

# Optimizing water and resource recovery facilities (WRRF) for energy generation without compromising effluent quality<sup>†</sup>

George A Ekama

Department of Civil Engineering, Future Water Institute, University of Cape Town, Rondebosch, 7701, Western Cape, South Africa

<sup>†</sup>Presented at the Joint IWA Large Wastewater Treatment (LWWTP) and Nutrient Removal and Recovery (NRR) Conference, Chongqing, China, 6–8 November, 2017

The primary separation unit (PSU) splits the organic load on the water and resource recovery facility (WRRF) between the primary sludge (PS) anaerobic digester (AD), where energy can be generated, and the biological nutrient removal (BNR) activated sludge (AS) reactor, where energy is consumed. With a CHONP element mass-balanced plant-wide stoichiometric and kinetic steady-state model, this paper explores quantitatively the impact of four cases of increasing organics removal efficiencies in the PSU on (i) settled wastewater characteristics, (ii) balanced solids retention time (SRT) of the Modified Ludzack-Ettinger (MLE) and University of Cape Town/Johannesburg (UCT/JHB) systems for lowest economical effluent N and P concentrations, (iii) reactor volume, (iv) energy consumption for aeration, pumping and mixing, (v) energy generation by AD of PS and waste activated sludge (WAS), (vi) N&P content of the PS and WAS AD dewatering liquor (DWL) and (vii) final effluent N and P concentrations with and without enhanced biological P removal (EBPR), and looks for an optimum WRRF layout for maximum energy recovery without compromising effluent quality. For the low biogas yield from the WAS AD, decreasing as the SRT of the BNRAS system gets longer and with the added complexity of N&P removal from the digested sludge DWL, makes AD of WAS undesirable unless P recovery is required. Because the wastewater biodegradable particulate organics (BPO) have a low N&P content, it is better to divert more biodegradable particulate organics to the PSAD with enhanced primary separation than digest WAS – the PSAD DWL can be returned to the influent with relatively small impact on final effluent N and P concentration.

## INTRODUCTION

Mass conservative plant-wide water and resource recovery facility (WRRF) models have been under development for the past 15 years. Recently these plant-wide models (PWM) have been extended to include P, which has added considerable complexity and size (many more components). The aim of these PWM models is not only to evaluate control strategies in WRRF under real-time dynamic influent loading conditions (Gernaey et al., 2014; Solon et al., 2017), but also to expose the significant interactions that the different unit operations of a WRRF have on one another, such as the impact of recycling the N and P in anaerobic digestion (AD) dewatering liquor (DWL) on the final effluent N and P concentrations (Lizzaralde et al. 2015; Kazadi Mbamba et al., 2016). Because reactor volumes and flows need to be specified before simulation, these models cannot (except by user trial and error) optimize reactor/unit sizes, solids retention times (SRT) and interconnecting flows to find an optimal WRRF layout for maximizing useful outputs like methane gas while keeping effluent N&P concentrations as low as possible. Overall WRRF layout optimization and sizing to meet specified objectives before simulation is best done with plant-wide steady-state models (Ekama, 2009). In this paper the CHON element mass balanced Plant-Wide Stoichiometric and kinetic Steady-State Model (PWSSM) of Ekama (2009) is extended to include P, to explore quantitatively the impact of four increasing organics (COD) removal efficiencies (40, 46, 52, 59%) in the primary separation unit (PSU) on (i) settled wastewater (WW) characteristics, (ii) balanced solids retention time (SRT) of the biological nutrient removal (BNR) system, (iii) reactor volume and SST area, (iv) energy consumption for aeration and pumping at this balanced SRT, (v) energy generation by anaerobic digestion (AD) of primary sludge (PS) and/or waste activated sludge (WAS), (vi) N&P content of the PS and WAS AD DWL with and without enhanced biological P removal (EBPR) and struvite precipitation, and (vii) final effluent N&P concentrations.

## Description of the plant-wide steady-state model (PWSSM)

The PWSSM spreadsheet developed for this investigation comprises interconnected primary separation unit (PSU), BNR activated sludge, aeration, secondary settling tank (SST), separate primary sludge (PS) and waste activated sludge (WAS) thickening, anaerobic digestion (AD) and dewatering, while maintaining water, CHONP and TOD material balances via stoichiometry over each unit operation and plant wide, where TOD is the total oxygen demand which is the COD plus the oxygen demand of the reduced N (TKN) with respect to nitrate.

The BNRAS models are based on WRC (1984), Wentzel et al. (1990), Henze et al. (2008), and Ekama (2009, 2011), which allow sizing standard BNR systems, such as the Modified Ludzack-Ettinger (MLE) and 4-stage Bardenpho N for removal by nitrification-denitrification (ND), and the University of Cape Town (UCT), Johannesburg (JHB) and 3- and 5-stage Bardenpho systems for N&P removal.

## CORRESPONDENCE

George A Ekama

## EMAIL

[george.ekama@uct.ac.za](mailto:george.ekama@uct.ac.za)

## DATES

Received: 9 July 2019

Accepted: 12 April 2021

## KEYWORDS

primary settling tanks  
biological nutrient removal  
anaerobic digestion  
energy generation  
energy consumption

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In this paper only the MLE (Fig. 1a), UCT (Fig. 1b) and JHB (Fig. 1c) systems are considered.

The AD model is that of Sötemann et al. (2005) using Monod kinetics to convert the COD of biodegradable particulate organics (BPO) to AD biomass ( $E$ ) and methane ( $1-E$ ), where  $E$  is the 'observed yield', i.e., the proportion of the biodegradable COD converted to AD biomass (0.07–0.04), which is a function of the AD biomass yield ( $Y_{AD}$ ) and endogenous respiration rate ( $b_{AD}$ ) and AD SRT.

In the energy model, methane gas generates electricity 15.1 kWh/kgCH<sub>4</sub> and a thermal efficiency of 45% estimated for steam turbine heat exchangers (Chang et al., 2014). The energy consumed by the AD itself was estimated from (i) 30 W/m<sup>3</sup> AD volume to maintain 37°C (Taricska et al., 2009; Liu and Liptak, 1997) and (ii) heating the AD influent to 37°C. From these considerations and the Monod hydrolysis rate of PS or WAS BPO (Ikumi et al., 2014), the AD needs to operate at the shortest possible SRT for maximum surplus energy and 10 d was selected for PS and 15 d for WAS. The WAS BPO is the biodegradable fraction of the OHO and PAO biomass. Pumping energy was calculated from the flows and static lift, viz. influent 5 m, sludge return ( $s = 1:1$ ) 2 m and mixed liquor ( $a = 6:1$ ,  $r = 1:1$ ) recycle 0.4 m.

The aeration model calculates the actual oxygen transfer rate (OTR, kgO/kWh) from the standard OTR (2.5 kgO/kWh) using the usual corrections for temperature (14°C), pressure (altitude 100 m amsl) and wastewater characteristics such as those given in Tchobanoglous et al. (2004). Only average aeration energy requirement was considered – peak aeration power is for sizing the aeration equipment, not for energy consumption by it.

The SST model is based on the idealized one-dimensional flux theory (1DFT, Ekama and Marais, 1986; Ekama et al., 1997) and a

flux rating of 0.8 is applied, which decreases the maximum applied flux [kgTSS/(m<sup>2</sup>·d)] to 80% of the 1DFT calculated maximum flux (Ekama and Marais, 2004). The flux theory constants  $V_0$  and  $n$  are calculated from the selected Diluted Sludge Volume Index (DSVI = 100 mL/g) with the equations of Ekama and Marais (1986).

The PST model is described below with the wastewater (WW) characterisation.

The remaining physical units such as thickening and dewatering are point concentrators of settleable solids (SS) to a selected TSS concentration, e.g., 5% total suspended solids (TSS) where 1%TSS = 10 000 mgTSS/L and the dissolved concentrations followed the water lines. A dewatered cake solids value of 25%TSS for disposal was assumed.

Mixing energy is usually around 5 W/m<sup>3</sup> reactor volume for the unaerated zones. The mixing energy is deemed not to change significantly with the comparison of the various scenarios presented, hence is not included in the presented calculations.

The combined PWSSM is general and a wide range of different input parameters can be entered to determine the effects of changes in WW characteristics, PSU and activated sludge settleability on (i) BNR system reactor volume, SST surface area and effluent quality, (ii) energy consumption and generation by AD of PS and WAS, and (iii) the effect of the N&P concentrations in the AD DWL on the BNR systems and effluent quality. A similar PWSSM has been developed by Wu and Ekama (2015). These steady-state models are aligned with the continuity, stoichiometry and kinetic principles of the dynamic simulation models (Ekama, 2009). They give similar results as the dynamic models under steady-state conditions and so can be used to optimally size bioprocess units of a WRRF for dynamic simulation model input.

