Modelling and characterisation of primary settlers in view of whole plant and resource recovery modelling

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Abstract
Characterisation and modelling of primary settlers have been neglected pretty much to date. However, whole plant and resource recovery modelling require primary settler model development, as current models lack detail. This paper focuses on the improved modelling and experimental characterisation of primary settlers. First, a new modelling concept based on particle settling velocity distribution is proposed which is then applied for the development of an improved primary settler model as well as for its characterisation under addition of chemicals (Chemically Enhanced Primary Treatment, CEPT). Second, another basic primary settler model, developed for control under chemicals addition, is presented. Third, the variation of the COD fractionation produced by primary settling is investigated, showing that typical wastewater ratios are modified by primary treatment. The latter provides a further argument for more detailed primary settler models in view of whole plant modelling as they clearly impact the downstream processes.

Keywords
Primary clarification model, particle settling velocity distribution, CEPT, ASM fractionation.

INTRODUCTION

The role of primary settling in wastewater treatment has often been neglected and very few efforts have been made for its optimisation and modelling (Lessard and Beck, 1988; Gernaey *et al.*, 2001; Ribes *et al.*, 2002). It has been neglected either because primary settling is not considered very influential for modelling purposes, or because the simple models proposed earlier were considered sufficiently robust to describe the primary settling tanks (PSTs) behaviour (Otterpohl and Freund, 1992). In many modelling case studies, the boundaries of the wastewater treatment plant (WWTP) are defined from the primary effluent onwards, i.e. using the primary effluent as model input, hereby keeping the primary settler out of the modelling scope. However, a better understanding and modelling of the processes taking place in PST result in a more accurate description of the primary effluent characterisation and sludge wastage. As such, it results in improved operation of the subsequent treatment phases, i.e. water and sludge treatment.

Improved primary settler models are also essential ingredients of whole WWTP descriptions. In this respect, Choubert *et al.* (2013) stated that based on combined expertise of modellers (Phillips *et al.* 2009) and sensitivity analysis (Petersen *et al.* 2002) profound effects of wastewater characterisation on modelling outputs (Henze *et al.* 2000) have been shown:

- Sludge production is influenced by the estimated inert particulate COD.
- Oxygen demand is influenced by the estimated total biodegradable COD.
- Anoxic denitrification rate and anaerobic phosphorus release are influenced by the estimated readily biodegradable COD.

- Effluent COD is influenced by the estimated inert soluble COD.

The importance of providing reliable wastewater characterisation, enabling the link with the industry-standard activated sludge models (ASM) (Henze et al., 2000), was also highlighted. Hence, the function of PSTs under the ASM framework should be reconsidered since the impact of primary treatment on wastewater fractionation may be significant.

In this context, the simulation study of Flores-Alsina *et al.* (2014) illustrated the considerable advantages given by the enhancement of the TSS removal in a PST on final effluent quality and operational costs. This enhancement can be obtained by addition of chemicals (combined or not with lamellar settling) in the primary treatment, which may increase TSS removal efficiency up to 90% (Tchobanoglous *et al.*, 2003).

Chemically enhanced primary treatment (CEPT) by addition of coagulants/flocculants, which is often operated under wet weather conditions, may be also pursued for maximising the organic material directed to biogas production and other resource recovery. It thus becomes directly involved in the design of the energy self-sufficient WWTP. CEPT can be applied to achieve many different objectives in wastewater treatment facilities: to increase the TSS removal performance of PST in primary only plants; to reduce organic loading rates thereby reducing demand on aerobic biological treatment facilities; lastly, it can permit increased hydraulic loading rates to existing PST, thus favouring plants that receive high wet weather flows. The first most significant application of CEPT was in the 1960s by Canadian and U.S. engineers to address eutrophication of the Great Lakes through chemical precipitation of phosphorus. Galil and Rebhun (1990) showed that the reduction in organic load using CEPT significantly reduced aeration tank volume in the downstream activated sludge process. More recently, in the U.S., with increased emphasis on CSO and SSO controls, agencies are seeking for inexpensive and compact solutions to manage wet weather flows, other than just increasing secondary treatment hydraulics and process capacity. CEPT has been extensively evaluated because of the minimal investment in new infrastructure. Indeed, hydraulic capacities of existing primary settlers can be increased by a factor of up to three, which is often sufficient to manage peak wet weather flows. Bench-scale (Melcer *et al.*, 2005, 2009) and pilot-scale (Melcer *et al.*, 2012; Newman *et al.*, 2013) demonstrations of wet weather treatment using CEPT have been conducted. These have led to the application of CEPT at full scale.

