)$$

where:

- f_{XBGP} = polyphosphate content of PAOs (mg polyphosphate/mgPAOVSS)
- = $f_{XBGP} - f_{XBGPBM}$
- f_{XBGP} = total P content of PAOs
- f_{XBGPBM} = P content of the PAO cell mass
- = 0.03 mgP/mgPAOVSS
- 3.286 = ISS/P ratio of polyphosphate

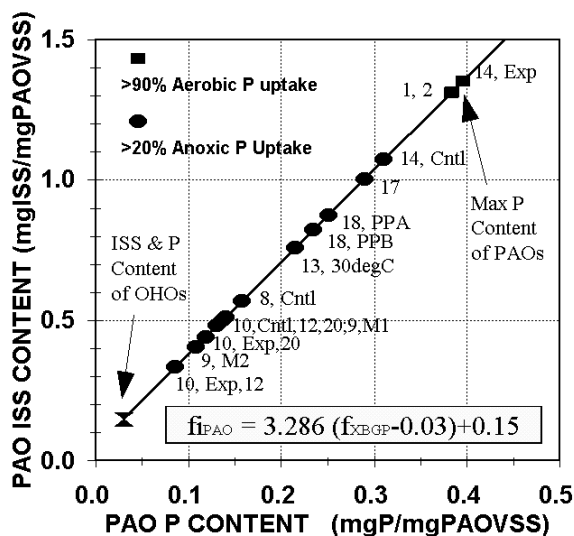


Figure 24

Estimated PAO inorganic solids (ISS) content (f_{IPAO}) vs. PAO P content (f_{XBGP}) for >90% aerobic P uptake BEPR (■) and variable anoxic-aerobic P uptake BEPR (●) in the 18 NDBEPR systems of investigations I1, I2, I8, I9, I10, I13, I14, I17 and I18 based on the measured f_{IPAO} value in the four enhanced PAO culture systems (I1) on one extreme ($f_{IPAO} = 1.30$, $f_{XBGP} = 0.38$, ■) and the P content of OHOs on the other ($f_{IPAO} = 0.15$, $f_{XBGP} = 0.03$, ●)

A plot of PAO ISS content vs. PAO P content is given in Fig. 24. The ISS/P ratio of the polyphosphate in Eq. (3) is the slope of the line in Fig. 24 and was obtained from the ISS and P content of the enhanced PAO culture systems (I1), i.e. >90% aerobic P uptake BEPR and the P and ISS content determined for OHOs, viz. ($f_{IPAO} - f_{IPAOMB}$)/($f_{XBGP} - f_{XBGPBM}$) = $f_{IPAOPP}/f_{XBGPP} = (1.30 - 0.15)/(0.38 - 0.03) = 1.15/0.35 = 3.286$. This ratio compares closely with the 3.19 mgISS/mgP ratio theoretically derived above and with the 3.23 ratio adopted for ASM2 and 2d. However, the PAO biomass ISS content (excluding polyphosphate) of 0.15 mgISS/mgVSS accepted in this model is very much lower than the 0.332 mgISS/mgVSS value accepted in ASM2 and 2d. Furthermore, in the model proposed here, the endogenous residue (of both OHOs and PAOs) and unbiodegradable particulate organics from the influent do not contain ISS, whereas in ASM2 and 2d, these unbiodegradable organics contain 0.11 mgISS/mgVSS. In both the model developed here and in ASM2 and 2d, influent ISS is included to add directly to the reactor ISS concentration, and hence TSS.

As described above, the P content of the PAOs (f_{XBGP}) was calculated with the Wentzel et al. (1990) BEPR model from the measured P removal and the PAO active fraction (f_{avPAO}). From this P content, the ISS content was calculated with Eq. (3), and the results for all 18 NDBEPR systems are shown in Fig. 24. The calculated vs. measured reactor ISS concentrations and VSS/TSS ratios for the 2 systems near the extremes of Eq. 3 are plotted in Figs. 25 to 28, i.e. system M2 of I9 with $f_{XBGP} = 0.108$ mgP/mgPAOVSS and the system of I17 with $f_{XBGP} = 0.290$ respectively, which yield from Eq. (3), PAO ISS contents (f_{IPAO}) of 0.41 and 1.14 mgISS/mgPAOVSS respectively. A reasonably good correlation is obtained and the influent ISS/COD ratio for the two investigations also is quite consistent (0.050 and 0.035 respectively), indicating that the relationship established between the P and ISS content of the PAOs (Eq. 3) is acceptable. For I18 on 2 parallel pilot scale (2 M ℓ /d) UCT systems, in which the influent ISS/COD ratio

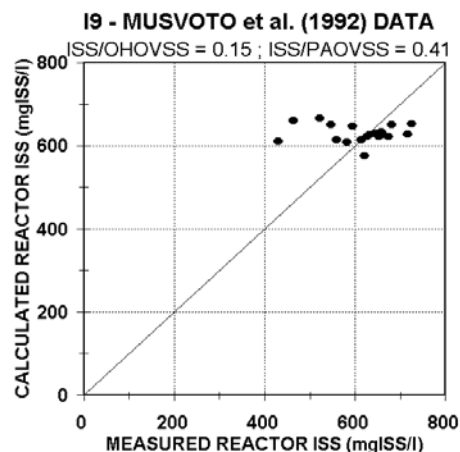


Figure 25

Calculated vs. measured sewage batch average reactor ISS concentration (●) for OHO and PAO ISS content (f_{IOHO} and f_{IPAO}) of 0.15 and 0.41 mgISS/mgVSS for the >20% anoxic P uptake BEPR UCT system of Musvoto et al. (1992) at 20 d sludge age

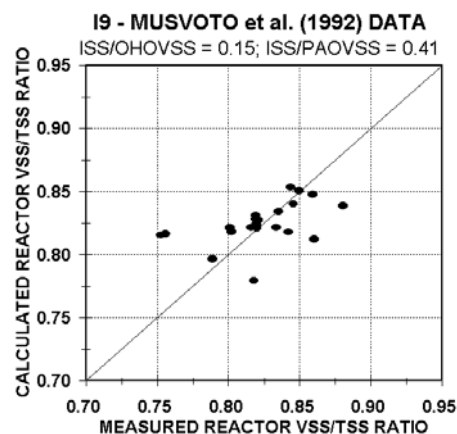


Figure 26

Calculated vs. measured sewage batch average reactor VSS/TSS ratio (●) for OHO and PAO ISS content (f_{IOHO} and f_{IPAO}) of 0.15 and 0.41 mgISS/mgVSS for the >20% anoxic P uptake BEPR UCT system of Musvoto et al. (1992) at 20 d sludge age

