A critical review of clarifier modelling: State-of-the-art and engineering practices

Benedek Gy. Plósz[1], Ingmar Nopens [2], Leiv Rieger[3], Alonso Griborio[4], Jeriffa De Clercq[5], Peter A. Vanrolleghem[6], Glen T. Daigger [7], Imre Takács[8], Jim Wicks[9] and George A. Ekama[9]

[1] Department of Environmental Engineering (DTU Environment), Technical University of Denmark, Miljøvej, Building 113, DK-2800, Kgs. Lyngby, Denmark (E-mail: beep@env.dtu.dk).
[2] BIOMATH, Department of Mathematical Modelling, Statistics and Bioinformatics, Coupure Links 653, 9000 Gent, Belgium (E-mail: ingmar.nopens@ugent.be).
[3] EnviroSim Associates Ltd., McMaster Innovation Park, 175 Longwood Rd S, Suite 114A, Hamilton, Ontario, L8P 0A1, Canada (E-mail: rieger@envirosim.com)
[4] Hazen and Sawyer, P.C., Hollywood, Florida, USA (E-mail: agriborio@hazenandsawyer.com)
[5] Faculty of Applied Engineering Sciences, University College Ghent, Schoonmeersstraat 52, 9000 Ghent, Belgium (E-mail: jeriffa.declercq@hogent.be).
[6] model*EAU*, Université Laval, 1065 avenue de la Médecine, Québec, Québec, G1V 0A6, Canada (E-mail : peter.vanrolleghem@gci.ulaval.ca)
[7] CH2M HILL Inc., 9193 South Jamaica Street, Englewood 80112, CO, USA (E-mail: glen.daigger@CH2M.com)
[8] Dynamita, 66 bis Ave du Parc d'Espagne Pessac 33600, France (E-mail: imre@dynamita.com)
[9] The Fluid Group, The Magdalen Centre, Robert Robinson Avenue, The Oxford Science Park, Oxford OX4 4GA, UK (E-mail: jim.wicks@thefluidgroup.com)
[10] Water Research Group, Dept of Civil Eng., University of Cape Town, Rondebosch, 7700, Cape, South Africa, (E-mail: george.ekama@uct.ac.za)

Abstract

This paper aims to provide a critical review of clarifier modelling approaches used in current wastewater engineering and tools not yet applied in practice. We address the development in the field with a particular emphasis on works published since the reference work by Ekama et al. (1997). We give insight into the current engineering practice, and identify potential pathways for future knowledge development and transfer into engineering practice. Furthermore, we believe there is a need for the development of a systematic clarifier modelling approach depending on the modelling objective. The latter includes (i) criteria for clarifier model selection, (ii) a set of protocols for clarifier model calibration and the related data collection requirement.

Keywords
Clarifier model; Computational fluid dynamic modelling; good modelling practice; one-dimensional modelling; process modelling; sedimentation tank; simulators; uncertainty.

INTRODUCTION

Promoting *good modelling practice* in wastewater engineering is paramount, thereby guiding engineers using models, and providing appropriate sets of *a priori* assumptions in model selection, model setup, calibration, and result interpretation. For this purpose, an IWA Scientific Technical Report has been elaborated by the IWA GMP Task Group (Rieger et al., 2012). However, its main focus is on the activated sludge portion of the plant and only a rather small section is dedicated to clarifier models, including typically used engineering practices. IWA's Activated sludge model family (ASM1/2/2d/3), has undergone significant development (Henze et al., 2000), and effectively found its way to practice in the past decades. Despite the progress made in the field of clarifier modelling since the publications by Krebs (1995) and the IWA STR (Ekama et al., 1997), it seems that many of these scientific findings have not entered into current engineering practice. Part of the reason for this shortcoming, we believe, is that an ASM-like, consensus-based clarifier modelling framework is still missing. The objective of this paper is (1) to identify how current clarifier modelling practice in *wastewater engineering* can benefit from recent advancements and (2) where future research should focus on to further streamline this knowledge transfer to practice. This paper will discuss current settler modelling practice, identify knowledge gaps, and come up with suggestions to further organize the knowledge transfer into engineering practice. The paper is meant to provide a position statement, serving as a starting point to develop a *systematic guideline for use of clarifier models* depending on the objectives.

BACKGROUND

Model portfolio and engineering practices

Clarifiers are the backbone of the activated sludge process and therefore need to get the same attention during model setup as the Activated Sludge Models (ASMs). Clarifier simulation models can be used at various levels of wastewater engineering, comprising design, construction, operation and diagnosis/trouble shooting. Depending on the objectives, a continuum of options in model complexity is available.

