Calculation of sludge production from aerobic ASP based on COD and BOD_5 – comparison of methods and model validation

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ABSTRACT: A 5-day Biological Oxygen Demand (BOD_5) is one of the parameters which are used to determine the amount of biodegradable organic substances in water environments. In dimensioning wastewater treatment plants, BOD_5 is used for determining organic loading rates which enter the wastewater treatment plant and affect such parameters as surplus sludge production and oxygen demand. Conventional "static" design methods are based on using BOD_5 as a representation of the amount of organic substrates in wastewater and then use empirically obtained coefficients for such parameters as biomass yield per BOD_5 removed or amount of oxygen required per BOD_5 oxidised to calculate surplus sludge production and oxygen demand. In contrast, new design methods taking advantage of dynamic activated sludge models (ASM) are based on COD (Chemical Oxygen Demand) fractions for determination of organic loading, oxygen demand and surplus sludge production. It has been found out during the course of work on wastewater treatment plant design and dynamic simulation that the results obtained from both approaches can vary significantly. Theoretical explanation of such behaviour is presented here and a design method on COD fractions is validated on two bench-scale SBR reactors operating on two different wastewater streams.

1 INTRODUCTION

During the course of work on AMP4 (Asset Management Programme) for one of the UK's water utilities it has been observed that sludge yields produced from dynamic process models (Henze *et al.*, 1987, Gujer *et al.*, 1999, Jeppsson) can be by far larger than the "industry norm" which usually quotes a value of about 0.8 $gSS/gBOD_{5,removed}$ regardless of the plant's operating conditions (e.g. sludge age, temperature) or the influent characteristics which have a major impact on biomass production, (ATV, 1999, M&Eddy, 2003). Differences between some calculated sludge yields and what has been specified by some water utilities may arise from the above mentioned sludge production process complexity as well as from the fact that dynamic process models calculate their rates based on COD fractions rather than BOD_5 and TSS. In some cases BOD_5 may not be a good representation of the amount of biodegradable organic substances in the influent, whereas COD is said to give more consistent and accurate results (Shelton, 1991). It is possible that under certain conditions BOD_5 may underestimate the amount of organics in wastewater and this is when differences between BOD_5 and COD based design methodologies may occur (Albertson, 1995). This will be further explained in the following chapters.

A practical problem in assessing surplus activated sludge production arose during an initial process design stage carried out on a large British municipal sewage works with high industrial content. Design of a new activated sludge plant for this works was assisted by dynamic process simulation performed in a commercial simulation package GPS-X (Hydromantis, Inc.). Prior to any simulations, influent COD and N fractions were determined and then the mathematical model was calibrated based on the analytical results obtained from 3 months of pilot plant operation, so that the model was able to accurately predict sludge production, oxygen demand and effluent COD and $N\text{-}NH_4^+$ concentrations.

One of the outcomes of the dynamic process simulation study was that the predicted sludge yield was found to be much higher than the assumed yield of 0.8 $gSS/gBOD_{5,removed}$. In an attempt to justify the results of the simulation, sludge production was also determined with static sludge production formulas as described in ATV A131E, (1991), and Metcalf& Eddy, (2003). These formulas are able to calculate sludge yields based on either influent BOD_5 and TSS or influent COD fractions. On top of this, predictive power of the static sludge production calculation method based on COD fractions was additionally evaluated against the measurements from two different sequencing batch reactors (SBRs) fed with presettled wastewater from two different wastewater treatment plants. Results of this model validation are a subject of this article.

2 SLUDGE PRODUCTION CALCULATION

2.1 *Biological vs. Chemical Oxygen Demand*

BOD$_5$ and COD tests are a measure of a relative oxygen-depletion effect of a waste contaminant and both of them have been widely adopted as a measure of organic pollution in water environments. Difference between BOD and COD is that BOD test measures an oxygen demand of biodegradable pollutants using a bioassay technique whereas the COD test measures an oxygen demand of both biodegradable and non-biodegradable pollutants by chemically oxidising a sample with potassium dichromate. For historical reasons, BOD$_5$ is more widely used than COD despite its major drawbacks (Albertson, 1995). This has been now slightly changing with the introduction of dynamic mathematical models of biological reactions which are based entirely on COD fractions, (Henze *et al.*, 1987, Gujer *et al.*, 1999, Jeppsson).