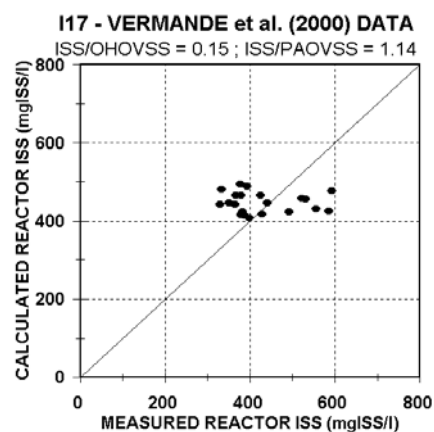


Figure 27

Calculated vs. measured sewage batch average reactor ISS concentration (●) for OHO and PAO ISS content (f_{IOHO} and f_{IPAO}) of 0.15 and 1.14 mgISS/mgVSS for the >20% anoxic P uptake BEPR UCT system of Vermande et al. (2000) at 10 d sludge age

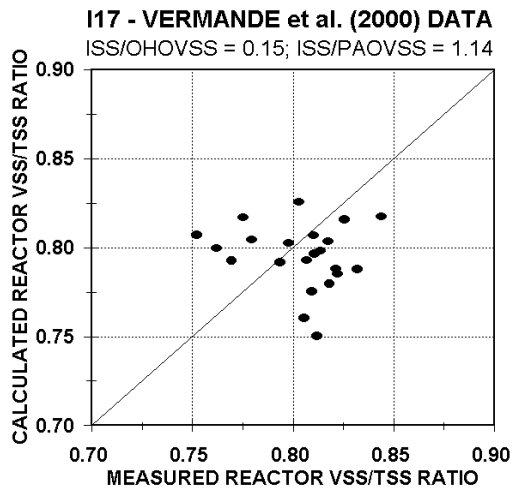


Figure 28

Calculated vs. measured sewage batch average reactor VSS/TSS ratio (●) for OHO and PAO ISS content (f_{iOHO} and f_{iPAO}) of 0.15 and 1.14 mgISS/mgVSS for the >20% anoxic P uptake BEPR UCT system of Vermande et al. (2000) at 10 d sludge age

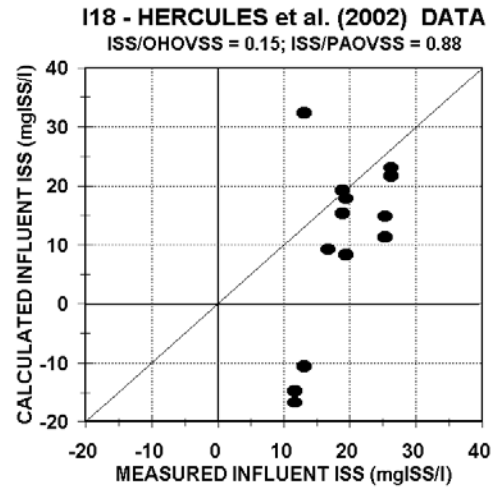


Figure 30

Calculated vs. measured steady state period average influent ISS concentration (●) for OHO and PAO ISS content (f_{iOHO} and f_{iPAO}) of 0.15 and 0.88 mgISS/mgVSS for the two 2 M ℓ /d UCT system pilot plants of Hercules et al. (2002) at 13.5 d sludge age for anoxic-aerobic P uptake BEPR and with high nitrate recycle to the anaerobic reactor

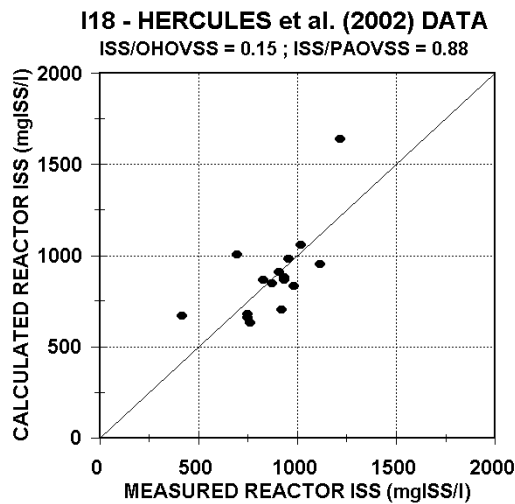


Figure 29

Calculated vs. measured steady state period average reactor ISS concentration (●) for OHO and PAO ISS content (f_{iOHO} and f_{iPAO}) of 0.15 and 0.88 mgISS/mgVSS for the two 2 M ℓ /d UCT system pilot plants of Hercules et al. (2002) at 13.5 d sludge age for anoxic-aerobic P uptake BEPR and with high nitrate recycle to the anaerobic reactor

(X_{iOHO}/S_{iOHO}) was measured, the calculated vs. measured reactor and influent ISS concentrations are shown in Figs. 29 and 30 respectively, for which f_{iOHO} is unchanged at 0.15 and $f_{iPAO} = 0.88$ and 0.82 obtained from the observed P removal. For the reactor ISS concentration (Fig. 29), the correlation is reasonable. The measured and calculated influent ISS/COD ratios are 0.041 and 0.025 mgISS/mgCOD respectively. The correlation between measured and calculated influent ISS/COD ratios is not very good and generally the calculated influent ISS concentrations are lower (with some -ve values) than those measured (Fig. 30). However, as in I12, it is possible that there is some bias in the measured values due to the experimental method, discussed below.

The above approach was followed for the remaining 8 NDBEPR

systems of I8 to I11 and I13 and the calculated influent ISS/COD ratios from all 18 NDBEPR systems are shown plotted vs. sludge age in Fig. 31, and together with the ratios from the 30 FA and ND systems in Fig. 32. It can be seen that the calculated influent ISS/COD ratios for the NDBEPR systems tend to fall below the measured ratios (lines), but superimpose well over the FA and ND ratios. Considering the significantly higher ISS in the PAO biomass (3 to 6 times) compared with OHO biomass, if there were significant error in the model, negative or very high influent ISS/COD ratios would be obtained, but this is not the case. The model can therefore be accepted as having the required relative sensitivity to the ISS contents of the OHOs and PAOs and the influent ISS concentration.

Figure 33 shows, vs. sludge age, the relative contribution to the reactor ISS concentration by the influent ISS and the ISS in the OHOs and PAOs; the last for >90% aerobic P uptake BEPR ($f_{iPAO} = 1.30$ mgISS/mgPAOVSS), and the VSS/TSS ratio for the measured Mitchells Plain influent ISS/COD of 0.031 and an OHO ISS content of 0.15 mgISS/mgOHOVSS. It can be seen that while the mixed liquor VSS/TSS ratio remains in a narrow range between 0.70 and 0.75 with sludge age from 5 to 30 d, which is in conformity with observation, the ISS in the PAOs is around 60% of the total ISS; the % of the ISS in the reactor originating from the influent increases from about 20% at 5 d sludge age to 40% at 30 d; and the OHOs contribute relatively little (20 to 10%) to the reactor ISS. Because of the high ISS content of PAOs, NDBEPR systems have significantly lower VSS/TSS ratios than ND systems and the influent ISS contributes between a quarter and a third of the total ISS in the reactor.