Most of the existing settling models make use of a unique settling velocity for all the particles, even though the particles are heterogeneous and the assumption of a single settling velocity is a too simplistic approach. Introducing the concept of particle settling velocity distribution (PSVD) in the model provides a better description of the behaviour of the particles in the PST. Moreover, even though little literature exists on the topic, a few studies have highlighted that a link exists between particle physical properties and particle biodegradation properties (Chebbo and Bachoc, 1992; Hvitved-Jacobsen *et al.*, 1998; Morgenroth *et al.*, 2002), emphasizing the need to focus more on how primary settler models and subsequent biological reaction models have to be complementary. Hence, models of an adequate complexity need to be developed for a more accurate description of the PST behaviour and the chemical/biological phenomena that may affect particles, their settling velocity and, as a consequence, their removal. Indeed, the efficiency of the PST directly influences the performance of the subsequent treatment units in WWTPs, since during settling organic matter and suspended solids of the influent, as well as pollutants associated with them, are removed. Not only does this determine the load to the downstream treatment steps, it is also critical in the evaluation of the benefits that the sludge treatment train will be able to accomplish (energy and nutrient recovery).

This work presents different ongoing developments related to the improved modelling and experimental characterisation of primary settlers. The paper is organised in four sections: (1) a new primary settling model based on particle settling velocity distribution (PSVD) is first proposed; (2) it is briefly illustrated how PSVD can also be used to characterise and model a CEPT process; (3) a simple primary settling model for CEPT is presented and (4) ASM fractionation in primary settlers is discussed.

PSVD FOR PRIMARY SETTLER MODEL DEVELOPMENT

A new dynamic primary settler model, based on the PSVD approach and inspired by the work of Maruéjouls *et al.* (2012) on retention tanks, was initially presented by Bachis *et al.* (2012). This model allows improved predictions in terms of effluent TSS compared to previous primary settling models. It was shown that by creating a number of particle classes that cover the settling velocity distribution, a vertical gradient of the concentration of each of the particle classes and the pollutants associated to them can be calculated.

The ViCAs (Vitesses de Chute en Assainissement) batch settling protocol developed by Chebbo and Gromaire (2009) is an excellent method to feed this type of PSVD-model, as it allows to experimentally determine the fraction of the different settling velocity classes, each characterised by a distinct settling velocity V_s. A ViCAs experiment consists in filling a settling column (H=60 cm, Ø=7cm) with a homogenized suspension. Solids settled during predefined time intervals are recovered at the bottom of the column and weighed for TSS. From the time evolution of the cumulated mass of particles settled since the beginning of the experiment one can calculate the distribution of settling velocities.

The PSVD model was implemented on the modelling and simulation environment WEST (mikebydhi.com). To describe the vertical gradient of particle class concentrations the settler is divided into a number of layers and a mass balance is calculated around each layer for each of the classes. Five particle classes with different (constant) settling velocities make up the core of the model.

Influent TSS fractionation into particle classes

Each particle class is assigned a fraction of the influent TSS. Given the dynamics of the wastewater composition, this assignment is, however, not constant. To assign the fraction of influent TSS to the classes, advantage is taken from the observation from multiple ViCAs experiments that the ViCAs curves are located higher for low TSS concentration and lower for high TSS. This means that high TSS samples contain a larger fraction of rapidly settling particles. Therefore, the assignment is made by interpolating the PSVD curve between two boundary curves (continuous lines on Figure 1). These are the boundaries delimiting the zone where most of the observed influent PSVD curves for the particular plant under study were located (results not shown). The upper limit of this zone is the ViCAs representing low influent TSS concentrations, while the lower limit is given for high influent TSS concentrations. The assignment for a sample with a certain TSS concentration is performed as follows: for a certain settling velocity (on the x-axis), the two corresponding limiting TSS fractions are determined (y-axis) and a linear interpolation is made between them from the influent TSS-value. Thus, the observed relation between PSVD and TSS concentration is used to define the fraction of each class of the influent TSS. The settling velocities characterising each class were calculated as the geometrical mean of the settling velocity boundaries of the class.