### Influent wastewater characteristics

For this investigation, WW characteristics used in previous studies were used (WRC, 1984; Ekama, 2009, 2011, Tables 1a to c). The PWSSM requires eight raw influent WW concentrations, the five organics components making up the COD, i.e., (i) volatile fatty acids (VFA), (ii) fermentable biodegradable soluble organics (FBSO), (iii) unbiodegradable soluble organics (USO), (iv) biodegradable particulate organics (BPO), (v) unbiodegradable particulate organics (UPO), and the three inorganics components, i.e. (vi) free and saline ammonia (FSA), (vii) ortho-phosphate (OP) and (viii) inorganic suspended solids (ISS). The particulate components (BPO, UPO, ISS) each subdivide into settleable and non-settleable fractions. Each of the five organics groups have a COD ( $f_c$ ), C ( $f_C$ ), N ( $f_N$ ) and P ( $f_P$ ) to mass ratio (Table 1). The raw WW component COD concentrations (Table 2) are calculated from the selected raw WW COD fractions (Table 3) and the organic N and P concentrations are calculated from the component COD concentrations and mass ratios (Table 1). The influent total Kjeldahl nitrogen (TKN) and total P (TP) are then the sum of the organic N and FSA and the organic P and OP, respectively. The proportions of the particulate components (BPO, UPO, ISS) that are settleable are selected and it is assumed the PSU removes 100% of these settleable components, while maintaining 100% water, COD, N, P and ISS mass balances. In this fractionation method the dissolved concentrations are the same in the primary sludge (PS) and settled and raw WW and the only settled WW fraction that is independent of the raw WW is the settled WW UPO fraction ( $f_{sup}$ ). The dissolved and non-settleable concentrations constitute the settled WW and the dissolved and settleable concentrations constitute the PS. By selecting increasing proportions of BPO, UPO and ISS that are settleable, the effect of the split of organics and ISS between the PSAD and the BNRAS system on the WRRF energy production and consumption and effluent quality was investigated (Table 4).

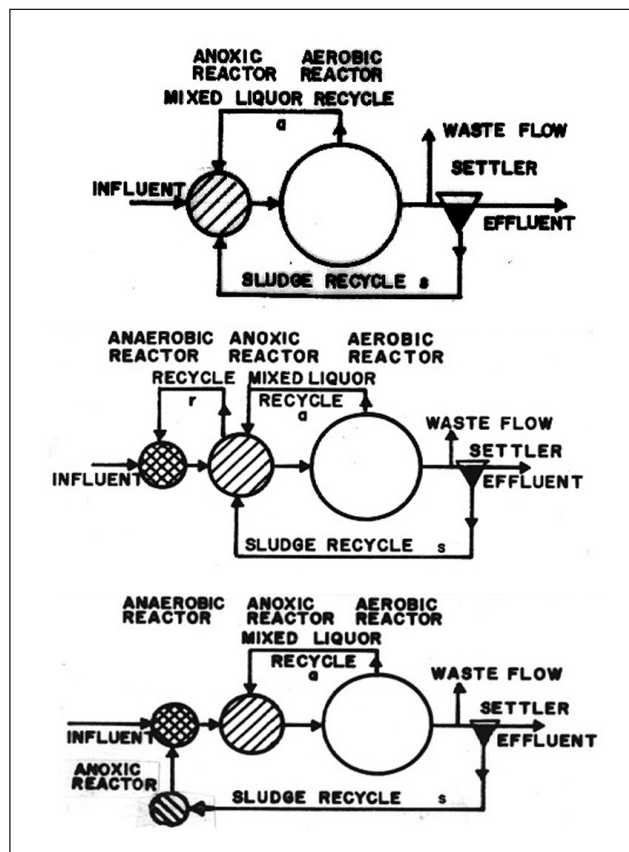


Figure 1. The Modified Ludzack-Ettinger (MLE, 1a, top), University of Cape Town (UCT, 1b, middle and Johannesburg (JHB, 1c bottom) BNR systems

**Table 1.** Organic component mass ratios and molar compositions used in this investigation to align with raw and settled wastewater concentrations used in previous papers (WRC, 1984; Ekama, 2009, 2011)

Group	COD	C	H	O	N	P	Composition in $C_xH_yO_zN_aP_b$ ( $x = 1$ )				
Ratio	$f_{cv}$	$f_c$	$f_H$	$f_o$	$f_N$	$f_P$	$x$	$y$	$z$	$a$	$b$
VFA	1.067	0.400	0.067	0.533	0.0	0.0	1.0	2.0	1.0	0.0	0.0
FBSO	1.420	0.470	0.076	0.427	0.017	0.010	1.0	1.942	0.681	0.030	0.008
USO	1.420	0.470	0.074	0.370	0.049	0.000	1.0	1.833	0.600	0.086	0.000
BPO*	1.500	0.510	0.069	0.392	0.019	0.010	1.0	1.623	0.577	0.032	0.008
UPO*	1.481	0.518	0.066	0.291	0.100	0.025	1.0	1.534	0.421	0.166	0.019

\*In this investigation settleable and non-settleable organics have the same composition. While this affects the split of N and P between the BNRAS and AD by the PSU, methods of measuring the compositions of settleable and non-settleable BPO and UPO are currently under investigation.

**Table 2.** Wastewater concentrations calculated from total COD concentrations (Raw 750, Settled 450) and mass ratios in Table 1 and fractions in Table 3. 100% settleable organics (BPO and UPO) and ISS removal in PSU is assumed. The settled WW concentrations conform to the observation that UPO and ISS are removed in greater proportion (84%, 80%) than BPO (47%) (Wentzel et al., 2006; Ikumi et al., 2014). Overall COD, N and P removals in PSU for given concentrations are 40.3%, 15.3% and 21.5% (Case 1)

	Raw WW	Settleable			Settled WW	Non-settleable			Dissolved			
		BPO	UPO	InOrg		BPO	UPO	InOrg	VFA	FBSO	USO	InOrg
COD	750	206	94	---	450	233	18	---	0	147	52	---
SuspS	416	137	64	38	177	155	12	10	---	---	---	---
TKN	60.0	2.6	6.4	---	51.1	3.0	1.2	---	0	1.7	1.8	43.3
TP	14.0	1.4	1.6	---	11.0	1.6	0.3	---	---	1.0	0.0	8.2
TOC	255	70.0	32.9	---	152.1	79.3	6.3	---	0.0	48.7	17.8	---

**Table 3.** Raw and settled wastewater fractions assumed in this investigation (WRC, 1984)

Fraction	Raw	Settled	Fraction	Raw	Settled
Unbiod. soluble COD ( $f_{sus}$ )	0.050	0.076	Unbio COD of settleable COD	0.319	0.000
Unbiod. particulate COD ( $f_{sup}$ )	0.130	0.029	FSA/TKN ratio	0.611	0.734
RBCOD of total COD ( $f_{bs}$ )	0.134	0.206	OP/TP ratio	0.600	0.721
RBCOD of biodeg COD ( $f_{bv}$ )	0.163	0.230	VSetS/TSetS ratio	0.789	0.000
Settleable COD of total COD	0.349	0.000	ISS to total COD ratio ( $X_{Ior}/S_{ti}$ )	0.087	0.045

**Table 4.** Percentage BPO, UPO and ISS particulates and overall COD, TKN, TP and TSuspS removals by primary separation (PST, rotary drum or filter) considered in this investigation

Scenario	% Particulates removal			Overall % removals			
	BPO	UPO	ISS	COD	TKN	TP	TSuspS
Case 1	46.9	83.9	80.0	40.3	15.3	21.5	57.7
Case 2	55.0	88.0	85.0	45.6	16.7	23.8	64.7
Case 3	65.0	92.0	90.0	52.1	18.1	20.5	73.0
Case 4	75.0	96.0	95.0	58.5	19.6	29.2	81.3

## SOME PRELIMINARY CONSIDERATIONS

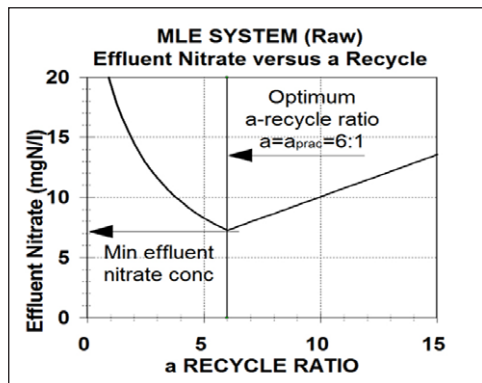
### The balanced BNRAS system sludge age (SRT)

The balanced SRT offers the lowest BNRAS system reactor volume because it is the shortest SRT at which it can be operated to ensure nitrification and achieve the lowest economical effluent nitrate concentration. At the balanced SRT, the denitrification performance of the primary anoxic zone is optimal because the maximum practical  $a$ -recycle ratio ( $a_{prac}$ , say 6:1) is equal to the optimum  $a$ -recycle ratio ( $a_{opt}$ ). At  $a_{opt}$ , the equivalent nitrate load on the anoxic zone, which is set by the influent TKN concentration and includes the dissolved oxygen (DO) recycled from the aerobic zone, is equal to its denitrification potential ( $D_{pi}$ ), which is set by the influent organics (COD) concentration. At  $a_{opt}$ , the effluent nitrate concentration ( $N_{ne}$ ) is lowest because a lower  $a$ -recycle ratio underloads the anoxic zone with nitrate and a higher  $a$ -recycle ratio overloads the anoxic zone with nitrate and discharges unnecessary

high DO to the anoxic zone, which reduces denitrification and increases effluent nitrate (Fig. 2). The maximum practical  $a$ -recycle ratio ( $a_{prac}$ ) is set at around 5 to 7:1 because increasing the ratio above this reduces the effluent nitrate concentration by only 1 to 2 mgNO<sub>3</sub>-N/L (<2%), which is not worth the increase in power costs from recycling 1x or 2x ADWF more.