Determination of influent ISS

A possible source of bias in the ISS concentration measurement is from the total dissolved solids (TDS) of the residual water before drying. If a 3 000 mgTSS/ ℓ sample is centrifuged in a 50 ml 30 mm diameter tube with hemispherical bottom, the residual water is about 10 ml, which at a TDS of 500 mg/ ℓ , contributes 5 mgISS. If

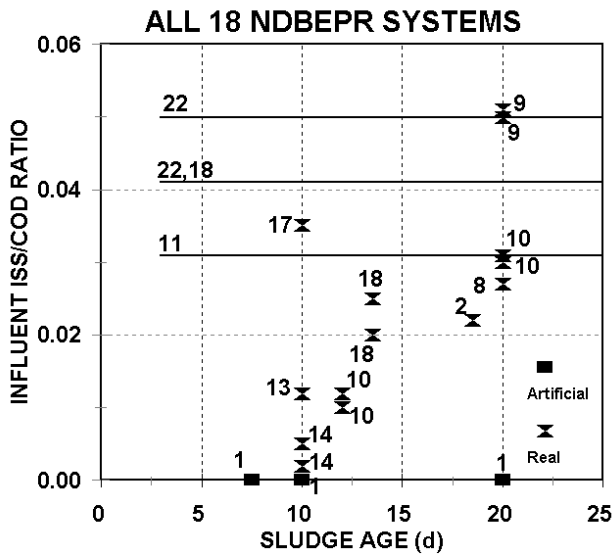


Figure 31

Calculated system average influent ISS concentration (as a ratio of the influent COD concentration) vs. sludge age for the 18 NDBEPR systems fed artificial (■, 1) and real (✱NDBEPR) WW with ratios measured in the laboratory (line, I11) and at the source WWTP (lines, I18, I22)

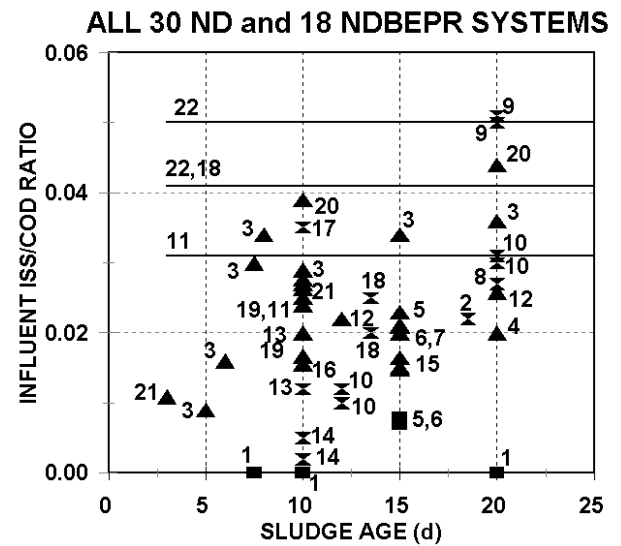


Figure 32

Calculated system average influent ISS concentration (as a ratio of the influent COD concentration) vs. sludge age for the 30 ND and 18 NDBEPR systems fed artificial (■, 5 and 6 ND, 1 NDBEPR) and real (▲ND, ✱NDBEPR) WW with ratios measured in the laboratory (line, I11) and at the source WWTP (lines, I18, I22)

the VSS/TSS ratio of the sludge is 0.80, this 5 mg ISS is $5/30 = 17\%$. Solid/liquid separation in the influent TSS and ISS concentration determination is usually done through weighed ashless filter papers (as was done in I11 and I18). If 1 l influent is filtered and again 10 ml residual water remains in the filter paper and solids before drying, then 5mgTDS is added to the influent ISS. For influent ISS concentrations around 20 to 40 mg/l, this is a bias of 25 to 12% upwards. The same applies if the ISS is measured as the difference between the total inorganic solids of unfiltered and filtered samples, as was done in I12. Moreover, the filter pore size is important because if too large, fine clay may pass through the filter medium. Clearly the TDS of the sample, the sample size, solid/liquid separation method and the solids concentration can significantly bias the ISS concentration upwards, causing a considerable loss of accuracy.

Precision is also a problem in the influent ISS method. After the initial drying step for the TSS, the filter paper, with its solids, is placed in a weighed crucible of mass generally >25g and incinerated at 600°C. The ash residue in the crucible is the ISS, which is the difference between two large masses, around 1 000 times greater than the ISS mass. This causes large variance in the ISS concentration.

To try to overcome these problems of accuracy and precision in the influent ISS measurement, various filtration media were tested. The best one was found to be glass fibre filters (GF/C Schleicher and Schüll GF52) because:

- their pore size is small enough (<1.0µ) to retain even very fine clay (tests with kaolin yielded >99% recovery);
- precision improved significantly because the glass fibre filters acted as very light mass crucibles - however, they needed to be pretreated by incineration for > 6 h prior to use to stabilise their mass; and
- their moisture retention was negligible.

This method was therefore used to measure the influent ISS/COD

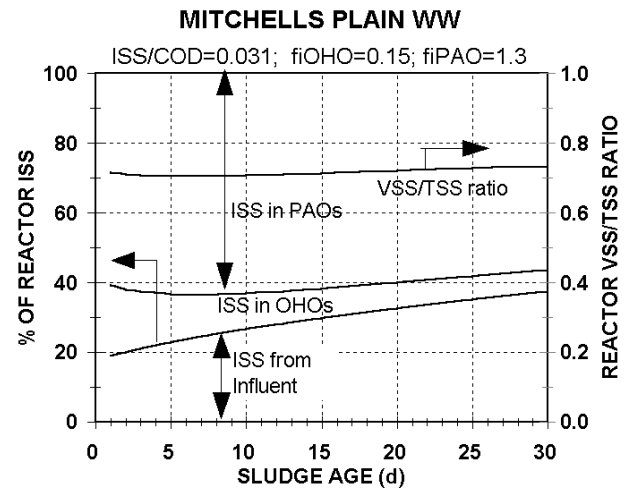


Figure 33

% of reactor ISS from the influent and in OHOs and PAOs (for >90% aerobic P uptake BEPR) and reactor VSS/TSS ratio vs. sludge age for the Mitchells Plain WWTP measured influent ISS/COD ratio of 0.031 mgISS/mgCOD and OHO and PAO ISS content of 0.15 mgISS/mgOHOVSS and 1.30 mgISS/mgPAOVSS

ratio of raw and settled wastewater at the Mitchell Plain WWTP (I22, Table 2). It is recommended that this method be adopted for measurement of influent ISS to build up a database for this wastewater characteristic for design.