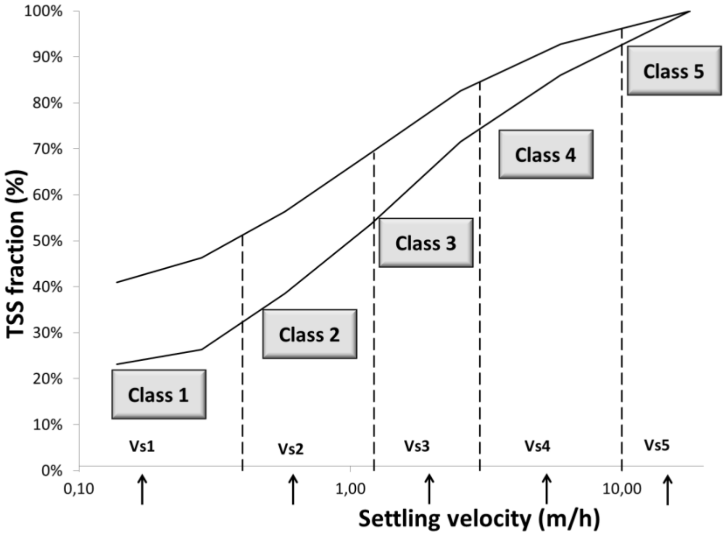

Figure 1 Fractionation of the ViCAs zone into 5 classes and upper and lower limits of the zone where most of the PSVD curves observed for the case study were found. Settling velocities characterising each class were calculated as the geometrical mean of the settling velocity boundaries of the class

Primary settler data

The performance of the five classes PSVD model was evaluated through the simulation of the data from the Eastern wastewater treatment plant of Québec City (Canada). Two series of data were available: one was the TSS 24h-evolution of the influent and effluent collected at the full-scale primary settlers during a sampling campaign conducted in 2010 (three days under dry weather flow conditions); the other data set contained online TSS values measured by turbidity sensors on a pilot-scale primary settler (2013) (one day under dry weather flow conditions).

The PSTs of the Eastern WWTP of Québec City are lamellar settlers, with a total surface of 27,000 m^2, treating a mean flow rate of 236,600 m^3/d during dry weather conditions. The 5 m^3 pilot-scale PST was installed in the same WWTP and it received the influent from the full-scale PSTs, treating a mean flow rate of 192 m^3/d.

Evaluation of the model performance

Model parameters were estimated by fitting the model to the data sets. The goodness-of-fit of the model was statistically evaluated through the calculation of the chi-squared criterion (weighted least squares). The assumption of independent and normally distributed measurement errors is made.

$$\chi^2(\theta) = \Sigma_{i=1}^{n}(\frac{1}{\sigma_i}(y_i - \hat{y}_i(\theta))^2$$

where y_i is the observed value; $\hat{y}_i$ (θ) is the simulated value for the parameter set θ; σ_i is the standard measurement error of the observation y_i and n represents the number of data points to which the model was fitted. The computed χ^2 is then compared to tabulated values of the chi-squared distribution for n-1-n_θ degrees of freedom (n_θ stands for the number of estimated parameters), to decide whether the model is justified by the data or not (Gujer, 2008).

Calibration results

The parameters estimated during the calibration consisted on the location of the five settling velocity class boundaries (see Figure 1, lower limit not visible). During the calibration of the model different settling velocities and, consequently, different sets of fractions were tested until a good model fit to the measured effluent TSS time series was achieved. Two of the four full-day data sets were used for the calibration, visibly resulting in a good fit for the effluent TSS concentrations (Figure 2). The calculated χ^2 for the two events is respectively 11 (Figure 2a) and 34 (Figure 2b). For 18 degrees of freedom (n=24 and n_θ=5) the observed χ^2 is in 99% of the cases smaller than the critical value 34.8. This means that the model is justified by the data, especially for the first simulation. The PSVD model's V_s values and limit TSS fractions resulting from the calibration are given in Table 1.

