Concentration-driven models revisited: Towards a unified framework to model settling tanks in WWTPs

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Abstract

This contribution introduces a new perspective on the modelling of settling behaviour aimed at providing a unified description of the processes taking place both in primary and secondary settling tanks for a more detailed operation and control in Water and Resource Recovery Facilities (WRRFs). First, experimental evidence is provided pointing out the flocculation state of sludge as an important common source of distributed behavior in different settling processes. Subsequently, a unified model framework considering several particle classes is proposed in order to describe this distributed settling behaviour as well as the effect of variations in flocculation state on the settling process. The result is a set of PDEs that are valid from dilute concentrations where they correspond to discrete settling to concentrated suspensions where they correspond to compression settling and can thus be used to model both primary and secondary settling tanks.

Keywords

Primary clarifier; secondary clarifier; clarification; compression; particle size distribution; settling velocity distribution

INTRODUCTION

In conventional WWTPs both primary (PSTs) and secondary settling tanks (SSTs) aim at separating suspended particles from the liquid phase through sedimentation. Although both unit processes depend on the same principle, i.e. settling due to gravity, the modelling approaches have been distinctly different. SSTs have been modelled with a single concentration variable for the particle phase, which means that this phase is considered as a continuum, like the liquid phase. Hence, all particles are indirectly assumed to be identical. We call this a concentration-driven model. In contrast, discrete settling in PSTs and the clarification zone of SSTs is characterized by distributed settling dynamics driven by individual particle properties (e.g. size, density). As the phenomenon of segregation between particles differing in size or density is challenging to model, mostly simplified models for PSTs and SST clarification have been used although recently, a more detailed model for PSTs was established based on particle classes with different settling velocities (Bachis et al., 2016).

Moreover, recent evidence in SSTs (Torfs et al., 2015) suggests that also for higher concentrations, settling dynamics cannot be solely attributed to concentration variations and that here too changes in individual particle properties such as size and density play an important role in affecting the settling velocities. Hence, although each settling process is still governed by its own specific dynamics, these dynamics can be attributed to a common source (i.e. variations in size and density leading to a distributed settling velocity) thus calling for a unified framework to describe the different processes.

EXAMPLES OF A COMMON SOURCE OF DYNAMICS IN DIFFERENT SETTLING PROCESSES

Discrete settling in PSTs and the clarification zone of SSTs

The discrete settling behaviour in the clarification zone of SSTs is often modelled by directly modifying classical concentration-based hindered settling velocity functions. Unfortunately, this approach is not generic enough for reliable effluent suspended solids predictions since it does not capture the true (distributed) settling behaviour using a single parameter set. Figure 1 shows measurements of settling at low concentrations of secondary sludge where particles of different size can be seen to settle sequentially in time thus confirming that settling at these low concentrations is governed by particle size and density. Moreover, Bachis et al. (2016) measured particle settling velocity distributions during batch settling of raw wastewater (Figure 2). These results clearly indicate that the settling behaviour in PSTs and the clarification zone of SSTs shows a distributed behaviour where the dynamics cannot be captured by a lumped variable such as concentration.

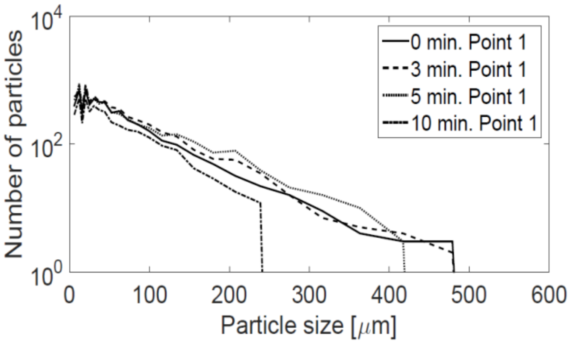

Figure 1. Example of clarification behaviour in SSTs. Changes in particle size distributions at the top of a settling column for a diluted sludge sample.