BOD$_5$ testing procedure is pretty sensitive to operating conditions like temperature or initial amount of seed, has to be done on fresh or very well preserved sewage and may not predict true oxygen requirements when substrate is of a specific nature and bacterial population needs adaptation period before being able to oxidise organic substances in the sample (Shelton, 1991).

Chemical Oxygen Demand (COD) has an advantage over BOD$_5$ as the analysis doesn't have to be performed under such strictly controlled conditions, testing procedure is much faster and additionally it gives a measure of the total energy in terms of oxygen and therefore can be used to formulate oxygen mass balance equations. This is the reason behind using COD fractions, not BOD$_5$ as state variables in ASM models (Henze *et al.*, 1987, Gujer *et al.*, 1999, Jeppsson). Unfortunately COD also takes into account the amount of organics which are non-biodegradable and therefore will not be oxidised in a wastewater treatment plant. Thus, before an assessment of oxygen demand or sludge production can be made, COD has to be split into biodegradable and non-biodegradable fractions, (Melcer, 2005), what requires an extra analysis and is a major reason behind lesser popularity of COD compared to BOD$_5$.

Deficiencies of a BOD$_5$ test may sometimes cause problems in assessing true amount of biodegradable organics in wastewater. Wrong preservation of samples, long delays between sampling and testing and the need for biomass adaptation to substrate can cause an underestimation of BOD$_5$ and in effect of BOD$_{\text{ultimate}}$. This would lead to an underestimation of sludge production and oxygen demand for a biological wastewater treatment process like activated sludge. This statement is in accordance with Albertson (1995), which claimed that using carbonaceous BOD$_5$ (CBOD$_5$) in raw wastewater and primary effluent for plant design could result in a 20-40% underdesign and concluded that CBOD$_5$ is an improper test for raw and settled influent wastewater. In contrast to BOD$_5$, COD is said to give accurate predictions of total oxygen demand and once COD fractionation into soluble/ particulate and biodegradable/ unbiodegradable fractions, (Melcer, 2005) are done properly, sludge production and oxygen demand values obtained from COD should be close to reality.

2.2 *Sludge production based on BOD$_5$ and TSS*

Total sludge production is affected by several components: biomass growth and decay, production of cell debris from endogeneous decay and sludge production due to inorganic solids (X$_{\text{II}}$) and non-biodegradable volatile suspended solids (nbVSS) in the influent.

Equation 1 describing observed sludge yield calculation method and presented underneath can be found in ATV A 131E, 1991.

$$Y_{obs} = Y - \frac{(1 - f_d) \cdot k_d \cdot Y \cdot SRT \cdot \theta^{(T-15)}}{1 + k_d \cdot SRT \cdot \theta^{(T-15)}} + a \cdot \frac{X_{TS}}{S_{BOD_5}} \qquad (1)$$

where:
Y – observed biomass yield, gTSS/gBOD$_5$
Y – theoretical biomass yield, gTSS/gBOD$_5$
f_d – cell debris fraction, --
k_d – endogeneous decay coefficient, d^{-1}
SRT – sludge retention time, d
θ – temperature dependency coefficient, --
X_{TS} – influent solids concentration, gSS/m^3
S_{BOD5} – influent BOD$_5$, gO$_2$/ m^3
T – temperature, ^{o}C
a – proportionality coefficient, --

Similar equation to Equation 1 can be found in Metcalf & Eddy, 2003 (Equation 2).

$$Y_{obs} = \frac{Y}{1 + k_d \cdot SRT} + \frac{f_d \cdot k_d \cdot Y \cdot SRT}{1 + k_d \cdot SRT} + \frac{Y_n}{1 + k_{dn} \cdot SRT} \cdot \frac{S_{NH}}{S_{BOD_5}} + \frac{nbVSS}{S_{BOD_5}} + \frac{f_{XII} \cdot X_{TS}}{S_{BOD_5}} \qquad (2)$$

where
Y_n – theoretical nitrifying biomass yield, gTSS/gBOD$_5$
k_{dn} – endogeneous decay coefficient for nitrifiers, d^{-1}
$nbVSS$ – non-biodegradable VSS concentration, gSS/m^3
f_{XII} – inert solids fraction, --

In both equations the first two terms are almost the same with the only difference that Equation 1 introduces temperature dependency (θ factor). Equation 2 accounts for biomass yield due to autotrophic biomass activity and treats separately the contributions from *nbVSS* and X_{II}. Equation1 is simplified in this respect and introduces an empirically obtained coefficient a, which ideally should be equal to:

$$a = {\left(nbVSS + X_{II}\right)} \Big/ {X_{SS}} \tag{3}$$

Equation 1 therefore avoids the need of measuring nbVSS and X_{II} in influent wastewater, but by introducing an empirical coefficient may loose its validity for specific types of wastewater.