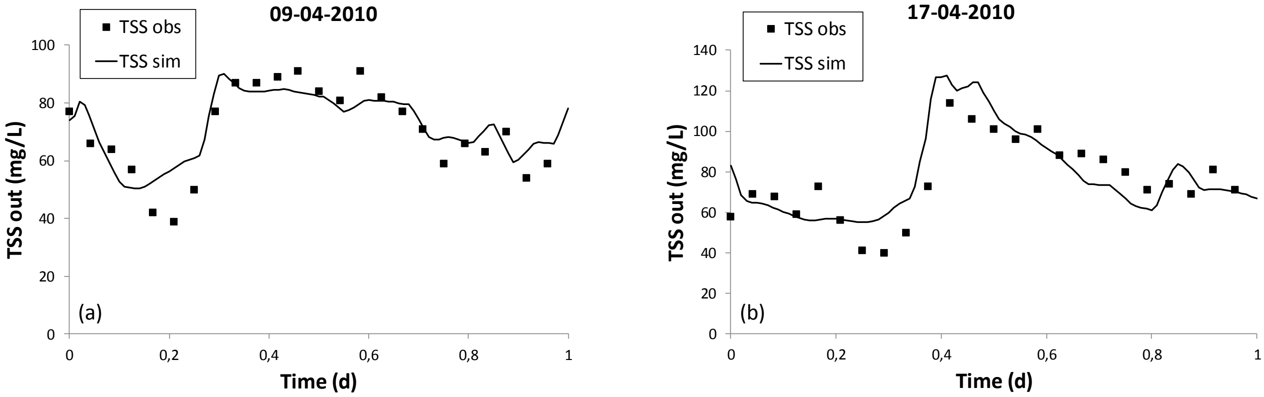

Figure 2 Model fit for effluent TSS concentrations during the calibration phase.

Table 1. Settling velocity (Vs) and boundary TSS fractions (F) associated to each of the 5 classes in the PSVD model and settling velocities used in the primary settling model from Lessard and Beck (1988).

	Class 1	Class 2	Class3	Class 4	Class 5
Class-characterising Vs (m/h)	0.06	0.70	1.91	5.48	13.36
F (high TSS-low TSS) (%)	32-51	22-19	20-15	18-11	8-4
	Dry weather		Wet weather		Return liquors
Vs Lessard&Beck (1988) (m/h)	1		2		10

Validation results

The remaining two full-day data sets were used to validate the model. One of the data sets was collected at the full-scale PST, the other was the data set with on-line turbidity data collected at the pilot primary settler treating the same wastewater.

Full-scale PST. The TSS concentrations were simulated quite well (Figure 3a). The χ^2-test resulted in an acceptable value (23) since in 90% of the cases the sum of squares is smaller than 26.

Pilot-scale PST. The pilot-scale PST was modelled in the same way as the full-scale PST, with adjusted dimensions. The PSVD-model was fed with influent TSS data obtained through a linear correlation from NTU data provided by the turbidity sensor located at the inlet of the pilot-scale PST. The PSVD-model parameters estimated above were applied as such. Figure 3b confronts the simulated effluent TSS concentrations with the observations from the turbidity sensor located at the effluent of the pilot-scale PST. Even if it failed the χ^2-test, it can be stated that, given the difference in configuration of the settler, a remarkably good fit is obtained.

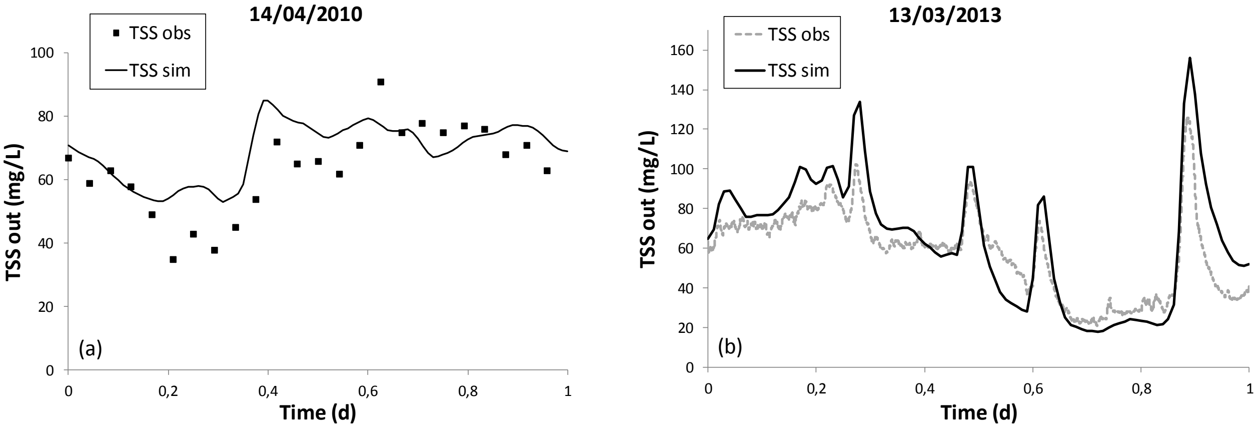

Figure 3 Model fit for effluent TSS concentrations during the validation phase of the full-scale PST (a) and the pilot-scale PST simulated with the same PSVD model and model parameters (b).