At  $a_{opt}$ , the effluent nitrate concentration ( $N_{ne}$ ) is lowest because a lower  $a$ -recycle ratio underloads the anoxic zone with nitrate and a higher  $a$ -recycle ratio overloads the anoxic zone with nitrate and discharges unnecessary high DO to the anoxic zone (the model considers a dissolved oxygen concentration of 2 mgO/L flowing within the  $a$ -recycle), which reduces denitrification and increases effluent nitrate (Fig. 2). The maximum practical  $a$ -recycle ratio ( $a_{prac}$ ) is set at around 5 to 7:1 because increasing the ratio above this reduces the effluent nitrate concentration by only 1 to 2 mgNO<sub>3</sub>-N/L (<2%), which is not worth the increase in power costs from recycling 1x or 2x ADWF more.





**Figure 2.** Effluent nitrate concentration vs mixed liquor a-recycle ratio from aerobic to primary anoxic zones

The balanced SRT for the MLE system (Fig. 1a) was first proposed by Van Haandel et al. (1982) and its determination by an iterative procedure is described in detail in Henze et al. (2008), viz., for given wastewater characteristics, the SRT is increased incrementally and the maximum unaerated sludge mass fraction ( $f_{xm}$ ), nitrification capacity ( $N_c$ ), denitrification potential of the primary anoxic zone ( $D_{p1}$ ) set equal to  $f_{xm}$ ,  $a_{opt}$  and  $N_{ne}$  are calculated. An  $a_{prac}$  is selected (say 6:1) and the SRT at which the  $a_{opt} = a_{prac}$  is the MLE system balanced SRT. An explicit equation for the balanced SRT of the MLE is given by Robertson and Ekama (2016) and Appendix 2.

The UCT and JHB systems also have a balanced system SRT. Explicit equations for these have not been derived because they are complicated by the iterative calculation which divides the influent FBSO between the polyphosphate accumulating organisms (PAO) and ordinary heterotrophic organisms (OHO). It is easiest to determine them with the iterative procedure by incrementally increasing the system SRT until  $a_{opt} = a_{prac}$  (say 6:1) (Robertson and Ekama, 2016). The main differences in the calculation for the balanced system SRT of the UCT and JHB systems compared with that for the MLE system are: (i) the influent FBSO has to be divided between the OHO and PAO (which get ~80–90%) with the fermentation model of Wentzel et al. (1985) or Wentzel et al. (1990), Henze et al. (2008), Ekama (2011); (ii) denitrification is mediated by OHO only; and (iii) the specific OHO denitrification rates in the primary and secondary anoxic zones at 20°C ( $K_{220}$ ,  $K_{320}$ ) are increased from 0.101 and 0.072 mgNO<sub>3</sub>-N/(mgOHVSS-d) in ND systems to 0.255 ( $K'_{220}$ ) and 0.114 ( $K'_{320}$ ) mgNO<sub>3</sub>-N/(mgOHVSS-d) in NDEBPR systems (Clayton et al., 1991; Ekama and Wentzel, 1999). Additionally, for the UCT system (iv) the primary anoxic sludge mass fraction ( $f_{x1}$ ) is the difference between the maximum unaerated sludge mass fraction ( $f_{xm}$ ) allowed at a particular SRT to ensure nitrification and the anaerobic sludge mass fraction ( $f_{xa}$ ), viz.  $f_{x1} = f_{xm} - f_{xa}$ , and for the JHB system (iv) the sum of the primary ( $f_{x1}$ ) and secondary ( $f_{x3}$ ) (underflow) anoxic sludge mass fractions ( $f_{x1} + f_{x3}$ ) is the difference between the maximum unaerated sludge mass fraction ( $f_{xm}$ ) allowed at a particular SRT to ensure nitrification and the anaerobic sludge mass fraction ( $f_{xa}$ ), viz.  $f_{x1} + f_{x3} = f_{xm} - f_{xa}$ .

Subject to the above four changes, the equation for the optimum a-recycle ratio ( $a_{opt}$ ) for the UCT system is the same as for the MLE system and the SRT at which  $a_{opt} = a_{prac}$  (say) 6:1 is the balanced SRT for the UCT system (Henze et al., 2008; Ekama, 2011). Similarly, the balanced SRT for the JHB system is the SRT at which the primary anoxic zone ( $f_{x1}$ ) is loaded exactly to its denitrification potential by the optimum a-recycle ratio ( $a_{opt}$ ) equal the maximum practical ( $a_{opt} = a_{prac}$ ) and the secondary anoxic zone ( $f_{x3}$ ) in the underflow is exactly large enough to denitrify the nitrate entering it to protect the VFA uptake by PAO in the anaerobic zone.

Setting the required SRT on a BNRAS plant is extremely important – if the SRT is not known accurately, the plant cannot be modelled accurately. Withdrawal of WAS from the underflow does not control SRT! The advantages of establishing and controlling SRT on BNR systems hydraulically by wasting from the reactor a fixed fraction of the reactor volume daily (as in Fig. 1) are outlined by Ekama (2010).

For the same wastewater characteristics and SRT, the mass of TSS in an NDEBPR reactor is 15–20% higher than in an ND reactor because (i) PAO produce more VSS per kgCOD than OHO due to their lower endogenous respiration rate (0.04/d compared with 0.24/d at 20°C) and (ii) there is additional ISS from the PAO polyphosphate content (3.286 mgISS/mgP). With chemical P removal, a higher ISS is expected from the phosphate precipitate that is formed by the dosed cation. The same applies to EBPR, except the ‘precipitate’ is polyphosphate and Mg, K and Ca cations in the influent are used by PAO to form it (Ekama and Wentzel, 2004). So for the same organic load, NDEBPR systems have larger reactors because (i) sludge production is higher and (ii) their balanced SRTs are longer to accommodate the anaerobic reactor.

### Determining the volume and SST area for a BNR system

Once the SRT of a BNRAS system is established, the mass of TSS in the reactor ( $MX_t$ , kgTSS) is known from the organic (and ISS) load on the reactor ( $FS_{ti} = Q_{ADWF} S_{ti}$ , kgCOD/d), where  $Q_{ADWF}$  is the average dry weather flow (ADWF),  $S_{ti}$  the total flow-weighted average influent COD concentration to the BNR system.  $MX_t$  is the product of the average reactor TSS concentration ( $X_{tave}$ ) and the reactor volume ( $V_R$ ), viz.  $MX_t = X_{tave} V_R$ . Hence the reactor volume is found by selecting a reactor TSS concentration ( $X_{tave}$ ). Selection of  $X_{tave}$  is done via a reactor volume and SST area cost minimization calculation (Ekama et al., 1997; Ekama, 2011). As  $X_{tave}$  increases so the reactor volume ( $V_R$ ) and its cost decrease and (for a selected sludge settleability) the SST area ( $A_{ST}$ ) and its cost increase. The combined cost will be a minimum over a range (~2 gTSS/L) of reactor TSS concentration and a TSS in this range is selected for the BNR-SST system. This reactor TSS for minimum combined cost increases for (i) raw WW, (ii) higher influent COD concentration, (iii) longer SRT and (iv) EBPR because these increase the mass of TSS in the reactor ( $MX_t$ ) without affecting the SST area. In contrast, the TSS for minimum combined cost decreases for (v) higher peak wet weather flow (PWWF) to ADWF ratio ( $f_q$ ) and (vi) poorer sludge settleability, because these increase the area of the SST without affecting the mass of TSS in the reactor ( $MX_t$ ). Required in this calculation is the link between the average reactor TSS concentration ( $X_{tave}$ ) and the aerobic reactor TSS concentration ( $X_{taer}$ ) because these are different for different BNR systems (Parco et al., 2018). For systems with the same TSS concentration in each zone, like the MLE and 3-, 4- and 5-stage Bardenpho systems,  $X_{tave} = X_{taer}$  and so  $X_{tave}$  can be replaced by  $X_{taer}$  in the cost minimization calculation. However, for UCT and JHB systems,  $X_{taer} \neq X_{tave}$  because the TSS concentration is not the same in each zone of the system. In the UCT system, the anaerobic zone TSS concentration is a factor  $r/(1+r)$  times  $X_{taer}$ , and for the JHB system, the underflow anoxic zone TSS concentration is a factor  $(1+s)/s$  times  $X_{taer}$ . From the equations relating sludge mass and volume fractions of different BNR systems with SST (or membranes) of Ramphao et al. (2006) or Parco et al. (2018), for the UCT system,  $X_{tave} = X_{taer} [1 - f_{xa} / (1+r)]$ , and for the JHB system,  $X_{tave} = X_{taer} / [1 + f_{x3} / s]$ . So for the UCT and JHB systems,  $X_{tave}$  needs to be replaced with these  $X_{taer}$  equations in the  $MX_{tave} = X_{tave} V_R$  because  $X_{taer}$  is the SST feed TSS concentration in these systems.