Sensitivity of the reactor VSS/TSS ratio

The experimental data from the 21 investigations show that the measured reactor ISS concentration, and hence the VSS/TSS ratio, is influenced by the influent ISS concentration, BEPR and sludge

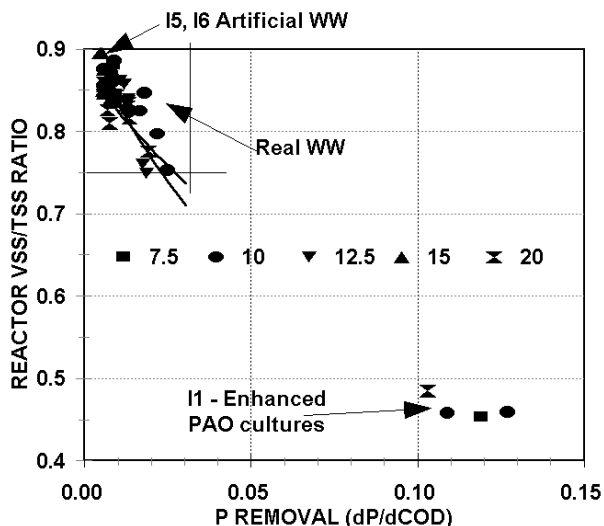


Figure 34

Measured (points) and calculated (lines) reactor VSS/TSS ratio vs. P removal for all 48 real and artificial wastewater systems of investigations 1 to 21 grouped in sludge ages 7.5, 10, 12.5, 15 and 20 d

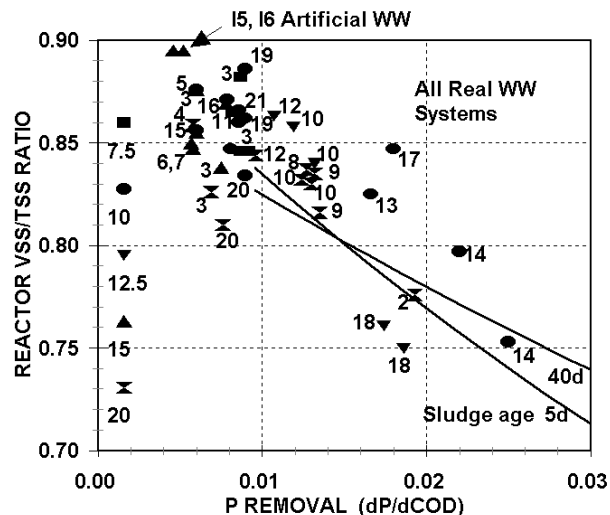


Figure 35

Measured (points) and calculated (lines) reactor VSS/TSS ratio vs. P removal for all 44 real (42) and artificial (2) wastewater systems of investigations 2 to 21 grouped in sludge ages 7.5, 10, 12.5, 15 and 20 days (enlargement of top right hand corner of Fig. 34)

TABLE 3 Model predicted reactor VSS/TSS ratio for sludge ages from 2 to 40 d (last column) for raw and settled wastewater characteristics (first column), influent ISS/COD ratio (second column) and type of activated sludge system (PAO P content, third column)				
Raw wastewater		Influent ISS/COD	PAO P content	VSS/TSS
COD (mgCOD/)	750	0.050	ND (No BEPR)	0.78 to 0.81
RBCOD (mgCOD/)	146	0.050	0.15 (Ax BEPR)	0.75 to 0.74
USCOD (mgCOD/)	53	0.050	0.38 (Aer BEPR)	0.68 to 0.70
UPCOD (mgCOD/)	113	0.030	ND (No BEPR)	0.84 to 0.85
ISS _{high} (mgISS/)	38	0.030	0.15 (Ax BEPR)	0.78 to 0.80
ISS _{low} (mgISS/)	23	0.030	0.38 (Aer BEPR)	0.71 to 0.74
Settled wastewater		Influent D ISS/CO	PAO P content	VSS/TSS
COD (mgCOD/)	450	0.035	ND (No BEPR)	0.76 to 0.81
RBCOD (mgCOD/)	146	0.035	0.15 (Ax BEPR)	0.70 to 0.69
USCOD (mgCOD/)	53	0.035	0.38 (Aer BEPR)	0.60 to 0.61
UPCOD (mgCOD/)	18	0.015	ND (No BEPR)	0.85 to 0.87
ISS _{high} (mgISS/)	16	0.015	0.15 (Ax BEPR)	0.73 to 0.75
ISS _{low} (mgISS/)	7	0.015	0.38 (Aer BEPR)	0.60 to 0.65
RBCOD, USCOD, UPCOD are respectively the influent readily biodegradable, unbiodegradable soluble and unbiodegradable particulate COD concentrations.				

age. The effect of BEPR and sludge age on the system average VSS/TSS ratio measured in the different systems of the 21 investigations are shown in Fig. 34, which includes the enhanced PAO cultures of I1, and in Fig. 35, which “zooms-in” on the real wastewater systems with VSS/TSS ratios from 0.75 to 0.90 and BEPR of 0.005 to 0.025 mgP removed per mgCOD removed [$\Delta P/\Delta COD = (P_{inl} - P_{eff}) / (COD_{inl} - COD_{eff})$]. The effect of BEPR is clear,

with VSS/TSS ratio decreasing significantly as $\Delta P/\Delta COD$ increases. In contrast, no significant effect of sludge age on the reactor VSS/TSS ratio is evident in the results. The model shows similar relative sensitivity as the experimental data to BEPR and sludge age. The predicted reactor VSS/TSS ratio for varying magnitude of P removal ($f_{X_{BGP}}$ 0.03 to 0.38 mgP/mgPAOVSS) for an influent ISS/COD ratio of 0.040 mgISS/mgCOD is also shown in Figs. 34 and 35 (lines). A better fit is not expected because the influent ISS is fixed at 0.04 mgISS/mgCOD. The predicted VSS/TSS ratios, representing the extremes of sludge age (5 and 40 d), follow the same slope as the experimental data. The predicted ratios start at lower values because the upper value (for zero BEPR) is fixed by the influent ISS/COD ratio = 0.040, higher than found for most of the 48 experimental systems (Fig. 32). To demonstrate the relative sensitivity of the predicted reactor VSS/TSS ratio to sludge age and magnitude of P removal, the predicted reactor VSS/TSS ratio for typical South African raw and settled wastewater characteristics, and PAO P content ($f_{X_{BGP}}$) of 0.03, 0.19 and 0.38 mgP/mgPAOVSS as representative of ND, anoxic P uptake BEPR and aerobic uptake BEPR systems respectively, is shown in Table 3. Clearly, sludge age has a minor influence on the reactor VSS/TSS ratio. If the estimates of the high and low influent ISS concentrations in Table 3 are reasonable, then the P content of the PAOs has a much larger influence on the reactor VSS/TSS ratio than the influent ISS, with the ratio decreasing markedly for

increasing PAOP content. For ND systems, the reactor VSS/TSS ratio ranges between 0.78 and 0.85 for raw wastewater and 0.76 and 0.87 for settled wastewater, depending on the influent ISS concentration. For NDBEPR systems with >90% aerobic P uptake BEPR, the reactor VSS/TSS ratio ranges between 0.68 and 0.74 for raw wastewater and 0.60 and 0.65 for settled wastewater. The ratio is lower for settled wastewater than raw wastewater because in settled wastewater a far greater proportion of the influent COD is RBCOD, so a greater proportion of the VSS mass is PAOs.