Further tests of the model were conducted by applying it to simulate TSS concentrations obtained from a 10-day sampling campaign at the Norwich (UK) treatment plant (Lessard and Beck, 1988). Supernatant liquors from the sludge treatment were returned to the primary inlet two or three times a day. Return of supernatant sludge liquors and storm sewage to the influent stream affected the wastewater composition, producing peaks of TSS concentrations that were reproduced in the effluent as well. Therefore, Lessard and Beck distinguished in their model three different streams: crude sewage, storm sewage and crude sewage with return liquors and attributed different settling velocities to them (1, 2 and 10 m/h respectively) (Table 1). Hence, in their work the unique settling velocity of their model had to be changed each time one of the three mentioned events occurred (Figure 4a). When applying the dynamic PSVD model no such changes are needed as it just needs the observed influent TSS concentrations. It is not only capable of taking into account these sudden changes, but also proves to better simulate the data (Figure 4b), especially with regard to the time delay of the peaks. Please note the remarkable finding that the ViCAs curves obtained in Québec City could be applied as such to the Norwich treatment plant with excellent predictive capabilities. The only calibration performed was the estimation of the class settling velocity boundaries.

In conclusion, a new dynamic primary settler model based on particle classes has been developed, showing to be effective in predicting effluent TSS concentration and providing increased accuracy in simulating the TSS dynamics at the outlet of a primary settler compared to existing dynamic settling models. The approach of taking into account the PSVD of the particles in the influent provides a type of primary settler model with very good prediction power for different sewages and weather conditions.

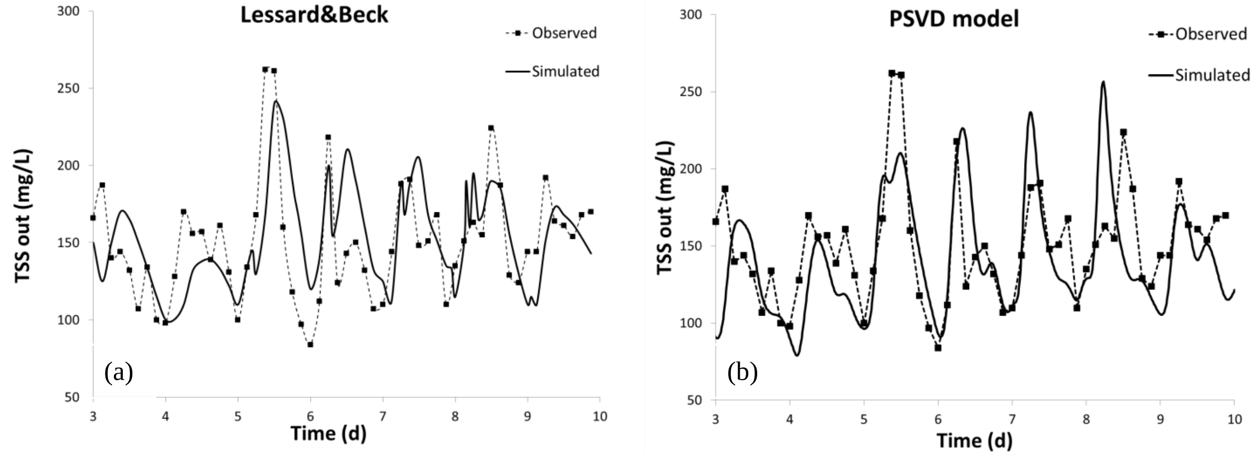

Figure 4 Model fit for effluent TSS concentrations in (a) the Lessard&Beck model and (b) the PSVD model.

PSVD FOR CEPT MODELLING

The effect of CEPT on the PSVD can also be characterised by means of ViCAs tests. To illustrate this, samples taken at the inlet of the pilot-scale PST after addition of coagulants/flocculants were subjected to the ViCAs test. Figure 5a illustrates that the inlet PSVD after chemical addition is shifted towards higher settling velocities and outside the typical reference zone of the primary settler influent without CEPT (Maruéjouls *et al.*, 2011). The effect is more pronounced for slow settling particles, which is the logical consequence of the aggregation of the particles produced by the addition of chemicals, making them grow in size and increase in settling velocity.

This experimental approach may thus be very well suited to model the effect of the addition of coagulation/flocculation chemicals on primary settling. Indeed, the curve with the appropriate PSVD (with or without chemical addition) may be used directly as input to the model, fractionating the TSS in the appropriate better settling fractions. Applying the model using the PSVD with chemical addition results in a significantly better TSS removal, as illustrated with the simulation of CEPT applied to the same influent situation (Figure 5b). Further confirmations are under study.