### Determining the capacity of an existing BNR system

For a given biological reactor volume  $V_R$  (and anaerobic mass fraction  $f_{xa}$  if applicable) and SST surface area ( $A_{ST}$ ), the average dry weather flow ( $Q_{ADWF}$ ) capacity (ML/d) can be calculated for

a particular WW with known characteristics. With the required (balanced) SRT known, the mass of sludge in the reactor ( $MX_r$ , kgTSS) per kgCOD/d load applied to the reactor [ $L_{sys}$  kgTSS/(kgCOD/d), which, when divided by SRT, is the specific sludge production rate,  $SSP_{COD,TSS}$  kgTSS/d per kgCOD/d, WRC (1984), Tchobanoglous et al. (2004)] is known, i.e.  $MX_r = L_{sys} \cdot Q_{ADWF} \cdot S_{li}$  where  $L_{sys}$  is a function of SRT and the WW characteristics and is different for ND ( $L_{ND}$ ) and NDEBPR ( $L_{EBPR}$ ) systems. Hence,  $Q_{ADWF} = V_r \cdot X_{tave} / (S_{li} \cdot L_{sys})$  ML/d. This equation has two unknowns,  $Q_{ADWF}$  and  $X_{tave}$ , so one more fact is required to determine  $Q_{ADWF}$ . This is obtained from the overflow rate on the SST. From the 1DFT, the overflow rate at PWWF must not be greater than the flux rating (0.8) times settling velocity of the sludge at the SST feed or aerobic zone TSS concentration ( $V_s$ ), i.e.,  $Q_{PWWF}/A_{ST} = 0.8 V_s = 0.8 V_0 \exp(-nX_{tave})$  (m/h). Converting  $Q_{PWWF}$  to ML/d and selecting a PWWF/ADWF ratio ( $f_q$ ), yields:

$$Q_{ADWF} = (24A_{ST} \cdot 0.8V_0) / (1000 f_q) \cdot \exp(-nX_{tave}) \text{ ML/d}$$

Then, substituting the above equations linking  $X_{tave}$  and  $X_{tave}$  for the different systems, yields:

MLE:  $X_{tave} = F \cdot \exp(-nX_{tave})$ ,  
 where  $F = (A_{ST} \cdot 0.8V_0 \cdot S_{li} \cdot L_{ND} \cdot 24) / (V_r \cdot f_q \cdot 1000)$ .

UCT:  $X_{tave} = G \cdot \exp(-nX_{tave})$ ,  
 where  $G = (A_{ST} \cdot 0.8V_0 \cdot S_{li} \cdot L_{EBPR} \cdot 24) / \{V_r \cdot f_q \cdot 1000 [1 - f_{xa} / (1 + r)]\}$

JHB:  $X_{tave} = H \cdot \exp(-nX_{tave})$ ,  
 where  $H = [A_{ST} \cdot 0.8 \cdot V_0 \cdot S_{li} \cdot L_{EBPR} \cdot 24 (1 + f_{x3}/s)] / (V_r \cdot f_q \cdot 1000)$

These equations are solved by finding the  $X_{tave}$  that equates the left- and right-hand sides. Once  $X_{tave}$  is found, the WRRF capacity is given by either of the  $Q_{ADWF}$  equations above.

### The four primary separation cases

The primary separation unit (PSU) splits the organic load between the PSAD, where energy can be generated, and the BNRAS reactor, where energy is consumed. The more organics diverted to the PSAD, the lower the organic load on the BNRAS system and the lower the energy consumption for aeration but the higher the influent TKN/COD ratio of the settled wastewater. This is because a much greater fraction of organics (COD) is particulate than TKN – most TKN is dissolved FSA, which passes through the PSU. The impact of four cases of particulates (BPO, UPO and ISS) removal by primary separation (Table 4) on the balanced system SRT of the MLE, UCT and JHB systems, their energy consumption, reactor volume, SST area and effluent quality (N&P) and energy production by PS and WAS AD and the N&P content of their dewatering liquor, are considered in this plant-wide study.

### RESULTS AND DISCUSSION

A selection of PWSSM results for the MLE- and UCT-based WRRFs for the four cases of PSU organics and ISS removal efficiencies are given in Table 5 and Figs 3 and 4 show the PWSSM outputs for the MLE and UCT-based WRRF for Case 1.

Once the reactor and SST have been sized for lowest combined cost for a selected organic load and PWWF/ADWF ( $f_q$ ) ratio, this total volume can be reassigned between the reactor and SST in different proportions over quite a wide range (AS 45–65% and SST 55–35% of combined volume) without negatively impacting the plant's ADWF capacity significantly (<3%, Fig. 5). This is because a larger reactor volume reduces the SST feed concentration which allows a higher overflow rate and hence a smaller SST.

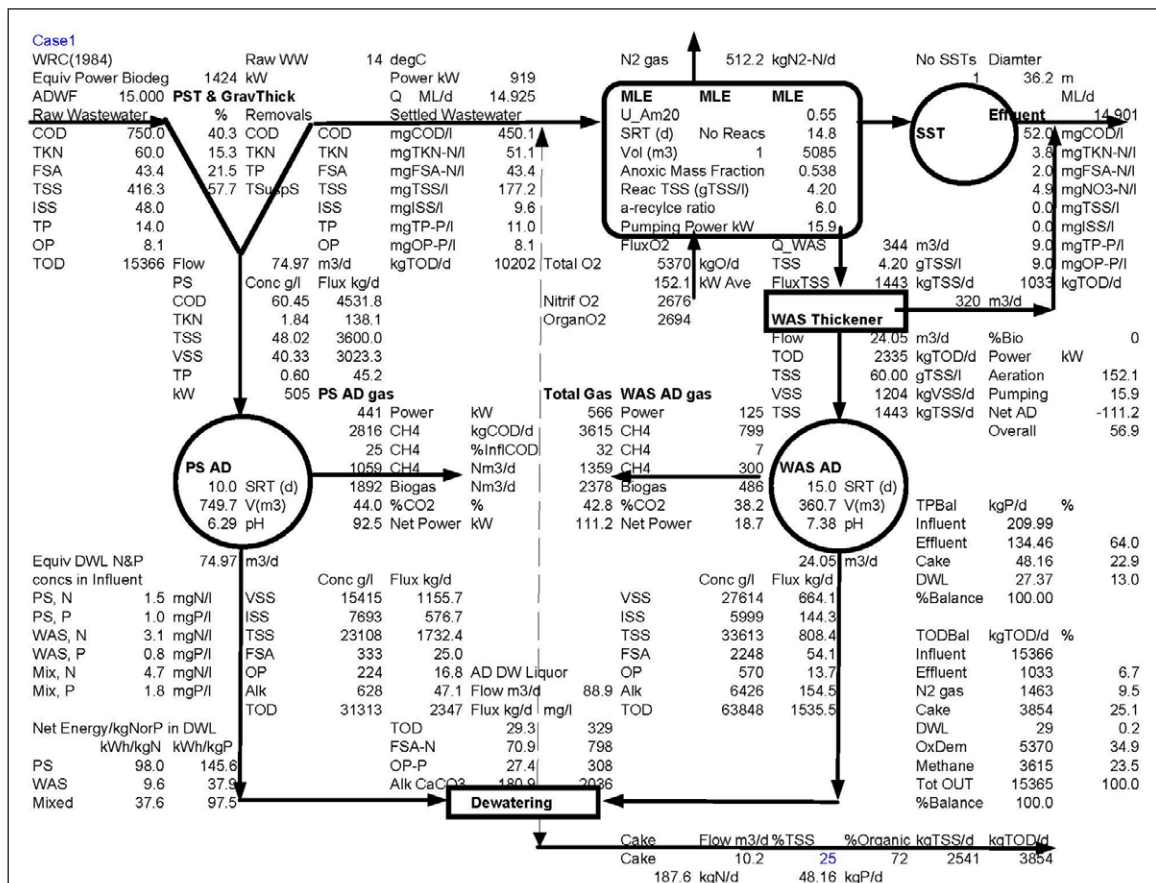
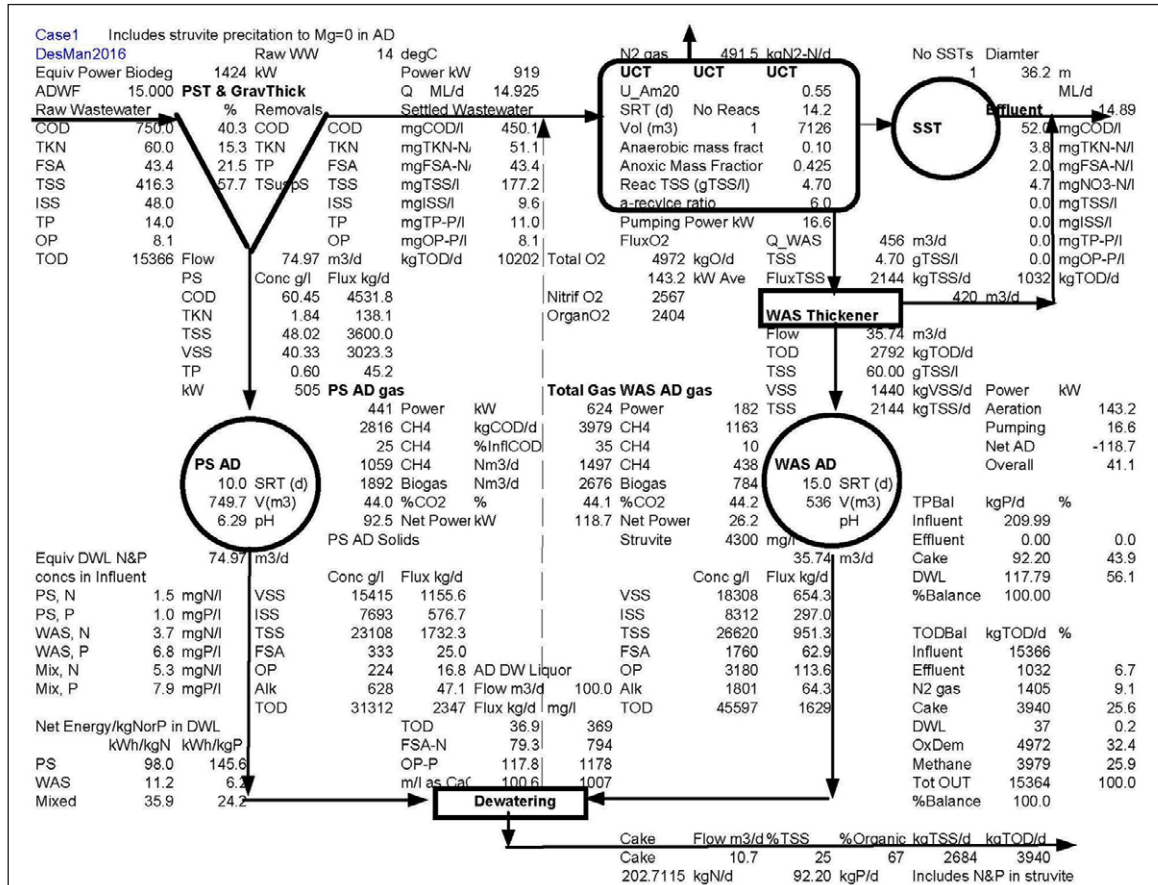
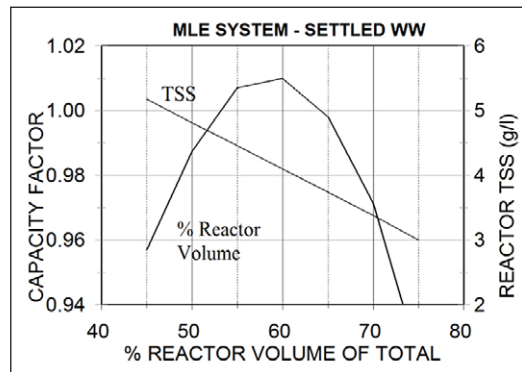