The sludge production due to autotrophic biomass growth is very small and therefore it is neglected in Equation 1.

2.3 *Sludge production based on COD fractions*

As an alternative to BOD-based calculation methods, sludge yield can be determined based on COD fractions. This approach has not been widely used due to much larger popularity of BOD_5 test over COD. However, as dynamic modelling of sewage works, which requires detailed influent wastewater composition based on COD fractions, is increasing in popularity, influent COD data should be more accessible and then, the equations presented underneath, (ATV A 131E, 1991, may be used more often.

$$X_{COD,bm} = COD_{bio\deg} \cdot Y \cdot \frac{1}{1 + k_d \cdot SRT \cdot \theta^{(T-15)}} \tag{4}$$

$$X_{COD,bm,inert} = f_d \cdot X_{COD,bm} \cdot SRT \cdot k_d \cdot \theta^{(T-15)} \tag{5}$$

$$X_{COD,tot} = X_{COD,bm} + X_{COD,bm,inert} + X_I \tag{6}$$

$$Y_{obs} = \frac{\dfrac{X_{COD,tot}}{VSS/_{TSS} \,.\, XCOD/_{VSS}} + X_{II}}{S_{BOD5}} \tag{7}$$

where

COD_{biodeg} – biodegdadable COD concentration, gCOD/m^3

Y – theoretical biomass yield, gCOD/gCOD

Y_{obs} – observed biomass yield, gTSS/gBOD_5

$X_{COD,bm}$ – sludge from biomass activity, gCOD/m^3

$X_{COD,bm,inert}$ – sludge from biomass decay, gCOD/m^3

X_I – inert particulate influent COD, gCOD/m^3

X_{II} – inert influent solids, gTSS/m^3

Equations above follow a similar approach to the equations based on BOD_5. Equation 4 represents production of solids due to biomass growth, Equation 5 models production of solids from biomass decay, Equation 6 sums these two numbers together and adds inert particulate COD in the influent. Then the unit of the result from Equation 6 is converted from gCOD/m^3 to gTSS/m^3 using two conversion factors: VSS/TSS and XCOD/VSS in the mixed liquor. Final observed yield is calculated by adding X_{II} which represents a concentration of inert suspended solids in the influent.

The COD-based method requires three parameters to be identified: COD_{biodeg}, X_I and X_{II}. XCOD/VSS is constant for biomass and is equal to 1.42 mgO_2/mgVSS. VSS/TSS in the mixed liquor is fairly constant and for intermediate sludge ages and municipal wastewater equals 0.80 approximately.

3 SIMULATION STUDY

The study on sludge yield calculation methods originated from a dynamic modelling and simulation project that was being done during a retrofit design of one of the UK's large municipal wastewater treatment plants. During the course of work some of the results which had been produced by the model were not in agreement with design parameters – one of such differences was in the sludge yield figure.

The plant was simulated using the ASM1 biological model and 1D Takàcs settling model implemented in a commercial wastewater simulator GPS-X, Hydromantis Inc. The dynamic plant model used in the study had been calibrated on the experimental data gathered during 3-months of operation of an on-site pilot plant receiving a proportion of full-scale works primary settled influent. Information which could not be obtained from the pilot plant like more detailed wastewater composition (COD and N fractions) was additionally obtained from batch test experiments in SBR reactors. Average influent COD, BOD_5 and TSS values were calculated as a combination of the pilot plant data, data from batch test experiments and historical measurements. Some of the parameters relevant for sludge yield calculations are shown in Table 1 alongside the parameters of the static yield calculation models.

Table 1. Most relevant input parameters used in sludge yield calculations with static and dynamic models.

Parameter	Value	Parameter	Value
Temp, ^oC	14	Y, gSS/gBOD_5	0.75
TSS, mg/l	218	Y, gCOD/gCOD	0.75
BOD_5, mg/l	138	a, --	0.60
COD, mg/l	548	θ, --	1.072
COD/BOD_5, --	4.0	k_d, d^{-1}	0.17
SRT, days	9.5	f_d, --	0.2
Q, m^3/d	12,090	f_{XII}, --	0.08
XCOD/VSS, --	1.45	f_{XI}, --*	0.105
VSS/TSS, --	0.82	f_{SI}, --**	0.06

* f_{XI} – particulate inert COD fraction, --

** f_{SI} – soluble inert COD fraction, --

Daily sludge production and sludge yield per removed BOD_5 and COD were calculated with a calibrated dynamic plant model as well as with the earlier described two static sludge production calculation methods (Equations 1 and 7). Calculated values and a design assumption are compared and listed in the Table 2 below.