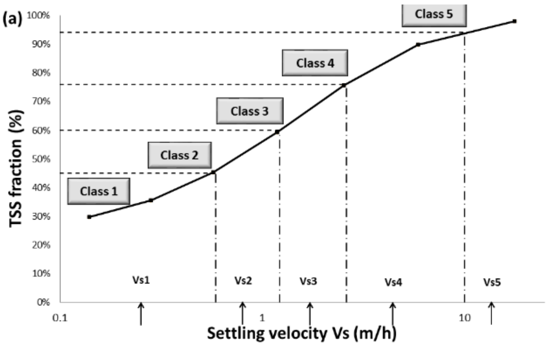

Figure 2. Example of settling behaviour in PSTs. Settling velocity distribution during settling of raw wastewater.

Hindered and compression settling in the thickening zone of SSTs

Hindered and compression settling have traditionally been considered as concentration driven processes where the settling velocity decreases with increasing concentration. However, this approach is not sufficient to explain recent experimental results. Figure 3 (left) shows how the settling behaviour of a sludge sample changes as it is subjected to different amounts of shear stress prior to settling. Significantly different settling dynamics can be observed even though the concentration of solids remains the same.

Figure 3 (right) shows changes in settling behaviour for a sludge sample after addition of loess (density $\rho \approx 1.7$ kg/l). Although the addition of loess will increase the concentration of suspended solids, the settling velocity increases which contradicts conventionally used models for hindered and compression settling that predict the opposite behaviour. These results indicate that also for hindered and compression settling changes in particle size and density should be considered as these are important factors to describe the variability in the settling process. This finding has important implications for the modelling of settling processes as it does not only show the need to step away from purely concentration-driven SST models but opens up new perspectives for a more unified settling framework which can be applied to all settling unit processes.

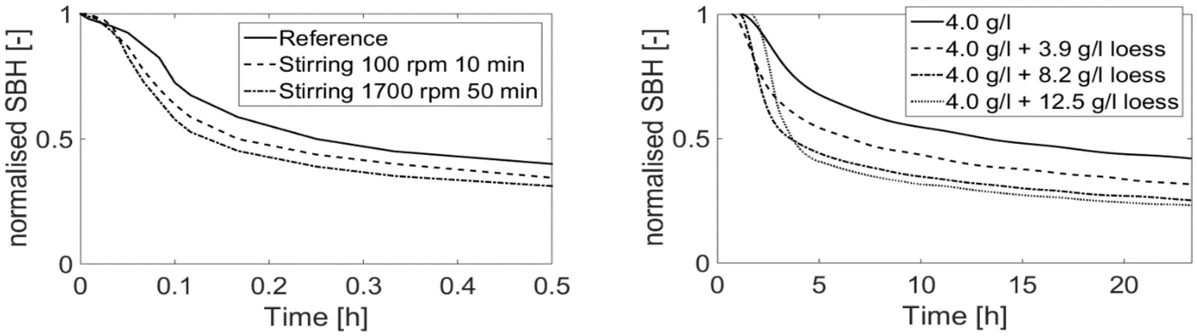

Figure 3. Normalized sludge blanket height (SBH) observerd in bacth settling experiments for a sludge sample which has undergone different amounts of shear stress (left) and different amounts of loess addition (right).

POTENTIAL APPLICATIONS OF A UNIFIED MODEL FRAMEWORK

The development of a unified framework which can capture the true variability in the settling behaviour would allow expanding the use of settler models beyond their current applications. For conventional SSTs this would not only allow improved predictions of effluent suspended solids but also to model the impact of polymer addition and increased hydraulic loadings. Moreover, a number of emerging technologies could also benefit from such improved settler models. For example, high-rate activated sludge processes receive increased interest due to their capability to efficiently up-concentrate organics into a well-digestible sludge. The specific process conditions (low sludge residence times and high sludge loading rates) impact the size and density of the flocs which have been shown to result in significantly different settling behaviour (Torfs et al., 2015). This emphasizes again the need for a framework that includes information on individual particle properties as such models will facilitate the elaboration of strategies leading to energy-neutral wastewater treatment.