Zero-dimensional (0-D) models. Simple 0-D model representations are practically ideal splitters of flow and solids, and are the simplest models around only having one parameter, the fraction of solids recirculated into the activated sludge reactors. In quite some WWTP simulations such model suffices, e.g., the predesign of reactor sizes.

One-dimensional (1-D) models. For design and operation, flux-based one-dimensional (1-D) clarifier models can be used. Current WWTP models usually combine ASM models (Henze et al., 2000) with 1-D tools. These models describe the hydrodynamic behaviour in 1 dimension and its interaction with the flocs that are settling. These are important elements to estimate the clarification and thickening behaviour as well as solids inventory of clarifiers in plant-wide process predictions. First- and second-order 1-D models are available. The 10-layer (first-order) model proposed by Takács *et al.* (1991) and the more recent suggested models (e.g., Plósz et al., 2007, De Clercq et al., 2008), based on 1-D advection-dispersion partial differential equation (PDEs) are examples. One important difference between first- and second-order models is the way discretisation (layer number) is approached, and thus the way dispersion is approximated.

Two- or three-dimensional (2-D/3-D) models. At the highest tier we find the 2-3D models which have been developed in Computational Fluid Dynamics (CFD). CFD is traditionally used for designing and optimising new and existing secondary clarifiers (e.g., placing baffles in underperforming clarifiers), and to detect the causes of malfunction of these process separation units. CFD models can incorporate hydrodynamics, flocculation, turbulence, sludge rheology, settling characteristics and temperature effects. These tools describe systems in more than one dimension, and are based on higher dimensional PDEs that are numerically solved.

Shortcomings in engineering practice

In current engineering practice, simple point-settlers, ideal-settler-with-volume and variations thereof are widely used. These models only model the separation of particles but not the settling behaviour. Therefore, some 0-D models are used with limitations imposed by state-point analysis on the solids transport. In a number of modelling projects the use of simple point or ideal clarifier models (phase separators) will be sufficient. In these models effluent solids or removal efficiency is a direct model input. Layered flux models (1-D) are usually required only under dynamic conditions, to model settling and to better represent effluent and underflow concentration changes

and sludge mass shifts when these are relevant to model the behaviour of the plant. However, effluent suspended solids predictions from 1-D models should not be taken for granted as these models were not designed for this purpose. The most well-known and used is the 10-layer model by Takács et al. (1991). The more recently developed second-order 1-D models (e.g., Plósz et al., 2007, De Clercq et al., 2008) are not yet available for engineering use in commercial WWTP simulators. An advantage of the latter models is that they allow a more effective calibration using measured settling parameters, as compared to first-order models (Plósz et al., 2011). The use of 2-D and 3-D CFD clarifier models still requires long computational times and high computational capacity. CFD is used for clarifier construction, optimisation and trouble shooting exercises in engineering practice. Also 2-D and 3-D models have been linked with whole plant simulators for the dynamic simulation of wet weather events and wet weather strategies (Griborio *et al*., 2010). One area that can potentially stimulate CFD use in wastewater engineering is in improving simpler clarifier models – in terms of model structure and calibration – used in WWTP simulations (De Clercq, 2003). The feasibility of this approach has been demonstrated (Plósz et al., 2007).
Unfortunately, in most scientific and engineering projects, even the well-described protocols (e.g., batch settling tests) are not standard applied. Usually sludge settleability is characterized in terms of sludge volume index (SVI) – which gives very limited information on sludge settleability (e.g., Dick & Vesilind, 1969). SVI data then is converted with empirical equations to the V_0 and n parameters in the flux zone settling velocity equation $V_S=V_0\exp(-nX_t)$ (Ekama *et al*., 1997). In that way, at least, the steady state 1-D flux theory or dynamic 1-D layered models can be used. With regard to typical (mostly non-academic) projects, the calibration of 1-D models almost always rely on settling velocity parameters inferred using some form of SVI-based correlation equation. This is a major reason why 0-D models are still used in most applications.

DILEMMAS IN SCIENCE

Uncertainties

The most critical issue in modelling settling is the inherent unpredictability of the sludge settling characteristics of the biomass and missing information about other particulate fractions. Furthermore, even in the most advanced models, empirical equations have to be used to describe settleability. The variability of settling behaviour significantly affects the actual SRT, and thus is a potential source of error in WWTP models (e.g., Plósz et al., 2011). These uncertainties have, by far, the biggest impact on simulation results. In practice, engineers may also try to compensate for this uncertainty by using high percentile SVIs in their designs but this practice could lead to overdesign of the clarifier infrastructure.