Figure 3. PWSSM results for the MLE BNR-based WRRF for PSU organics removal Case 1 including AD of PS and WAS but excluding the return of N&P in dewatering liquor to the MLE system



**Figure 4.** PWSSM results for the UCT BNR-based WRRF for PSU organics removal Case 1 including AD of PS and WAS and N&P removal in the sludge cake due to struvite precipitation but excluding the return of N&P in dewatering liquor to the UCT system. From the Mg content of polyphosphate ( $Mg_{0.27}K_{0.22}Ca_{0.12}$ ) about 25% of the PAO P released in AD precipitates with Mg as struvite (Harding et al., 2010)



**Figure 5.** Capacity factor as % of design capacity obtained from cost-minimization procedure and reactor TSS concentration versus reactor volume as % of total combined reactor of SST

**Table 5.** Plant-wide steady-state model results for primary separation Cases 1 to 4 (Table 4) for the MLE and UCT BNR based water and resource recovery facilities (WRRF)

		MLE	MLE	MLE	MLE	UCT	UCT	UCT	UCT
		Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
<b>5.1 Settled wastewater</b>									
Flow rate	ML/d	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
COD	mg/L	450.1	410.0	361.6	313.2	450.1	410.0	361.6	313.2
TKN	mgN/L	51.1	50.3	49.5	48.6	51.1	50.3	49.5	48.6
FSA	mgN/L	43.4	43.4	43.4	43.4	43.4	43.4	43.4	43.4
TSuspS	mg/L	177.2	148.0	113.3	78.6	177.2	148.0	113.3	78.6
ISuspS	mg/L	9.6	7.2	4.8	2.4	9.6	7.2	4.8	2.4
TP	mgP/L	11.0	10.7	10.4	10.0	11.0	10.7	10.4	10.0
OP	mgP/L	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1
TKN/COD	mgN/mg	0.113	0.123	0.137	0.155	0.113	0.123	0.137	0.155
TP/COD	mgP/mg	0.025	0.026	0.029	0.032	0.025	0.026	0.029	0.032



**Table 5 continued.** Plant-wide steady-state model results for primary separation Cases 1 to 4 (Table 4) for the MLE and UCT BNR based water and resource recovery facilities (WRRF)

		MLE	MLE	MLE	MLE	UCT	UCT	UCT	UCT
		Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
<b>5.2 Primary sludge</b>									
Flow	m <sup>3</sup> /d	75.0	85.0	97.1	109.2	75.0	85.0	97.1	109.2
COD flux	kg/d	4 532	5 135	5 861	6 586	4 532	5 135	5 861	6 586
TKN flux	kg/d	138	150	163	177	138	150	163	177
TP flux	kg/d	45	50	56	61	45	50	56	61
TSS flux	kg/d	3 600	4 037	4 556	5 074	3 600	4 037	4 556	5 074
VSS flux	kg/d	3 023	3 425	3 908	4 390	3 023	3 425	3 908	4 390
<b>5.3 BNR activated sludge systems</b>									
SRT (d)	BNRAS	14.8	17.4	23.2	38.0	13.7	15.4	18.5	25.2
Volume	m <sup>3</sup>	5 085	4 936	4 980	5 429	6 923	6 875	7 019	7 462
Anoxic mass fraction		0.538	0.550	0.550	0.550	0.414	0.450	0.450	0.450
Reactor MLSS (mgTSS/L)		4 200	4 200	4 200	4 300	4 700	4 700	4 700	4 700
SST diam.	M	36.2	36.2	36.2	36.8	39.4	39.4	39.4	39.4
a-recycle ratio		6.0	4.8	3.3	2.4	6.0	6.0	3.4	2.0
Nitrific	kgO/d	2 675	2 751	2 836	2 904	2 562	2 599	2 701	2 788
Organic	kgO/d	2 694	2 381	1 955	1 546	2 388	2 057	1 657	1 270
Total	kgO/d	5 369	5 074	4 710	4 345	4 949	4 654	4 298	3 962
FluxTSS WAS, kgTSS/d		1 443	1 192	902	613	2 159	1 907	1 596	1 216
<b>5.4 Final effluent</b>									
COD	mg/L	52.0	52.0	52.0	52.0	52.0	52.0	52.0	52.0
TKN	mgN/L	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Nitrate	mgN/L	4.9	5.0	5.1	5.1	4.7	4.8	5.0	5.3
Ortho-P	mgP/L	9.0	9.0	9.0	9.1	0.0	0.0	0.4	2.0 <sup>(1)</sup>
<b>5.5.1 Sludge treatment (primary sludge)</b>									
PS AD	SRT (d)	10	10	10	10	10	10	10	10
Volume	m <sup>3</sup>	750	850	971	1 092	750	850	971	1 092
Power	kW(100%)	441	517	610	704	441	517	610	704
CH <sub>4</sub>	kgCOD/d	2 816	3 300	3 897	4 493	2 816	3 300	3 897	4 493
CH <sub>4</sub>	%InflCOD	25.0	29.3	34.6	39.9	25.0	29.3	34.6	39.9
<b>5.5.2 Sludge treatment (waste activated sludge)</b>									
WAS AD	SRT (d)	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Volume	m <sup>3</sup>	371	308	233	155	540	477	399	304
Power	kW(100%)	126	101	70	39	186	160	129	94
CH <sub>4</sub>	kgCOD/d	807	646	447	250	1 185	1 022	822	602
CH <sub>4</sub>	%InflCOD	7.2	5.7	4.0	2.2	10.5 <sup>(2)</sup>	9.1	7.3	5.4
kW	Aeration (energy use in activated sludge system and not AD)	154.6	146.1	135.6	125.1	142.7	134.0	123.9	114.1
kW	Pumping	15.9	15.9	15.9	15.9	16.6	16.6	16.6	16.6
kWsurplus <sup>(3)</sup>	AD PS	92.5	112.4	137.4	162.3	92.5	112.4	137.4	162.3
kWsurplus <sup>(3)</sup>	ADWAS	18.2	13.4	7.2	1.5	27.3	22.4	16.4	10.8
<b>5.6 Dewatering liquor – equivalent concentrations in influent</b>									
PS, FSA	mgN/L	1.51	1.77	2.10	2.42	as for MLE (left)			
PS, OP	mgP/L	1.02	1.20	1.42	1.64	as for MLE (left)			
WAS, FSA	mgN/L	3.16	2.53	1.73	0.95	3.84	3.19	2.43	1.71
WAS, OP	mgP/L	0.80	0.64	0.44	0.24	6.78	6.64	6.16	4.93
Mix, FSA	mgN/L	4.76	4.39	3.91	3.44	5.38	5.00	4.57	4.16
Mix, OP	mgP/L	1.83	1.85	1.87	1.89	7.86	7.92	7.69	6.70
<b>5.7 Surplus energy from AD per kgN or P in dewatering liquor (kWh/kgN or kWh/kgP)</b>									
PS (N)	kWh/kgN	98.0	101.5	104.8	107.1	as for MLE (left)			
PS (P)	kWh/kgP	145.6	150.3	154.8	158.0	as for MLE (left)			
WAS (N)	kWh/kgN	9.2	8.5	6.7	2.5	11.4	11.3	10.8	10.1
WAS (P)	kWh/kgP	36.3	33.4	26.2	9.8	6.5	5.4	4.3	3.5
<b>5.8 Total oxygen demand (TOD) balance (TOD = COD + 4.57 TKN)</b>									
Influent	kgTOD/d	15 366	15 366	15 366	15 366	15 366	15 366	15 366	15 366
Effl (USO)	kgTOD/d	1 033	1 033	1 032	1 032	1 032	1 032	1 031	1 031
N <sub>2</sub> gas	kgTOD/d	1 464	1 483	1 507	1 531	1 401	1 421	1 438	1 459
Cake	kgTOD/d	3 845	3 799	3 742	3 686	3 944	3 898	3 842	3 782
DWL	kgTOD/d	30	29	28	27	38	37	36	35
Ox Dem	kgTOD/d	5 369	5 074	4 710	4 345	4 949	4 654	4 298	3 962
Methane	kgTOD/d	3 623	3 946	4 344	4 743	4 001	4 322	4 719	5 095
Tot OUT	kgTOD/d	15 364	15 364	15 364	15 364	15 364	15 364	15 364	15 364
%Balance	%	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