Table 2. Sludge production and sludge yield results from simulation and static models vs. design assumptions.

Calculation	Sludge prod.	Yield	Yield
	kgSS/day	kgSS/kgBOD$_5$	kgSS/kgCOD
Simulation	2440	1.357	0.343
BOD$_5$-based	2410	1.340	0.339
COD-based	2430	1.353	0.342
Design	1440	0.80	-------

Results obtained from the static models agreed with dynamic model prediction within approx. 1.5% margin. This shows that in this particular case the ASM model and the BOD$_5$ and COD-based slue production calculation methods are consistent with one another if we can assume that the influent fractionation had been done properly.

The average calculated sludge yield is equal to 1.35 kgSS/kgBOD$_5$ (or 0.34 kgSS/kgCOD). This value is much higher from the design value of 0.80 kgSS/kgBOD$_5$. In order to provide an explanation for this discrepancy between the calculated values and the designed assumption based on experience, three hypotheses were formed.

The incoming wastewater has a very high COD/BOD$_5$ ratio of 4.0 where in normal municipal wastewater one would expect this value to vary between 1.8 to 2.2. Such a high COD/BOD$_5$ could mean that the incoming wastewater carries a high proportion of particulate non-biodegradable COD fraction (X_I) which is not a substrate for microorganisms but is directly incorporated into the bacterial flocs and adds to sludge production. The measurements however showed that this fraction is not overly excessive and is within standard limits for primary settled wastewater (Melcer, 2004, Lagarde *et al.* 2005).

The second hypothesis was looking at the influent BOD$_5$/BOD$_\infty$ ratio and the evolution of Biological Oxygen Demand over time (Figure 1). A normal curve for carbonaceous BOD with suppressed Nitrification follows exponential characteristics as shown in Figure 1 (curve 1). For this type of BOD evolution over time, BOD$_5$/BOD$_\infty$ is equal to about 0.66. In cases where biomass needs to adapt to new or less easily biodegradable substrate, oxygen demand in a sample may evolve similarly to curve 2. In this case BOD$_\infty$ and therefore total biological oxygen demand will be the same as in curve 1, but BOD$_5$ will be smaller, because throughout the acclimatisation period no or very little oxygen consumption will occur. If we then base our design on BOD$_5$, an aeration system will be under-designed and actual SRT of the plant will be lower from the design value due to an underestimation of sludge production. Curve 3 is shown to picture a situation where total BOD is very low due to either low biodegradability of the substrate or toxicity present in the wastewater sample.

No intermediate BOD values were determined during the BOD analysis and therefore it cannot be said, whether the oxygen demand evolution in time in our case could be similar to curve 2.

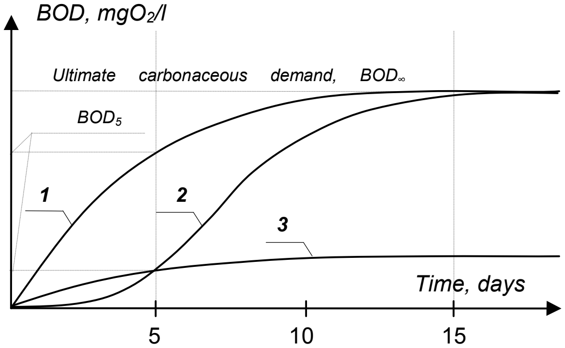

Figure 1 Possible evolution patterns of BOD in time

The third possible reason for low BOD$_5$/COD could be improper preservation of samples which could result in substrate decomposition before the actual analysis commenced. Such a situation is graphically presented in Figure 2. Curve 2 in Figure 2 depicts what would have happened to a BOD curve if the sample was analysed some time after collection and the sample had not been preserved. In this situation both BOD$_5$ and BOD$_\infty$ are lower from the true values that would have been otherwise obtained on fresh wastewater.

It is very probable that wrong preservation of samples and long time lags between sample collection and analysis were the cause of low BOD$_5$ readings as there were indications of malpractices in the external laboratory responsible for sample analysis. It was also reported that BOD concentrations measured on-site on fresh samples were consistently higher from the ones measured in a laboratory.