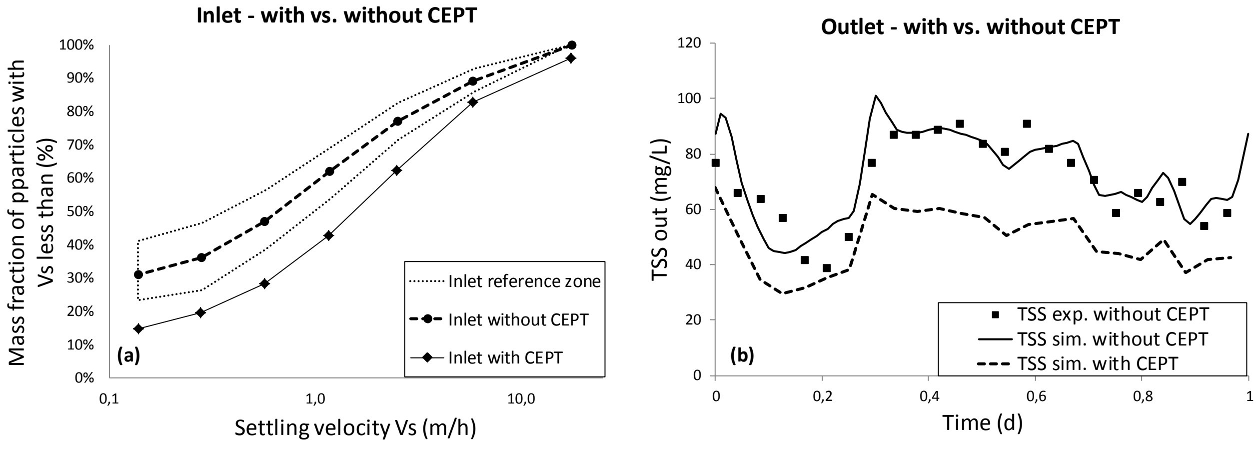

Figure 5 (a) Comparison of PSVD observed at the PST inlet during operation without CEPT and with CEPT. The reference zone illustrates typical PSVD observed at the PST inlet in Québec City, Canada, without CEPT (Maruéjouls *et al.*, 2011). (b) PSVD model fit for effluent TSS concentrations without CEPT and simulation with CEPT.

SIMPLIFIED CEPT MODEL

As an alternative to the relatively complex PSVD model, a simple model for chemically enhanced primary settlers was developed by Tik *et al.* (2013) with the dedicated objective of having a model that can be used for the development of a controller for chemical addition. Without the need for ViCAs characterisation, the effect of alum addition was modelled by varying two settling characteristics in the settling velocity function: the overall particle settling velocity (V_0) (Figure 6a) and the fraction of non-settleable suspended solids (f_{ns}) (Figure 6b). The proposed model allows the primary settlers' outlet concentration of TSS to be properly simulated during an experiment of full-scale alum addition with step concentration changes (Figure 6c) and seems sufficiently robust to satisfactorily describe dry weather conditions as well as wet weather conditions. Further validation on other case studies is required to confirm the usefulness of the model for this type of control development and tuning studies.