HOW TO DEVELOP SUCH A UNIFIED MODEL FRAMEWORK

From the examples above, distributed properties such as particle size and density were shown to be key factors in describing the settling processes in WWTPs. Existing secondary settling models such as the traditional Takács model (Takács et al., 1991) and the more recent Bürger-Diehl model (Bürger et al., 2013) do not account for distributed behaviour of particles; they simply describe the solids by means of a lumped concentration variable. Recently, a new model for PSTs, called the Particle Settling Velocity Distribution (PSVD) model (Bachis et al., 2016), has been presented. The PSVD model does include distributed settling behaviour by introducing a number of classes with different settling velocities. However, this model only covers the discrete settling regime and can therefore not be applied to SSTs. Moreover, neither of these settling models consider changes in flocculation state due to aggregation and break-up processes even though these changes will significantly influence the final settling behaviour. Table 1 provides an overview of existing 1D settler models for PST and SST as well as the processes considered in each of these models.

Table 1. Overview of processes considered in existing 1D PST and SST models.

	Application field	Discrete settling	Hindered settling	Compression settling	Flocculation/break-up processes
Takács model	SST	No	Yes	No	No
Bürger-Diehl model	SST	No	Yes	Yes	No
PSVD model	PST	Yes	No	No	No

It is the purpose of this contribution to introduce a new perspective on the modelling of settling in WWTPs aiming to provide a unified description of the processes taking place both in PSTs and SSTs. Therefore, we will start from the existing the Bürger-Diehl model for SSTs (Bürger et al., 2013) as this model already includes hindered and compression settling in its underlying PDE as well as an appropriate numerical scheme to solve this PDE. The Bürger-Diehl model can be further extended by combining knowledge from several existing approaches. These include the PSVD model in PSTs but can also be found outside of the WWT modelling domain such as models for polydisperse sedimentation as presented by Berres et al. (2003) or Population Balance Models (PBMs) describing the mechanisms of flocculation and breakage (Nopens et al., 2015). The remainder of this contribution provides the conceptual steps to extend the Bürger-Diehl model into a unified framework that can be used to describe the settling dynamics in different settling unit processes.

The Bürger-Diehl secondary settler model

The model equation is the following PDE for the local concentration X:

$$
\begin{aligned}
\frac{\partial X}{\partial t} = \\
& -\frac{\partial}{\partial z}\left(v_{\mathrm{c}}(z,t)\,X\right) && \text{convective bulk flow}\\
& -\frac{\partial}{\partial z}\left(v_{\mathrm{hs}}(X)\,X\right) && \text{hindered settling}\\
& +\frac{\partial}{\partial z}\left(d_{\mathrm{comp}}(X)\frac{\partial X}{\partial z}\right) && \text{compression settling}\\
& +\frac{Q_{\mathrm{f}}(t)X_{\mathrm{f}}(t)}{A}\delta(z) && \text{incoming feed flow}
\end{aligned}
$$

Here, z is the depth measured from the feed inlet and X is the total suspended solids concentration. The feed inlet at z=0 is modelled as a point source with the delta function $\delta(z)$. The phenomenon of dispersion at the inlet is not considered - this is not the focus here and it can be included at a later stage. Note that the bulk velocity depends on z, since the inlet flow is divided into the upward/downward flows in the clarification/thickening zones. The hindered settling velocity and compression functions have the following forms:

$$
\begin{aligned}
v_{\mathrm{hs}}(X) &= v_0 V(X),\\
d_{\mathrm{comp}}(X) & \begin{cases} = 0 & \text{for } 0 \leqslant X \leqslant X_{\mathrm{crit}},\\ > 0 & \text{for } X > X_{\mathrm{crit}}, \end{cases}
\end{aligned}
$$

where v_0 is the maximum settling velocity for a single particle and the function $V(X)$ can represent any hindered settling function from literature (exponential, power-law, rational…) (Cho et al., 1993; Diehl, 2015; Takács et al., 1991; Vesilind, 1968). For example, for the Vesilind expression we would have $V(X) = \exp(-r_V X)$. The parameter X_{crit} is the critical concentration above which the sludge forms a network that can be compressed and d_{comp} is a compression function (De Clercq et al., 2008; Ramin et al., 2014).