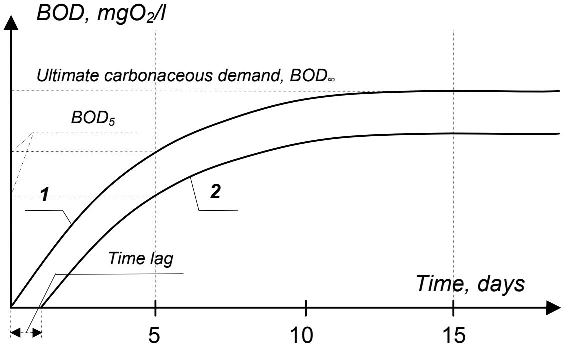

Figure 2 Possible effect of wrong sample preservation on the evolution of BOD in time.

4 LABORATORY EXPERIMENTS

As it is feared that the uncertainty associated with BOD$_5$ testing is high and the test suffers from many disadvantages compared to a COD test, it was decided to investigate the predictive capability of a sludge production model based on COD fractions and compare the model predictions against measurements.

Laboratory experiments mentioned in this paper were carried out in a different project on dynamic simulation of a municipal wastewater treatment plant. In order to characterise wastewater for the purpose of dynamic modelling and obtain some kinetic parameters, two aerated batch reactors were operating continuously for a period of about 3 months. Some of the data measured during the operation of these reactors was taken to validate the sludge yield calculation method based on COD. The experimental set-up is presented in Figure 3.

Reactors were manually fed and decanted between a bottom water level of 3-litres and a top water level of 9-litres, giving a hydraulic retention time of 8 hours at BWL. A logging dissolved oxygen probe monitored the oxygen and temperature levels. Mechanical mixers and paddle stirrers were combined with aeration stones and timers to ensure good mixing and control over in-situ dissolved oxygen levels (Table 3).

The reactors were maintained to a sludge age of approximately 14 days and this determined the operating F:M for each rig. To allow a quasi steady-state operation of the system, influent wastewater to each reactor was diluted prior to being fed to the reactor, so the feed would always have the same COD concentration of 200 mgO$_2$/l and 300 mgO$_2$/l respectively.

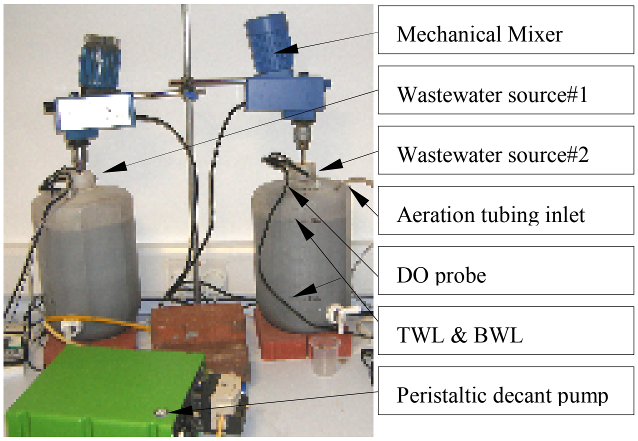

Figure 3 Experimental setup

Table 3. Cycle times.

Cycle	Time
Aerate (preceded by manual fill)	23.0 hours
Surplus	End of aerate period
Settle & Decant	1.0 hours

Both reactors were under operation for a period of 50 days. In each day the feed and final effluent COD and TSS, MLSS and MLVSS at BWL, MLSS at TWL and volume of sludge wasted were measured in each reactor. In addition, for the period of two weeks VSS was tested in the influent and effluent of each reactor in order to assess the VSS/TSS ratio.

All measured data was collated in a table format and was used as input to a COD-based sludge production equation and for preparation of a sludge mass balance in each reactor and determination of an observed sludge yield.

5 MODEL VALIDATION

5.1 *Calculation of the observed sludge yield*

Sludge production model based on COD fractions was validated by comparing its predictions against the measured data from two SBR reactors. Sludge production was calculated for both wastewater sources. Main inputs to the model were: Inlet COD and TSS, temperature and sludge age. Other model inputs were made of measured and standard influent and model stoichiometry and kinetic parameters. The measured parameter set consisted of: an inorganic solids fraction in the inlet (f_{XII}), inert particulate COD fraction in the inlet (f_{XI}), soluble inert COD fraction in the inlet (f_{SI}) and VSS/TSS ratio in the mixed liquor. Standard parameters were: XCOD/VSS ratio, temperature dependency parameter (θ), biomass decay rate (k_d), theoretical heterotrophic biomass yield (Y) and fraction of inert COD from biomass decay (f_I). Values of the standard parameters were kept the same for both wastewater streams and were taken from literature, (ATV, 1999, M&Eddy, 2003). Values of these parameters are listed in Table 4.