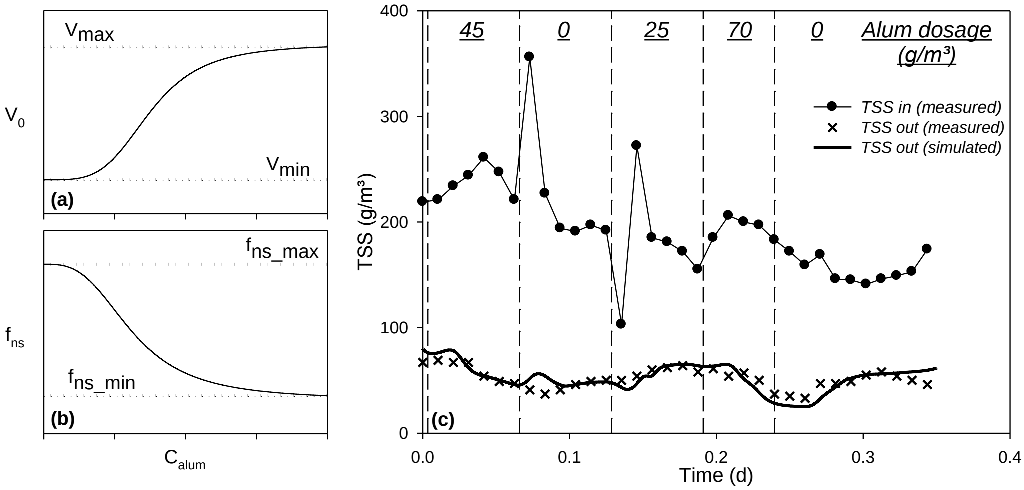

Figure 6 Dependency of (a) the non-settleable fraction of TSS (f_{ns}) and (b) settling velocity, V_0, on alum concentration (C_{alum}); (c) experimental (inlet and outlet) and simulated (outlet) TSS concentrations of a full-scale experiment in Québec City, Canada, on August 25th, 2011. The flow rate was approximately constant at 9,300 m^3/h (Tik *et al.*, 2013).

With this model Tik *et al.* (2013) developed a successful control loop using effluent turbidity measurements that could reduce alum addition by 30% compared to a constant alum addition and yielding the same performance in terms of maximum TSS concentration in the primary effluent.

ASM FRACTIONATION IN PRIMARY TREATMENT

Primary treatment removes particles from the wastewater and as such changes its composition. These changes can be expressed in terms of several calculated ratios of traditional pollutant characteristics (Table 2). Fractionation of wastewater is thus affected by primary settling, thus impacting the subsequent treatment processes (Kristensen *et al*. 1992, Pasztor *et al*. 2009).

For the correct model-based evaluation of a WWTP in which ASMs are used to describe the subsequent bioreactor models, a proper prediction of the primary effluent into the ASM input fractions is required. However, the effect of the PST on these fractions is frequently overlooked or oversimplified (the fractions in the PST are assumed to remain constant under all conditions). Note that the models described above only focus on TSS removal prediction and do not consider variations in fractionation in the primary settler.

Table 2. Differences in typical ratios of traditional wastewater characteristics of raw influent and primary effluent of municipal wastewater treatment (redrafted after Rieger *et al.*, 2012) and comparison with Québec City ratios.

		Ratio	Unit	n1)	mean	Std% 2)		n	Mean	Std%
Reference	Raw influent	Ntot/CODtot	g N/g COD	12	**0.095**	17%	Québec	8	**0.089**	1%
		N-NHx/TKN	g N/g N	13	**0.684**	8%		8	**0.482**	13%
		CODtot/BOD5	g COD/g BOD	12	**2.060**	11%		8	**2.062**	32%
		TSS/CODtot	g TSS/g COD	12	**0.503**	18%		11	**0.573**	14%
		BOD5/BOD∞	g BOD/g BOD	7	**0.655**	7%		8	**0.859**	6%
	Primary effluent	Ntot/CODtot	g N/g COD	9	**0.134**	35%		8	**0.123**	2%
		N-NHx/TKN	g N/g N	11	**0.755**	4%		8	**0.509**	9%
		CODtot/BOD5	g COD/g BOD	9	**1.874**	31%		8	**1.931**	20%
		TSS/CODtot	g TSS/g COD	9	**0.380**	21%		11	**0.426**	9%
		BOD5/BOD∞	g BOD/gBOD	6	**0.644**	10%		8	**0.894**	4%

1) number of answers; 2) standard deviation in %

Therefore, to better describe the subsequent biological treatment by providing a good fractionation, primary settling was also studied from an ASM point of view, taking inlet and outlet samples from primary settlers at three different WWTPs (Eindhoven, Roeselare and Québec City). The samples were analysed in terms of COD fractions into four components: the readily biodegradable COD, S_B; the slowly biodegradable COD, XC_B; the inert soluble COD, S_U; the inert particulate COD, $X_{U,Inf}$ (notation from Corominas *et al.*, 2010). For the Québec City samples, these fractions were determined by combining a respirometric protocol together with total (COD) and soluble (sCOD) COD analysis and ultimate BOD (UBOD) measurements (Petersen *et al.*, 2003). S_B directly resulted from the respirometric test on the wastewater sample, while XC_B, S_U and $X_{U,Inf}$ were calculated as follows: $XC_B = UBOD - S_B$; $S_U = sCOD - S_B$; $X_{U,Inf} = COD - sCOD - XC_B$. For the WWTPs of Eindhoven and Roeselare both a respirometric evaluation and the STOWA method (Roeleveld and van Loosdrecht, 2002) were applied. The two protocols resulted in different COD fractions for the same wastewater sample. Nevertheless, both showed that primary treatment has a significant impact on the ASM1 fractions. Primary treatment yielded a significant variation of the particulates ratio ($XC_B/X_{U,Inf}$) (on average 1.9 to 1.2 for the Eindhoven, 1.1 to 0.5 for the Roeselare and 1.5 to 1.8 for the Québec City experiments), while, as expected, the soluble ratio (S_U/S_B) was not affected by the primary settler (Figure 7).