Application to design

Because of the relative insensitivity of the VSS/TSS ratio to sludge age, generally assumed for many years in design but now given an experimental and modelling basis, the reactor VSS/TSS ratio can be calculated for different influent ISS/COD ratios. In conformity with the equation structure and symbol system of Ekama et al. (1983), WRC (1984) and Wentzel et al. (1990), the masses of VSS, ISS and TSS in the reactor, the last two calculated with the ISS model, and the VSS/TSS ratio (f_i) are given by:

$$\frac{MX_v}{MS_{ii}} = (1 - f_{S'us} - f_{S'up}) \left[\left(1 - \frac{\% f_{Sb's}}{100} \right) \frac{Y_H R_s}{(1 + b_{HT} R_s)} (1 + f_{EH} b_{HT} R_s) + \frac{\% f_{Sb's}}{100} \frac{Y_G R_s}{(1 + b_{GT} R_s)} (1 + f_{EG} b_{GT} R_s) \right] + \frac{f_{S'up} R_s}{f_{cv}} \quad (4)$$

$$\frac{MX_{io}}{MS_{ii}} = (1 - f_{S'us} - f_{S'up}) \left[\left(1 - \frac{\% f_{Sb's}}{100} \right) \frac{Y_H R_s}{(1 + b_{HT} R_s)} (f_{iOHO}) + \frac{\% f_{Sb's}}{100} \frac{Y_G R_s}{(1 + b_{GT} R_s)} (3.286(f_{XBGP} - f_{XBGPIM}) + f_{iOHO}) \right] + \frac{X_{ioi} R_s}{S_{ii}} \quad (5)$$

$$\frac{MX_t}{MS_{ii}} = (1 - f_{S'us} - f_{S'up}) \left[\left(1 - \frac{\% f_{Sb's}}{100} \right) \frac{Y_H R_s}{(1 + b_{HT} R_s)} (1 + f_{EH} b_{HT} R_s + f_{iOHO}) + \frac{\% f_{Sb's}}{100} \frac{Y_G R_s}{(1 + b_{GT} R_s)} (1 + f_{EG} b_{GT} R_s + 3.286(f_{XBGP} - f_{XBGPIM}) + f_{iOHO}) \right] + \left[\frac{f_{S'up}}{f_{cv}} + \frac{X_{ioi}}{S_{ii}} \right] R_s$$

$$f_i = \frac{MX_v}{MX_t} \quad (7)$$

where:

- MX_v = VSS mass in reactor (kgVSS)
- MS_{ii} = COD mass load on reactor (kgCOD/d)
- Q_i = average dry weather flow (ADWF, M ℓ /d)
- S_{ii} = flow weighted average influent COD concentration entering biological reactor (mgCOD/ ℓ)
- MX_{io} = mass of ISS in reactor (kgTSS)
- MX_t = mass of TSS in reactor (kgTSS)
- $f_{S'up}$ = influent unbiodegradable particulate COD fraction
- $f_{S'us}$ = influent unbiodegradable soluble COD fraction
- $f_{Sb's}$ = influent readily biodegradable (RB) COD fraction with respect to biodegradable COD
- $\%$ = percentage influent RBCOD taken up by PAOs
- = 100% for enhanced PAO culture systems of

Wentzel et al. (1989a)

- = 0 if system is ND, i.e. no PAOs
- >0 if system is NDBEPR, increasing with increasing BEPR (usually 70 to 90)
- Y_H, Y_G = yield coefficient for OHOs and PAOs
- = 0.45 mgVSS/mgCOD
- b_{HT}, b_{GT} = endogenous respiration rate for OHOs and PAOs at T °C
- = 0.24/d and 0.04/d respectively at 20°C ($\theta_b = 1.029$ for both)
- θ_b = temperature sensitivity coefficient for endogenous respiration
- R_s = system sludge age (days)
- f_{EH}, f_{EG} = endogenous residue fraction of the OHOs and PAOs
- = 0.20 and 0.25 respectively
- f_{cv} = COD/VSS ratio of organics = 1.48 mgCOD/mgVSS
- f_{iOHO} = inorganic content of OHO cell mass
- = 0.15 mgISS/mgOHOVSS
- f_{iPAOBM} = inorganic content of PAO cell mass (without polyphosphate)
- = 0.15 mgISS/mgPAOVSS
- f_{XBGP} = total P content of PAOs
- f_{XBGPIM} = P content of PAO cell mass (without polyphosphate)
- = 0.03 mgP/mgPAOVSS
- X_{ioi} = influent ISS concentration entering biological reactor
- f_i = VSS/TSS ratio of reactor sludge.

In Eqs. (4) to (6), all the influent RBCOD is assumed to be taken up by the PAOs; if this is not the case, then the $f_{Sb's}$ ratio needs to be reduced to take account of this. For ND systems, $f_{Sb's}$ must be set to zero to ensure zero growth of PAOs. If this is not done, MX_v will be incorrectly predicted especially for long sludge age systems because PAOs have a very low endogenous respiration rate compared with OHOs.