Table 4. Standard (wastewater-independent) parameter values used in Yield calculations.

Parameter	Unit	Value
XCOD/VSS	---	1.49
θ	---	1.072
k_d	d^{-1}	0.17
f_I	---	0.2

Wastewater type dependent inlet COD and TSS fractions and VSS/TSS ratio in the MLSS for each SBR are listed in Table5.

Table 5. Wastewater type and system dependent stoichiometric parameters.

Parameter	Unit	Sewage 1	Sewage 2
f_{XI}	---	0.25	0.25
f_{SI}	---	0.12	0.10
f_{XII}	---	0.18	0.19
VSS/TSS_{SAS}	---	0.80	0.80

The “measured” sludge production and sludge yield were determined from various TSS and volume measurements, which were then used to create a sludge mass balance in the reactor (Equation 8).

$$\Delta M^{n} = MLSS_{TWL}^{n+1} \cdot V - MLSS_{TWL}^{n} \cdot V + V_{feed}^{n} \cdot TSS_{eff}^{n} + 50ml \cdot MLSS_{BWL}^{n} + V_{SAS}^{n} \cdot MLSS_{TWL}^{n} \tag{8}$$

Solids mass production in the n-th SBR cycle (ΔM^n) is equal to an observed increase in MLSS between two cycles plus what is lost due to effluent solids, what is drawn off at the bottom water level (BWL) for sampling and wasted at the top water level (TWL) to maintain a required constant sludge age.

"Measured" sludge yield in each SBR cycle was calculated as a simple ratio between the solids mass production and the incoming COD load (Equation 9).

$$Y^{n} = \Delta M^{n} \Big/ COD_{inlet}^{n} \cdot V_{feed}^{n} \tag{9}$$

"Measured" sludge yields were compared against the calculated sludge yields for each wastewater source in each day for a period of 50 days. Calculated sludge yields were obtained from Equations 4 to 7. The obtained results are shown in Figures 4 and Figure 5 below. Each figure presents the measured and predicted sludge yields for each day of operation of the SBRs. The measured yields have error bars associated with each point (measurement). A detailed description of uncertainty assessment for the experimental yield determination will be presented in the following paragraph.

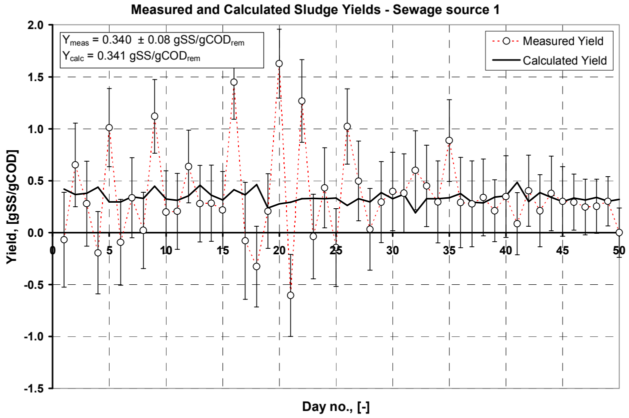

Figure 4 Measured and calculated sludge yields in SBR1

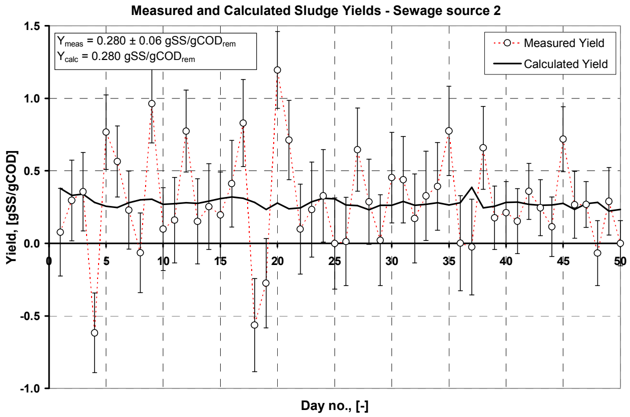

Figure 5 Measured and calculated sludge yields in SBR2

The average measured and calculated yields from each SBR and for an entire experiment duration period are shown in Table 6.