The total flux of solids across in the settling tank is thus dependent on convective flow, hindered settling and compression settling and can be written as

$$F(X, X_z, z, t) = \underbrace{\left(v_{\mathrm{c}}(t) + v_{\mathrm{hs}}(X) + \frac{d_{\mathrm{comp}}(X)}{X}\frac{\partial X}{\partial z}\right)}_{\text{velocity of solids movement}} X \tag{1}$$

with X the local sludge concentration and $X_z = \partial X / \partial z$ its spatial derivative.

In order to obtain a unified modelling framework that can describe the effect of changes in flocculation state on the settling behaviour, the following specific changes/additions need to be made to the Bürger-Diehl model. First of all a number of classes need to be introduced to represent the flocculation state of the sludge. Subsequently, these different classes allow to extend the existing model with distributed settling behaviour such as discrete settling and to account for the effect of flocculation state on hindered and compression dynamics. Finally, the model can also be augmented with reaction terms to describe changes in flocculation state due to operational and loading conditions. These different steps are introduced sequentially below.

Extension to several particle property classes

The flocculation state of the sludge can be captured by dividing the total sludge concentration X amongst a number of particle classes based on either size, density (or a combination of the former) or even directly on settling velocity distributions depending on the available knowledge and data.

Hence,

$$X = \sum_{i=1}^{n} X_i$$

for n particle classes each having a certain concentration X_i.

A well-flocculated sludge will have a larger concentration of particles in the large/dense/fast class and a lower concentration of particles in the class of small/open/slow particles.

Instead of a single nonlinear convection-diffusion PDE, this will result in a system of PDEs, one for each particle property class. Such a set of PDEs has been presented in literature (Berres et al., 2003) for classes of particles having different sizes and densities. In its most general treatment, each particle class has its own settling velocity function which depends on all classes' concentrations and spatial derivatives. However, practical application of the general model by Berres et al. (2003) would require the definition of constitutive functions for the dependencies of the settling behaviour on all concentrations and partial derivatives, making it quite complex. Therefore, we choose to follow a simpler approach here and will only add a number of specific dependencies required to capture the dynamics of settling in WWT.

As a first step we maintain the assumption that hindered and compression settling are function of the total sludge concentration. Hence, particles of all classes will settle at the same velocity and we only need to redistribute the total flux (Eq. 1) over the different particle property classes. (Note that although this may seem trivial at this point, the distribution of the flux over different classes is essential for further model extension with discrete settling and flocculation processes in the next steps). The following can then describe the flux in a certain class *i*.

$$F_i(X, X_z, X_i, z, t) = \left(v_{\mathrm{c}}(t) + v_{\mathrm{hs}}(X) + \frac{d_{\mathrm{comp}}(X)}{X} \frac{\partial X}{\partial z} \right) X_i \qquad (2)$$

and the system of PDEs modelling the changes in concentration for all classes will have the following form:

$$\frac{\partial X_i}{\partial t} = -\frac{\partial}{\partial z} \left(F_i(X, X_z, X_i, z, t) \right) + \frac{Q_{\mathrm{f}}(t) X_{\mathrm{f},i}(t)}{A} \delta(z), \quad i = 1, \ldots, n \qquad (3)$$

with $X_{\mathrm{f},i}$ the concentration of class *i* in the feed flow. Once we have a system of PDEs describing the change in concentration for different classes, we can specify certain class-dependent processes such as distributed settling behaviour and reaction terms to describe the migration of particles between the different classes (i.e. flocculation and break-up).