<sup>(1)</sup> EBPR decreases because lower WW BPO generates less OHO biomass which results in less FBSO conversion to VFA in the anaerobic reactor.

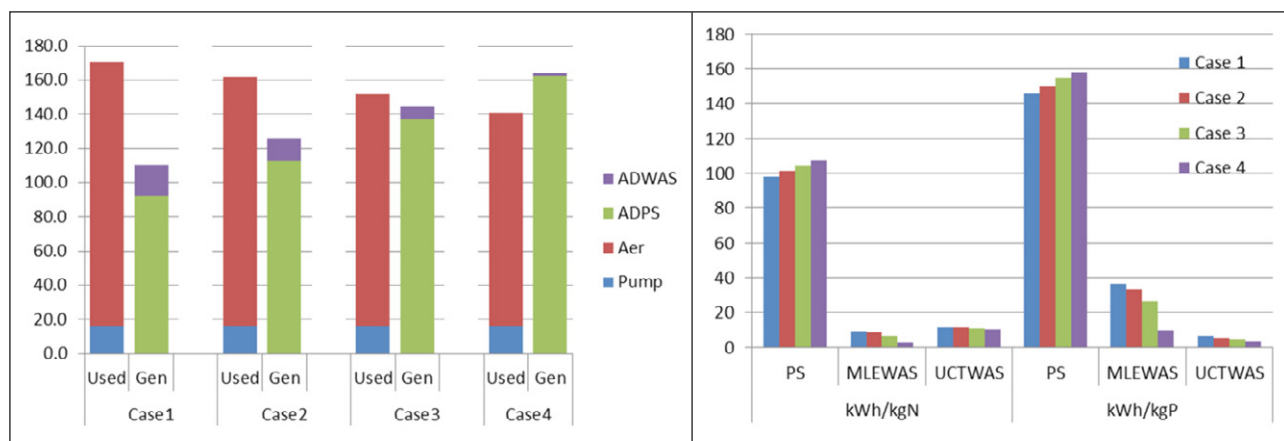
<sup>(2)</sup> Methane generation for EBPR WAS is higher than MLE WAS because PAO generate more biomass per kgCOD utilized in the BNR system due to their low endogenous respiration rate. <sup>(3)</sup> Surplus energy indicates the net energy available from CH<sub>4</sub> generation after deducting the quantity used in AD for heating requirements (i.e., to maintain a temperature of 37°C).

The reactor volume advantage of the JHB system over the UCT system is apparent, not real. In the JHB, the secondary anoxic reactor in the underflow has a higher (~twice) TSS concentration than in the other reactors. In contrast, in the UCT, the anaerobic reactor has a lower (~half) the TSS concentration than in the other reactors. So for the same mass of sludge in the reactor (same SRT), the reactor volume of the JHB system is smaller than that of the UCT system. However, the balanced SRT for lowest effluent N (and P) of the JHB system is longer (by ~2 d) than that of the UCT system, which results in a larger mass of sludge in the JHB system. Therefore, with each at their balanced SRT and an a-recycle of (say) 6:1, the effluent nitrate concentration from both is lowest and similar and the reactor volumes of the JHB and UCT systems are closely similar. Therefore, in the interests of brevity, the JHB system will not be considered further – its results are similar to the UCT system.

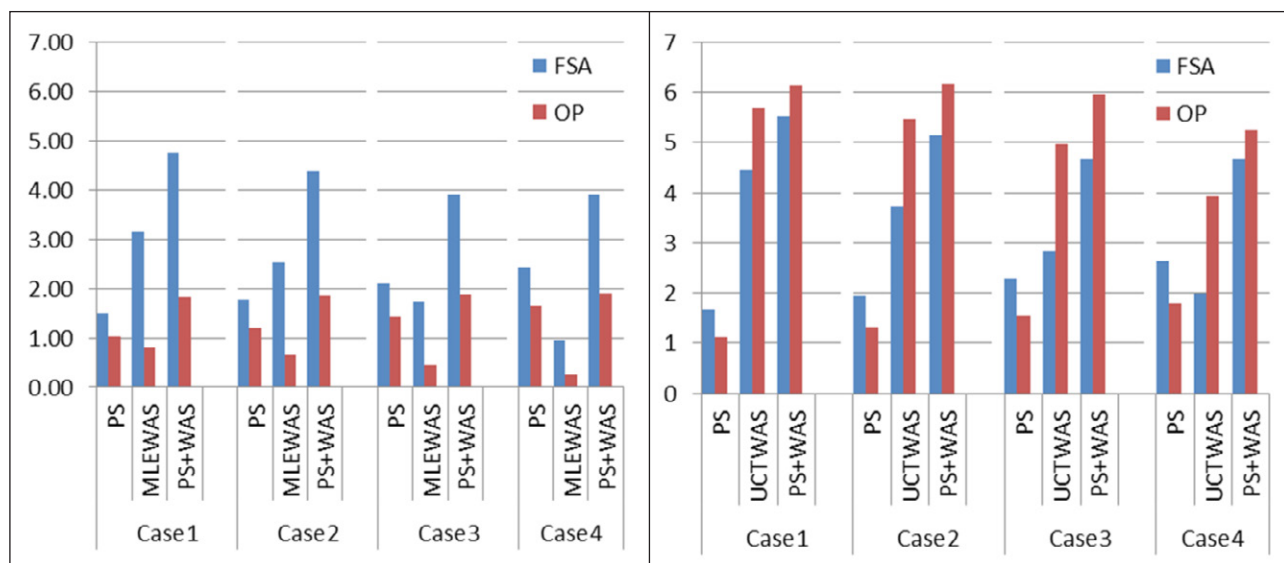
Unless N&P removal/recovery from AD DWL liquor is included in the WRRF, digesting WAS from MLE ND or from UCT/JHB NDEBPR systems should not be considered – the low energy yield from the AD of WAS, which decreases as SRT of the WAS increases (Table 5.7, Fig. 6), is not worth having to deal with the high N&P concentrations in the DWL (Table 5.6, Fig. 7), which, if not removed, have a major impact on the BNRAS effluent N&P

concentrations when recycled back to the influent. For greater energy generation without compromising effluent quality and without AD DWL N&P removal technologies, it is better to increase the organics removals in the PSU and produce more PS for AD than digest WAS (Fig. 6).