A plot of the reactor VSS/TSS ratio (f_i) vs. influent ISS/COD ratio is given in Figs. 36 and 37 respectively for the raw and settled wastewater characteristics listed in Table 3 for ND systems (no BEPR), anoxic-aerobic P uptake BEPR (i.e. reduced PAO P content, $f_{XBGP} = 0.19$ mgP/mgPAOVSS) and aerobic P uptake BEPR (i.e. maximum PAO P content, $f_{XBGP} = 0.38$ mgP/mgPAOVSS). The small effect of sludge age is also shown by plotting the f_i value for each of the three types of systems at 10 and 30 days sludge age. The influent ISS/COD ratio was measured at the Mitchells Plain WWTP for the raw and settled wastewater at around 0.045 and 0.042 mg ISS/mgCOD respectively (Table 2). From Fig. 37 for the Mitchells Plain WWTP, which treats settled wastewater in an ND system at 20 to 30 d sludge age, the predicted VSS/TSS ratio is around 0.80 for the measured influent ISS/COD ratio of 0.040 (Table 2). The year 2002 measured annual average VSS/TSS ratio obtained from plant performance results was around 0.85. This indicates that either the ISS model predicts the reactor ISS mass too high in relation to the VSS mass, or that the measured influent ISS/COD ratio of 0.040 is too high (Table 2). As indicated in Fig. 32, it is possible that the measured ratio of 0.040 mg ISS/mgCOD is on the high-end for Mitchells Plain settled wastewater, even though it was measured at around this value on two separate occasions (Table 2). The laboratory units generally yielded influent ISS/COD ratios for strained raw wastewater (see above) below 0.040, between 0.015 to 0.030 mgISS/mgCOD. An influent ISS/COD ratio of 0.021 yields a reactor VSS/TSS ratio of 0.85. It should be noted that generally influent ISS concentrations are very small in magnitude and what may appear to be a large percentage

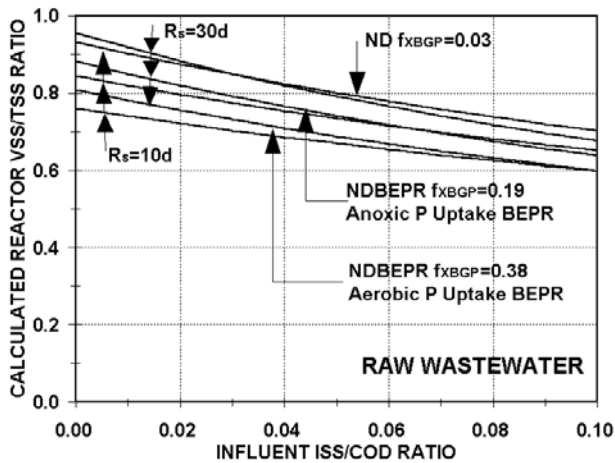


Figure 36

Calculated reactor VSS/TSS ratio for raw wastewater vs. influent ISS/COD ratio at 10 and 30 d sludge age for ND systems (no BEPR) and NDBEPR systems with anoxic ($f_{xBGP}=0.19$) and aerobic ($f_{xBGP}=0.38$) P uptake BEPR

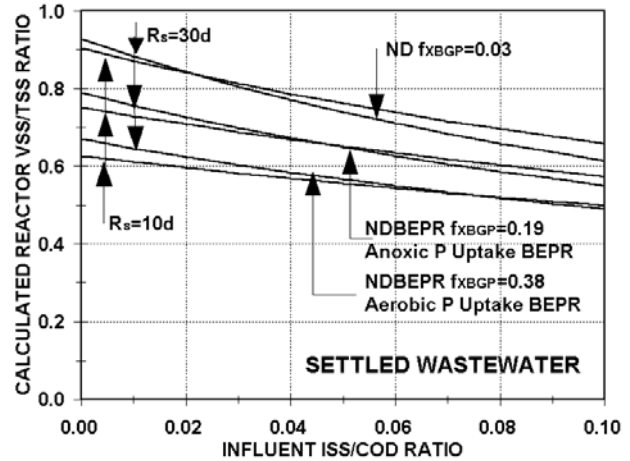


Figure 37

Calculated reactor VSS/TSS ratio for settled wastewater vs. influent ISS/COD ratio at 10 and 30 d sludge age for ND systems (no BEPR) and NDBEPR systems with anoxic ($f_{xBGP}=0.19$) and aerobic ($f_{xBGP}=0.38$) P uptake BEPR

difference in ISS/COD ratio is actually a small difference in ISS concentration, e.g. for the settled wastewater of 450 mgCOD/l and ISS/COD ratios of 0.03 and 0.04, the influent ISS concentration are 13.5 and 18 mgISS/l respectively.

The ISS model indicates that for ND systems at short to intermediate sludge ages (<15 d) and NDBEPR systems at all sludge ages, the influent ISS plays a relatively small role in determining the reactor ISS mass. For these systems, the ISS mass is most strongly influenced by the active biomass, in particular the P content of the PAOs in NDBEPR systems. It is mainly for long sludge age ND systems that the influent ISS/COD ratio strongly influences the reactor VSS/TSS ratio (Figs. 20 and 33).

The conceptual basis for ISS model is accumulation of influent ISS in the reactor and the uptake of inorganic dissolved solids by the biomass, in particular the PAOs. If no other changes in IDS between influent and effluent take place (e.g. precipitation or dissolution), then the model predicted effluent IDS vs. sludge age for influent IDS of 400 mg/l as shown in Fig. 38. It can be seen that the longer the sludge age, the less IDS is taken up. This is because the longer the sludge age, the longer the OHO and PAO endogenous processes have continued resulting in increased return of IDS back to the liquid phase. Uptake of IDS in NDBEPR systems is much higher than in ND systems due to the significantly higher inorganic content of PAOs and the return is much less because the endogenous rate of PAOs is very slow (0.04/d) compared with OHOs (0.24/d).

The ISS model shifts the uncertainty in design from selecting a reactor VSS/TSS ratio to selecting an influent ISS/COD ratio. As illustrated in Figs. 36 and 37, selection of an influent ISS/COD ratio for a particular activated sludge system fixes the reactor VSS/TSS ratio, or, as was done in the past, selection of the reactor VSS/TSS ratio presumed a certain influent ISS/COD ratio. Once a VSS/TSS ratio is selected that conforms to the influent ISS/COD ratio and the system type (ND, anoxic or aerobic P uptake NDBERR), there is little difference between the empirical approach of assuming a constant VSS/TSS ratio with sludge age and the ISS model because of the insensitivity of the ratio to sludge age (Figs. 20 and 33, see below). Measurement of the influent ISS/COD ratio is possible, but a database of values needs to be assembled to develop greater confidence in the experimental method and realistic ranges

of values. The greatest uncertainty in the model is selecting the P content of the PAOs (f_{xBGP}). This is not a problem of the ISS model itself, but rather a deficiency in the BEPR models. With significant anoxic P uptake BEPR, the P content of the PAOs is uncertain (Fig. 24), and consequently also the biological P removal. Factors that promote and suppress anoxic P uptake BEPR in NDBEPR systems are discussed by Sötemann et al. (2003). The conservative approach would be to assume 100% aerobic P uptake BEPR, i.e. $f_{xBGP} = 0.38$ mgP/mgPAOVSS, because this leads to the lowest VSS/TSS ratio and hence the highest TSS mass in the reactor. This also gives the highest biological P removal that can be expected, and conforms with the steady state BEPR model of Wentzel et al. (1990) and the simulation models ASM2 (Henze et al. 1995) and UCTPHO (Wentzel et al. 1992).