Specification of distributed settling behaviour

At low concentrations such as occur in the primary clarifier or in the clarification zone of the secondary clarifier, sludge particles typically undergo discrete settling behaviour. As the discrete settling velocity is considered independent of concentration each particle class will settle at its own characteristic velocity ($v_{0,i}$).

Moreover, recent experimental evidence (Locatelli et al., 2015) revealed that also during the hindered settling regime, the settling velocity of flocculated particles exhibits a distributed behaviour. This can be seen by the large fluctuations in the settling velocity profiles during the hindered settling regime (Figure 4). These fluctuations and thus the width of the settling velocity distribution decreases with increasing concentration (Figure 4 - right). Once the sludge reaches the compression region, hardly any fluctuations can be observed. We can thus assume that the compression function shows no distributed behaviour but will only depend on the local concentration X and its derivative X_z.

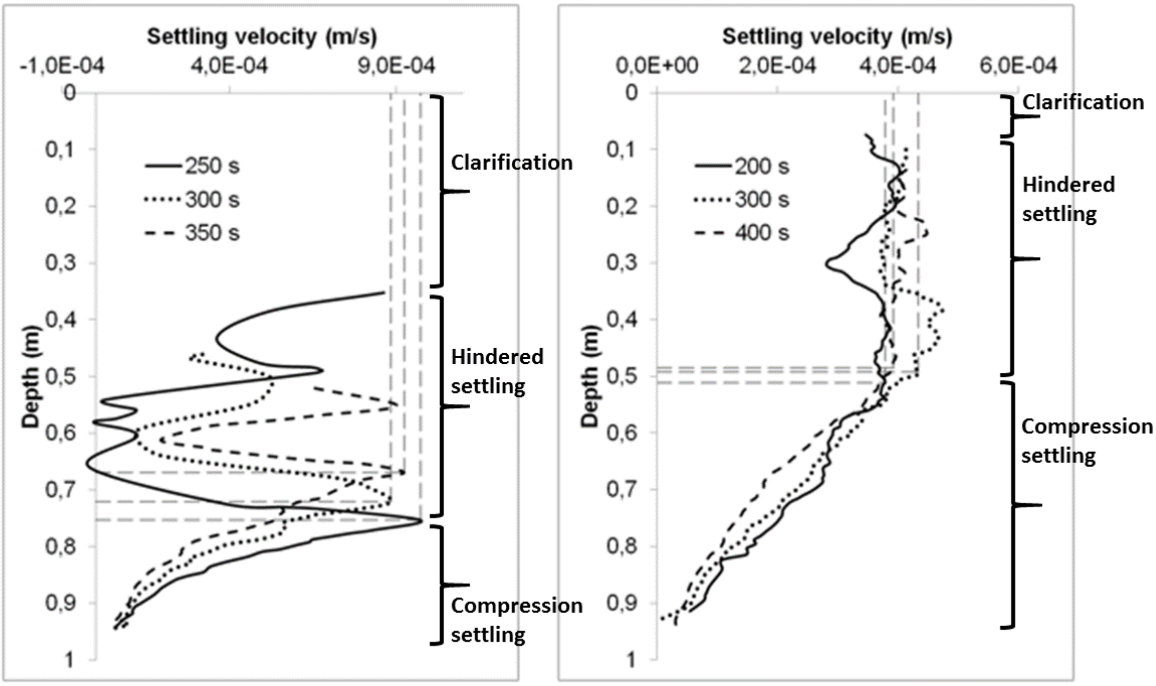

Figure 4. Settling velocity profiles recorded with an ultrasonic transducer during batch settling at an initial concentration of 1.5 g/l (left) and 4.6 g/l (right).