Data availability and measurement techniques

In general, the level of mathematics of settling tank models in one, two or even three dimensions has gone far beyond the level of measurement quality with which these models are fed. This means that the lack of experimental methods (e.g. data to calibrate settling velocity functions including hindered and compression settling) and high-resolution data (e.g. concentration profile) is what is most limiting the use of advanced settling models. Even CFD model implementations include empirical equations, describing the sludge clarification, thickening and compaction behaviour. Besides the additional data requirements, the development of specific and easy-to-use experimental setups is needed to properly test these model advancements. Currently, no practical methods are available for measuring sludge settling behaviour outside the zone settling range (Ekama and

Marais, 2004). Still, recent studies have proposed relatively complex methods to measure the concentration and pressure profiles during batch settling (De Clercq et al., 2005), providing the required information to model the zone and compression settling behaviour. In the foreseeable future, however, models will continue to rely on empirical functions for the assessment of the hindered settling velocity and the excess pore pressure. Such innovative techniques, nevertheless, need to be further explored in how they can address some of the issues with regard to shortage of data. Communicating the current lack of data and measurement techniques to the research community thus is a crucial step.

PERSPECTIVES

To close the gap between research and practice and outline potential developments, the full paper will address:

- A critical review of current engineering practice including
    - Typical demands on clarifier models
    - Clarifier models applied
- An overview on published clarifier models from simple zero-dimensional to fully three-dimensional models
- A list of topics to be included in a guideline for good clarifier modelling practice.

REFERENCES

De Clercq, B. (2003). *Computational fluid dynamics of settling tanks: development of experiments and rheological, settling, and scraper submodels*. Ph.D. Thesis, BIOMATH, Ghent University, Belgium.

De Clercq, J., Jacobs, F., Kinnear, D., Nopens, I., Dierckx, R., Defrancq, J. and Vanrolleghem, P.A. (2005). Detailed spatio-temporal solids concentration profiling during batch settling of activated sludge using a radiotracer. *Water Res*. **39**, 2125-2135.

De Clercq, J., Nopens, I., Defrancq, J. & Vanrolleghem, P. A. (2008). Extending and calibrating a mechanistic hindered and compression settling model for activated sludge using in-depth batch experiments. *Water Res*. 42(3), 781–791.

Dick, R. & Vesilind, P. (1969). The sludge volume index - what is it? J. WPCF 41(7), 1285–1291.

Ekama, G.A., Barnard, J.L., Günthert, F.W., Krebs, P., McConcordale, J.A., Parker, D.S., Wahlberg, E.J. (1997). *Secondary Settling Tank: Theory, Modelling, Design and Operation*. Scientific and Technical Report No. 6. IAWQ, London, UK. 105–116.

Ekama, G.A. and Marias, P. (2004) Assessing the applicability of the 1D flux theory to full scale secondary settling tank design with a 2D hydrodynamic model. *Water Res.*, **38**, 495-506.

Griborio, A., Rohrbacher, J., McGehee, M., Pitt, P., Latimer, R., Clark, J., and Gellner, J. (2010). Combining Stress Testing and Dynamic Linking of Whole Plant Simulators and CFD for the Evaluation of WWTP Wet Weather Capacity. *Proceedings Water Environment Federation 83rd Annual Conference and Exposition*, New Orleans, October 2-6, 2010, pp. 112 – 136.

Henze, M., Gujer, W., Mino, T. and van Loosdrecht, M.C.M. (2000). *Activated Sludge Models ASM1, ASM2, ASM2D and ASM3*. IWA Scientific and Technical Report No. 9. IWA Publishing, London, UK.

Krebs, P. (1995). Success and shortcomings of clarifier modelling. *Wat. Sci. Technol*., **31**(2), 181–191.

Plósz, B. G., Weiss, M., Printemps, C., Essemiani, K. and Meinhold, J. (2007). One-dimensional modelling of the secondary clarifier - factors affecting simulation in the clarification zone and the assessment of the thickening flow dependence. *Water Res*. **41**, 3359–3371.

Plósz, B.G., De Clercq, J., Nopens, I., Benedetti, L., Vanrolleghem, P.A. (2011) Shall we upgrade one-dimensional secondary settler models used in WWTP simulators? – An assessment of model structure uncertainty and its propagation. *Water Sci. Technol.*, **63**(8), 1726–1738.

Rieger L., Gillot, S. Langergraber, G., Ohtsuki, T., Shaw, A., Takács, I. and Winkler, S. (2012). *Guidelines for Using Activated Sludge Models*. IWA Scientific and Technical Report, IWA Publishing, London, UK. pp. 150.