The similarity of the empirical approach of assuming a constant VSS/TSS ratio with sludge age and the proposed ISS model is shown in Figs. 39 and 40 for raw and settled wastewater and ND and NDBEPR systems, the latter for 100% aerobic P uptake ($f_{xBGP} = 0.38$ mgP/mgPAOVSS). For the raw and settled wastewaters in Table 3 and influent ISS/COD ratios of 0.044 and 0.024 mgISS/mgCOD respectively, yields from Eqs. (4) to (7) the reactor VSS/TSS ratios listed in Table 4. Accepting these VSS/TSS ratios as constant with sludge age for the empirical approach, the VSS/TSS ratios and mass ISS in the reactor vs. sludge age calculated with the ISS model and the empirical approach are compared in Figs. 39 and 40. In Fig. 39, it can be seen that while the VSS/TSS ratio is significantly different for the different system types ranging from 0.60 to 0.83, for each system the VSS/TSS ratio is approximately constant with sludge age. Closely constant VSS/TSS ratio with sludge age cannot be predicted by the ISS model considering influent ISS only for both ND and NDBEPR systems; an ISS content of OHOs (and PAOs if present) has to be accepted to achieve this. Figure 40 shows the same behaviour, that while different systems have significantly different masses of ISS in the biological reactor (per the mgCOD load per day on the reactor), the empirical approach of assuming a constant VSS/TSS ratio with sludge age and the ISS model predict virtually the same ISS mass in the reactor. Consequently, the problem with the empirical approach is not that it is incorrect, but that it provides no guidance on the VSS/TSS ratio to select. The ISS model provides a basis for

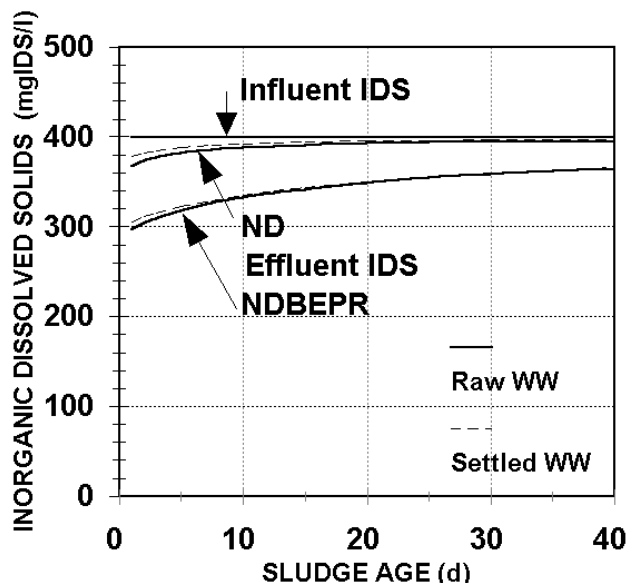


Figure 38

Calculated effluent inorganic dissolved solids (IDS) concentration vs. sludge age for raw and settled wastewater for an influent IDS concentration of 400 mg/l for ND and NDBEPR systems with aerobic P uptake BEPR showing the extent of IDS uptake by OHOs in ND and OHOs and PAOs in NDBEPR systems

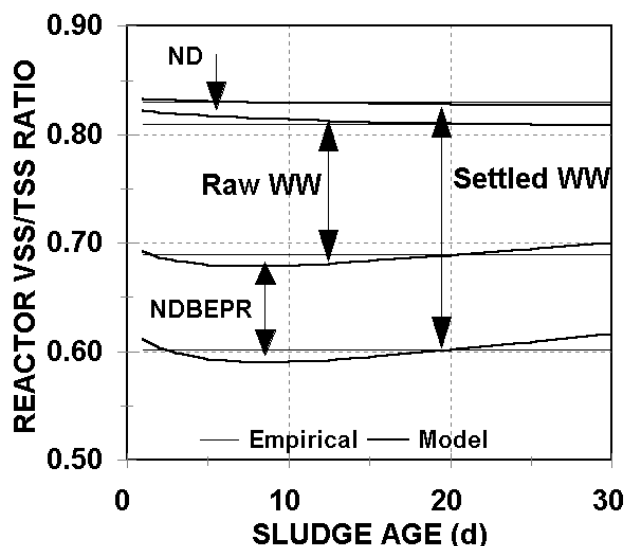
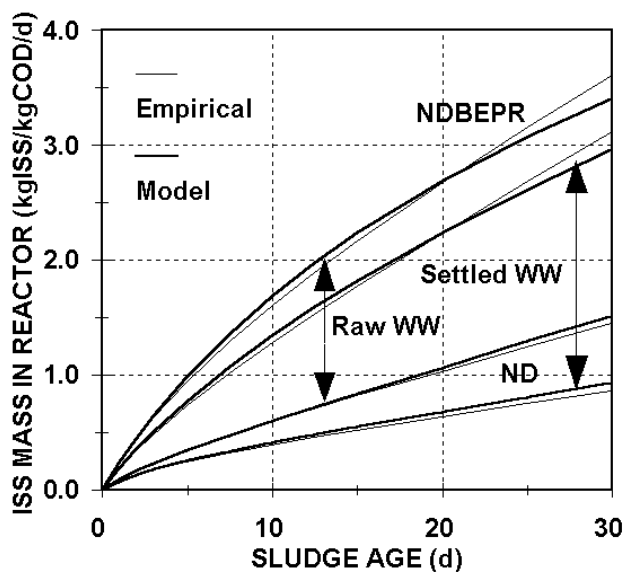


Figure 39

Reactor VSS/TSS ratio vs. sludge age showing similarity between ISS model predicted values and the former empirical approach (constant VSS/TSS ratio with sludge age) provided the correct VSS/TSS ratio is selected for the empirical approach

Figure 40
Mass of ISS in reactor per mass COD load on reactor per day vs. sludge age showing similarity between ISS model predicted values and the former empirical approach (constant VSS/TSS ratio with sludge age) provided the correct VSS/TSS ratio is selected for the empirical approach



VSS/TSS ratio selection in conformity with influent wastewater characteristics and the type of activated sludge system.

The influent ISS/COD ratios calculated for the Mitchells Plain raw wastewater used in the laboratory systems and measured at the WWTP should be used with caution. Influent ISS/COD ratios need to be measured at a number of WWTPs to gain confidence in the analytical procedure and develop realistic ranges for this ratio.

Conclusions

A simple predictive model for estimating activated sludge reactor ISS (and hence TSS) concentration has been developed. It is based on the accumulation of influent ISS in the reactor, an ordinary heterotrophic organism (OHO) ISS content (f_{iOHO}) and a variable

phosphate accumulating organism (PAO) ISS content (f_{iPAO}) proportional to their P content (f_{XBGP}) due to the uptake of inorganic dissolved solids (IDS) from the bulk liquid. This model can be readily integrated into existing steady state or dynamic simulation activated sludge models because these models formed the basis for determining the OHO and PAO ISS contents; and the OHO and PAO VSS concentrations in these models are known from the predictions. This will eliminate having to guess the reactor VSS/TSS for design, but will require the influent ISS concentration to be known. Currently, this concentration is not measured as part of typical wastewater characterisation analyses. It is recommended that in future this be done with the glass fibre filtration and incineration method suggested.