Table 6. Average measured and calculated results for both reactors

Yield [gSS/gCOD]	Source 1	Source 2
Measured	0.340	0.280
Measurement error	0.08	0.06
Calculated	0.341	0.280

Average predicted and measured yields agree with each other very well. The measurement errors are however pretty large comparing to the tightness of fit between the measured and predicted values. This is due to the fact that the positive and negative errors are evenly distributed and cancel each other out. The calculated yield trend lines lie pretty close and within the measured value error bars except a few outliers. It is worth noting that the large errors observed in day 4, 5, 9, 12, 18, 20 and 25 have the same error "pattern", i.e. high or low measurements for both wastewater sources had been observed. It is suspected that this might be due to errors introduced by improper scale calibration or wrong oven temperature which caused underestimation or overestimation of sludge yields for both wastewater streams at the same time and which was not accounted for in the uncertainty analysis.

Both figures (Figure 4 & 5) display a similar model fit pattern with several outliers in the first 30 days of operation when the system was still in a non-steady operation and a close fit during the last 20 days when the system reached a steady-state.

Uncertainty analysis

Experimental sludge yield determination uncertainty was calculated as a function of elemental systematic (bias) and random uncertainties associated with each measurement. These elemental uncertainties are then used to calculate the final uncertainty of the observed yield. The resulting uncertainty was calculated from the uncertainty propagation equation with comparable systematic and random errors (Equation 10).

$$s_{\bar{Z}} = \sqrt{\sum_{i=1}^{P}\left[\left(\frac{\partial f(x_1, x_2, \ldots, x_P)}{\partial x_i}\right)^2 \sum_{r=1}^{R}\left(s_{\bar{x}_i}^2 + \left(\frac{\Delta x_{ir}}{\sqrt{3}}\right)^2\right)\right]} \tag{10}$$

where s is a standard deviation and Δx represents a maximum systematic error (bias).

s_Z represents uncertainty of a function f with a confidence level of 67%. Uncertainty of the mean sludge yield value (over an entire period of operation) was calculated accordingly from Equation 11.

$$s_{\bar{Z}} = \frac{s_Z}{\sqrt{N}} \tag{11}$$

where N is a number of measurements taken.

The list of elemental uncertainties used in the uncertainty propagation calculation is presented in Table 7 below.

Table 7. Elemental uncertainties used in the uncertainty calculations

Uncertainty	Unit	Value
Water level	mm	2
Inlet COD concentration	mg/l	40
Waste sludge volume	ml	20
MLSS concentration	mg/l	50
Sample volume at BWL (50ml)	ml	2
Sample volume to measure the effluent SS	ml	2
Weighing scale accuracy	mg	0.2
Waste sludge volume	ml	20

Percent contributions of each elemental uncertainty in the total uncertainty of the measured sludge yield are shown in Figure 6. The largest portion of the total error is due to uncertainty in sample volume at BWL which constitutes about 45% of the error. The second and third largest contributors are total volume and influent COD uncertainties with roughly 25% and 20% contributions respectively. These results show that in order to improve the accuracy of sludge yield determination in a biological reactor, the reactor volume needs to be increased, so the proportion of sludge withdrawn from the system with the sample taken at BWL to an entire sludge mass in the system is minimised.

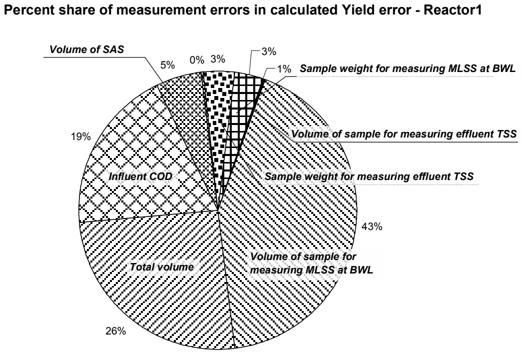

Figure 6 Percent contributions of elemental measurement uncertainties in a combined yield uncertainty.