While the additional organics removal in the PSU increases the settled wastewater TKN/COD ratio (Table 5.1), and so also the balanced SRT of the BNR systems (Table 5.3), the reduced organic load on the AS results in approximately the same mass of TSS in the reactor, with the result that the AS reactor volume (Table 5.3) and effluent N&P concentrations remain closely the same (Table 5.4). This results in (i) greater energy generation in PSAD (Table 5.5, Fig. 6), (ii) less energy consumption in the AS even though the SRT in the AS is longer (Table 5.3) and (iii) a low N&P DWL which can be returned to the influent without significant impact on the effluent N&P concentrations (Table 5.6, Fig. 7). This conclusion follows from the N&P composition of the settleable BPO, which, according to the best information available (Wentzel et al., 2006), has a ~5x lower N composition than OHO and PAO biomass and ~2.5x and ~25x lower P composition than OHO and PAO biomass in ND and NDEBPR systems, respectively. The higher the N&P composition of the settleable BPO, the more N&P in the DWL of the PSAD.



**Figure 6.** (a) (left) Energy (in kW) used in aeration (Aer) and pumping (Pump) and generated in AD of PS and MLE system WAS for Cases 1 to 4 of increasing primary separation and (b) (right) energy generated per kgN or P in the DWL of AD of PS, MLE system WAS and UCT system WAS. For the UCT system, N and P removal from the DWL by struvite precipitation resulting from the Mg content of polyphosphate is included (Fig. 4)



**Figure 7.** Increase in FSA-N and OP-P concentrations (in mg/L influent flow) from returning the dewatering liquor (DWL) from AD of PS, WAS and combined PS and WAS from the MLE system (Fig. 7a left) and the UCT system (Fig. 7b, right) for Cases 1 to 4 of increasing primary separation. These concentrations were not taken into account in the sizing of the MLE and UCT systems (Table 5)



## CONCLUSIONS

With a CHONP element mass-balanced plant-wide stoichiometric and kinetic steady-state model, the impact of four increasing organics removal efficiencies in the primary separation unit were explored quantitatively on the settled wastewater characteristics, the balanced SRT of the MLE and UCT/JHB systems, reactor volume, energy consumption for aeration and pumping at this balanced SRT, the energy generation by the primary sludge (PS) anaerobic digestion (AD) and waste activated sludge (WAS) AD, the N&P content of the PS and WAS AD DWL with and without enhanced biological P removal (EBPR) and the final effluent N and P concentration.

Once the activated sludge (AS) reactor (say 60% of total volume) and secondary settling tank (SST, remaining 40% of total volume) have been sized for lowest construction cost (Ekama et al., 1997) for a selected organic load and peak wet weather flow to average dry weather flow ratio (PWWF/ADWF), this total volume can be reassigned between the AS reactor and SSTs in different proportions over quite a large range (AS 45–65% and SST 55–35% of total volume) without decreasing the plant's ADWF capacity (<3%).

Unless N and P removal/recovery from AD dewatering liquor (DWL) liquor is included in the WRRE, digesting WAS from MLE ND or UCT/JHB NDEBPR systems should not be considered – the low energy yield from the AD of WAS, which decreases as SRT of the WAS increases, is not worth having to deal with the high N and P concentration DWL it produces, which, if N and P are not removed, has a major impact on the effluent N and P concentrations when recycled back to the influent.

From the above, for greater energy generation without compromising effluent quality and without AD DWL N and P removal technologies, it is better to increase the performance of the primary separation unit (PSU) and produce more primary sludge for AD than digest WAS. While the additional organics removal in the PST increases the settled wastewater TKN/COD ratio, and therefore increases the balanced SRT of the MLE, UCT and JHB systems for lowest economical effluent nitrate concentration, the reduced organic load on the AS results in approximately the same mass of TSS in the reactor, with the result that the AS reactor volume and effluent N and P concentrations remain closely the same for increasing organics removal in the PSU. This results in greater energy generation in PS AD and less energy consumption in the AS even though the SRT in the AS is longer.

The prioritized goal in wastewater treatment remains to ensure human and environmental health. Hence, the strategies to minimize energy requirement or recover energy during wastewater treatment processes should not be at the expense of the quality required for effluent discharged to receiving water bodies. According to Ekama et al. (2011), power consumption in the developed countries is usually within the range of 5–10 kW/person, while around 0.02 kW/person energy is available for recovery from wastewater. The energy use (and carbon emissions) from other human activities have been quantified as much higher in comparison to that used for wastewater treatment and treated wastewater has much greater value as a potential fresh-water source than the energy it contains or is consumed in its treatment (Ekama, 2009; Ekama et al., 2011).

The adoption of changing paradigms, which involve the transition of wastewater treatment plants (WWTPs) to water resource recovery facilities (WRRFs), requires understanding the technologies available to reduce recycling pollutant loads and their application in holistic (system-wide) approaches to decision making. Several side-stream technologies are available and are recognized as efficient to reduce N and P concentrations in the

sludge return liquors. Examples of applicable technologies for side-stream N removal (most based on efficient ways of ammonia oxidation) are SHARON, ANNAMOX and the Biological Augmentation Batch Enhanced process, marketed as BABE. The solutions available for P removal or recovery include conventional coagulation, flocculation and sedimentation using metal-salts for P chemical precipitation, up to more complex processes with chemical crystallization in up-flow fluidized bed reactors with dosages of Ca or Mg in controlled pH conditions and allowing for a high-phosphate recovery in the form of struvite. Examples of these technologies are marketed as Ostara Pearl, WASSTRIP, AIRPREX, Crystalator, Calprex™, Phospat™ amongst others.

## ACKNOWLEDGEMENTS

The final paper was edited by Dr David Ikumi.

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## APPENDIX 1

### List of abbreviations

IDFT	one-dimensional idealized flux theory
AD	anaerobic digestion
ADWF	average dry weather flow
AS	activated sludge
BNR	biological nutrient removal
BNRAS	biological nutrient removal activated sludge
BPO	biodegradable particulate organics
C	carbon
COD	chemical oxygen demand
d	day
DSVI	diluted sludge volume index
DWL	dewatering liquor
EBPR	enhanced biological P removal
FBSO	fermentable biodegradable soluble organics
FSA	free and saline ammonia
H	hydrogen
InOrg	inorganic
ISS	inorganic suspended solids
JHB	Johannesburg NDEBPR system
kWh	kilowatt hour
ML	megalitre
MLE	modified Ludzack-Ettinger ND system
N	nitrogen
ND	nitrification denitrification
NDEBPR	nitrification denitrification enhanced biological P removal
O	oxygen
OHO	ordinary heterotrophic organism
OP	ortho-phosphate
OTR	oxygen transfer rate
P	phosphorus
PAO	phosphorus accumulating organism
PS	primary sludge
PST	primary settling tank
PSU	primary separation unit
PWM	plant-wide model
PWSSM	plant-wide steady-state model
PWWF	peak wet weather flow
SRT	solids retention time
SS	settleable solids
SSP	specific sludge production
SST	secondary settling tank
TKN	total Kjeldahl nitrogen

TOD	total oxygen demand
TP	total phosphorus
TSS	total suspended solids
TSuspS	total suspended solids
UCT	University of Cape Town NDEBPR system
UPO	unbiodegradable particulate organics
USO	unbiodegradable soluble organics
VFA	volatile fatty acids
WAS	waste activated sludge
WRC	Water Research Commission
WRRF	water and resource recovery facility
WW	wastewater

### List of symbols

2.86	electron accepting oxygen equivalent of nitrate (gO/gNO <sub>3</sub> -N)
<i>a</i>	nitrogen composition of organics molN/mol
<i>a</i> <sub>opt</sub>	optimum mixed liquor a-recycle ratio
<i>a</i> <sub>prac</sub>	maximum practical mixed liquor a-recycle ratio
<i>A</i> <sub>ST</sub>	surface area of secondary settling tank
<i>b</i>	phosphorus composition of organics molP/mol
<i>b</i> <sub>AT</sub>	ANO endogenous respiration rate at T°C/d = $b_{A20}(1.029)^{(T-20)}$ where $b_{A20} = 0.04/d$
<i>b</i> <sub>HT</sub>	OHO endogenous respiration rate at T°C/d = $b_{H20}(1.029)^{(T-20)}$ where $b_{H20}$ is the rate at 20°C = 0.24/d
<i>D</i> <sub>p1</sub>	denitrification of the primary anoxic reactor (mgNO <sub>3</sub> -N/L influent)
<i>E</i>	fraction of biodegradable organics converted to biomass and endogenous residue
<i>f</i> <sub>C</sub>	carbon to mass ratio
<i>f</i> <sub>cv</sub>	COD/mass ratio (gCOD/gVSS for particulates and gCOD/g for soluble)
<i>f</i> <sub>cvUPO</sub>	COD/VSS ratio of influent UPO = 1.481 mgCOD/mgVSS (see Table 1)
	Similarly, each of the influent organics types (VFA, FBSO, USO, BPO and UPO) and biomass (OHO and PAO) has a <i>f</i> <sub>cv</sub> , <i>f</i> <sub>C</sub> , <i>f</i> <sub>H</sub> , <i>f</i> <sub>O</sub> , <i>f</i> <sub>N</sub> and <i>f</i> <sub>P</sub> mass ratio (g element/gVSS for particulates and g element/g for soluble)
<i>f</i> <sub>H</sub>	hydrogen to mass ratio
<i>f</i> <sub>H</sub>	unbiodegradable fraction of OHO biomass = 0.20 mgVSS/mgOHOVSS
<i>f</i> <sub>iOHO</sub>	inorganic suspended solids (ISS) content of OHO (0.15 mgISS/mgOHOVSS)
<i>f</i> <sub>N</sub>	nitrogen to mass ratio
<i>f</i> <sub>O</sub>	oxygen to mass ratio
<i>f</i> <sub>P</sub>	phosphorus to mass ratio
<i>f</i> <sub>q</sub>	PWWF/ADWF ratio
<i>f</i> <sub>S<sup>bs</sup></sub>	fraction of total COD that is readily biodegradable = $[S_{bsai} (VFA) + S_{bsfi} (FBSO)]/[S_{ti}]$