The model was validated with data measured on 48 aerobic,

TABLE 4 Calculated reactor VSS/TSS ratios with Eqs (4 to 7) for the raw and settled wastewater characteristics in Table 3 for accepted P contents of PAOs (f_{XBGP}) of ND (No BEPR), significant anoxic P uptake BEPR (Ax BEPR) and aerobic P uptake BEPR (Aer BEPR) systems.						
Wastewater	Raw wastewater			Settled wastewater		
Influent ISS	0.044 mgISS/mgCOD			0.024 mgISS/mgCOD		
System Type	ND	Ax BEPR	Aer BEPR	ND	Ax BEPR	Aer BEPR
f_{XBGP}	0.03	0.19	0.38	0.03	0.19	0.38
VSS/TSS	0.81	0.75	0.69	0.83	0.71	0.60

anoxic-aerobic nitrification denitrification (ND) and anaerobic-anoxic-aerobic ND biological excess phosphorus removal (BEPR) systems operated in 21 investigations conducted in the Water Research Laboratory at the University of Cape Town over the past 15 years. These systems had sludge ages varying from 3 to 20 days, nominal hydraulic retention times from 9 to 48 h and were fed artificial or real wastewater from the same Mitchells Plain wastewater treatment plant.

From the enhanced PAO cultures investigation, the PAO ISS content (f_{iPAO}) for 100% aerobic P uptake BEPR was calculated to be 1.30 mgISS/mgPAOVSS. From the ND systems fed artificial or real wastewater, the OHO ISS content (f_{iOHO}) was estimated to be around 0.15 mgISS/mgOHOVSS. These calibrated OHO and PAO ISS contents were then applied to NDBEPR systems. For the systems exhibiting more than 90% aerobic P uptake BEPR, the predicted ISS correlated well with that measured. However, for systems exhibiting significant anoxic P uptake BEPR, for which the P content of the PAOs was lower, the correlation was poor. A linear relationship between the P and ISS contents of the PAOs was established i.e., $f_{iPAO} = 3.286 (f_{XBGP} - f_{XBGPBM}) + f_{iPAOBM}$ mgISS/mgPAOVSS, where f_{XBGP} is the total P content of the PAO biomass, which significantly improved the correlation between calculated and measured reactor ISS concentrations. The 3.286 factor is the ISS content of the PAO intracellular polyphosphate which precipitates in the drying step of the TSS-VSS test procedure. This value correlates very closely with the 3.19 mgISS/mgP value theoretically estimated for polyphosphate and the 3.23 value included in ASM2 and 2d.

With the ISS contents of the OHO and PAOs established, the influent ISS concentration to account for the measured reactor ISS concentration was calculated as a ratio of the influent COD concentration (X_{iO}/S_{iO}). For artificial feed systems, as expected, this ratio was very low (0.000 to 0.007) and for the real wastewater systems, it varied between 0.01 and 0.05 for both ND and BEPR systems. Because the influent ISS concentrations were not measured in 18 of the 21 investigations, it was not possible to validate this rather large variation in influent ISS concentration. In 1 of the 3 investigations in which the influent ISS concentration was measured, a reasonably close correlation between calculated and measured influent ISS/COD ratio was obtained, i.e. 0.0267 (28.1 mgISS/l) vs. 0.0308 (32.5 mg ISS/l) in I11 on a fully aerobic laboratory system. In the 2nd and 3rd investigations, the difference between calculated and measured influent ISS/COD ratio was much larger, i.e. in I18 on two 2Ml/d NDBEPR plants 0.0213 (13.1 mgISS/l) vs. 0.0413 (25.3 mgISS/l) and in I12 on two laboratory ND systems, 0.0248 (12.2 mgISS/l) vs. 0.0915 (47.0 mgISS/l). Because influent ISS concentrations measured at the

wastewater treatment plant with an improved analytical procedure yielded values in the range 0.040 to 0.050, the very high measured value for I12 was almost certainly affected by bias resulting from the analytical procedure. The improved procedure reduced bias and increased precision of the measured ISS concentration.

The validated model reflected the observed reactor VSS/TSS sensitivity to sludge age and BEPR. Sludge age does not affect the VSS/TSS ratio much, whereas the the magnitude of P removal per influent COD ratio ($\Delta P/\Delta COD$) affects it significantly, decreasing as $\Delta P/\Delta COD$ increases.

Two parameters are required to use this reactor ISS concentration model: the influent ISS concentration; and the P content of the PAOs (f_{XBGP}). The influent ISS concentration generally is not measured in wastewater characterisation analyses, so that, until a database is developed from which reasonable values can be estimated for raw or settled wastewaters, this concentration will need to be guessed. However, within a reasonable variation of influent ISS concentration, the $\Delta P/\Delta COD$ has the largest influence on the reactor ISS concentration and VSS/TSS ratio. Because the steady state and dynamic simulation models that include BEPR are generally based on the aerobic P uptake BEPR kinetics as developed by Wentzel et al. (1989b, 1992), the effective PAO P content is about 0.38mgP/mgPAOVSS. Sometimes significant anoxic P uptake BEPR takes place in NDBEPR systems, which reduces the BEPR, the $\Delta P/\Delta COD$, the P content of the PAOs (Ekama and Wentzel, 1999; Vermande et al., 2000), and hence also PAO ISS content.

The ISS model is integrated into the steady state model equations for organic solids (VSS) mass in the reactor including OHOs for ND systems, and additionally PAOs for NDBEPR systems. Until BEPR models can predict the reduction in P content of PAOs, and hence P removal, with significant anoxic P uptake BEPR, it is recommended that the P content of PAOs (f_{XBGP}), which is proportional to the ISS content of the PAOs, be selected to suit the system type to obtain an estimate of the reactor VSS/TSS ratio, i.e. 0.03 for ND, 0.19 for anoxic P uptake BEPR and 0.38 for aerobic P uptake BEPR.

Applying the calibrated ISS model to design showed that the reactor VSS/TSS ratio is not very sensitive to sludge age. This means that once an appropriate VSS/TSS ratio is selected to suit a particular wastewater and system type, it can be assumed in design to remain constant with sludge age. A constant VSS/TSS ratio with sludge age has been assumed in design for more than two decades, but now with the proposed ISS model is given an experimental and modelling basis. Some guidance for VSS/TSS ratio selection obtained from the ISS model is given.

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