The distributed dynamics for discrete settling and the decreasing distributed behaviour during hindered settling can be included in the model by Eq. 4. In this equation, the parameter $X_{\text{trans}} \geq 0$ represents the transition concentration between discrete and hindered settling.

$$v_{\text{dhs},i}(X) = \begin{cases} v_{0,i} & \text{if } X < X_{\text{trans}} \\ v_{0,i} V(X - X_{\text{trans}}) & \text{if } X \geqslant X_{\text{trans}} \end{cases} \tag{4}$$

The corresponding behaviour of these functions is illustrated in Figure 5. At concentrations below the transition concentration X_{trans}, the settling behaviour in each particle property class i is governed by its discrete settling velocity $v_{0,i}$ (Figure 5 - left) and the settling velocity over the different classes shows its maximum distribution (Figure 5 - right). As the concentration increases ($X \geq X_{\text{trans}}$), the particles will start to hinder each other's settling behaviour. Hence, the settling velocity decreases and the distribution of settling velocities becomes narrower until at high concentrations (5.9 g/l for the example in Figure5), all particle classes show approximately the same settling velocity. This gradual reduction in distributed behaviour corresponds to the observations made from the experimental data of Locatelli et al. (2015) in Figure 4.

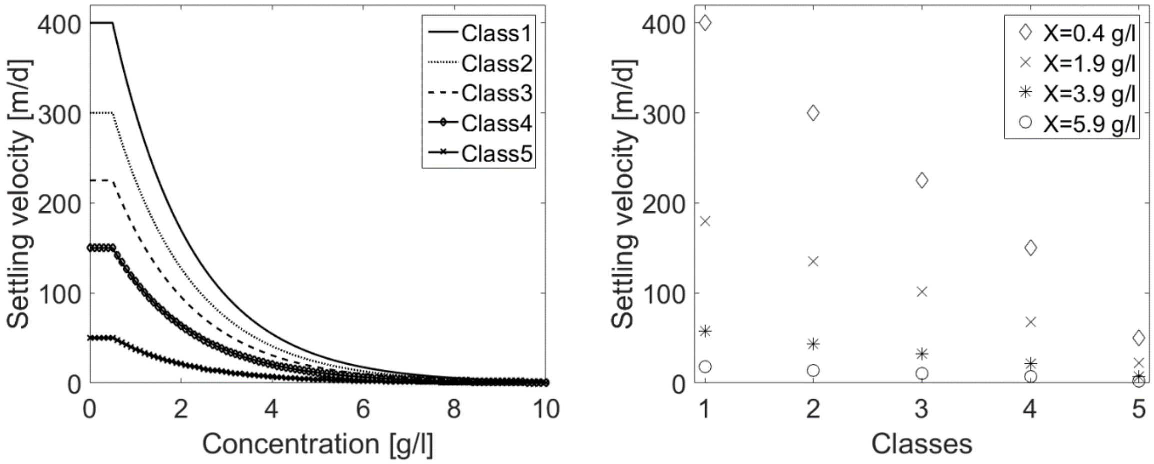

Figure 5. Example of settling velocity in function of concentration for different particle property classes (left) and the corresponding change in settling velocity distribution with increasing concentration (right). For this example the exponential hindered settling velocity function of Vesilind (1968) was used.

For the example presented in Figure 5, the transition between discrete and hindered settling causes an abrupt change in settling behaviour which may feel counter intuitive from a physical perspective. This abrupt change is a specific feature of the exponential hindered settling function of Vesilind (1986) that was selected for this example. Alternative hindered settling functions that allow a smooth transition between the two settling regimes are also available in literature such as the rational function by Diehl (2015):

$$V(X) = \frac{1}{1 + (C/\bar{C})^q},$$

where $\bar{C}$ and q are constants.

When Eq.4 is used to describe discrete and hindered settling, the total flux function thus becomes

$$F_i(X, X_\mathrm{z}, X_i, z, t) = \left(v_\mathrm{c}(z,t) + v_{\mathrm{dhs},i}(X) + \frac{d_\mathrm{comp}(X)}{X}\frac{\partial X}{\partial z} \right) X_\mathrm{i}. \tag{5}$$

The corresponding set of PDEs are valid from the dilute concentrations, for which they coincide with discrete settling models, to the concentrated suspensions in which the sediment is described as a permanently networked, compressible porous layer and can thus be used to model both primary and secondary settling tanks.

