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

Article



**10 authors**, including:


Ingmar Nopens
Ghent University



Leiv Rieger
inCTRL Solutions Inc.



Peter A Vanrolleghem
Laval University



Glen T Daigger
University of Michigan

# 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 outline paper aims to provide a critical review of secondary settling tank (SST) modelling approaches used in current wastewater engineering and develop tools not yet applied in practice. We address the development of different tier models and experimental techniques 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, identify how recent developments can be transferred to engineering practice and pinpoint limitations and potential pathways for further development of models and measurement techniques. As a follow-up to the present work, we believe there is a need for the development of a protocol for systematic clarifier modelling depending on the modelling objective and in line with good modelling practice.

**Keywords**
Clarifier model; Computational fluid dynamic modelling; one-dimensional modelling; zero-dimensional modelling; process modelling; sedimentation tank; simulators; parameter variability.

## 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/validation, result interpretation and documentation. 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 secondary settling tank (SST) models, limited to 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 SST modelling since the publications by Krebs (1995) and the IWA Scientific and Technical Report (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, the authors believe, is that an ASM-like, consensus-based set of SST models is still missing. Another reason might be the lack of internationally accepted SST modelling guidelines, i.e. procedures to suggest SST models for specific tasks, which are as simple as possible, but fulfil the needs and list the data required to feed and calibrate/validate the models. Compiling such guidelines requires insights both from practice and academia and consensus building. This paper is intended to serve as a basis for the development of an SST modelling guideline according to current knowledge and practice.

The outline paper is organised as follows: first, the available model portfolio is briefly introduced; next, engineering practice is reviewed, highlighting shortcomings; finally, scientific knowledge gaps are identified. Conclusions are drawn and potential future developments listed. The outline 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.

## MODEL PORTFOLIO

Depending on the objectives, a continuum of options in SST model complexity is available (Table 1). SST models can characterize performance, given specification of the characteristics of the feed sludge (e.g., hindered settling velocity). These characteristics, however, show high variability in WWTPs, and are not predicted by any available models used in practice!

*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. Additionally, 0-D models can also be used with limitations imposed by state-point analysis on the solids transport (Daigger and Roper, 1985; Lynggaard-Jensen *et al*., 2009). In these models, effluent solids or removal efficiency can be either a direct model input or a function of the flow rate through the SST.

*One-dimensional (1-D) models.* For design and operation, flux-based one-dimensional (1-D) clarifier models can be used. 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. In WWTP simulators, 1-D SST model implementations additionally require numerical integration methods – an area investigated, most notably, by Jeppsson and Diehl (1996) and Bürger et al. (2011).

*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). 2-D and 3-D models predict tank hydrodynamics, internal processes and internal configurations, allowing visualization of the internal conditions in the clarifier, like position of the sludge blanket and flow pattern (examples of 2-D and

3-D outputs presented in Fig. 2). Typically, multidimensional CFD models are based on the following principles: (1) continuity of conservation of fluid volume; (2) conservation of momentum; (3) conservation of mass of solids, including the modeling of the settling behavior of the particles; and (4) turbulence modeling equations. Additionally, some models, e.g., De Clercq (2003). Griborio (2004), McCorquodale *et al*. (2005), Weiss *et al*. (2007) have incorporated the rheology of the activated sludge, and some models, e.g., Parker *et al*. (2008), have attempted to simulate and quantify the flocculation-deflocculation processes in SSTs.

## ENGINEERING PRACTICE INCLUDING MODEL SHORTCOMINGS

### SST models

SST models can be used at various levels of wastewater engineering, comprising design, construction, operation, control and diagnosis/trouble-shooting (Table 2). One of the principal constraints for the general use of the more sophisticated SST models is that sludge characteristics are determined largely by the characteristics of the upstream activated sludge system. Since sludge characteristics significantly determine SST performance, and it is not possible to clearly characterize or predict these characteristics, the utility of sophisticated SST models thus is somewhat compromised relative to routine practice.

*0-D models*. 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.

*1-D models.* Current WWTP models often combine ASM models (Henze et al., 2000) with 1-D tools. 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 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.

*2-D/3-D models.* 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. 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).

**Data availability in typical projects**

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.