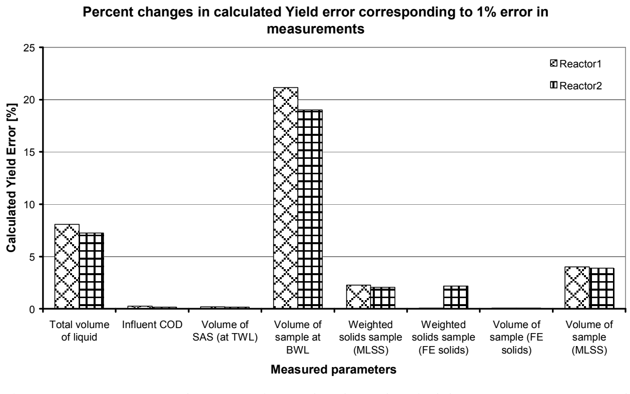

Figure 7 Percent changes in calculated Yield error corresponding to 1% error increase in the measurement.

Additionally, sensitivity to changes in each elemental error was investigated to see which measurement error introduces the biggest uncertainty in the result. The analysis showed that again uncertainty in a determination of the sample volume taken at BWL contributed to the largest increase in the final result. Results of the analysis are presented in Figure 7 above.

5.2 *Sensitivity analysis of the model*

Sensitivity analysis was performed on the COD-based sludge yield calculation model in order to see which input parameters have the highest influence on the model result. The sensitivity analysis was performed on the model for Reactor 1 (Wastewater Source 1) for 4 different temperatures: 25.6°C, 20°C, 15°C and 10°C. First temperature is the average operating temperature inside the reactor. At this temperature the model was very sensitive to a temperature dependency factor, θ. Analysis was then done at three other operating temperatures to see whether the sensitivity would decrease at temperatures closer to 15°C for which all the kinetic parameters had been obtained. The sensitivity to θ is zero at that temperature. For temperatures other than 15°C sensitivity to θ becomes large and increases as the difference between the operating temperature and 15°C gets larger.

Other parameters having a substantial effect on the model prediction are VSS/TSS ratio in the MLSS, XCOD/VSS ratio and theoretical yield Y. Stoichiometric and kinetic parameters like f_{XII}, f_{XI}, f_{SI}, k_d or f_I do not have a very large impact on the model predictions. Bar chart showing the results of the sensitivity analysis is presented below in Figure 8.

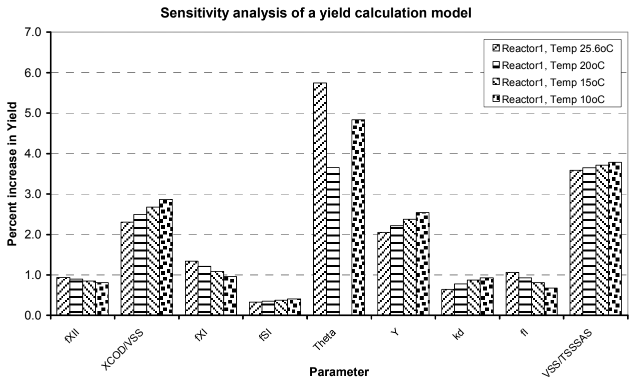

Figure 8 Sensitivity of the sludge yield model to various input parameters.

6 CONCLUSIONS

Proper estimation of sludge production in a plant is very crucial as it determines the sludge age at given tank volumes and affects the size of sludge treatment facilities like sludge thickening, digestion, dewatering, etc.

Simple biomass yield calculations based on single parameter Y_{obs} can only be used on existing plants where sludge production and incoming organics and solids loads are regularly measured and monitored. For designing new plants or retrofitting of the existing plants for which such information had not been recorded, it is not appropriate to judge Y_{obs} s without any further calculations, because Y_{obs} is very dependent on various operating parameters like influent composition, SRT and temperature to mention some. A BOD_5 based method from ATV A 131E proved to give adequate sludge yield predictions in activated sludge systems. This method is partly theoretical and partly empirical and the empirical parameter may cause it to be invalid for "unusual" wastewater types with high industrial contents. Also because BOD_5 tests are more difficult to perform and need skilled staff, the BOD_5 data has greater uncertainty than the COD data. Therefore a COD based method is likely to be more reliable than a BOD_5-based method. Through experiments it was found that the COD-based method gave very accurate sludge yield predictions without any need for model calibration. It can therefore be used for sludge production calculations.

It is recommended to calculate sludge production using both methods during the design stage and to compare the results from both methods in order to avoid making a mistake due to errors in one of the two data sets.

It is felt that COD-based dimensioning methods and COD data will be used more and more often as all state-of-the-art dynamic wastewater treatment models are based on COD fractions rather than BOD_5.

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