$f_{sup}$	unbiodegradable particulate organics (UPO) COD fraction of total COD	$N_c$	nitrification capacity = nitrate generated by nitrification mgNO <sub>3</sub> -N/L influent
$f_{sus}$	unbiodegradable soluble organics (USO) COD fraction of total COD	$N_{ne}$	effluent nitrate concentration mgNO <sub>3</sub> -N/L
$f_{sb's}$	fraction of biodegradable COD that is readily biodegradable $= [S_{bsai} (VFA) + S_{bsfi} (FBSO)]/[S_{bsai} (VFA) + S_{bsfi} (FBSO) + S_{bpi} (BPO)]$	$N_{ouse}$	nitrogen concentration of the unbiodegradable soluble organics (USO) mgN/L
$FS_{ti}$	daily influent COD flux (kgCOD/d) = $Q_{ADWF} S_{ti}$	$N_{te}$	effluent TKN concentration mgN/L = $N_{ouse} + N_{ae}$
$f_{x1}$	primary anoxic sludge mass fraction	$N_{ti}$	influent TKN concentration mgN/L
$f_{x3}$	secondary anoxic sludge mass fraction	$O_a$	dissolved oxygen concentration in the aerobic reactor mgO/L
$f_{xa}$	anaerobic sludge mass fraction	$O_s$	dissolved oxygen concentration in the underflow from SST mgO/L
$f_{xm}$	maximum unaerated mass fraction of system	$Q_{ADWF}$	average dry weather flow (ML/d)
$f_{xt}$	total unaerated mass fraction of system ( $\leq f_{xm}$ )	$Q_{PWVF}$	peak wet weather flow (ML/d)
$K_{1T}$	$1_{st}$ (fast) denitrification rate in primary anoxic reactor of ND system due to readily biodegradable organics (VFA+FBSO) at $T^\circ C = K_{120}(1.20)^{(T-20)}$ where $K_{120}$ is the rate at $20^\circ C = 0.720$ mgNO <sub>3</sub> -N/(mgOHOVSS-d)	$r$	mixed liquor recycle ratio from primary anoxic to anaerobic reactor
$K_{2T}$	2 <sup>nd</sup> denitrification rate in primary anoxic reactor(s) of ND system due to slowly biodegradable organics (BPO) at $T^\circ C = K_{220}(1.08)^{(T-20)}$ where $K_{220}$ is the rate at $20^\circ C$ $= 0.101$ mgNO <sub>3</sub> -N/(mgOHOVSS-d)	$R_s$	solids retention time (SRT) or system sludge age (d)
$K_{3T}$	denitrification rate in secondary anoxic reactor(s) of ND system due to endogenous respiration at $T^\circ C =$ $K_{320}(1.029)^{(T-20)}$ where $K_{320}$ is the rate at $20^\circ C$ $= 0.072$ mgNO <sub>3</sub> -N/(mgOHOVSS-d)	$s$	underflow recycle ratio
$K'_{2T}$	2 <sup>nd</sup> denitrification rate in primary anoxic reactor(s) of UCT system due to slowly biodegradable organics (BPO) at $T^\circ C = K'_{220}(1.08)^{(T-20)}$ where $K'_{220}$ is the rate at $20^\circ C$ $= 0.255$ mgNO <sub>3</sub> -N/(mgOHOVSS-d)	$S_{bsai}$	VFA COD concentration in influent
$K'_{3T}$	denitrification rate in secondary anoxic reactor(s) of NDEBPR system due to endogenous respiration at $T^\circ C = K'_{320}(1.029)^{(T-20)}$ where $K'_{320}$ is the rate at $20^\circ C$ $= 0.114$ mgNO <sub>3</sub> -N/(mgOHOVSS-d)	$S_{bi}$	biodegradable organics (VFA+FBSO+BPO) COD concentration in influent
$K_{nt}$	Monod half saturation coefficient for ANO mgFSA-N/L $= K_{n20}(1.123)^{(T-20)}$ where $K_{n20}$ is the coefficient at $20^\circ C$ $= 1.0$ mgN/L	$S_{bsfi}$	fermentable biodegradable soluble (FBSO) COD concentration in influent
$L_{EBPR}$	EBPR system load factor – kgTSS in reactor per kgCOD/d load on reactor	$S_f$	safety factor on nitrification
$L_{ND}$	ND system load factor – kgTSS in reactor per kgCOD/d load on reactor	$S_{ti}$	influent flow weighted total organics COD concentration mgCOD/L
$L_{sys}$	system load factor – kgTSS in reactor per kgCOD/d load on reactor	$T$	temperature in $^\circ C$
$MX_t$	mass of TSS in reactor = $V_R X_{tave}$	$V_0$	coefficient in flux theory settling velocity equation $V_s = V_0 e^{-nX_t}$ m/h
$n$	coefficient in flux theory settling velocity equation $V_s = V_0 e^{-nX_t}$ m/h	$V_R$	volume of biological reactor (m <sup>3</sup> )
$N_{ae}$	effluent ammonia concentration mgN/L $= K_{nt} (b_{AT} + 1/R_s)/[(1-f_{xt})\mu_{AmT} - (b_{AT} + 1/R_s)]$ for $f_{xt} < f_{xm}$ $= K_{nt}/(S_f - 1)$ for $f_{xt} = f_{xm}$ mgFSA-N/L	$V_s$	settling velocity (m/h) of activated sludge at $X_t$ kgTSS/m <sup>3</sup>
		$x$	carbon composition of organics molC/mol (= 1.0)
		$X_{IOi}$	flow-weighted average influent ISS concentration (mgISS/L)
		$X_{taer}$	TSS concentration in aerobic reactor
		$X_{tave}$	volume-weighted average TSS concentration in biological reactor
		$y$	hydrogen composition of organics molH/mol
		$Y_{AD}$	biomass yield of the acidogens in AD = 0.113 g biomass VSS/gCOD substrate utilized
		$Y_H$	OHO VSS based yield coefficient $= 0.45$ mgVSS/mgCOD
		$z$	oxygen composition of organics molO/mol
		$\mu_{AmT}$	ANO maximum specific growth rate at $T^\circ C/d$ $= \mu_{Am20} (1.123)^{(T-20)}$ where $\mu_{Am20}$ is the rate at $20^\circ C$



## APPENDIX 2

### Explicit equation for balanced SRT of the MLE system

An explicit equation for the balanced SRT of an MLE system has been derived, viz.

$$R_{sBalMLE} = \frac{CE+D-AB+AS_f K_{2T} \frac{Y_H}{\mu_{AmT}} - E \left[ Af_{n0} Y_H + S_{ti} \frac{f_{nUPO} f_{s'up}}{f_{cvUPO}} \right]}{A(Bb_{HT} + K_{2T} Y_H) - AS_f b_{AT} K_{2T} \frac{Y_H}{\mu_{AmT}} - b_{HT} (CE+D) + Eb_{HT} \left[ Af_{n0} Y_H f_H + S_{ti} \frac{f_{nUPO} f_{s'up}}{f_{cvUPO}} \right]} \quad (A2.1)$$

subject to  $R_{sBalMLE}$  values yielding  $f_{xm}$  greater than  $f_{x1min}$  in

$$f_{xm} = f_{x1} \geq f_{x1min} = \frac{f_{Sb's}(1-f_{cv} Y_H)(1+b_{HT} R_s)}{2.86 K_{1T} Y_H R_s} \quad (A2.2)$$

where the composite parameters

A = influent biodegradable organics (VFA+FBSO+BPO) as mgCOD/L =  $S_{bi} = S_{ti}(1-f_{s'us}-f_{s'up})$

B =  $f_{Sb's} (1-f_{cv,OH} Y_H)/2.86$

C = influent minus effluent TKN concentrations =  $N_{ti} - N_{te}$  mgN/L

D =  $(a_{prac} O_a + s O_s)/2.86$

E =  $(a_{prac} + s)/(a_{prac} + s + 1)$  = proportion of nitrate recycled to primary anoxic reactor(s) in MLE and UCT systems