## SCIENTIFIC KNOWLEDGE GAPS

For greater application of 1-D and CFD models to SSTs, it is important to further develop and implement models that describe the clarification, settling and compression behaviour of the sludge across the *entire concentration range with measurable parameters* than to develop further advances in the mathematics of these models. It is in the specification of sludge settling characteristics that even the multi-D CFD modelling of SSTs is the most deficient of and lags far behind the mathematical developments for solving the complex CFD equations. Currently no widely accepted and easy to implement methods are available for measuring sludge settling behaviour outside the zone settling range. Therefore, it has been accepted (cautiously) in CFD modelling of SSTs to date that the zone settling behaviour equation (Eq. 1) modified to include $f_{ns}$ and the $r_P$ exponential term for dilute concentrations, applies to the full range of concentrations found in SSTs. Most CFD models for SSTs use Eq. 2 at this current stage of development. The $r_P$ value has a direct effect on $X_{TSS,eff}$ and because it cannot be measured directly on the activated sludge, it is actually a model calibration parameter using measured $X_{TSS,eff}$ in SST performance tests. However, this includes the effect of the internal features of the SST that are not completely covered by the CFD-model, and, therefore, $r_P$ cannot actually be considered a sludge characteristic as it compensates for model deficiencies. It thus applies only to the specific SST simulated.

**Measurement techniques and data availability**

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.

## CONCLUSIONS AND OUTLOOK

To close the gap between research and practice and outline the potential directions for development, this critical review gives an overview on published clarifier models, current engineering practice and on typical demands on clarifier models. We draw the conclusions that all tiers of SST models can significantly benefit from increasing data availability and improved measurement techniques to make them more accurate.

This deserves attention in future and will likely be the key to improved understanding, further improved SST models and their use in engineering practice. Innovative techniques thus need to be further explored at an academic level in how they can address some of the issues with regard to the shortage of data.

Communicating these perspectives to the research community is a crucial first step forward. In the future, a protocol is needed on the choice of an appropriate SST model for the purpose and accompanying requirement for data collection and calibration/validation.

## ACKNOWLEDGEMENTS

Peter Vanrolleghem holds the Canada Research Chair on Water Quality Modelling. The authors acknowledge the financial support obtained through the TECC project co-funded by the Fund for Scientific Research-Flanders (Belgium) and the Québec Ministry of Economic Development, Innovation and Exports (MDEIE).

## REFERENCES

Bürger, R., Diehl, S., Faras, S. and Nopens, I. (2011). Simulation of the secondary settling process with reliable numerical methods. In: *Proceedings of the 8th International Symposium on Systems Analysis and Integrated Assessment (WATERMATEX2011)*. San Sebastian, Spain, June 20-22, 2011.

Daigger, G.T., Roper. R.E. (1985). The relationship between SVI and activated sludge settling characteristics. *J. WPCF*. Vol 57, No.8, pp 859-886.

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.

Jeppsson, U. and Diehl, S. (1996) An evaluation of a dynamic model of the secondary clarifier. *Wat. Sci. Tech,* **34**(5-6), 19-26.

Lynggaard-Jensen, A., Andreasen, P., Husum, F., Nygaard, M., Kaltoft, J., Landgren, L., Møller, F. and Brodersen, E. (2009). Increased performance of secondary clarifiers using dynamic distribution of minimum return sludge rates. In: *Proceedings of the 10th IWA Conference on Instrumentation, Control and Automation (ICA)*, Cairns, Australia, June 14-17, 2009.

Griborio, A. (2004). *Secondary Clarifier Modeling:A Multi-Process Approach*. Ph.D. Thesis, University of New Orleans, New Orleans, Louisiana, USA.

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.

McCorquodale, J.A., Griborio, A., and Georgiou, I. (2005). A public domain settling tank model. In: *Proceedings Water Environment Federation 78th Annual Conference and Exposition*, Washington, D.C., USA, October 29–November 2, 2005, pp. 2546-2561.

Parker, D.S., Merlo, R., Jimenez, J. and Wahlberg, E. (2008). Analyzing wet weather flow management using state of the art tools. *Wat. Sci. Tech.*, **57**, 1247-1251.

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.

Weiss, M., Plósz, B.G., Essemiani, K. and Meinhold, J. (2007). Suction-lift sludge removal and non-Newtonian flow behavior in circular, secondary clarifiers: Numerical modelling and measurements. *Chem. Eng. J.*, **132**, 241-255.