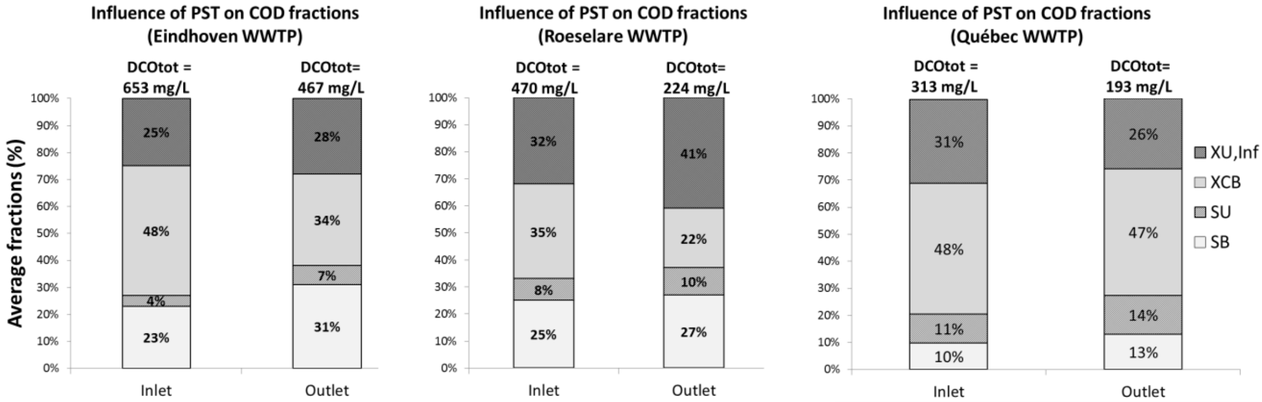

Figure 7 Evolution of COD fractions before and after a PST at three WWTPs: Eindhoven (The Netherlands), Roeselare (Belgium) (both by the STOWA protocol) and Québec City (respirometric protocol).

In the Québec WWTP a more detailed analysis was conducted. The wastewater samples could be classified into two types: a low loaded one (sampled at nighttime) and a heavily loaded one (sampled at daytime). According to this classification, by comparing inlet and outlet samples different trends in the aforementioned ratios were noticed: the particulate ratio ($XC_B/X_{U,Inf}$) systematically decreases for daytime samples, but increases for wastewaters collected at nighttime. Moreover, some work was also conducted on samples collected after addition of chemicals. It was found that both the particulate and the soluble ratios tend to increase, i.e. the primary effluent contains relatively more biodegradable material than the influent.

These first results, although requiring further investigation, show that primary treatment has a significant impact on the ASM1 fractions. Therefore, the influence of the PST on the wastewater characterisation cannot be neglected and a proper COD fractionation into model variables can significantly improve simulation results. For instance, by applying the PSVD model concept to the mass balances of the ASM fractions in the primary settler model, i.e. having five classes for each of the ASM fractions, it will be possible to make them settle at different velocities, allowing the observed increase in ratios to be predicted properly. This will result in an appropriate fractionation at the primary settler effluent.

CONCLUSIONS

All studies presented in this contribution focus on primary settlers. The authors believe that PSTs need to be properly modelled and characterised in view of whole plant and resource recovery modelling. A new experimental and modelling approach, based on Particle Settling Velocity Distributions (PSVD), is proposed, and was shown to successfully predict TSS effluent concentrations on the basis of influent TSS time series and a number of ViCAs characterisation experiments. Simulation results under calibration and validation of the model were presented. It is illustrated that this approach can also be used to characterise primary influent under addition of chemicals, representing a potentially useful tool for the modelling of PSTs under CEPT. In addition, a simpler settler model, in view of controller development for CEPT, was presented as an alternative to the particle classes-based model. Finally, wastewater fractionation results obtained for the influent and the effluent of PSTs have shown, for the first time, that the primary settler produces a significant change in the wastewater composition ratios and, as a consequence, in the ASM fractionation of the wastewater. Hence, it can be anticipated that a more detailed primary settler model with explicit consideration of ASM fractions may be needed to properly feed the subsequent bioreactor models of a whole plant and resource recovery model.

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