The flocculation state of the sludge will not only cause distributed settling behaviour but will also influence the transition between the different settling regimes (characterised by X_trans and X_crit). For example, aerobic granular sludge is known to have a low tendency to coagulate under reduced hydrodynamic shear (de Kreuk and van Loosdrecht, 2004). This feature causes granular sludge to undergo discrete settling at concentrations where conventional activated sludge experiences hindered or compression settling. The presented framework can be applied to granular sludge by simply setting a high transition concentration.

As a second example the impact of the flocculation state with respect to the onset of compression settling (characterised by a bend in the batch settling curve) is illustrated in

Figure 3 (left). When shear is applied prior to settling, the sludge water interface reaches the compression zone at a much lower sludge blanket height (and thus in a more concentrated state). A more concentrated sludge blanket at the onset of the compression zone indicates a higher critical concentration.

The proposed unified model structure allows to include this effect in a dynamic way by describing the transition concentrations (X_{trans} and X_{crit}) as weighted functions of the concentrations in the different classes.

Specification of flocculation processes

The equations presented above allow modeling the effect of changes in the flocculation state of the incoming feed flow (through $X_{\mathrm{f},i}$(t)). In order to incorporate the effect of changes in operational and load conditions on the particle distribution, these equations can be further extended with reaction terms *r* describing flocculation/break-up processes. As flocculation and break-up are shear dependent, the reaction rates will (mainly) depend on the incoming flow rate and the settler's configuration (e.g. baffles).

$$\frac{\partial X_i}{\partial t} = -\frac{\partial}{\partial z}\left(F_i(X, X_z, X_i, t)\right) + \frac{Q_{\mathrm{f}}(t) X_{\mathrm{f},i}(t)}{A}\delta(z) + r(Q_{\mathrm{f}}, X_i, X) \tag{6}$$

The reaction terms $r(Q_{\mathrm{f}}, X_i, X)$ can be based on flocculation jar experiments (Gong et al., 2011) or can be derived from Population Balance Models (PBMs) which allow detailed modelling of the dynamics of distributions (Nopens et al., 2015).

An alternative and simple approach would be to assume that flocculation/break-up is mostly occurring in the flocculation well. In this case the flocculation well can be described as a CSTR prior to the actual SST where flow dependent flocculation and break-up processes give rise to a certain particle class distribution that can subsequently be fed as input to the 1D SST model. This approach would remove the need to add reaction terms to each PDE. However, it is only valid for well-designed clarifiers where flocculation is indeed (approximately) limited to the flocculation well.

CONCLUSIONS

Experimental evidence of sludge settling at different concentrations and under different conditions showed that the flocculation state of the sludge (i.e. variations in size and density leading to a distributed settling velocity) is an important factor influencing the settling behaviour in all settling unit processes in WWTPs. Hence, current modelling practice where the settling behaviour only depends on a lumped variable such as concentration is insufficient to describe the true settling dynamics in WWTP processes.

Therefore, an extension of existing modelling frameworks is proposed including different particle classes to represent the flocculation state of the sludge. The results is a unified framework which allows to describe the true distributed settling behaviour over the entire concentration range from the dilute limit, for which they coincide with discrete settling (for example for PSTs, granular sludge and clarification in SSTs), to the concentrated limit in which the sediment is described as a permanently networked, compressible porous layer (for example at high concentrations in the sludge blanket of SSTs). Moreover, the proposed framework can be further augmented with reaction terms to describe the migration of particles between different classes in order to capture the effect of changes in operational and loading conditions on the flocculation state and the associated settling behaviour. Ultimately, this would allow introducing more rigour into the way settling tanks are modelled leading to much more detailed operation and control both in current WWTPs as well as future WRRFs.

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